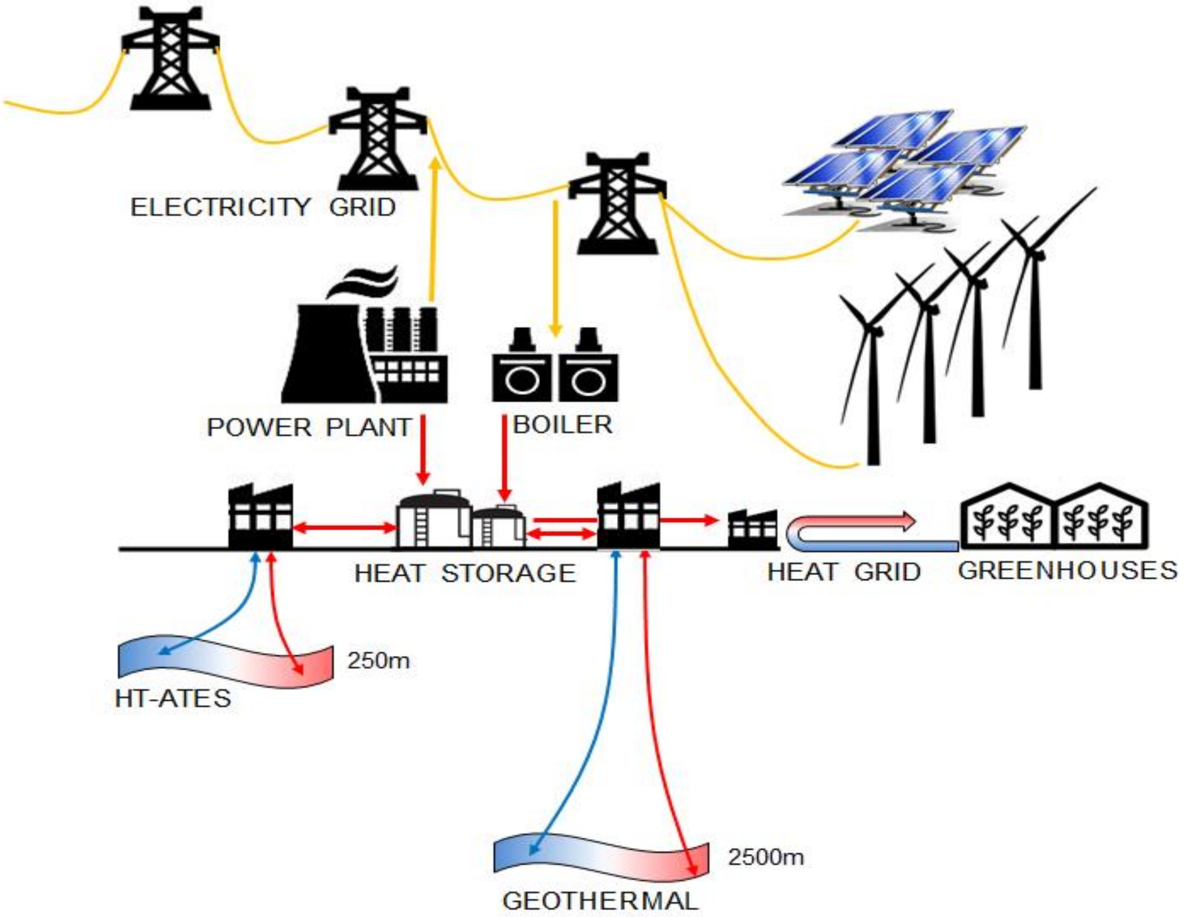
Prospects for HT-ATES in the Dutch energy system

Potentials, applications and business cases of High-Temperature Aquifer Thermal Energy Storage



Master's thesis
Maxim Wesselink
July 2016

Utrecht University

TNO innovation for life

Colophon

Credits:	30 ECTS
Starting date:	February 22, 2016
Author:	Maxim Wesselink (3631966) m.a.wesselink@students.uu.nl Schoolstraat 34 3581 PW Utrecht
University:	Utrecht University (UU) Faculty of Geosciences Copernicus Institute of Sustainable Development
Master program:	Sustainable Development – *track* Energy & Materials
Supervisor UU:	Wen Liu, PhD, Researcher Copernicus Institute of Sustainable Development
Second reader UU:	dr. ir. Wina Crijns-Graus, Assistant Professor Copernicus Institute of Sustainable Development
Internship organisation:	TNO Utrecht Princetonlaan 6 3584 CB Utrecht
Supervisor TNO:	dr. Joris Koornneef, Strategy Consultant Department Sustainable Geo Energy
Date:	July 21, 2016
Cover page illustration:	HT-ATES in a smart integrated energy system (Koornneef, 2016)

Abstract

The main heat sources of numerous district heating networks are unable to produce all required heat, due to fluctuating demand throughout seasons. Consequently, inefficient natural gas-fired boilers are often used to compensate for peak heat demand, while there is a surplus capacity or even surplus production of heat during summer. Seasonal thermal energy storage can store heat from the main heat sources during summer and produce it at peak demand in winter, thereby increasing the energy efficiency of district heating networks.

A promising technology to facilitate seasonal thermal energy storage is *high-temperature aquifer thermal energy storage*(HT-ATES). After technical issues led to the shutdown of most HT-ATES projects in the 1980s, there currently is renewed interest for HT-ATES as proven solutions have since become available to the technical issues.

To facilitate its implementation, this thesis aims to develop a methodology for HT-ATES potentials assessment and to identify the conditions, drivers and barriers for HT-ATES implementation. Through literature research and brainstorm sessions with experts, the parameters relevant for HT-ATES potentials were mapped and classified. Parameter values, formulas and boundaries were proposed and integrated in a methodology to design frameworks for the assessment of the theoretical, technical and market potential of HT-ATES. The market potential assessment framework was applied to two quantitative case studies to illustrate the application of the frameworks and develop quantitative insights in conditions, drivers and barriers for implementation. A market potential of 14 kt of avoided CO_2-emissions was found in Groningen; no market potential was found in the Rotterdam case study.

The potential assessment frameworks provide a step-by-step methodology that can be used in future research to fully quantify HT-ATES potentials. The case studies revealed promising prospects for HT-ATES in combination with geothermal heat and exposed shortcomings and weaknesses in the policy package in the Netherlands.

Preface

This thesis is the final part of my master's programme in Sustainable Development (*track* Energy & Materials) at Utrecht University. I conducted my research from February to July 2016, during an internship at Dutch research institute TNO under the supervision of Dr. J.M. Koornneef. Supervision on behalf of Utrecht University was provided by Dr. W. Liu. The thesis presents frameworks for theoretical, technical and market potential assessment of *high-temperature aquifer thermal energy storage* and provides insights in the main conditions, barriers and drivers for implementation of this technology. With this work I aim to contribute to the methodological development of the integrated assessment of HT-ATES. Moreover, I hope to stimulate its implementation by providing policy makers, scientists and potential investors with the first publicly available insights in relevant market factors.

This thesis is the product of the academic and personal skills I acquired throughout my student years. The internship and this resulting thesis have been a great learning experience that will prove helpful in my further career. I am proud to say that this thesis is entirely my authentic work and the result of five months of hard work and dedication to contributing to a more sustainable energy system.

I would not have been able to write this thesis without the support and kind cooperation of colleagues, external experts and stakeholders. Several persons I want to thank in particular for their contributions. Firstly, I thank Joris Koornneef for our discussions that stimulated my creativity and forced me to critically look at my own work. I also thank Wen Liu for her critical feedback on my written work, which helped me to clearly communicate my insights. Furthermore, I want to thank Sander-Luc Visser of Warmestad Groningen and Hans Wassenaar of AVR for their cooperation in my case studies. I also thank TNO colleague Maarten Pluymaekers and Berenschot consultant Rutger Bianchi for our brainstorm sessions.

Finally, I thank my friends and family for their support and understanding during the challenging period behind me.

Utrecht, July 2016
Maxim Wesselink

Executive summary

Background and research aim
In many district heating networks, the main (baseload) heat sources are unable to fully adapt their heat supply to the heat demand that fluctuates considerably during seasons. Consequently, these heat sources cannot be utilized to their full potential and additional natural gas-fired peak boilers are required. If summer surplus heat is stored and utilized in winter, the main heat sources can operate more efficiently and the need for peak boilers is reduced. This can potentially increase the energy efficiency of district heating networks and reduce greenhouse gas emissions, natural gas use and costs. Against a backdrop of dangerous climate change, dwindling fossil fuel reserves and rising natural gas prices, it is of great importance to study the potential of seasonal thermal energy storage in district heating networks.

A promising technology for thermal energy storage in this context is *high temperature aquifer thermal energy storage*(HT-ATES). Similar to proven *aquifer thermal energy storage*(ATES) technology, HT-ATES utilizes the natural insulating properties of the subsurface to store large amounts of thermal energy in aquifers at low costs and negligible use of surface area. Contrary to ATES, HT-ATES stores heat from *external* sources at temperatures of 50-140^{o}C instead of <30^{o}C. This facilitates use on a larger scale and for more diverse applications.

However, no studies have been conducted yet to identify the applications of HT-ATES in different settings and to quantify its potential. Furthermore, the general conditions, drivers and barriers for HT-ATES application are not characterised in scientific literature. The research goal of this thesis is therefore twofold:

1. To develop frameworks for the quantitative assessment of the theoretical, technical and market potential of HT-ATES;
2. To identify the conditions, drivers and barriers for HT-ATES implementation

Insight in potentials provides policy makers and scientists with insight in what role HT-ATES can potentially play in a more sustainable energy system. Characterization and analysis of drivers and barriers for HT-ATES implementation serves as the basis to determine the effectiveness of current policies and regulations and identify options for improvement.

Methodology
For the development of the potential assessment frameworks, literature and document research was conducted and brainstorm sessions with experts were held. Based on this, relevant parameters were mapped and classified in the appropriate potential category. Parameter values, formulas and boundaries were proposed and, together with relevant data sources, integrated in a step-by-step assessment methodology for the theoretical, technical and market potential. The technical and market potential frameworks target the year 2020 to provide insight in short- to medium-term potentials. To assess the effectiveness of the current policy package and identify the best options for improvement, a *business-as-usual* and an *alternative* policy package were drafted for the market potential framework.

Two case studies were conducted using the developed market potential assessment framework. The subject of the first case study is a to-be built district heating network using geothermal heat in Groningen. In the second (smaller) case study, a large waste incineration plant in the Rotterdam port that will provide heat to a provincial district heating network is the subject. Required data was acquired through interviews with employees of selected proprietors, as well as from public data. The impact of the two policy packages was assessed in each case study. The used criterion for a case study to be included in the market potential is that the HT-ATES LCOE must be lower than the reference boiler LCOE or the weighted average selling price of heat, depending on the proprietor setting.

Results, implications and recommendations

The step-by-step frameworks for the assessment of the theoretical, technical and market potential can be used in future research to fully quantify the potentials, either in the Netherlands or another region of interest. The HT-ATES 2020 market potential is an indication of how much HT-ATES can contribute to CO_2-emission reduction on the short term, given market factors such as policies and regulations, economic factors and societal factors. The main requirement to be part of the market potential is that, given these market factors, there has to be a viable business case for HT-ATES from the perspective of a private investor. Consequently, the market potential is a realistic indication of how much HT-ATES implementation is realistic in 2020.

The 2020 HT-ATES technical potential is a measure of how much HT-ATES implementation is possible in 2020 from a technical perspective. The technical potential is larger than the market potential, but with the right stimulatory measures this difference can be reduced. The theoretical potential is an indication of how much HT-ATES implementation is ultimately possible, without technical restrictions. It is an indication of its potential in the far future and reveals the effect of technical restrictions. It is therefore not a realistic representation of how much HT-ATES implementation can be achieved on the short term.

In the Groningen case study a viable business case for HT-ATES was defined, with a potential to abate 14 kt of CO_2-emissions within its 15-year economic lifetime. Moreover, the case study revealed the potentially good prospects for HT-ATES in combination with geothermal heat in the Netherlands, which is largely the result of SDE^+ subsidy. The development of natural gas prices was identified as one of the main factors that influence the HT-ATES business case for proprietors of thermal grids and its peak boilers in general. No viable business case was defined in Rotterdam based on the assumptions that were made, but a large potential for HT-ATES under slightly different conditions was identified. The business case of HT-ATES in Rotterdam proved to be highly dependent on the ratio between heat surplus in summer and heat shortage in winter. This balance was also identified as a highly influential factor on the HT-ATES business case in Groningen.

The development of the market potential assessment framework as well as its application on two case studies also revealed several **shortcomings and weaknesses in the existing policy package** of the Netherlands, for which the following solutions are proposed:

- The natural gas energy tax rate in the first tax bracket is one fourth of the rate on electricity, which has an inhibiting effect on HT-ATES business cases as well as solutions for more sustainable heating. Levelling the natural gas energy tax rate in the first bracket to half the rate on electricity is recommended.
- A potential vulnerability to unethical use of the SDE^+ subsidy scheme was identified. Extra SDE^+ for geothermal heat can be requested by injecting geothermal heat in a HT-ATES. However, only the heat produced by HT-ATES and consequently utilized by end users is ethically eligible for SDE^+.
- The heat law(*Warmtewet*) currently does not enable heat suppliers to pass on EU ETS CO_2 taxes that can be allocated to final heat consumers. Enabling heat suppliers that fall under the EU ETS to pass on CO_2 taxes facilitates investments in efficiency improvement with HT-ATES.

In addition to improvements to existing policies and regulations, the following **additions to the existing policy package** are proposed:

- To stimulate district heating with more sustainable and/or efficient heat sources, a heat ladder that ranks different types of heat suppliers can be introduced. Further research is required to identify appropriate instruments to enforce it.
- Heat sources are currently not directly discouraged to discharge potentially useful heat into the atmosphere or surface water. A tax on every GJ of potentially useful heat that is dumped is

proposed to encourage investments in technologies such as HT-ATES, which make useful employment of this heat possible.

- Information about HT-ATES is still scarcely available. To increase the awareness of HT-ATES and to provide potential investors with the knowledge to analyse its business case, an information program is proposed. Some of the information required for such a program can be found in this thesis.

Further research into the proposed changes and additions to the policy package is required to assess potential side-effects and identify the best strategies for execution.

Table of Contents

1 Abbreviations and symbols

ALT = Alternative policy scenario
ATES = Aquifer thermal energy storage
AVR = Afvalverwerking Rijnmond
BAU = Business-as-usual policy scenario
BTES = Borehole thermal energy storage
COP = Coefficient of performance
CHP = Combined heat and power
DH = District heating
EIA = Energy investment rebate
EU ETS = European Union emissions trading system
HIP = Heat in place
HT-ATES = High-temperature aquifer thermal energy storage
LCOE = Levelized cost of energy
P2H = Power to heat
RE = Renewable energy
SDE = Stimulation of sustainable energy production
SDGH = Shallow direct geothermal heat
TNO = Netherlands organization for applied scientific research
VAT = Value-added tax

2 Introduction

2.1 Societal background

The current Dutch energy system is highly dependent on fossil fuels, notably coal, oil and natural gas. A total of 187 Mt CO_2-equivalents were emitted in the Netherlands in 2014 (CBS, 2015) and as the main contributors to these emissions, the combustion of fossil fuels is largely responsible for anthropogenic global warming (IPCC, 2014). Moreover, natural gas reserves are finite and unconventional sources such as shale gas bring environmental concerns. Furthermore, reliance on fossil fuels forms a potential threat to energy security. This particularly holds for natural gas, which - with a market share of 93% in 2013 - is the dominant fuel for space heating in the Netherlands (Schoots & Hammingh, 2015). Diplomatic relations with main supplier Russia are currently under pressure(Botje & Broer, 2014), while domestic production is at a record low and is unlikely to increase again in the future (Rijksoverheid, 2016; Schoots & Hammingh, 2015). There is thus an urgent need for alternatives to natural gas to provide clean, safe and reliable space heating for generations to come.

This fact was also recognized by minister Henk Kamp of economic affairs, in a visionary letter to the House of Representatives about his ambitions for sustainable heat (Kamp, 2015). District heating is mentioned as one of the key options to improve energy efficiency and reduce natural gas use in urban environments. Contrary to re-investing in the existing gas infrastructure, constructing heat distribution infrastructure facilitates flexibility. Heat sources can be diversified and changed to more sustainable alternatives both now and in the future, at reasonable costs (Van den Wijngaart, Folkert, & Elzenga, 2015). But to ensure high efficiency, flexibility and affordability, storage of thermal energy is required in district heating systems (Christidis, Koch, Pottel, & Tsatsaronis, 2012; Fragaki, Andersen, & Toke, 2008).

Heat demand in district heating networks is characterised by strong peaks and lows within days and weeks, which can be levelled with relatively small-scale and affordable storage solutions such as water tanks. However, these are not a solution for the strong seasonal difference in heat demand. In many district heating networks, the main heat suppliers are unable to deliver all the heat that is required on cold winter days. The extra heat required to keep up with demand is produced by central natural gas boilers with relatively high operational costs and low efficiencies (Gustavsson, Dodoo, Truong, & Danielski, 2011). During the summer season, on the other hand, baseload heat sources sometimes produce more heat than required and have to release it into the atmosphere or water. Consequently, the energy efficiency of district heating networks can be improved if surplus summer heat can be stored and utilized in winter (Figure 1).

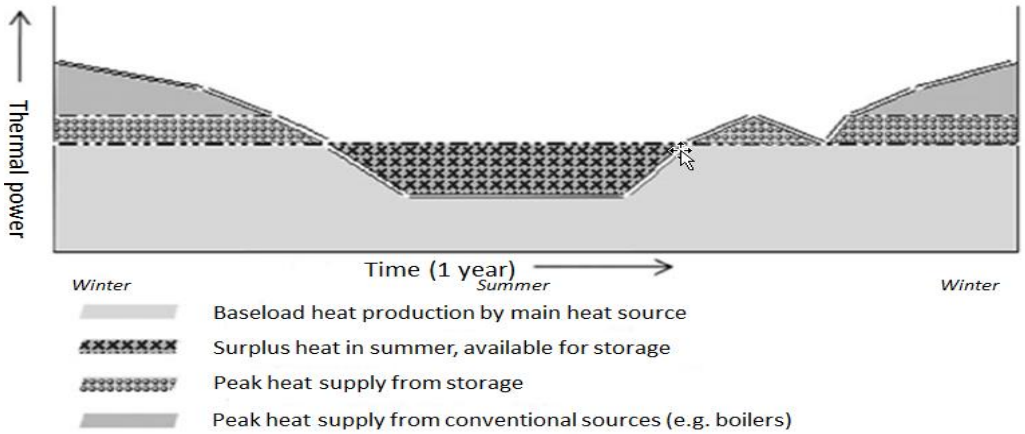


Figure 1 *Graph illustrating the mismatch between supply and demand of heat in a district heating network – in this example horticulture using geothermal heat - and the potential role of seasonal thermal energy storage in decreasing that mismatch. Adapted from: Drijver et al. (2012).*

An excellent place to store large amounts of thermal energy for seasonal timespans is the subsurface. Besides its good isolating properties, the subsurface provides a huge potential storage volume while keeping interference with other surface activities at a minimum. This makes it particularly suitable for urban environments (Réveillère, Hamm, Lesueur, Cordier, & Goblet, 2013). Moreover, the storage medium is already there, which means fewer construction materials are required than for many alternative heat storage alternatives, keeping costs and embedded energy low. For these reasons, underground seasonal thermal energy storage has already gained popularity on smaller scales. Open *aquifer thermal energy storage*(ATES) systems and closed *borehole thermal energy storage*(BTES) systems are becoming more common for heating and cooling offices and other non-residential buildings (ATES) and dwellings (BTES) (Taskforce WKO, 2009). A total of 2740 ATES installations in the Netherlands were registered in 2013 (CBS, 2014), and a special advisory taskforce for the development of ATES installed in 2008(Taskforce WKO, 2009) strived for a growth to 18.000 installations in 2020. BTES installations do not require registration in the Netherlands, but amounted to an estimated and rapidly rising figure of 25 000 systems in 2009. The suitable subsurface conditions and stimulatory measures in the past make the Netherlands a leading country in the application of ATES, while BTES is significantly less widespread compared to countries like Sweden and Austria (Taskforce WKO, 2009).

ATES installations generally have a capacity of 0,2-10 MW (Van der Krogt, 2011) and storage temperatures of up to 30^{o}C (Drijver, Aarssen, & Zwart, 2012). BTES installations are smaller with a capacity of 4-10 kW (Van der Krogt, 2011). As a result, applications and savings potential are limited despite the popularity of ATES in the Netherlands. The energy savings potential in district heating systems is potentially large, but storage solutions of a larger scale are required for storing their summer heat surplus. Currently, biomass- or natural gas-fired CHP plants and waste incinerators are popular heat sources in the Netherlands, but recently geothermal and solar heat are getting increasing attention as a means to decarbonise district heating networks. When solar thermal energy is employed as heat source, the summer heat surpluses will further increase.

One of the promising technologies for the required large-scale seasonal thermal energy storage is *high-temperature aquifer thermal energy storage*(HT-ATES; see Figure 2). HT-ATES systems are similar to ATES systems in the way they use the water in porous aquifers as a storage medium, but have higher storage temperatures of at least 60^{o}C. Storing thermal energy at higher temperatures has a number of advantages. First, it can often be used directly for heating purposes, removing the high operational costs of heat pumps or boilers and expensive modifications to building heating systems that are required for low-temperature heating with ATES installations. Moreover, the exergy of the supplied heat is higher in HT-ATES installations, which makes it suitable for more applications. The higher energy content per m^3 of water also means that the energy storage capacity per unit of aquifer storage volume is greater. Consequently, less water has to be pumped up to provide an equal amount of heat to the end user and a higher thermal power can be reached. Finally, the energy savings of the entire installation can be higher than in ATES installations as no electricity is consumed by heat pumps, which consume more electricity than all other components in regular ATES systems together (Drijver et al., 2012; Drijver, 2012).

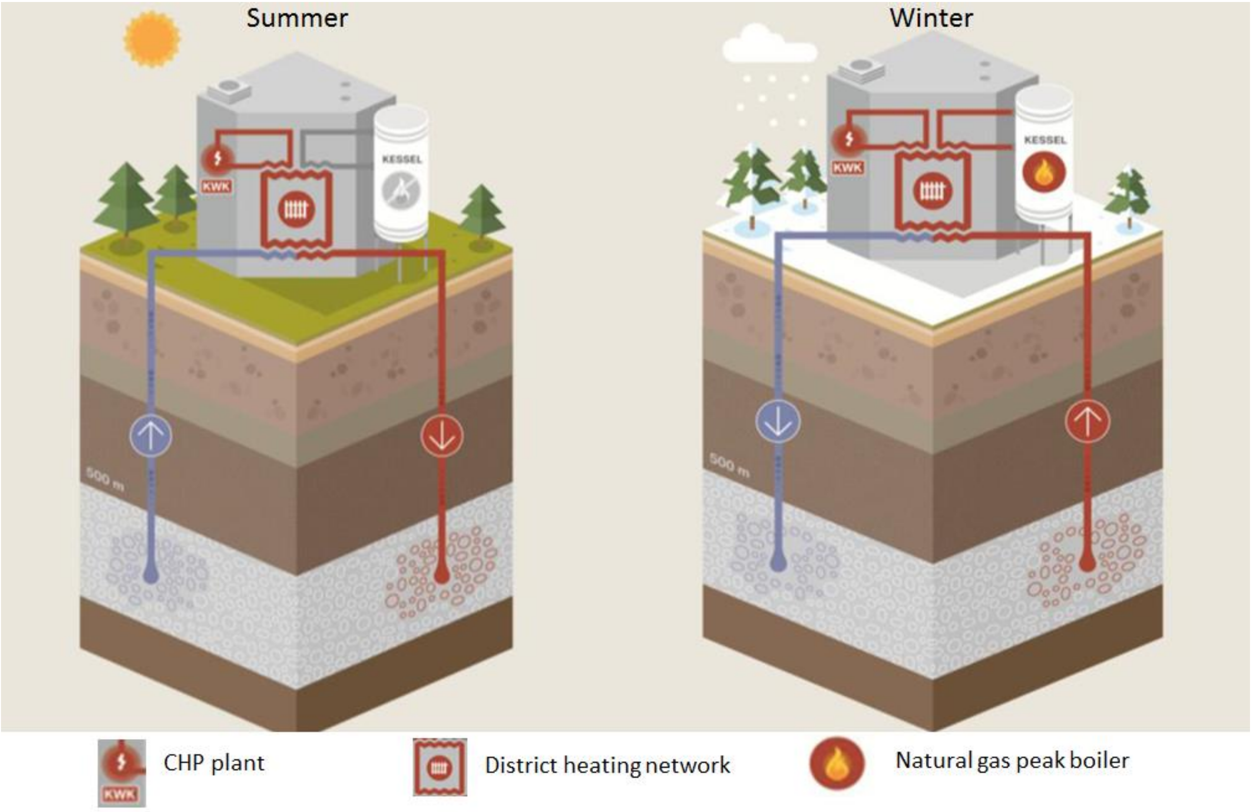


Figure 2 *Schematic overview of HT-ATES in a district heating network with a CHP plant as its main heat supplier, and additional peak heat supply from a natural gas boiler. In summer(left), formation water from the cold well is pumped up to cool the CHP plant; the hot water subsequently pumped down into the hot well. In winter, the hot water is pumped up to provide additional heat when the CHP plant's waste heat alone is insufficient to meet the heat demand from the district heating network. If heat demand exceeds the combined power of the HT-ATES and CHP plant, a natural gas peak boiler produces additional heat. From: TUM (2014)*

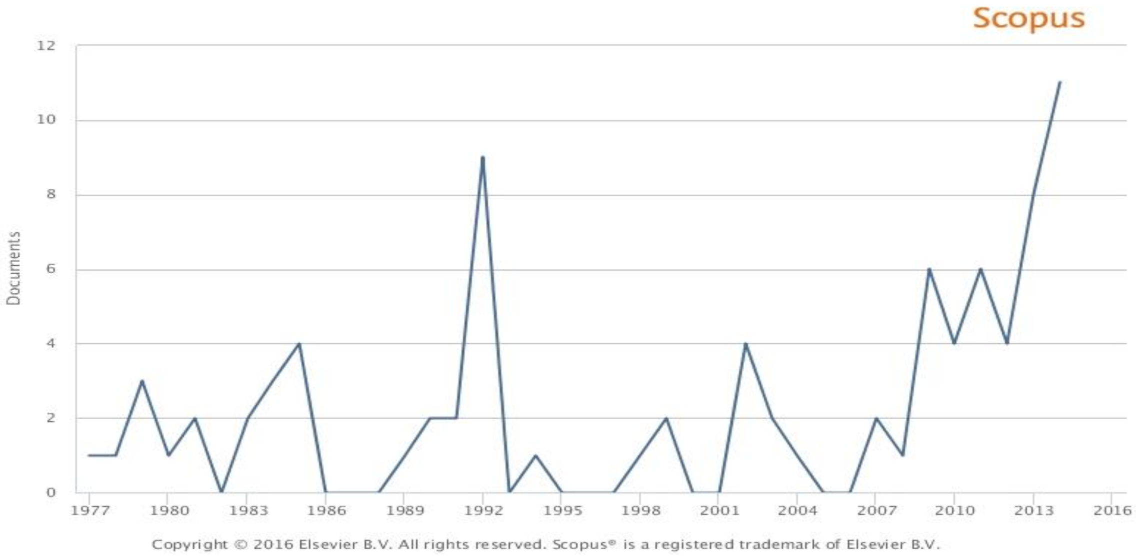
2.2 Scientific background

Storing water at higher temperatures in aquifers comes with a number of additional challenges compared with regular ATES. Following the development of HT-ATES technology in the 1970s, a number of experimental and pilot plants were built in the 1980s. Sanner & Knoblich (1999) give an overview of the challenges that arose at these plants. The main problems were of a technical nature, e.g. clogging of pipes due to precipitation of minerals, corrosion of components in the groundwater system and low efficiencies due to several processes in the aquifers (notably buoyancy flow) as well as the surface systems. After extensive research in the 1985-1995 period these issues were deemed solvable, and today there are proven solutions (Drijver et al., 2012; Sanner & Knoblich, 1999). With the availability of means to deal with technical issues, and against the backdrop of rising energy prices and increased attention for CO_2 emission reductions, there is now renewed interest for HT-ATES (Figure 3).

Regular (low temperature) ATES systems have already proven to be a sustainable alternative to conventional heating and cooling technologies for large office buildings and residential complexes. ATES has grown from a theoretical concept to a technically and commercially viable system that is now widespread in the Netherlands (Drijver et al., 2012). ATES systems absorb heat from buildings in summer to cool them, and return this heat in winter to heat the same buildings. On a larger scale, HT-ATES has the potential to fulfil a similar role in district heating systems, by shifting existing thermal energy in time. Moreover, its scale and higher temperature enable it to play an important role in future sustainable energy systems with increasing shares of variable renewables. Connected to the electricity grid and combined with power-to-heat(P2H) technology - which converts electricity into heat –, HT-ATES can store electricity surpluses that would otherwise not have a useful or affordable purpose, and produce it as useful heat when needed (Böttger, Götz, Lehr, Kondziella, & Bruckner, 2014). Consequently, HT-ATES can play an important role in the expansion and integration of variable renewables in energy systems (Siemer, Schöpfer, & Kleinhans, 2016). On a smaller scale, HT-ATES can provide CHP plants with flexibility in their electricity to heat production ratio, which results in a strategic advantage that can increase both efficiency and profitability (Christidis et al., 2012; Fragaki et al., 2008).

With the renewed interest in HT-ATES of scientists and policy makers alike, successful pilot projects may induce changes in Dutch legislation – which currently prohibits HT-ATES - that pave the way for this technology in the near future (e.g. skb, 2013). Knowing that HT-ATES installations may be allowed in the Netherlands within ten years (see section 3.2), there is a remarkable knowledge gap in scientific literature: the lack of quantitative assessments of HT-ATES potential. The potential of HT-ATES to reduce primary energy use, reduce CO_2 emissions and save costs has been widely acknowledged (e.g. Drijver et al., 2012; Jeon, Lee, Pasquinelli, & Fabricius, 2015), but no quantitative research has been done to support this statement with numbers. Furthermore, insight in conditions, drivers and barriers for HT-ATES implementation is still very limited.

For insight in regional or national renewable energy(RE) developments in the future, it is imperative to quantify their potential as well as the part that can be realised on shorter time scales (Resch et al., 2008, p. 4048). The same holds for energy efficiency technologies and technologies that facilitate high shares of RE, such as HT-ATES. Qualitative research resulting in hotspots for HT-ATES in the Netherlands has already been conducted by Huismans (2016), but it is unknown how much primary energy and emission savings HT-ATES can provide at the individual hotspots and on a national scale. Such estimations are essential to provide policy makers with a feeling of what the role of this technology can be in meeting (CO_2-)emission reduction targets and improving energy security. Moreover, market potential analysis can provide insight in which policies are necessary to increase HT-ATES implementation. Considering the urgency of the threat of global warming and the need to improve the energy security in the future, it is imperative to fill this knowledge gap.



Copyright © 2016 Elsevier B.V. All rights reserved. Scopus® is a registered trademark of Elsevier B.V.

Figure 3 *Number of publications per year with keywords "high temperature aquifer thermal energy storage" in either the title, abstract or keywords section, as obtained from a search in the Scopus database with range 1977-2014 (February 19, 2016).*

2.3 Research objectives

The research objective of this thesis is to contribute to the methodological development on the integrated assessment of HT-ATES by developing a framework for the theoretical, technical and market potential assessment of HT-ATES in the Netherlands. It also aims to identify the main conditions, barriers and drivers of HT-ATES implementation by conducting a market potential assessment of case studies. The following sub questions will be studied:

1. *How can the theoretical and technical potential of HT-ATES in the Netherlands in 2020 be calculated?*

   Knowing the technical potential of a technology can help scientists and policy makers determine what role it can play in the long run. A framework is developed to facilitate quantification in future research.

2. *How can the market potential of HT-ATES in the Netherlands in 2020 be assessed for a business-as-usual and an alternative policy scenario?*

   The market potential provides a relatively realistic picture of how much deployment of HT-ATES is realistic in the short- to mid-term future and how this number may be influenced by market factors. A framework is developed that is subsequently applied on case studies (sub question 3).

3. *What is the business case for selected case studies in 2020 in a business-as-usual scenario and in an alternative scenario?*

   The business case for HT-ATES is influenced by the setting in which it is applied. A market potential assessment of case studies representative for different settings is conducted using the market potential assessment framework (sub question 2). In particular, the levelized cost of energy(LCOE) for HT-ATES compared to the reference technology is studied. (Quantitative) insight in conditions, drivers and barriers for HT-ATES implementation is acquired in the case studies.

This thesis research will contribute to the development of insight in HT-ATES potential in the Netherlands on the short (market potential) and long (theoretical and technical potentials) term. Besides facilitating a full quantification of the theoretical, technical and market potentials, developing the frameworks for potential assessments provides insight in conditions, drivers and barriers of HT-ATES business cases. In-depth analysis of case studies further deepens these insights that are lacking in scientific literature to date, and add to the understanding of the different types of applications of HT-ATES. By providing a first impression of what can be done to stimulate HT-ATES development, the case studies also facilitate the decision making process. Potential investors may benefit from the provided insight in how a viable business case for HT-ATES can be created. Together, these contributions may potentially help mitigate the societal problems of anthropogenic global warming and finite fossil resources and improve energy security.

3 Theory

3.1 Potential studies on renewable energy potentials

In studies of renewable energy(RE) or technology potentials, a distinction is generally made between metrics such as theoretical potential*,* technical potential*,* realisable potential*,* economic potential and market potential (Figure 4). However, often only a selection of these different potentials is analysed, depending on the aim of the study. Moreover, there is no consensus on definitions and methodology, making different studies difficult to compare and limiting their transparency (Verbruggen et al., 2010). An overview of the definitions proposed over the years, their critique and proposed improvements is given by Verbruggen et al. (2010). Verbruggen et al. distinguished between bottom-up and top-down approaches. The bottom-up approach starts at the achieved(installed) RE capacity in a reference year and describes how these can be increased, thereby considering existing barriers and the policies to remove them. The top-down or downward approach starts with the theoretical potential which is the physical resource base, and reduces it with conversion efficiencies, prices and policies to get to e.g. the market potential. As HT-ATES is not yet implemented in the Netherlands, a top-down vision is chosen for the frameworks. However, it will become apparent in the methods (section 0) that elements of a bottom-up approach will also appear during the assessment of case studies. The definitions of the different potentials used in this study are given in the next paragraph. They are largely based on IEAGHG (2011), but in some parts slightly adjusted to increase their applicability for HT-ATES, which is not a RE source in itself.

RE potentials can be illustrated in a pyramid (Figure 5), in which the theoretical potential is on the bottom and the market potential in the top. The remaining potential decreases in the process of determining the potentials (indicated by the red arrows). The starting point is the **theoretical potential**, which for the purpose of this study is defined as: **the total storage capacity in the subsurface(in TJ) of an area that is suitable for HT-ATES**. The **technical potential in this study is defined as the theoretical potential corrected for technical restraints, such as recovery efficiency and drilling restrictions**. R&D can improve recovery efficiencies and remove some of the technical restraints. Therefore the technical potential can vary over time (Resch et al., 2008). Consequently, determining the technological potential has to be preceded by analysis of the expected technological status in the target year. The realisable and economic potentials will not be addressed in this study due to time restrictions. The first is of limited relevance as the reference technology(peak boilers) is dominated by operational costs and can continue to play a role in peak heat supply next to HT-ATES. Therefore, the stock turnover rate of peak boilers is of limited importance. The latter is considered of limited relevance as the goal of the case studies is to conduct a realistic business case assessment from a relevant investor’s perspective, including the drivers and barriers that may apply.

While the economic potential often only comprises a comparison of lifetime costs with those of another technology, the market potential provides a more realistic insight into the real costs for private investors by taking into account relevant drivers and barriers. **The market potential is defined here as the share of the technical potential that can be realised at acceptable costs for a relevant investor, taking into account the costs of the reference technology, financial parameters such as required return on equity, and obstacles and drivers, such as taxes, subsidies and regulations**. Many of these drivers and barriers are influenced by policies and, therefore, policy makers potentially have a large impact on the future market potential of a technology.

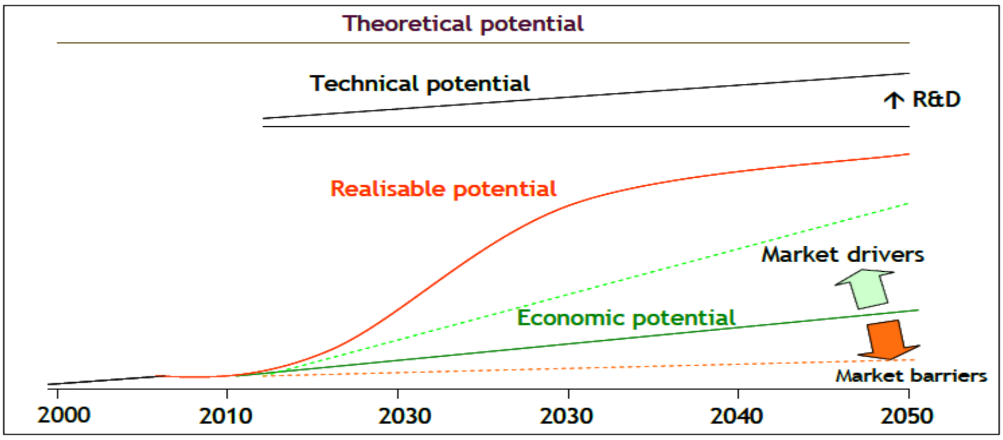


Figure 4 *Graphical representations of the definitions for potentials used in a study by Resch et al. (2008). The technical potential can be increased with R&D, the realisable potential depends on deployment rates and the market potential can be greater or smaller than the economic potential, depending on market drivers and barriers. From: Resch et al. (2008)*

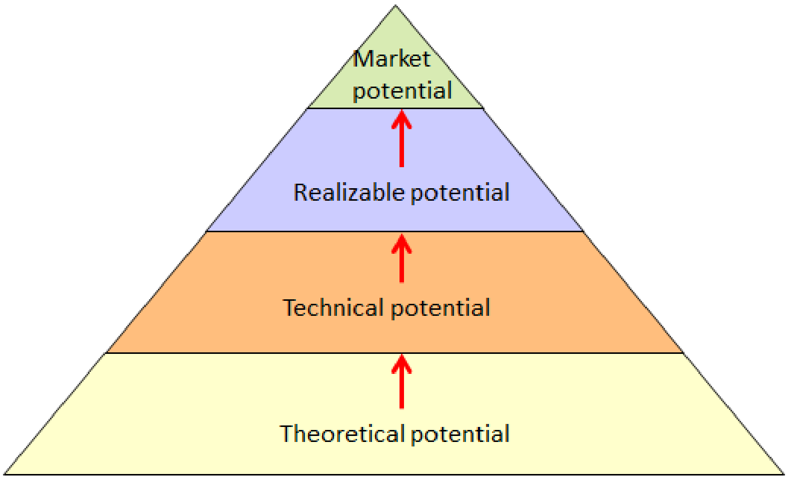


Figure 5 *An illustration of the different technology potentials as a pyramid. In a top-down approach, the starting point is the base of the pyramid. The arrows indicate the assessment sequence that is followed to reach the top of the pyramid: the market potential.* The width of the pyramid indicates the relative size of potentials.

3.2 Regulation relevant to HT-ATES in the Netherlands

The impact of policies on HT-ATES deployment is currently very strong in the Netherlands. Provincial authorities are in charge of the shallow subsurface up to 500m below ground level. HT-ATES is currently prohibited in this depth range, as storage temperatures above 25-30°C (depending on province) are not allowed. Furthermore, energy balance[1] is required, which is not feasible for HT-ATES. Finally, effects on aquifer water quality are relatively large due to the impacts of high temperatures as well as the consequently required water treatment. Therefore, HT-ATES installations can currently only be applied in pilot projects in the Netherlands. For each pilot project an integral assessment of advantages and disadvantages must be made, in which the most important aspect is usually to what extent shallower aquifers above the storage aquifer(s) are warmed (Drijver et al., 2012; Drijver, 2012).

---

[1] To achieve energy balance the average temperature difference between the hot and cold storage must equal the ambient aquifer temperature, and the seasonal flow rate of heating and cooling water must be equal. In normal ATES systems, energy balance is required to sustain its cooling and heating capacity. Unequal heating and cooling may increase or decrease the overall aquifer temperature, which impairs either the cooling or heating ability of the system (Zeghici, Oude Essink, Hartog, & Sommer, 2015). HT-ATES systems differ from ATES systems in that they do not have a cooling function and have an external heat source. Therefore, energy balance is not feasible for HT-ATES.

The purpose of pilot projects is to gain practical experience and data on e.g. chemical and microbiological impacts and warming of more shallow aquifers. This knowledge can be used for the revision of legislation for HT-ATES (Drijver, 2012; Schout, Drijver, Gutierrez-Neri, & Schotting, 2014). The only planned pilot project in the Netherlands will take place in the province of Zuid Holland. The GeoMec -4P pilot in Vierpolders will use HT-ATES to complement a deep geothermal well that supplies heat to a horticultural area. Decisions about revision will be made in the sixth year after the start of the pilot's operation. Continuation of the pilot depends on this decision (Provincie Zuid Holland, 2012).

The Dutch national Ministry of Economic Affairs is responsible for the subsurface deeper than 500m below ground level. At these depths there are no temperature restrictions. Nevertheless, applications are time consuming and difficult, since HT-ATES falls under the mining category due to the lack of more specific legislation for ATES. The planned HT-ATES pilot projects in the Netherlands use shallow(<500m) aquifers, as suitable layers in this depth range are widespread in the Netherlands and drilling costs increase with depth. HT-ATES projects in deeper aquifers have been applied in the past, however, and still are in operation in Germany (Koornneef, Griffioen, Pluymaekers, & Boxem, 2015).

The definitions of different types of aquifer thermal energy storage systems recognized by Drijver et al. (2012), are partially in accordance with current Dutch legislation. Only ATES falls within the allowed temperature limit (Table 1).

Table 1 *Overview of different types of aquifer thermal energy storage and their temperature range as defined by Drijver et al. (2012). MT-ATES = Medium Temperature Aquifer Thermal Energy Storage.*

Name	Temperature production water	Typical application
ATES	<30°C	(Collectives of) large buildings or houses
MT-ATES	30-60°C	(Collectives of) large buildings or houses
HT-ATES	<60°C	District heating networks

3.3 Previous work on the potential of HT-ATES in the Netherlands

Based on the REGIS II 3D hydrogeological model of the shallow(<500m depth) subsurface (TNO, 2005), Pluymaekers et al. (2013) produced HT-ATES suitability maps indicating which geological layers are promising for HT-ATES and where they are located in the Netherlands. In bachelor thesis research by Huismans (2016), these suitability maps were overlain in ArcGIS with maps containing locations of relevant surface conditions such as waste heat availability, current and planned district heating networks and heat demand from horticulture and households. Moreover, areas used for drinking water production, military purposes and Natura 2000 areas were excluded. The resulting map shows where surface and subsurface conditions required for HT-ATES are in proximity of each other (Figure 6). Those areas were identified as potential hotspots for HT-ATES installations. This approach follows the framework of Multi Criteria Decision Analysis(MCDA) in a way similar to the approach Bloemendal, Olsthoorn, & Van de Ven (2015) used for identification of global ATES hotspots based on climatic and subsurface conditions.

The aquifers deemed suitable for HT-ATES by Pluymaekers et al. (2013) were selected using economic criteria, such as an expected levelized cost of energy(LCOE) below 6 EUR/GJ. This means that a lot of theoretically and technically feasible storage capacity is excluded from the suitability maps for economic reasons. Moreover, the maximum expected LCOE criterion neglects the variety in LCOEs of the reference technology, to which HT-ATES is compared in the methodology of this study. On top of this, part of the suitable areas selected by Pluymaekers et al. (2013) were deemed unsuitable by Huismans (2016) based on additional regulatory and practical restrictions, as well as vicinity to demand and supply of heat. Therefore, the work of Pluymaekers et al. (2013) is not compatible with this study's methods for the assessment of the Dutch national theoretical, technical and/or market potential. Huismans' maps are useful for the selection of case studies, as they show where the basic requirements are present for HT-ATES market potential in the near future.

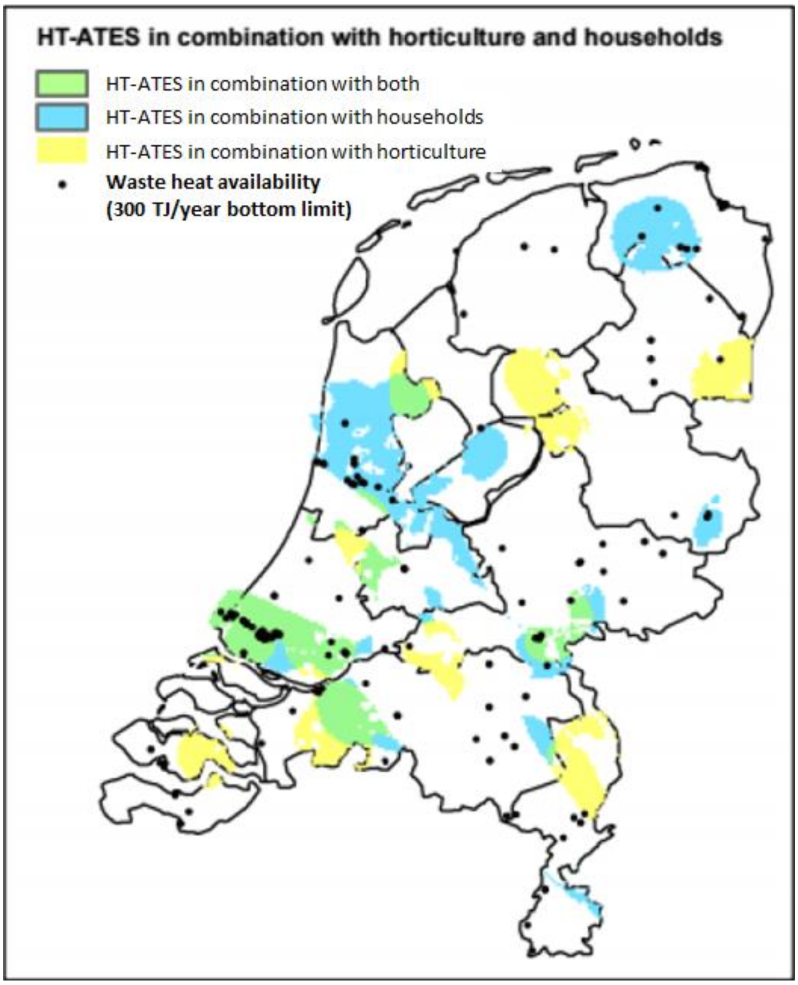


Figure 6 *Map indicating where suitable subsurface and surface conditions for HT-ATES overlap. From: Huismans (2016).*

In a study with the goal to map the opportunities and potential of shallow direct geothermal heat(SDGH; 0-1000m below ground level) for the horticultural sector in the Netherlands, Hellebrand, Post, & In 't Groen (2012) gathered data of aquifers in the 0-1000m depth range to select suitable aquifers for SDGH. This resulted in maps of the estimated depth, thickness and expected flowrate of four suitable formations – the Brussels sand, the formation of Breda, the formation of Oosterhout and the formation of Maassluis. As the subsurface requirements for SDGH are highly similar to those for HT-ATES (M.P.D. Pluymaekers, personal communication, June 7, 2016), these estimations can be used for the subsurface assessment of case studies when local information is not available in the REGIS II 3D hydrogeological model. The flowrate maps can be found in Appendix 3.

4 Methods

In the following, the methods of this study are discussed in three parts following the order of the sub questions. The first part explains how the frameworks for theoretical and technical potential assessment were composed. In the second part the methods for the market potential assessment framework are explained. The third part explains the market potential assessment of case studies, including the selection of case studies, gathering of data, market potential assessment and sensitivity analysis.

4.1 Framework design for theoretical and technical potential

A top-down approach for RE potential studies starts with the calculation of the theoretical potential for a certain area. From this point on, increasing restrictions can be applied to get the technical potential, realisable potential, and so on (see section 3). Before the theoretical and technical potential frameworks were composed, an in-depth study of literature and reports was conducted to identify the parameters that influence the theoretical potential. Parameter values, formulas and boundaries were determined based on literature about ATES, HT-ATES, geothermal and geohydrology. Setting boundaries is particularly important to ensure that the potentials that will eventually be quantified strictly represent the definition of HT-ATES. Moreover, clear boundaries prevent overlap with potentials of alternative technologies or activities that use aquifers or could otherwise interfere with HT-ATES. As little literature about HT-ATES is available, complementary brainstorm sessions were held with experts J.M. Koornneef and M.P.D. Pluymaekers.

Based on the literature research and brainstorm sessions, a basic methodology for the assessment of the theoretical and technical potential was decided on and converted into a framework. Subsequently, the parameters with proposed values and relevant formulas were added to the relevant steps in the framework. Current work on HT-ATES potentials (see section 3.3) was finally added as information soucres where applicable. Although the general methodology can be applied anywhere, the parameter values, assumptions and existing work were selected specifically for a national potential assessment of the Netherlands.

Next, a target year was chosen. Setting a target year is required for both the technical and the market potential, as many factors that influence their outcome are time dependent. Although a target year further in the future has the advantage that more time is available to deploy the entire potential before the target year passes, it was chosen to use 2020 as the target year. This has the benefit that the uncertainty of the input parameters – particularly those for the case studies, such as demand profile – is smaller, making the results more reliable. Moreover, demonstrating the potential of HT-ATES on the short term increases the pressure on policy makers to change the legislation prohibiting it, as the potential can only be realised when HT-ATES is allowed. Finally, the urgency of the need for alternative heat sources for space heating asks for insight in what HT-ATES can contribute on the short term. This is demonstrated by the target year of the Dutch Agreement on Energy for Sustainable Growth, which has 2020 and 2023 as its primary time horizons (Schoots & Hammingh, 2015).

4.2 Framework design for national market potential

To isolate the market potential from the technical potential, many additional conditions, drivers and barriers must be taken into account. These parameters are defined by surface conditions and other non-physical conditions, which are different at each location. To assess which share of the technical potential is interesting for an investor, it was assumed that investors are interested in the lowest costs and highest financial benefits. Consequently, a certain hotspot can only be counted as part of the market potential if the calculated *levelized cost of energy*(LCOE) of HT-ATES is lower than the reference LCOE. The LCOE is defined as the price that stored heat must be sold for to reach a *net present value*(NPV) of zero, and can be calculated with the following formula(Pawel, 2014):

$$LCOE = \frac{\text{Discounted lifetime costs of an investment}}{\text{Cumulated energy generated by investment}}$$

The outcome of the formula is a price per unit of thermal energy produced from a lifecycle cost perspective, in this thesis EUR/GJ_{th}.

To identify the conditions, divers and barriers that determine the market potential, literature research on the market potential of other technologies was conducted. Relevant drivers and barriers were modified and adopted in the HT-ATES market potential assessment framework. Furthermore, document research was conducted, expert brainstorm sessions were held with J.M. Koornneef and R. Bianchi and the parameters of the HT-ATES tool(see section 4.3.2) were studied to complement the literature research.

4.2.1 The reference LCOE

The calculation method of the reference LCOE depends of the setting of a case study (Figure 7). Many settings with different proprietors of the HT-ATES system and the different parts of a district heating network(heat supply, thermal grid and heat delivery) are theoretically possible. Most of these settings can be posted within one of the following three categories:

1. The HT-ATES proprietor is responsible for the entire district heating network, i.e. the main heat source(s) and thermal grid, until delivery and billing at the final heat consumers.
2. The HT-ATES proprietor is the (main) heat supplier, but is not the proprietor of the thermal grid nor is the party responsible for delivery and billing of heat at final heat consumers.
3. The HT-ATES proprietor is also proprietor of the thermal grid and is responsible for delivery and billing of heat at final consumers, but buys (the bulk of) the required heat from another party: the proprietor of the main heat source.

For each category, the basic method for market potential assessment is the same. Only the reference LCOE that the HT-ATES LCOE must be compared to is calculated differently and depends on the proprietor's role(s) in the district heating network:

1. In this category the alternative for the HT-ATES proprietor is generally to produce the peak heat with natural gas boilers. Therefore, the LCOE of the HT-ATES must be compared to the LCOE of these boilers (or other type of peak heat supply system used).
2. In this category the HT-ATES proprietor usually is not the proprietor of the peak heat supply systems, as these are generally located within the thermal grid. Consequently, rather than producing the peak heat with another heat source, the alternative of the HT-ATES proprietor is to sell less heat. Therefore, the reference that the HT-ATES LCOE must be compared to is the weighted average selling price of the peak heat produced by the HT-ATES.
3. In this category, the HT-ATES proprietor is usually also the proprietor of the peak heat supply systems located in the thermal grid. Therefore – like in category 1 – the LCOE of the HT-ATES must be compared to the LCOE of these peak heat supply systems.

Although in category 2 the reference is technically not a LCOE, the reference costs per GJ from a lifecycle costing perspective are referred to as reference LCOE in the remainder of this thesis.

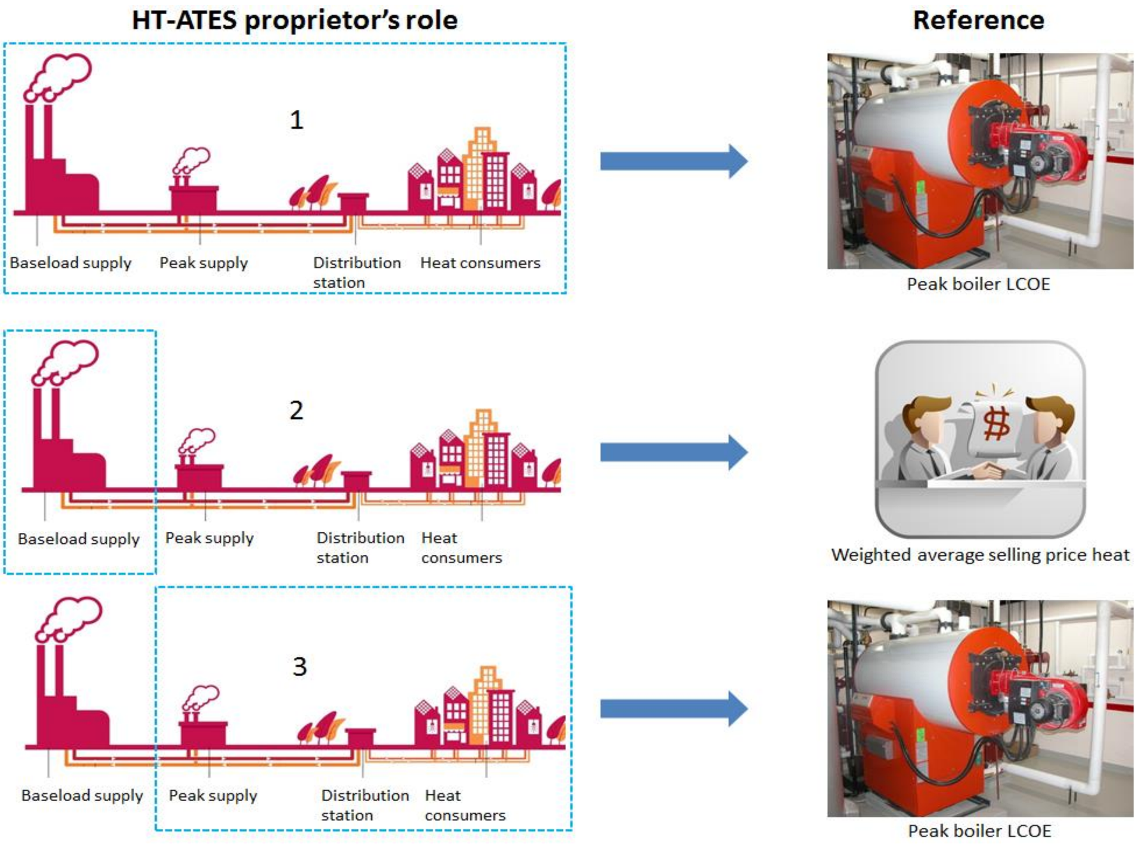


Figure 7 *Scheme indicating which reference is used to compare the HT-ATES LCOE with in different proprietor roles (1-3). The blue dashed boxes delineate the role of the prospective HT-ATES proprietor in the district heating network. Original image (left) from: Eneco (2016).*

4.2.2 Boundary conditions

HT-ATES is embedded within a district heating network with different components, such as heat supply, heat infrastructure and heat demand, which may each have different owners. When thermal and electric energy systems become increasingly integrated in the future and P2H technology enables HT-ATES to play a key role in the flexibility of these systems, this embeddedness will become even more complex. Consequently, it is crucial in HT-ATES market potential assessment that clear boundaries are defined between HT-ATES and the energy systems in which it is embedded. This also holds for the peak heat supply systems that are the alternative to HT-ATES.

Figure 8 visualizes the embeddedness of HT-ATES in a district heating network and illustrates the boundaries that were chosen for the market potential assessment framework. For both the reference technology and HT-ATES, baseload heat supply facilities, the thermal grid and heat demand are considered external factors, i.e. their costs are not considered in the HT-ATES market potential assessment. Nevertheless, they are responsible for parameters that affect the market potential of HT-ATES. Heat suppliers provide the heat injected in HT-ATES and therefore the **marginal costs for injected heat** were taken into account. The HT-ATES **ΔT** is determined by the temperature of the supplied heat and the temperature of the thermal grid return flow, which in turn depends on the degree of cascading of heat on the demand side of the district heating network. The number of full load hours of both the HT-ATES and the reference peak supply systems depends on the **heat supply profile** of the main heat supplier and the **heat demand profile** from the heat consumers.

If the main heat supplier is the investor in HT-ATES but does not own the thermal grid (category 2 in section 4.2.1), the reference LCOE is an agreement between the heat supplier and the thermal grid operator. This value must be retrieved from the investor and boundaries are therefore not relevant.

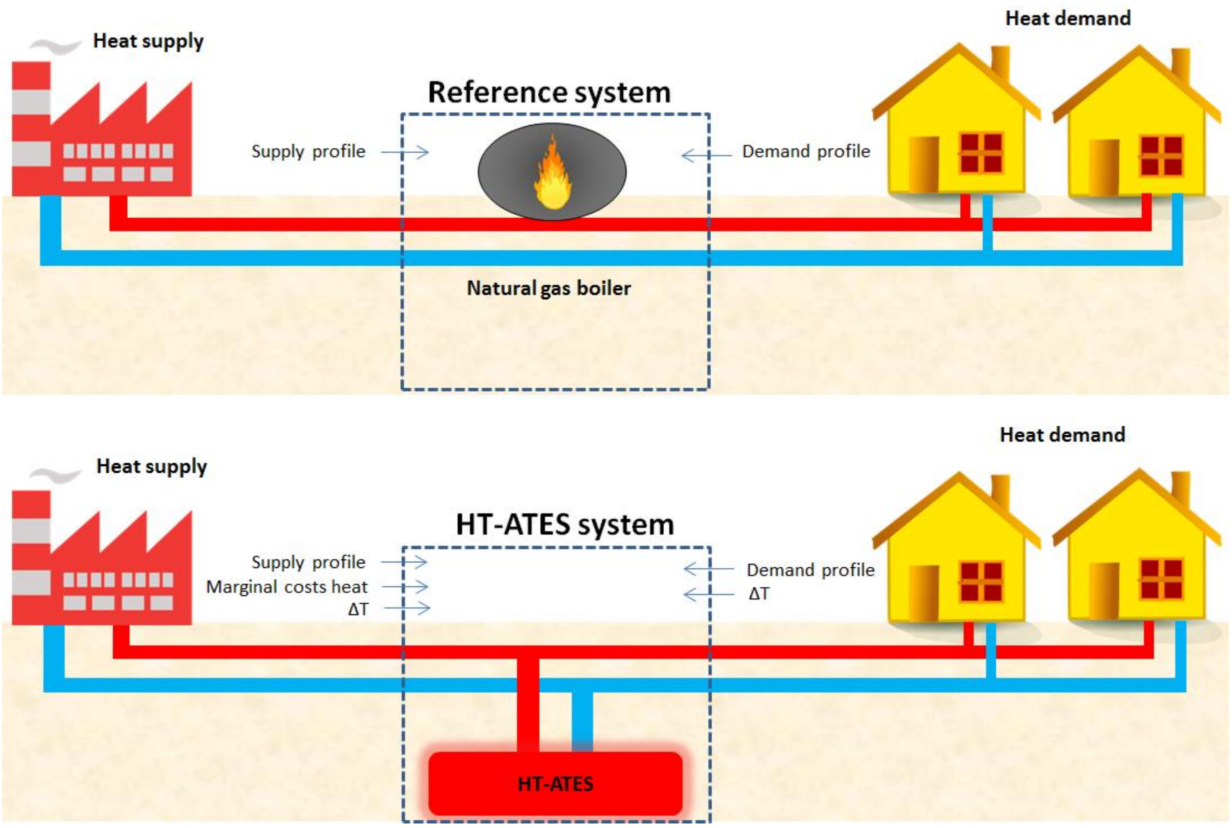


Figure 8 *A schematic and simplified illustration of a district heating network with and without HT-ATES. In the reference system a natural gas boiler or other peak heat supply system provides heat during cold winter days. HT-ATES can (partially) take over this task. The dashed box around the natural gas boiler and HT-ATES depict the boundaries applied in the market potential assessment framework; the arrows going into the box are external factors from the district heating network taken into account. Different types of heat demand and supply sources can replace or complement those depicted in this figure.*

4.2.3 Policy scenarios

To assess the effectivity of current policies and regulations on the HT-ATES market potential and to identify the best changes or additions to the existing policy package, two policy scenarios were developed. Document research – mainly on the websites of government bodies RVO and Belastingdienst - was conducted to identify which existing subsidies, tax rebates, regulations and other policies potentially affect the market potential of HT-ATES. These were put in the *business-as-usual* (BAU) scenario, representative of the existing policies and regulations. As 2020 is the target year of the market potential assessment framework, the BAU policies and regulations were corrected for changes planned for implementation before 2020. Subsequently, literature research on best practices and strategy reports was conducted and brainstorm sessions were held with experts J.M. Koornneef(several dates) and R. Bianchi(May 17, 2016) to design an *alternative*(ALT) policy scenario. The ALT scenario consists of adapted versions of the policies and regulations in the BAU scenario, as well as new policies and regulations. It is designed to increase the HT-ATES market potential compared to the BAU policy package, or more generally to stimulate investments in CO_2-emission reduction measures. Both scenarios only influence the policies and regulations context in 2020, not the technological or societal status, which are the same in both scenarios.

By applying the HT-ATES market potential framework to each case study twice – once with each policy scenario –the effectiveness of both packages as well as individual policies and regulations can be compared. This results in improved insight in the extent to which policy makers can stimulate HT-ATES deployment rates, and provides a first indications of which policies are most effective.

4.3 Market potential assessment of two representative case studies

To show how to use the market potential assessment framework, the framework was applied on two case studies. In addition to applying the framework, the case studies served to provide detailed, quantitative insights in the influence of conditions, drivers and barriers, including the influence of existing and hypothetical policies. Finally, the case studies show different applications of HT-ATES.

4.3.1 Case studies selection

A number of criteria were used to select the two case studies. The first criterion was that each case study needed a different type of main heat source, a different proprietor perspective(see 4.2.1) and a different demand composition (new dwellings, old dwellings, flats, company buildings, horticulture, industry). Different proprietor perspectives imply a different methodological approach(see 4.2.1), which is ideally demonstrated in the case studies. Different heat suppliers have different heat supply profiles and are subject to different policies and regulations. Different demand compositions results in different demand profiles. Choosing case studies with different demand and supply situations can provide insight in which situations are most favourable for HT-ATES and which implementation and operation strategies best fit each situations.

The second criterion was that the access to required data is good. Preference was therefore given to case studies that TNO employees already have connections with.

The final criterion was that the case studies had to be chosen from areas marked as suitable for HT-ATES on the maps of Huismans (2016). This ensures vicinity of potentially suitable subsurface (presence of suitable aquifers) and surface (vicinity of demand, supply and a heat grid) conditions, i.e. the basic requirements for HT-ATES. Due to data availability, the HT-ATES suitability maps of Huismans (2016) are restricted to areas where suitable aquifers occur within the 150-500m depth range. Considering the higher drilling costs and risks associated with depths greater than 500m (De Zwart, 2009), it was assumed that a business case is currently unlikely for deep(>500m) HT-ATES.

Based on the described criteria, Groningen and Rotterdam were selected as case studies. In Groningen, a new district heating network using geothermal heat is planned to heat dwellings in the north-western part of the city. In Rotterdam, a large waste incineration plant currently provides heat to the centre of Rotterdam and nearby cities. Large expansions of the district heating network to other parts of the province are planned for the near future.

4.3.2 Data collection and market potential assessment

For reasons of confidentiality, heat demand and supply profiles as well as other key data could not be retrieved for the Rotterdam case study. Therefore, a detailed quantitative case study of Groningen was conducted, while a less detailed and partially quantitative case study of Rotterdam was conducted to illustrate another setting for HT-ATES.

For the quantitative market potential assessment, the HT-ATES calculation tool of TNO was used. This Microsoft Excel tool, which can calculate the LCOE of ATES, HT-ATES, geothermal wells and power plants, was created and discussed by Pluymaekers et al. (2013). Demand and supply profiles of a single year with a weekly resolution can be entered into the tool together with subsurface parameters of the selected aquifer. Selection criteria for aquifers are discussed in the theoretical potential assessment framework. The tool consequently calculates how much heat is injected and produced by the HT-ATES in which week, based on technical parameters of the district heating network (e.g. temperatures of the supply and return flow). The HT-ATES production profile is the basis for the LCOE calculation of both the HT-ATES and the reference boiler (if applicable), as the total thermal energy produced in a year – the denominator of the LCOE formula(see section 4.2) – is equal for both. The parameters based on which the costs are calculated can be altered in an input-output sheet. The parameters used in these case studies are listed in appendix 1.

The parameter values used in the Groningen case study are listed Table 8. As the district heating network in Groningen will develop during the lifetime of a HT-ATES system, the calculation tool was altered to allow LCOE calculation based on the projected demand and supply profiles of each year. Profiles were available for 2017-2033 and were estimated by consultancy Greenvis for the company responsible for the entire district heating network (Warmtestad Groningen). It was assumed that demand in 2034 (the last year of the HT-ATES economic lifetime) is identical to 2033. The hourly resolution of the demand and supply profiles was lowered to a weekly resolution for this case study for reasons of confidentiality. These profiles, together with other case-specific parameter values not available in public documents were acquired during an interview with an employee of Warmtestad Groningen(see Appendix 4).

For the calculation of the reference boiler LCOE, the HT-ATES tool was stripped down and adapted to exclude calculations only relevant for HT-ATES. The heat demand in each year – which was previously determined with the HT-ATES tool based on supply and demand profiles – is equal for the reference boiler LCOE calculation. Any heat produced by the peak boilers on top of the HT-ATES heat production - which can be required when the combined power of the storage tanks and HT-ATES are lower than the demand load – was neglected due to time restrictions. Similar to HT-ATES LCOE calculations it was assumed that the above-ground storage tanks level the supply capacity shortages and surpluses that coincide within the same day or week. It was thus assumed that the peak boilers have a seasonal function, like HT-ATES.

For the market potential assessment of HT-ATES in Rotterdam, the proprietor perspective of waste incinerator AVR was chosen after a preliminary analysis of the benefits that different likely proprietors may potentially get from HT-ATES. An interview with AVR energy expert H. Wassenaar was conducted to acquire insight in the strategic environment that AVR operates in, and acquire as much non-confidential information as possible about the facilities, energy flows and technical characteristics (see Appendix 6). A demand profile was drafted using the demand distribution profile of the Groningen case study and the published ambition to realise 20 PJ of demand in the district heating network in 2020. It was assumed that 50% of this heat demand is directed to AVR. Heat demand in the 15-year period after 2020 (i.e. the HT-ATES economic lifetime) was assumed equal to 2020 due to the low availability of public data on the planned development of the heat infrastructure and the large uncertainty in the timeline of these developments. An estimated profile of AVR’s heat supply capacity to the district heating network was drafted based on the interview and public data about AVR’s facilities. It was assumed that the distribution of thermal and electric power of all of AVR’s facilities together are equal to the average distribution of hot water, steam and electricity production of the household waste incineration facility, which is the dominant facility in terms of capacity. Capacity reductions due to maintenance were incorporated in the profile in the weeks in which the projected heat demand is lowest.

Due to the proprietor setting in the Rotterdam case study (see section 4.2.1), the reference that the HT-ATES LCOE must be compared to is the weighted average selling price of heat. As this price is confidential, a formula developed by ECN for the SDE$^+$ value corrections was used to calculate the average value of sold heat (Lensink & Van Zuijlen, 2016).

4.3.3 Sensitivity analysis

To deal with the uncertainty in the model outcomes (the HT-ATES LCOE or reference boiler LCOE) caused by uncertainty in its input parameters, a sensitivity analysis was conducted. Using the *one-factor-at-a-time* method the factor with the strongest impact on the model output was identified. Moreover, it was assessed to what degree variations in one parameter value can change the output of the market potential assessment. In the Rotterdam case study, sensitivity analysis was only conducted on the two input parameters with the highest uncertainty and influence on the HT-ATES LCOE. No sensitivity analysis on the reference price was conducted.

5 Results

5.1 Theoretical and technical potential framework

The findings of literature research and expert brainstorm sessions are first discussed in section 5.1.1. In section 5.1.2, a framework is presented that integrates these findings in a step-by-step methodology for the assessment of the theoretical and technical potentials of HT-ATES.

5.1.1 Results of literature research and expert brainstorm sessions

The theoretical potential is ideally only limited by the available storage volume, while technical barriers to fully exploit this volume determine the technical potential (see Theory). The storage volume is delineated by the definition of HT-ATES in terms of its storage medium and its classification relative to direct geothermal energy, medium temperature aquifer thermal energy storage(MT-ATES) and ATES. The following main aspects therefore need to be further studied and defined to set the boundaries of the theoretical potential:

- Minimum permeability
- Depth range
- Impermeable layer requirements

Some of these aspects would normally be considered higher up in the potentials pyramid (i.e. in the assessment of market potential), but due to the complexity and magnitude of the subsurface, restrictions are required to keep the theoretical potential realistic and measurable. Further relevant parameters and formulas for theoretical and technical potential assessment are discussed after the three listed aspects that determine the boundaries.

Permeability

HT-ATES uses aquifers for thermal energy storage, since the carrier of thermal energy (water) can be retained in large quantities within an aquifer. This is caused by the relatively high porosity of aquifers, i.e. the voids between grains of sand or porous rock in aquifers are relatively large and plentiful compared to other subsurface layers. While porosity indicates the fraction of the aquifer volume that consists of pore space, permeability is a measure of how easily water can flow through the porous material. Permeability thus adds to porosity the extent to which pores are interconnected. A certain level of permeability is required to achieve an acceptable flowrate in the HT-ATES installation. The most important aquifer characteristic that determines the flowrate is transmissivity, which is calculated by multiplying an aquifer's permeability with its thickness.

In their selection of potentially suitable aquifers for HT-ATES in the Netherlands, Pluymaekers et al. (2013) use a minimal permeability of 100 Dm. In personal communication (April 15, 2016), M.P.D. Pluymaekers stated that this value is slightly conservative and was chosen with economic motives. For the assessment of the theoretical potential, economic motives are not relevant. Although there is no given permeability value below which injection and extraction of water is impossible, a minimal permeability of 50 Dm is proposed. It is reasonable to assume that aquifers with a permeability below this value will never be used for HT-ATES (M.P.D. Pluymaekers, personal communication, April 15, 2016), as the achievable transmissivity would be too low. Nevertheless, even lower minimal permeability values could also be argued for, as this number is an estimation.

Depth

Aquifers can be found in a large depth range in the subsurface, ranging from a few meters to kilometres below ground level. Although aquifers hold water by definition and could thus theoretically be used for hot water storage, very deep aquifers cannot be assigned to HT-ATES potential. The reason for that is the risk of overlap between the potentials of HT-ATES and direct geothermal heat from aquifers. Kramers, Van

Wees, Pluymaekers, Kronimus, & Boxem (2012) used a minimum aquifer ambient temperature of 40°C as a criterion for inclusion in their direct geothermal heat resource assessment of the Netherlands. An option is thus to limit the HT-ATES theoretical potential to aquifers with an ambient temperature below 40°C. Assuming an average thermal gradient in the Netherlands of 31°C/km (Van Heekeren & Bakema, 2015), and an average temperature of the subsurface at ground level of 10°C (KNMI, 2000), this translates to a maximum aquifer depth of 968 meters.

Similarly, overlap with drinking water reserves, ATES and MT-ATES are a risk at shallower depth ranges. However, no theoretical potential assessments of ATES or MT-ATES have been conducted yet to the author's knowledge. Moreover, consensus on the exact definitions of ATES, MT-ATES and HT-ATES to rule out overlap, seems to be lacking. To rule out overlap with (future) drinking water reserves, a minimum depth in the Netherlands is proposed that equals the local depth of the fresh/salt water interface. In the Netherlands, salt water in the context of drinking water is defined as water with a minimum chloride concentration of 150 mg Cl^-/L. Where the fresh/salt water interface lies deeper than 200m below ground level, a minimum depth of 200m can be used to prevent unnecessary exclusion of storage potential. No suitable methods to prevent overlap with ATES and MT-ATES could be found, so this potential overlap is not addressed in this framework. An update can be made in future research. Aquifer space that is already being used by ATES or MT-ATES can already be deducted from the potential, though.

Impermeable layer

A key requirement for an aquifer to be suitable for HT-ATES is the presence of impermeable layers above and below it. These layers generally contain high shares of clay (Van der Krogt, 2011). Without such layers, vertical density-driven movements of hot storage water would drastically reduce recovery efficiency. Moreover, above-lying aquifers would warm up to intolerable levels, which is particularly a problem in shallow aquifers as it may threaten drinking water reserves and induce minor ground movements (Drijver, 2012). According to Drijver (2012) a safe minimum thickness of an impermeable layer is 30 meters.

Temperature

The amount of thermal energy that can be stored depends inter alia on the difference between the injection temperature and return temperature (ΔT), i.e. the temperature of the hot waste water injected in the aquifer minus the temperature of that water after it has been used in the district heating network[2]. In the calculation of the theoretical potential, boundaries for these temperatures have to be assumed to calculate the maximum storage potential. A minimal return temperature of 20°C is proposed as it can be expected that even with technological progress, the heating water will always remain at least as warm as the room temperature of connected buildings or greenhouses.

As direct heat application is one of the main advantages that distinguishes HT-ATES from ATES, it is assumed that no heat pumps are applied. The maximum temperature depends on the technological status in the target year, but for the calculation of the energy content of water for the theoretical potential an assumption must be made nonetheless. An injection temperature of 150°C is proposed for the theoretical potential (J. Koornneef, personal communication, April 11, 2016). The resulting value of ΔT is therefore 150-20=130°C. For the technical potential, ΔT is harder to choose as best available technology means something else for the district heating(DH) networks that potentially use HT-ATES heat, than for HT-ATES itself. There is currently a trend towards district heating networks with lower temperatures due to numerous advantages of such networks (see e.g. Lund et al., 2014), while the technical potential of HT-ATES installations increases when the temperature drop in DH networks increases, i.e. when supply temperatures are high and return temperatures low. While the technology for high supply temperatures is available (e.g. from waste incineration plants), these high temperatures are undesirable for district heating

---

[2] HT-ATES has a closed water flow, i.e. thermal energy is exchanged with the district heating network through a heat exchanger

networks and technological progress is made to allow using lower supply temperatures. Further research is required on how to treat this contraposition. As best available technologies are theoretically capable of heating with very high or very low temperatures, and designing a DH network in which cascading heat demand enables the exploitation of this full temperature range, using the same ΔT as in the theoretical potential can be argued for.

Formula heat in place

The scientific literature about HT-ATES is limited, but a lot of similarities exist between HT-ATES and direct geothermal energy. In a potential study of direct geothermal energy in the Netherlands, Kramers et al. (2012) used the following formula to calculate *heat in place*(HIP):

$HIP = \gamma(Tres - Tsur)h$, where $\gamma = \Phi(Cw \cdot \rho w) + (1 - \Phi)Cr \cdot \rho w$

Where HIP=aquifer heat content [PJ/km^2]; T_{res}=reservoir ambient temperature [^{o}K]; T_{sur}=surface temperature [^{o}K]; h=aquifer thickness [m]; y=heat capacity [GJ/m^2]; Φ=porosity; C_w=heat capacity water [J/kg ^{o}K]; ρ_w=water density; and C_r=heat capacity rock [J/kg ^{o}K]. The second part of the formula ($(1 - \Phi)C_r \cdot \rho_w$) refers to the heat capacity of the porous material, which is not relevant when aquifers are used for HT-ATES (M.P.D. Pluymaekers, personal communication, April 15, 2016). T_{res} and T_{sur} refer to the reservoir and surface temperature respectively, and can be replaced by production temperature ($T_{production}$) and return flow temperature (T_{return}) for HT-ATES calculations. The formulas of Kramers et al. (2012) can thus be transformed as follows to calculate HT-ATES theoretical storage potential:

$HIP = \gamma(T_{production} - T_{return})h$ with $\gamma = \Phi(C_w \cdot \rho_w)$

An important assumption made in this formula to simplify the calculation of the volume of an aquifer, is that its thickness is constant. This simplification is reduced in the potential assessment frameworks by dividing aquifers in segments (section 5.1.2).

Recovery efficiency

The recovery efficiency(ε) of a HT-ATES installation is defined by (Schout et al., 2014) as "*the ratio between the recovered amount of energy and the stored amount of energy, with respect to the ambient temperature (T_a), when equal amounts of water are injected and produced*"(p. 282). It is calculated with the following formula:

$$\varepsilon = \frac{V_p \cdot C_w \cdot \left(\overline{T}_p - T_a\right)}{V_i \cdot C_w \cdot (T_i - T_a)} = \frac{\overline{T}_p - T_a}{T_i - T_a}$$

V_p and V_i are the produced and injected amounts of water [m^3], C_w is the volumetric heat capacity of water [J/(m^3 K)], T_p is the average temperature of the produced water [^{o}K] and T_i the injection temperature [^{o}K]. The amount of produced water does not always equal the amount of injected water(Drijver, 2012). If this is the case, the first (not simplified) part of the formula above is required to calculate recovery efficiency.

The formula above can only be used to calculate recovery efficiency when a HT-ATES installation is already installed and operational. Therefore, it cannot be used to determine the technical potential. HT-ATES recovery efficiencies stated in literature vary greatly. Drijver (2012) states a range of 50-80%, while Willemsen (2010) states that efficiencies of 70-90% are possible. Significantly lower efficiencies due to unforeseen issues in both subsurface and surface elements of installations have also been reported (e.g. Koornneef et al., 2015). These mostly date back to before the year 2000, though, and it is assumed that they are outdated due to technological progress and operational experience. On the other end, the highest theoretical recovery efficiency of 90% is not supported by any other literature. In consultation with J.M. Koornneef and M.P.D. Pluymaekers, a recovery efficiency range of 60-85% is proposed for the framework.

Using this wide range of values in the calculations takes into account the importance of and uncertainty in recovery efficiencies.

Drilling

Another factor that potentially limits the technical potential is the accessibility of the theoretical storage capacity. Possible reasons are impenetrable rock formations above aquifers, or depths that are beyond reach. As a maximum depth of 968 meters was defined earlier in this section, depth is not a technical restriction for HT-ATES. Moreover, as the Netherlands is located in a delta, it can be assumed that there are no impermeable rock formations that block access to aquifers in the chosen depth range (J.M. Koornneef, personal communication, April 11, 2016). In other regions, however, such formations may exist and need to be taken into account when determining the technical potential. Although shallow gas formations may cause issues in the Netherlands, this is only the case when drilling operations are not well prepared for this risk (M.P.D. Pluymaekers, personal communication, April 15, 2016) and is thus not a technical limitation. Structures above ground level that obstruct access are assumed to be absent, as it is usually possible to start drilling from another nearby location where these obstructions are not present.

5.1.2 The framework

The framework in Table 2 is a step-by-step guideline for the assessment of the theoretical and market potential of HT-ATES. Relevant data sources complement the steps, boundaries and parameters. Although the basic steps are universal, all data sources and some of the parameter (value) assumptions are applicable to the Netherlands only.

Table 2 *Framework for the calculation of the HT-ATES theoretical and technical potentials. Mentioned data sources, as well as parameter values with the annotation 'NL', apply only to assessment of the theoretical potential in the Netherlands.*

Step	Task	Description
1	**Define boundary conditions for the theoretical potential**	To prevent overlap with other (RE) potentials, the following boundaries are proposed: • Minimum aquifer porosity of 50 Dm • Minimum aquifer depth of 200 meters(NL); shallower if formation water is brackish/salt (>150 mg Cl^-/L) • Maximum aquifer depth of 968 meters(NL); • Minimum impermeable layer thickness of 30 meters; • Exclude aquifer space already used by ATES or MT-ATES installations.
2	**Create database of suitable aquifer segments**	Lay a grid over the area of study with cells of e.g. 2x2 km. Create a database with all major aquifers in the Netherlands and divide them into the grid sections. Exclude sections that are ruled out by the requirements described in step 1. Use input data from REGIS II (0-500m) and ThermoGIS(>1000m) databases or, if unavailable, literature (e.g. Hellebrand et al., 2012)
3	**Calculate specific heat capacities**	Calculate the specific heat capacity(γ) of each aquifer segment using the formula $\gamma = \Phi(C_w \cdot \rho_w)$, where γ=heat capacity (GJ/m^2), Φ =porosity; C_w=heat capacity water (J/kg ^{o}K), and p_w=water density(kg/m^3).
4	**Calculate storage capacity of segments**	Calculate the total thermal energy storage capacity of each aquifer segment using the formula $HIP = \gamma(T_{injection}-T_{return})h$, where HIP=thermal energy storage capacity(PJ/km^2) and h= average section thickness(m). Use $T_{injection}$=150^{o}C and T_{return}=20^{o}C (NL).
5	**Calculate storage capacity of area**	Sum up the thermal energy storage capacities of all aquifer segments to get the total HT-ATES theoretical potential of the area of study.
6	**Calculate savings**	Calculate fuel and emission savings per year by assuming that all thermal energy that can be stored(step 5) replaces heat generated with natural gas boilers.
		→ **Theoretical potential**
7	**Correct for drilling restrictions**	Deduct those aquifer segments that are not accessible due to e.g. impermeable rock formations. These formations are not present in the typical HT-ATES depth range in the Netherlands.
8	**Correct for injection and return temperatures**	Due to the use of a target year in the technical potential, $T_{injection}$ and T_{return} may differ from the theoretical potential. Recalculate HIP with the appropriate temperatures using the formula in step 4.
9	**Recalculate storage capacity of area**	Sum up the thermal energy storage capacities of all aquifer segments and multiply with the recovery efficiency range of 0,6-0,85
10	**Calculate savings**	Calculate fuel and emission savings per year by assuming that all thermal energy that can be stored(step 9) replaces heat generated with natural gas boilers.
		→ **Technical potential**

5.2 National market potential framework

The findings of literature research and expert brainstorm sessions are first discussed in section 5.2.1. In section 5.2.2, a framework is presented that integrates these findings in a step-by-step methodology for the assessment of the market potential of HT-ATES.

As the factors influencing the market potential are more country-specific than those affecting the theoretical and technical potentials, most of section 5.2 is specifically focused on the situation in the Netherlands. The basic steps of the framework are universal, though.

5.2.1 Results of literature research and expert brainstorm sessions

The most important market factors are divided here into *policies and regulations, economic factors, technical factors* and *societal factors,* and are discussed in that order. The two policy scenarios influence only the policies and regulations, which are therefore discussed for both scenarios.

Policies and regulations

Policy makers have a large set of strategies that they can employ to either stimulate or repress technologies. Vedung, Bemelmans-Videc, & Rist (1998) categorized these policy instruments into sticks, carrots and sermons, i.e. regulations, economic means and information respectively. Van der Doelen (1998) proposed a further distinction between stimulative and repressive forms for each type of policy instrument. While stimulative instruments enhance the legitimacy of or acceptance for a policy, repressive instruments secure its effectiveness. Similarly, regulations generally apply more authoritative force than economic means, which in turn are more authoritative than providing information. Applying the different types of policies in a balanced way and in the right sequence may enhance its effectiveness (Van der Doelen, 1998).

In the following, policies that can be employed to stimulate HT-ATES implementation are discussed, taking into account the requirements for a balanced and effective policy package. First, existing policies and regulations are discussed. Subsequently, policies and regulations that could be added to this package in an ALT scenario are discussed. Finally, an overview is given of the policies that are quantitatively used in the market potential assessment of case studies. Proposed changes to existing policies in the ALT scenarios are also presented in this overview.

Existing policies and regulations

After document reviewing and expert brainstorm sessions, no planned changes in existing policies and regulations before 2020 were found. Therefore, the existing policies and regulations are used for the 2020 BAU scenario.

Excluded areas

Drilling for a HT-ATES installation is not possible in certain areas due to local restrictions in the use of the surface or subsurface. Military practice areas and Natura 2000 areas are examples of excluded surfaces, while (potential) drinking water reserves are excluded subsurface areas. As depths below 200m or within the fresh water depth range (if shallower than 200m) were excluded in the theoretical potential framework, it can be assumed that drinking water reserves are already excluded. In countries where drinking water is produced from deeper aquifers than in the Netherlands, this may not necessarily be the case, depending on which depth ranges were chosen for the theoretical potential. It can reasonably be assumed that the military and valuable natural assets have higher priority than thermal energy storage in any political environment. However, HT-ATES is only required near areas where supply and high demand for heat coincide. This is usually the case in urban environments, while the military and natural assets are usually found outside urbanized areas. Therefore competition for space is unlikely and no policy scenarios are applied to this political factor.

Water law / *Waterwet*

As explained in the theory, HT-ATES in aquifers shallower than 500 meters below ground level is not allowed due to maximum injection temperatures of 25-30°C and the requirement of energy balance. For the purpose of this market potential framework, however, it was assumed that these restrictions in the water law do not exist. Therefore, there is no difference regarding these requirements in the BAU and ALT scenarios.

Energy Investment Rebate(EIA) / *Energie-investeringsaftrek*

The EIA is a regulation that allows the project developer to deduct 58% of the investment in an energy efficiency-improving technology from the earnings before tax. HT-ATES is one of the approved technologies that is eligible for EIA (RVO, 2016a).

Stimulation of Sustainable Energy Production (SDE^+) / *Stimulering Duurzame Energieproductie*

The SDE^+ is a subsidy that encourages production of renewable energy by compensating for its higher generation costs compared to non-renewable energy. It applies to biomass, solar PV, hydro, wind and geothermal projects. The amount of subsidy is determined by the difference between the generation costs per unit of heat by e.g. a specific geothermal doublet and the current price of non-renewable heat. If the price of non-renewable energy drops below a certain threshold, however, the SDE^+ does not further increase (RVO, 2016b).

HT-ATES is not a form of energy production and is therefore not eligible for SDE^+ stimulation. Yet, SDE^+ is relevant when HT-ATES is combined with a heat source that is eligible for SDE^+. SDE^+ stimulation is limited to a certain number of full load hours per year. The higher this number, the more profitable it is to increase the number of full load hours of the subsidized heat source. HT-ATES can facilitate a higher number of full load hours by storing extra heat produced in summer and delivering it in winter, provided that winter peak demand exceeds the power of the heat source.

Currently, geothermal heat production is eligible for SDE^+ stimulation for 5500 full load hours annually for a period of 15 years. Horticulturalist Paul Grootscholten of project GeoMEC-4P uses geothermal heat for his crops and has advanced plans to connect his geothermal well with HT-ATES. He considers the lowering of the former 7000 SDE^+ full load hours to 5500 as an important barrier for new similar projects (personal communication, April 20, 2016). Geothermal heat from depths beyond 3500m below ground level are eligible for 7000 SDE^+ full load hours.

The EU Emissions Trading System (EU ETS)

The EU ETS applies to the energy intensive industry and the power sector. Space heating itself does not fall under it and is left for national regulation (Schoots & Hammingh, 2015). Waste incineration plants generally produce useful electricity and heat, but – depending on member nations' interpretation of the European legislation - are excluded from the EU ETS (Bragadóttir, Magnusson, Seppänen, Sundén, & Yliheljo, 2016). Direct geothermal heat and solar heat do not directly emit CO_2. Therefore the only heat sources that fall under the EU ETS are fossil fuel-fired power plants and industrial processes using fossil fuels[3].

There is no direct influence of the EU ETS CO_2 prices on the business case of HT-ATES, as HT-ATES does not directly emit greenhouse gasses. However, if extra heat is produced for injection in HT-ATES, the amount of CO_2 tax increases. This extra tax can be allocated to HT-ATES and thus indirectly influences its business case.

---

[3] There are a number of exceptions to this general rule, see e.g. Stork et al. (2013). In this report those exceptions will be mentioned and taken into account if applicable to one of the case studies.

An important consideration is how many free emission allowances are granted. Rules regularly change and on top of that the installation of HT-ATES may entice the heat producer to produce more heat in summer to increase sales in winter. As a result, the share of emission allowances that need to be paid for is highly uncertain. For the market potential framework it is proposed that for each case study it is inquired how many emission permits were required in the most recent year and which share of those permits was free. This ratio can then be assumed to be equal in the target year.

When the actual costs of emissions that can be attributed to waste heat for HT-ATES have been calculated, it is still unclear how this affects the business case for HT-ATES. Waste heat becomes more costly when more CO_2 tax is paid during its production. That would theoretically make storing and using all waste heat more attractive. In practice, however, this is not more feasible than without CO_2 tax as the price per sold unit of heat is unlikely to increase as a result of the price cap for heat as regulated in the heat law(*Warmtewet,* see below). In the BAU scenario it therefore does not make sense to include CO_2 prices in the techno-economic analysis. In the ALT scenario, an alteration in the heat law is assumed to take place which allows passing on emission costs of heat to its final consumers. This makes investing in HT-ATES more interesting as the emission costs that would be paid by the heat producer if waste heat is discharged in summer, are paid by the heat consumer if summer waste heat is stored and sold during winter. This advantage can be simulated in the market potential assessment of case studies by increasing the heat sales price with the emission costs allocated to a unit of heat. Allocation of emissions between the primary product(electricity, products or services) and the secondary product(heat) can be based on energy content, as this is the functional unit for the final consumer of heat who eventually pays for the emissions.

Energy taxes

Taxes on natural gas consist of energy tax, a sustainable energy levy and VAT. The energy tax per m^3 of natural gas normally decreases with a higher annual consumption (see Table 3), but this does not apply to gas used in peak boilers of district heating systems. These peak boilers fall within the first (<170.000 m^3/year) energy tax bracket to which the highest energy tax rate applies, even if they consume more natural gas. However, the government stimulates relatively sustainable or efficient district heating systems by making an exception to this rule for peak boilers if at least 50% of the waste heat of a CHP, waste incinerator or power plant is used in a district heating network, or geothermal heat is the main supplier (Belastingdienst, 2016a; Kamp, 2015).

When comparing the energy tax of natural gas and electricity in the first tax bracket(<170.000 m^3 and <10.000 kWh respectively) on an energy content basis, it stands out that energy tax per unit of energy is currently almost four times higher for electricity than for gas. In 2015 this number was over six times higher. This has significant implications for the transition to a sustainable heat supply, e.g. by discouraging investments in household scale heat pumps (Den Ouden, Hoeksema, & Graafland, 2015). Investments in district heating networks are also discouraged. As the maximum consumer price of heat is determined by the gas price (see *Heat law*), a higher energy tax on natural gas increases the heat price. As a result, heat can also be sold to grid operators at a higher price in case the heat producers do not own the grid. This makes a business case for HT-ATES more likely, as the reference is the average price that heat is sold for. Considering that electricity is produced from natural gas with an efficiency of roughly 50%, the energy tax on natural gas is ideally half that of electricity instead of one fourth (Den Ouden et al., 2015). Table 3 shows the new energy tax tariffs with this change implemented on the first natural gas tax bracket, while keeping energy tax on electricity at the current level. Lowering the energy tax on electricity would be inconsistent with the desire to create a green tax system that encourages energy savings.

Like the energy tax, the sustainable energy levies per GJ decrease with higher natural gas consumption. An overview of the levy rates is given in appendix 2. Enterprises such as the district heating operator can deduct the VAT on natural gas from the VAT they charge to consumers of their heat. Therefore, VAT is left out of the framework. Energy tax and sustainable energy levy rates of 2016 are used in the framework, as projections of these taxes do not exist.

Table 3 *An overview of the energy tax rates in the Netherlands for natural gas and electricity. The BAU tax rates are the 2016 official tax rates taken from Belastingdienst (2016b) and converted to EUR/GJT The ALT tax rate in the first tax bracket for natural gas is levelized with the first tax bracket of electricity. The other tax brackets are equal to BAU rates. The energy content of natural gas is assumed to be 9,769 kWh/m*^{3}.

		BAU tax rate		**ALT tax rate**	
Natural gas (m3/year)	**Electricity (MWh/year)**	**Natural gas (EUR/GJ)**	**Electricity (EUR/GJ)**	**Natural gas (EUR/GJ)**	**Electricity (EUR/GJ)**
0-170.000	*0-10*	7,16	27,97	13,99	27,97
170-1.000.000	*10-50*	1,98	13,88	1,98	13,88
1.000.000-10.000.000	*50-10.000*	0,72	3,70	0,72	3,70
>10.000.000 (private)	*>10.000 (private)*	0,34	0,30	0,34	0,30
>10.000.000 (business)	*>10.000 (business)*	0,34	0,15	0,34	0,15

The heat law (Warmtewet)

One of the main purposes of the heat law is to protect owners of dwellings that are connected to a district heating network. The law's '*niet meer dan anders'* regulation entails that the price of heat may not exceed the costs of heating the same house with a household scale natural gas boiler. Although this prevents excessive heating costs for consumers, the law has received criticism as well. This has mostly to do with unfair competition due to a relatively low energy tax on natural gas (as compared to electricity) and the way natural gas grids are financed (Tigchelaar, 2015). Moreover, external costs of natural gas combustion are not included in the price consumers pay for natural gas. If households connected to a district heating network receive waste heat from a non-renewable(but efficient) heat source subject to the EU ETS, the external costs *are* paid for through the CO_2 tax. However, these cannot be passed on to the final consumer of the heat. In the ALT scenario it is therefore assumed that the heat law is modified to allow passing CO_2 tax on to the final consumers.

Other policies and regulations

Here, policies and regulations are discussed that do not yet exist in the Netherlands, but could play a key role in stimulating HT-ATES.

A heat ladder

By order of energy company and grid operator Eneco, De Beer, Slingerland, & Meindertsma (2014) published the heat ladder: a report with assessment criteria for the sustainability of heat sources in district heating networks. District heating networks have the advantage that any available source of heat can be used (Lund et al., 2014). However, the carbon footprint of e.g. waste heat from a coal plant is significantly larger than that of direct geothermal heat. In the light of ambitious decarbonisation targets and the many sustainable alternatives to district heating (e.g. solar boiler, heat pumps), it is important that a transition to more sustainable heat supply to district heating networks is stimulated. This is not only possible with more sustainable heat sources, but also by increasing the energy efficiency of heat sources. HT-ATES can provide efficiency improvements by preventing discharge of waste heat in summer, as well as facilitate an increase the production of (sustainable) geothermal heat per well, by facilitating year-round operation at higher power. This way, the full potential of a geothermal well is utilized, potentially improving its business case and sustainability.

Based on a ranking of heat sources on sustainability and efficiency, policies and regulations can be developed to phase out unsustainable and inefficient sources. This can be done using sticks or carrots, e.g. prohibiting heat sources with an energy efficiency below a certain threshold or imposing an extra tax for the most polluting heat sources. This stimulates HT-ATES as it can help increase the efficiency of existing plants.

Heat discharge tax

Probably the most direct method to stimulate HT-ATES investments is to prohibit or discourage the discharge of heat into the atmosphere or surface water. In Denmark, for example, it is mandatory for waste incineration plants to feed all waste heat into a district heating network (Bioregional, 2015). A carrot approach in the Netherlands could be a fine for every GJ of waste heat above a temperature threshold that is discharged by heat sources. In the context of this thesis this heat discharge tax applies only to heat sources connected to district heating networks, and the temperature threshold could be the temperature of the district heating network water. However, this could be considered unfair. If implemented in reality, a heat discharge tax could therefore potentially be applied to heat sources not connected to district heating networks as well. Further research on the consequences of such a policy is required though.

Information program

Two important reasons for insufficient investments in energy efficiency measures, are the lack of means or willingness to invest. These can be addressed with carrots or sticks, of which all of the above-mentioned factors are examples. A third reason for insufficient investments can be that companies lack awareness or knowledge. This can be addressed with sermons, i.e. the provision of information to potential investors by policy makers. The Rijksdienst voor Ondernemend Nederland(RVO), an executive body of the Ministry of Economic Affairs that stimulates entrepreneurs, already provides information about different energy efficiency measures such as ATES. HT-ATES, however, is not mentioned on their website. In fact, not a single government website mentions the technology, with the exception of the Kamerbrief Warmtevisie – a long document that few investors will read. The group of potential investors that have the willingness and means to save energy but lack the knowledge of state-of-the-art technologies to do so, may benefit from inclusion of HT-ATES information of the RVO website.

Policies and regulations for quantitative market potential assessment of case studies

Not all of the discussed policies and regulations discussed are quantifiable in a case study. Some are hard-to-quantify regulations(sticks) or information(sermons), while others are only relevant on a national scale rather than case study scale (e.g. excluded areas).

Table 4 contains the policies and regulations that are used as input for the quantitative market potential assessment of case studies (sections 5.3 and 5.4). EIA is increased by 20% to assess the impact of lowering capex; SDE$^+$ full load hours for direct geothermal heat are increased to the full number of hours in a year; energy tax on natural gas is levelled with tax on electricity; the EU ETS CO_2 price is increased to 30 EUR/tonne; the heat law is changed to allow passing on CO_2 tax to final heat consumers; and a heat discharge tax of 1,42 EUR/GJ of heat is introduced – equivalent to 0,05 EUR/m^3 of natural gas that is indirectly discharged.

The following factors are not translated into input factors: excluded areas, water law, heat law, heat ladder and the information program. However, the effects of the heat ladder and changes in the heat law are qualitatively represented by a proxy: the energy tax. A higher energy tax on natural gas has a similar effect as the discouragement of fossil heat sources with the heat ladder, and the increase of the reference price for heat in the heat law.

Table 4 *An overview of the input factors for techno-economic analysis of case studies in a business-as-usual(BAU) and alternative(ALT) scenario.*

Policy or regulation	BAU value	ALT value
EIA	58%	78%
SDE$^+$	Subsidy for 5500 (500-3500m) or 7000 (>3500m) full load hours	Subsidy for 8760 full load hours
Energy tax	4x lower tax on gas than on electricity based on final energy (Table 3)	Equal energy tax on electricity and gas based on final energy (Table 3)
EU ETS CO_2 price	n.a.	30 EUR/tonne
Heat law	ETS CO_2 costs cannot be passed on to final heat consumers	ETS CO_2 costs may be passed on to final heat consumer
Heat discharge tax	-	1,42 EUR/GJ

Economic factors

Many economic factors influence the business case of a HT-ATES project, but only the most important ones are required to make a first assessment. These factors are discussed in the following. If the outcome of a first assessment is positive, detailed calculations can be made that include more factors. Many economic factors vary between case studies and their exact values cannot be determined until a detailed, expensive and time consuming study is conducted. For some of these factors, average values are assumed that are based on expert estimates. Other factors vary too much and need to be determined for each case study individually.

Capital expenditure (capex)

The capital or investment costs are expenditures that are made before the HT-ATES installation commences operation. The main capital expenditures are the costs for drilling and a submersible pump. Drilling costs are assumed at 1000 EUR/m depth/well (there are two wells) and the price of a submersible pump is assumed to be 100,000 EUR.

Operational expenditure (opex)

The operational costs are expenditures that are made during HT-ATES operation. Opex consists of fixed and variable expenditures. The main variable expenditures are heat purchase and electricity costs for the submersible pumps, while the main fixed expenditures are related to maintenance (e.g. pump replacement; operation). The heat price must be determined for each case study individually and electricity costs are assumed at 50 EUR/MWh. Using the coefficient of performance(COP) of the submersible pump (which is case specific due to e.g. varying ΔT and depth) and the ATES recovery efficiency, the variable expenditures can be calculated. The fixed expenditure is assumed to be 1% of capex.

Full load hours

Full load hours refer to the number of hours per year that a HT-ATES installation delivers heat at full capacity, and can be calculated with the following formula:

$$Full\ load\ hours = \frac{thermal\ energy\ produced\ by\ HT - ATES\ in\ a\ year(MWh)}{HT - ATES\ thermal\ \ power\ (MW)}$$

Production power is lower than injection power due to losses in the subsurface, and thus the energy content per m^3 of produced water is lower than the energy content of the injected water.

Together with the maximum flow rate and ΔT, the number of full load hours determines the amount of thermal energy that has been produced by a HT-ATES in a year. The higher the number of full load hours, the lower the investment costs per unit of thermal energy produced from the aquifer. The number of full load hours is thus one of the key factors that determines the LCOE(Pluymaekers et al., 2013) and therefore the business case of HT-ATES installations.

The number of full load hours are determined by the demand profile of the district heating network that the HT-ATES system is connected to. Therefore, this parameter is case-specific and has to be determined from the demand-supply profiles acquired from the relevant parties at each case study.

It is assumed that the storage capacity of the aquifer is not a limiting factor, as this can usually be prevented by selecting an appropriate aquifer (at least in the Netherlands where suitable aquifers are relatively widespread).

Economic lifetime

Whereas ΔT , maximum flow rate and full load hours together determine how much thermal energy can be extracted from a HT-ATES per year, the economic lifetime determines the number of years – and thus the *total* amount of thermal energy - over which capex can be amortised. There is little experience with the technical lifetime of HT-ATES installations as very few are operational today. The installations that were operational in the 1970s and 1980s generally had short technical lifetimes due to the issues such as corrosion (Sanner & Knoblich, 1999). As solutions to these issues exist today, these lifetimes are no longer representative. Regular ATES installations are generally designed to have a lifetime equal to that of the building it supplies heat and cold to, which is usually 30-50 years (Bloemendal, Olsthoorn, & Boons, 2014). The main difference between ATES and HT-ATES is that the temperature of the water in the latter is higher, which was also the reason for most issues in the 1970s and 1980s. However, Kramers et al. (2012) quote technical lifetimes of geothermal doublets – which produce water of temperatures in the same range as HT-ATES – of 30 years. Based on this, it can be assumed that the technical lifetime of a well-maintained HT-ATES installation is in the same order of magnitude as a geothermal doublet. Due to the high level of uncertainty, however, a shorter economic lifetime of 15 years is assumed following Pluymaekers et al. (2013).

Inflation

Inflation rates in the Netherlands between 2000 and 2015 are displayed in Figure 9. For the LCOE calculations in the 2020-2034 period (the 15 years of HT-ATES economic lifetime after the target year), the average inflation rate over the 2000-2015 period – 2,0065% - is taken.

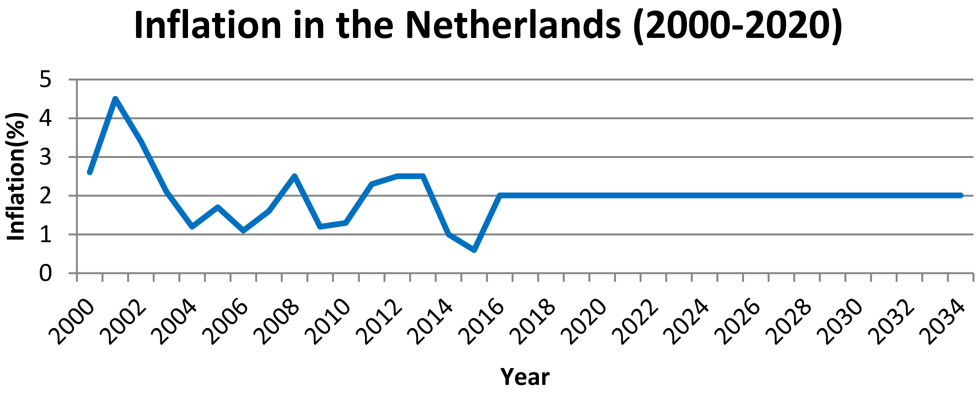


Figure 9 *Inflation rates in the Netherlands between 2000-2015(CBS, 2016) and the average of this period as a projection for the period 2016-2034.*

Natural gas price

The higher the price of natural gas, the higher the LCOE of boilers, and hence the more likely it is that HT-ATES has a business case. The consumer price of natural gas in the Netherlands consists of four components: the base price, energy tax, sustainable energy levy and VAT. The energy tax, sustainable energy levy and VAT are political factors and have been discussed previously. The base price of natural gas depends on many market factors and is volatile, making projections for 2020 uncertain. Here, the 2013 European Commission's reference scenario 2020 prediction of 80 $/boe (2010 price level) is used (European Commission, 2014). Assuming 1 boe=1700 kWh, a calorific value of 9,769 kWh/m^3 and the 2010 exchange rate used in the report (1€=1,36$), this equals 0,338 EUR/m^3. Correcting this for inflation (Figure 9) yields 0,40 EUR/m^3 or 11,51 EUR/GJ at 2020 price level. Gas prices after 2020 are highly uncertain and reliable projections are not available. Therefore, it is assumed here that the natural gas price after 2020 does not change. Prices between 2020 and 2034 are not corrected for the expected average inflation due to the high uncertainty range. An overview of the calculated natural gas price in each year as well as the applicable taxes and levies is given in appendix 2. To assess the impact of uncertainty in gas prices in 2020 and beyond, a sensitivity analysis must be conducted.

Electricity price

The price development up to 2020 and beyond is highly uncertain. This is partially a result of the transition to sustainable energy generation. In addition, the electricity price for driving the submersible pump has a small influence on the LCOE (as HT-ATES has a very high COP, typically in the range of one to several hundred). The HT-ATES tool standard electricity price of 50 EUR/MWh is therefore adopted in this framework.

Loan interest rate and discount rate

The large upfront investments in projects such as HT-ATES generally necessitate a loan, e.g. from a bank. Often a share of the capex is also equity. Here it is assumed that 80% of capex is a bank loan with an 8% interest rate and the remaining 20% is equity. The pursued interest on this equity by its provider is called *required return on investment*(RRI) or *discount rate*. A private discount rate of 15% is assumed for private investors and a 5% social discount rate for public investors. If case study-specific discount rates are provided, using those is preferred.

Technical factors

Technical factors are those factors that are directly related to the design and technical restrictions of the HT-ATES system, energy supplier and/or energy consumer, and cannot (or only slightly) be altered by market forces or operational strategies. Nevertheless, these factors have a very high impact on the economic profitability of the system.

Flow rate

The flow rate is the maximum amount of hot water(in m^3) that can be pumped up from a HT-ATES per hour. Together with ΔT, it determines the thermal power of the system. If the maximum flow rate is low, natural gas boilers may be required on the coldest winter days to meet heat demand. Similarly, insufficient capacity may be available to get all excess waste heat into the aquifer on a hot summer day. This negatively affects the business case for HT-ATES as it potentially reduces the amount of energy that can be produced per year. The thermal power of HT-ATES is generally lower than that of a natural gas-fired peak boiler, which makes HT-ATES a baseload heat source within peak heat supply. Consequently, boilers are often still required in addition to HT-ATES on the coldest days.

The maximum flow rate depends on a number of parameters that are different for each aquifer. Next to transmissivity (see section 6.1.1), the applied pump pressure, which for safety reasons need to be limited to 10% of the hydrostatic pressure (Pluymaekers et al., 2013), is an important parameter. The maximum flow rate must be determined for each case study individually as local subsurface conditions can vary considerably.

ΔT

ΔT represents the temperature difference between water produced from the hot well and water flowing back into the cold well after passing through a heat exchanger. ΔT is determined by the heat source, the HT-ATES recovery efficiency and the amount of heat extracted from the water in the district heating network (which depends on the degree of cascading demand). The higher ΔT, the higher is the storage capacity of the hot well and the higher is the *coefficient of performance*(COP) of the aquifer, as more energy is transported per m^3 of water that is pumped up. If less electricity is used by the pump to provide the same amount of thermal energy, opex decreases and consequently the LCOE decreases.

Different heat sources deliver waste heat with different temperatures. Depending on the type of heat demand (e.g. old dwellings or horticulture) and the age of district heating networks, return temperatures also vary considerably (e.g. Lund et al., 2014). Therefore case specific values have to be used. These can be corrected for the target year based on modifications scheduled for implementation before 2020.

Recovery efficiency

The recovery efficiency of HT-ATES systems can be calculated using the formula given in section 6.1.1. A higher efficiency means that more energy can be produced and less heat purchase is required. This results in a lower LCOE. Extensive, case-specific research of the subsurface is required to determine the recovery efficiency, so an efficiency assumption must be made. As a sensitivity analysis will be conducted for each case study, the previously established efficiency range of 60-85% (section 6.1.1) is replaced by its median of **72,5%** for case-specific market potential assessment.

Societal factors

Even when there is a viable business case after considering regulatory, financial and technical aspects, lack of social acceptance may complicate implementation of a project. Wüstenhagen, Wolsink, & Bürer (2007) divide social acceptance into three dimensions that can be both independent and interdependent: socio-political acceptance, community acceptance and market acceptance. Socio-political acceptance reflects the level of public support for a technology or policy in a broad sense. Community acceptance refers to the degree of acceptance of specific projects and their siting decisions by local stakeholders, such as local residents and authorities. A strong discrepancy can exist between socio-political acceptance and community acceptance of a specific technology. Wind power, for instance, has a high degree of socio-political acceptance in many countries in the light of the need for a transition to renewable energy supply. Yet, community acceptance is often lacking in communities located near the wind turbines, as they deal with the direct impacts on their surroundings. Market acceptance refers to the degree of market adoption of innovations, which depends on factors such as investor acceptance and path-dependencies of companies. The two other dimensions can also limit market acceptance: if there is no general support for an innovation or community acceptance is lacking, there is no market for an innovation (Wüstenhagen et al., 2007).

Lack of social acceptance of HT-ATES is not unthinkable. Although the technology does not have the problem of visual impacts that wind turbines deal with, concerns over the injection and production of hot water in the subsurface may be an issue. The earthquakes caused by natural gas production in the Dutch province of Groningen have negatively impacted both its socio-political acceptance and community acceptance, and several carbon capture and storage projects in the Netherlands experienced severe local objection in the past. As HT-ATES is often bound to urban environments, particularly community acceptance could be an issue.

Despite the potentially strong impact of societal factors on the market potential of HT-ATES, an assessment of societal factors is not part of this study due to time restrictions. Until further research into societal factors is conducted, any HT-ATES market potential calculated with the framework in this study therefore is preliminary.

5.2.2 The framework

In Table 5 the factors discussed in section 5.2.1 have been adopted into a step-by-step framework to assess the market potential of HT-ATES in the Netherlands. The basic framework can also be used for other countries or regions, but data sources as well as most assumptions and parameter values are specific for the Netherlands.

Table 5 *Framework for the calculation of the HT-ATES market potential.*

Step	Task	Description
1	**Start with the technical potential database**	The aquifer sections that remain after step 8 of the technical potential are the starting point for the further selection process based on market factors.
2	**Select hotspots**	Using the methodology and criteria of Huismans(2016), select the locations where sufficient demand and supply of heat coincide with suitable aquifer sections. Omit sections located in excluded areas.
3	**Acquire demand and supply profiles**	If a district heating network is already established or planned at a hotspot, contact the main heat producer and network operator. Gather expected demand-supply profiles for the target year, technical data and economic data of the chosen HT-ATES proprietor[4]. If there is no (planned) district heating network, exclude the hotspot from the database.
4	**Perform a quick scan of the subsurface**	Using subsurface databases such as REGIS II (The Netherlands) or literature (e.g. Hellebrand et al., 2012), select the most suitable aquifer in the vicinity. Calculate the expected maximum flowrate.
5	**Calculate the injection and production profile of HT-ATES**	This step is greatly simplified by using a HT-ATES calculation tool such the one described by Pluymaekers et al. (2013). Based on the mismatch between the demand and supply profiles, calculate for each week how much heat is available for injection and how much potential demand for stored heat exists. Correct for efficiency and HT-ATES power to get the actual injection and production profiles.
6	**Calculate the HT-ATES LCOE**	Using the parameters of section 6.2.1 and the HT-ATES injection-production profile, calculate the LCOE in the BAU and ALT scenarios.
7	**Compare HT-ATES LCOE to reference**	Calculate the reference LCOE or reference price of heat (see section 4.2.1) for the BAU and ALT scenarios. If the HT-ATES LCOE is lower than the reference, there is a viable business case for HT-ATES and the hotspot is part of the HT-ATES market potential.
9	**Calculate savings**	For the case studies with a viable business case, calculate how much natural gas would be required to generate this amount of final energy produced by HT-ATES. Calculate avoided boiler CO_2-emissions assuming 56,4 kg CO_2/GJ (Zijlema, 2013).
10	**Sensitivity analysis**	Conduct sensitivity analysis to assess the robustness of the results
11	**Calculate market potential**	Add up the energy and CO_2-emission savings of each case study with a viable business case for HT-ATES within the area of interest.
		→ Market potential

---

[4] Select the HT-ATES proprietor based on a preliminary investigation of the benefits that each potential proprietor would potentially get from HT-ATES.

5.3 Case study 1: Groningen

5.3.1 Background

Groningen is a university city with approximately 200.000 inhabitants in the north of the Netherlands (Figure 10). Like in many cities in the Netherlands, natural gas is predominantly used for spatial heating and no district heating network is present. However, the municipality decided to construct a district heating network with a sustainable heat source in the north-western part of the city to progress towards its goal of being carbon neutral by 2035. The heat programme is planned to contribute 15% to reaching this goal, which corresponds to heating and cooling approximately 40.000 household equivalents (Van Huissteden, 2015). Geothermal heat was chosen as the grid's main heat source, in part due to the favourable geothermal gradient locally. Construction of the grid starts late 2016 and drilling of the geothermal well is planned to commence in the second half of 2017 (Appendix 4). Watercompany Groningen and the municipality together started Warmtestad Groningen, the organisation responsible for construction and operation of the entire district heating network (Van Huissteden, 2015).

The planned location of the geothermal well is near the Zernike Science Park north of the city centre. At just over 3500m deep, the well is expected to produce formation water at 116^{o}C from the Slochteren formation. Due to its vicinity to the Slochteren gas fields, 1 m^{3} of natural gas is expected to be produced per m^{3} of formation water. After separation of the gas the water flows through a heat exchanger that cools it down to 50^{o}C, after which it is pumped back into the formation. The water in the district heating network is kept below 100^{o}C for legislative reasons. The formation gas is directly burned in a small CHP plant next to the geothermal well. Its power varies according to the flow rate – and thus power – of the geothermal well, as the natural gas cannot be stored. With an expected maximum flowrate of 200 m^{3}/hour the thermal power of the geothermal well is 11,37 MW$_{th}$, while the CHP plant has a maximum thermal power of 1,04 MW$_{th}$. Consequently, for every GJ of heat produced by the well-CHP combination, 0,92 GJ originates from the geothermal well and 0,08 GJ originates from the CHP plant. As the geothermal well and CHP plant are linked and both use energy from the subsurface, the heat production of the CHP plant is added to the geothermal heat production and treated as one in this case study. A 1000 m^{3} storage tank serves as a buffer on timescales ranging from hours to several days. Four 10,5 MW gas-fired peak boilers distributed over the district heating network provide extra capacity during peak demand (Appendix 4).

Figure 10 shows the route of the thermal grid from the geothermal well to the different neighbourhoods. Eventually, the network is projected to supply heat to approximately 11.700 household equivalents (Van Huissteden, 2015). In the first phase, approximately 20 buildings in the neighbourhoods Paddepoel and Selwerd will be connected, while 40 more buildings in Paddepoel and Selwerd, as well as in Vinkhuizen, Kostverloren and Zernike will be connected in the second phase. The main pipelines will be buried under a bicycle road. Many buildings in Groningen have collective gas-fired boilers coupled to an internal water circulation system. These buildings, as well as other large buildings, will first be connected to the district heating network as this can be done relatively cheaply and easily. Smaller buildings, such as dwellings with individual gas boilers, can be connected once the primary thermal grid is finished and the 'low hanging fruit' (i.e. large buildings with collective heating systems that require little investments to be connected) has been connected. The possibility of connecting Suikerunie and Smurfit Kappa, two industrial companies with large heat demand, is currently being studied. The district heating network is constructed primarily for existing buildings on purpose, to avoid risks like those taken in Den Haag – where a geothermal project went bankrupt when the building rate of new households to be connected to the grid stayed below expectations and thus insufficient demand remained (Platform Geothermie, 2013; Van Huissteden, 2015; Appendix 4).

Although the flowrate of a geothermal well can be regulated, and therefore no heat needs to be wasted in summer, HT-ATES can play an important role in making the planned district heating network more sustainable and profitable. In summertime, heat demand can decline to 10% of the geothermal power. However, it is undesirable to let the well's flowrate fall below 90 m^3/hour from a technical point of view (see Appendix 4). From an economic point of view it is desirable to operate at full power as much as possible, as more SDE^+ subsidy can be received and the capex can be spread out over more units of produced heat. On cold winter days, heat demand can be up to four times the geothermal power when the grid is completed. Peak heat supply from natural gas boilers is required then, but natural gas is expensive and it is unknown how its price will develop in the future. Therefore, both risk and costs would be lower if peak heat demand is supplied by the geothermal well, which has relatively low operational costs. HT-ATES can facilitate this by injecting extra geothermal heat in summer and producing it in winter. Although HT-ATES power is typically too low to supply all peak heat demand, it can significantly reduce the amount of full load hours of gas boilers. Moreover, HT-ATES acts as an additional heat source and thus increases the security of supply, e.g. when there are technical problems with the geothermal well. Another potential destination for extra heat in summer is an absorption cooler that can reduce the cold shortage in the ATES system of the University of Groningen. This 2,5 MW connection could consume about 15.000 GJ_{th} per summer (see Appendix 4).

In the next section (5.3.2) a quantitative study of the planned Groningen district heating network using the market potential assessment framework will be performed, to assess whether there is a viable business case for HT-ATES. If there is a viable business case, the district heating network in northwest Groningen can be added to the 2020 market potential of HT-ATES.

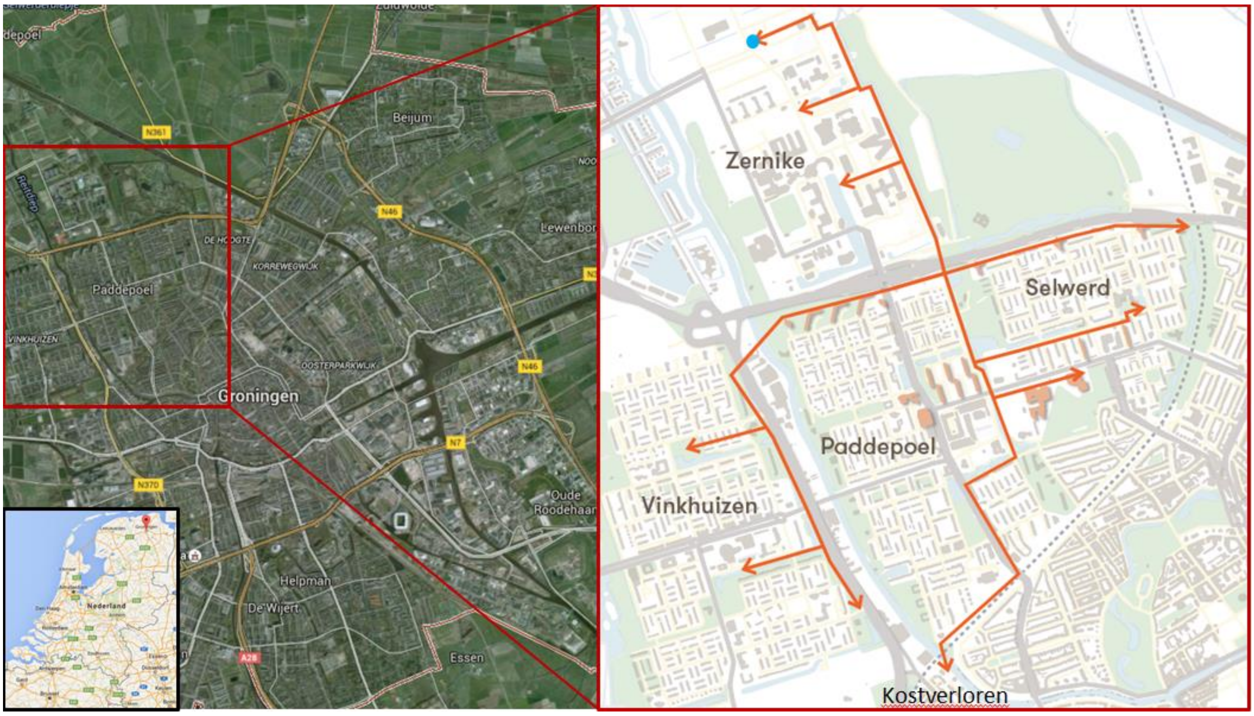


Figure 10 *The route of the planned district heating network in the northwest of Groningen and the location of Groningen in the Netherlands. The blue dot indicates the planned location of the geothermal well. From: Google Maps (left image) and Energy Valley Top Club (2015)(right image).*

5.3.2 Market potential assessment

Subsurface assessment

The salt/brackish water interface around Zernike is located at a depth of approximately 50 meters below ground level. As exploration wells for drinking water are useless below this interface, no well measurements are available locally beyond approximately 100 meters depth. The REGIS II database is thus not useful for finding a suitable aquifer for HT-ATES near Zernike. Deep geological models such as the deep Digital Geological Model(TNO, n.d.) do contain wells up to several kilometres, but their resolution in the relevant depth range is too low to use. Therefore, the estimations of Hellebrand, Post, & In 't Groen (2012) are used (see section 3.3).

Based on key parameters summarized in Table 6, the formation of Oosterhout is selected as the most suitable formation for HT-ATES. While its depth and temperature range is similar to that of the Brussels Sand and the formation of Breda, its flow rate is estimated to be significantly higher, partially due to its thickness. The formation of Maassluis is excluded as an option as it does not occur locally or no well data is available to indicate its presence. As the chosen formation's flow rate range of 55-100 m^3/hour is rather broad, the average of 77,5 is used here. Similarly, the depth of the base is assumed to be 375m below ground level. The average of the thickness range is 125m; half of this is deducted from the base depth to reach the assumption that the well reaches until the middle of the formation at 312,5m. A sensitivity analysis is conducted in section 5.3.3 to deal with the uncertainty in these assumptions.

Table 6 *An overview of key parameters in the Zernike area for four formations studied by Hellebrand et al. (2012).*

Parameter	Unit	Brussels Sand	Formation of Breda	**Formation of Oosterhout**	Formation of Maassluis
Depth of base	Meters	301-450	301-450	**301-450**	n.d.
Net thickness[5]	Meters	31-60	0-50	**101-150**	n.d.
Flow rate	m^3/hour	1-15	25-50	**55-100**	n.d.

n.d. = no data available or the formation is not present locally.

Heat demand and supply profiles

Figure 11 shows the 2020 profiles of demand for heat from the district heating network, as well as supply of heat from the geothermal well and the CHP combined. The purple dashed line shows the maximum amount of geothermal/CHP heat that can be produced in a week. Where the supply line lies below this line, demand for heat is higher than the maximum supply capacity during at least part of a week. The graph shows that this is only the case in week 2, but nevertheless there is a heat shortage in weeks 1-16 and 41-53. This is the result of lowering the resolution of the demand-supply data from hourly to weekly: during most of the week demand exceeds supply, but in the same week the opposite also happens during at least one hour. Without storage, the geothermal well and CHP do not produce more heat than demanded at any given moment. Therefore the weekly capacity is only supplied by the geothermal well and CHP if demand equals or exceeds its power during the entire week.

---

[5] The net thickness represents the thickness of the formation from which water can be extracted.

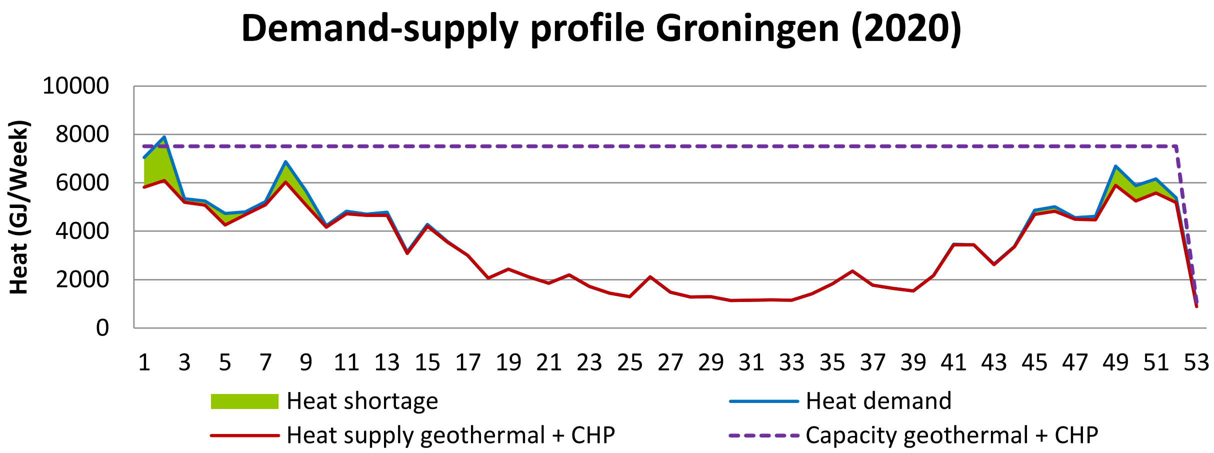


Figure 11 *Graph showing the heat demand, heat supply by geothermal well + CHP and maximum capacity of geothermal well + CHP for each week in 2020. The area highlighted in green represents the part of heat demand that cannot be supplied by the geothermal well and CHP.*

As - with the exception of week 2 - deficient and surplus capacity of the geothermal well/CHP coincides only within a single day or week, simple above-ground storage tanks suffice to cover this mismatch. A cheap central natural gas boiler would likely be the cheapest option to generate the heat deficit in week 2. It can thus already be concluded from Figure 11 that a viable business case for HT-ATES – which is particularly suitable to cover seasonal mismatches between demand and supply - is almost certainly impossible with the assumed heat demand in 2020. However, as the district heating network will still be in development after 2020, demand will grow further.

Figure 12 shows the same demand-supply profiles for the situation in 2034. Compared to 2020, heat demand exceeds the capacity of the geothermal well/ CHP during more weeks, while the heat shortage in these weeks is also higher. However, the amount of heat that could potentially be produced by a HT-ATES system – equal to the green area lying above the purple dashed line – remains small compared to the amount of heat that is available for injection – equal to the area below the purple dashed line and above the blue demand line. This means that the geothermal well and CHP combined have a significant capacity surplus over the year as a whole. If the geothermal well and its CHP would operate at full power year-round, approximately 391 TJ of heat is generated, while the heat demand of the entire year sums up to approximately 285 TJ (Table 7).

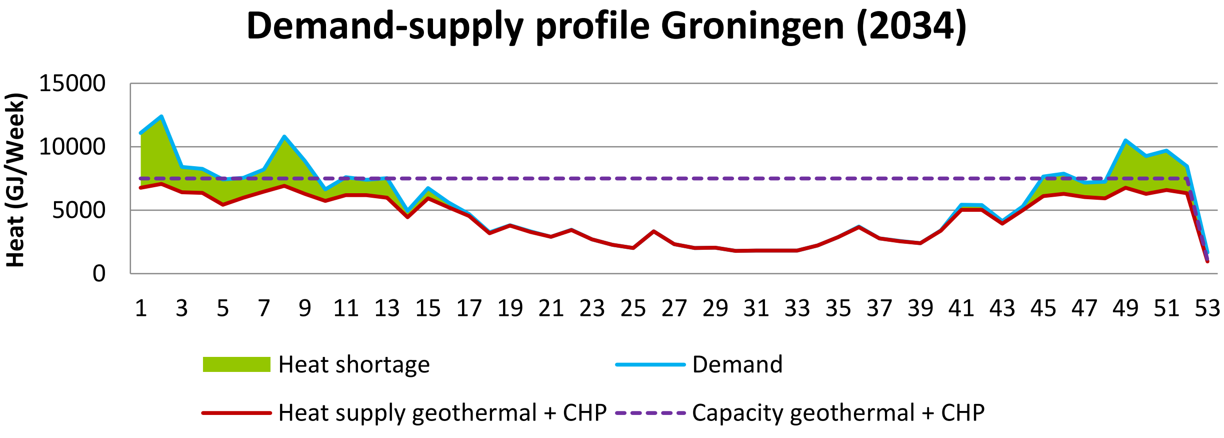


Figure 12 *Graph showing the projected heat demand, heat supply by geothermal well and CHP and maximum capacity of geothermal well + CHP for each week in 2034. The area highlighted in green represents the part of heat demand that cannot be supplied by the geothermal well/CHP.*

Table 7 *Overview of key demand and supply numbers from Figure 11 and Figure 12.*

	2020	2034
Sum of heat demand	181.019 GJ	284.894 GJ
Sum of geothermal heat supply	172.025 GJ	232.813 GJ
Annual capacity geothermal heat supply	391.375 GJ	391.375 GJ
Full load hours geothermal well + CHP	3850,4 hours	5211,0 hours

HT-ATES gross LCOE calculations

Having interpreted the demand-supply profiles qualitatively in the previous paragraph, the next step is to conduct a quantitative assessment of the HT-ATES LCOE in two policy scenarios using the HT-ATES tool. These will subsequently be compared to the reference LCOE to determine if there is a business case. However, to illustrate how different demand-supply profiles (Figure 11 and Figure 12) influence the production and injection of a HT-ATES, the *original* HT-ATES tool (which uses demand-supply profiles of a single year) is first run twice with the input parameters in Table 8: once for 2020 and once for 2034. Subsequently, the *modified* HT-ATES tool is run with the demand-supply profiles of each of the years 2020-2034, to calculate the HT-ATES LCOE taking into account the demand growth until 2030 (Figure 13).

An overview of the most important input parameter values for the HT-ATES tool is given in Table 8. A full list of the parameters used in the HTO tool can be found in appendix 1. The HT-ATES injection and production profiles for 2020 and 2034 are depicted in Figure 14 and Figure 15. Key graph indicators as well as other relevant operational indicators are listed in Table 9.

The conclusion drawn from Figure 11 is confirmed by Figure 14: the heat demand remaining for a HT-ATES installation in 2020 - after the existing surface buffer tanks have levelled the demand-supply mismatch within daily or weekly timescales – is almost negligible at 383 GJ per year. The overcapacity of the geothermal well and its CHP plant is apparent from the 359 injection/production ratio. For a balanced HT-ATES system this ratio is ideally as close to 1,38 as possible, considering that 27,5% of the injected energy cannot be recovered (and therefore the ratio can never be smaller than 1,38). The high capital expenditure for a HT-ATES can only be spread over 29 full load hours per year, which is reflected in a very high LCOE value of **545,79 EUR/GJ** if the demand size in 2020 would remain constant for 15 years.

The injection and production profile for 2034 (Figure 15) has a better balance as a result of the higher demand for heat. Instead of the 359 GJ injected for each GJ produced in the normal demand scenario, only 4,15 GJ is injected for each GJ of heat produced by the HT-ATES. The amount of heat produced is still modest compared to the production potential, as is consequently the number of production full load hours: 1634. Nevertheless, the LCOE - if this demand size would remain constant for 15 years - is much lower than in 2020: **12,91 EUR/GJ**.

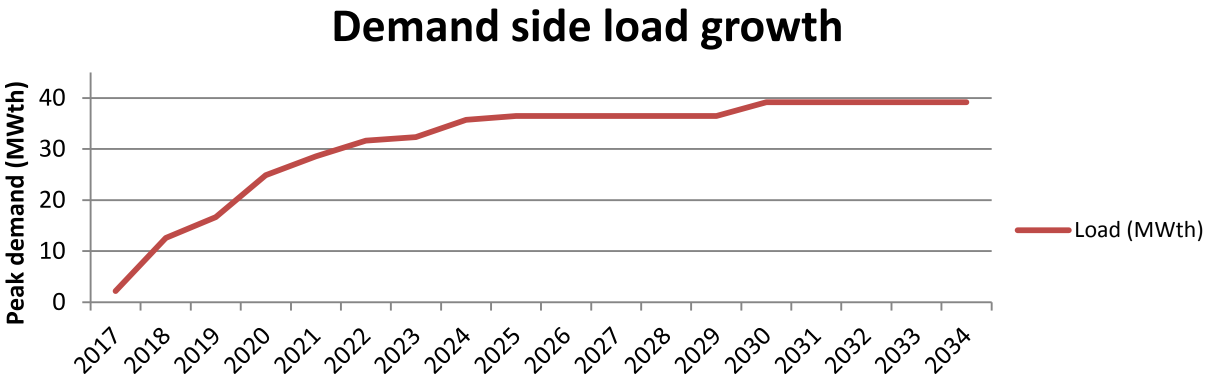


Figure 13 *The projected growth in peak demand connected to the district heating system of Groningen.*

Table 8 An overview of the main parameter values used in the HT-ATES tool to calculate the LCOE of a HT-ATES.

Parameter	Unit	Value
Combined geothermal + CHP power	MW_{th}	12,41[a]
Production temperature geothermal well + CHP	°C	116[a]
Cascaded final water temperature of return flow	°C	60[a]
HT-ATES recovery efficiency	%	72,5
Heat in HT-ATES at day one	GJ	174.257[b]
Maximum flowrate HT-ATES	m^3/hour	77,5
Depth of well	Meters below ground level	312,5
Economic lifetime	Years	15[d]
Capital expenditure	Euro	1.480.883[c]
Share of equity in investment	%	20[d]
Share of loan in investment	%	80[d]
Loan rate	%	8[d]
Loan term	Years	15[d]
Discount rate	%	6[e]
Marginal cost of geothermal heat	EUR/GJ	2[a]
Electricity price for pumps	EUR/MWh_e	50[d]
Maintenance costs per year	Euro	14.809[f]
Inflation	%	2,0065

a: Parameter value provided by Warmtebedrijf Groningen

b: Equal to the heat stored in the HT-ATES after week 53 in 2020 when running the model with an initial heat content of 0 GJ*. Due to the surplus injection potential of 359 times the production in 2020, changing this parameter has no influence on the amount of heat produced unless lower than 383 GJ (the production in 2020)*

c: Calculated by the HT-ATES tool based on temperatures, flow rate, depth and standard costs for drilling, pump, heat exchanger(Pluymaekers et al., 2013)

d: Standard parameter value in HT-ATES tool

e: Van Huissteden (2015)

f: 1% of capex

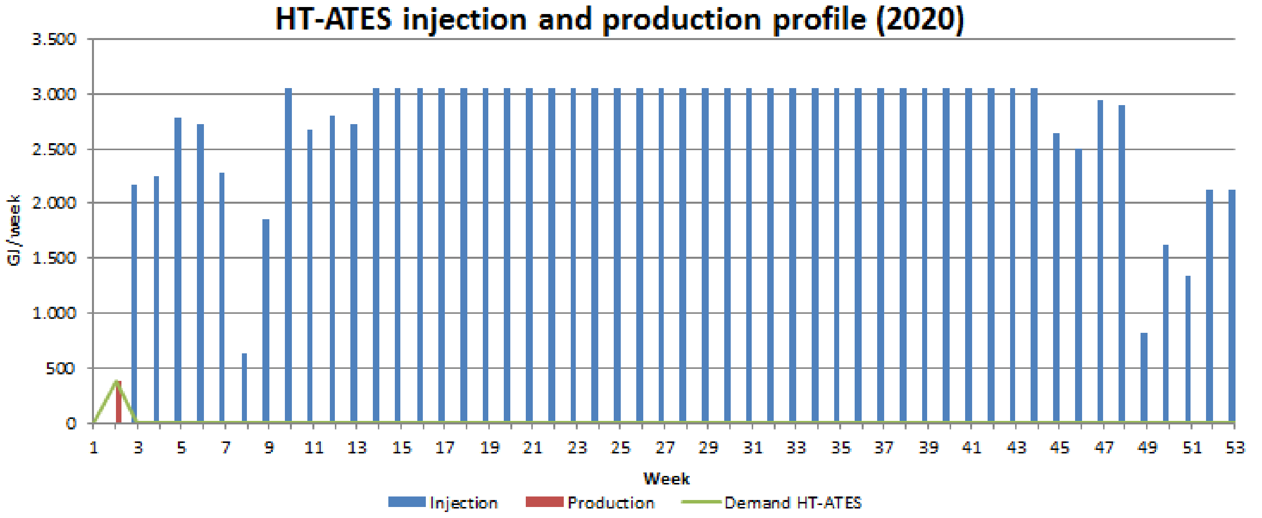


Figure 14 *The HT-ATES injection and production profile in 2020 as calculated by the HT-ATES tool. Injection refers to the maximum amount of heat that can potentially be injected into the HT-ATES, based on the availability of surplus geothermal heat and the injection power of the HT-ATES (5,04 MW). The amount of heat that is injected in reality is determined by an operator based on the expected demand profile in the next winter.*

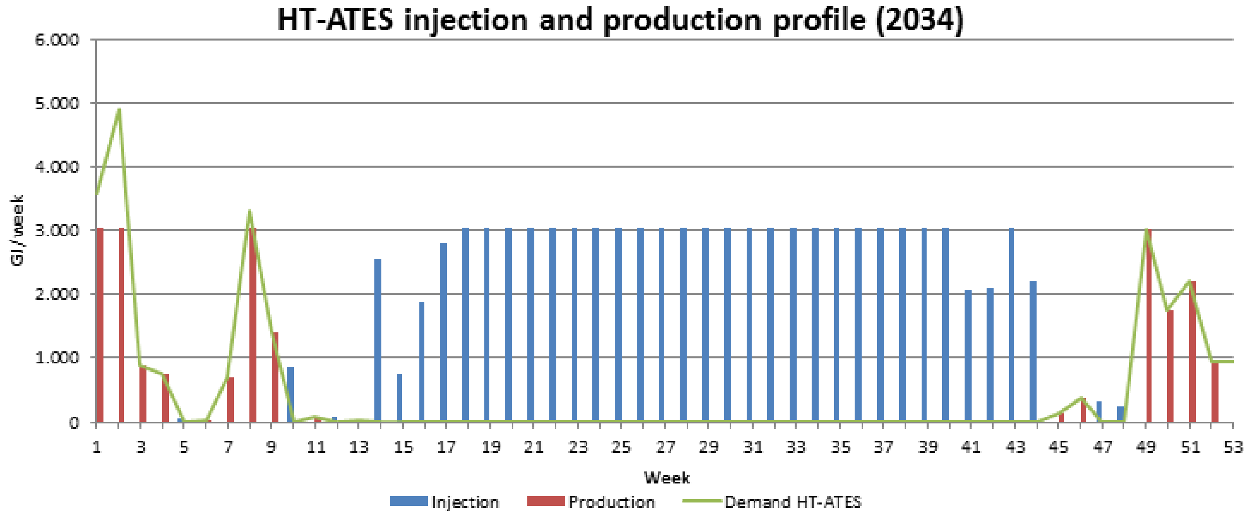


Figure 15 *The HT-ATES injection and production profile in 2030 as calculated by the HT-ATES tool. Injection refers to the maximum amount of heat that can potentially be injected into the HT-ATES, based on the availability of surplus geothermal heat and the injection power of the HT-ATES (5,04 MW). The amount of heat that is injected in reality is determined by an operator based on the expected demand profile in the next winter.*

HT-ATES full load hours increase between 2020 and 2034 due to the growth of heat demand (Table 9), while other factors influencing the LCOE remain constant (Table 8). Therefore, it is expected that the LCOE calculated with the demand-supply profiles of all 15 years of the HT-ATES economic lifetime, is between the LCOE values found using only the 2020 and 2034 demand profiles. Indeed, running the modified HT-ATES tool for all 15 years results in a LCOE of **18,51 EUR/GJ**.

Table 9 *Overview of key operational indicators of the HT-ATES tool for each year between 2020 and 2034. Some years are stacked as demand is equal in each of them.*

	Unit	2020	2021	2022	2023	2024	2025-2029	2030-2034
Heat available for injection	GJ	137.753	122.839	111.975	109.603	98.231	96.022	89.114
Sum produced heat	GJ	383	2.710	6.560	7.679	13.384	15.281	21.498
Ratio injection:production	-	359:1	45:1	17:1	14:1	7:1	6:1	4:1
Power HT-ATES (injection)	MW_{th}	5,04	5,04	5,04	5,04	5,04	5,04	5,04
Power HT-ATES (production)	MW_{th}	3,65	3,65	3,65	3,65	3,65	3,65	3,65
Annual production capacity	GJ/year	115.232	115.232	115.232	115.232	115.232	115.232	115.232
Full load hours HT-ATES (production)	hours	29	206	499	584	1017	1162	1634

Table 10 *Overview of the input data and calculation steps required to calculate the extra SDE$^+$ subsidy acquired with HT-ATES for each scenario. The values for 'Required heat injection for HT-ATES production' are calculated assuming perfect foresight of heat demand, i.e. no more heat is injected than required for production, taking into the account recovery efficiency.*

	Unit	2020	2021	2022	2023	2024	2025-2029	2030
Required heat injection for HT-ATES production	GJ	528	3.738	9.048	10.592	18.461	21.079	29.652
Power geothermal well	MW_{th}	11,37	11,37	11,37	11,37	11,37	11,37	11,37
Required full load hours to produce stored heat	Hours	12,9	91,3	221,0	258,8	451,0	514,9	724,5
Full load hours geothermal well without storage	Hours	3850,4	4274,4	4582,1	4647,4	4941,4	5006,3	5211,0
Full load hours geothermal well including storage	Hours	3863,3	4365,7	4803,1	4904,6	5392,4	5521,3	5935,4
Extra SDE$^+$ full load hours in BAU scenario	Hours	12,9	91,3	221,0	258,8	451,0	514,9	724,4
Extra SDE$^+$ full load hours in ALT scenario	Hours	12,9	91,3	221,0	258,8	451,0	514,9	724,4
Extra SDE$^+$ subsidy per year in BAU scenario	Euro	161,5	1141,5	2763,1	3234,8	5637,6	6436,9	9055,5
Extra SDE$^+$ subsidy per year in ALT scenario	Euro	161,5	1141,5	2763,1	3234,8	5637,6	6436,9	9055,5

Policy scenarios and the net LCOE

The aforementioned LCOE value of 18,51 EUR/GJ is defined here as the gross LCOE. To get the net LCOE – which will ultimately be compared to the reference net LCOE to determine if there is a viable business case - the effects of policies and regulations as described in section 5.2.1 are included. In this case study, only the SDE$^+$ subsidy, EIA and energy tax apply. A heat discharge tax is not applicable, as the flowrate of the geothermal well can be controlled to prevent overproduction. The EU ETS does not apply to geothermal heat either, as there are no direct CO_2-emissions. In this section the HT-ATES net LCOE is calculated. The energy tax scenario is taken into account in the calculation of the reference LCOE in the next section.

As the storage of heat in the HT-ATES enables more production and sales of heat from the geothermal well, the SDE$^+$ subsidy received for the geothermal well is increased. This extra subsidy is attributed to the HT-ATES business case, as it is because of the storage that more subsidy is granted. The SDE$^+$ subsidy for the geothermal well in Groningen amounts to 12,5 EUR/GJ produced. This is 10,5 EUR/GJ higher than the marginal costs of producing extra heat for the HT-ATES, and is therefore expected to have a significant positive effect on the HT-ATES business case. SDE$^+$ subsidy is granted for a maximum of 7000 full load hours as the well reaches just beyond 3500m below ground level.

In Table 10, the annual extra SDE+ subsidy due to HT-ATES is calculated for each policy scenario. The extra SDE$^+$ is calculated with the heat produced by HT-ATES rather than the injected heat, as only the produced heat is used by final consumers. The SDE income is incorporated in the LCOE calculation by adding the SDE+ as an income factor in the HT-ATES tool. Although the LCOE normally takes into account only costs, this strategy can be justified by treating the SDE+ as a discount on the heat purchasing costs that turns the latter into a negative costs, i.e. an income. The effect of the EIA on the gross LCOE in both policy scenarios is calculated as a tax discount. The intermediate LCOE calculations in Table 11 allow for comparison of the impact of the EIA and SDE+ subsidy. Finally, the net LCOE is calculated for both policy scenarios by incorporating both the IEA and SDE$^+$ (Table 11).

In the overview of the different LCOE values (Table 11) it can be seen that, as expected, the impact of the SDE+ subsidy on the HT-ATES LCOE is strong. SDE+ reduces the LCOE by 14,74 EUR/GJ in both the BAU and ALT scenario. This number is equal in both policy scenarios as the current(BAU) maximum SDE+ full load hours(7000) are not exceeded (Table 10). The fact that 12,5 Euro of SDE+ reduces the LCOE by 14,74 EUR/GJ is a consequence of the annual payment of SDE+: this income reduces the amount of money required from a bank loan and thus reduces the interest paid.

The effect of the EIA on the LCOE (-2,25/-3,03) is smaller than the effect of SDE+ subsidy (-14,74), but nevertheless significant. The effects of SDE and IEA combined result in a net LCOE of 1,52 EUR/GJ(BAU) and 0,74 EUR/GJ(ALT). Whether the HT-ATES net LCOE is lower than the reference LCOE in either of the policy scenarios, will be assessed in the next sections.

Table 11 *An overview of the HT-ATES levelized cost of energy(LCOE) in EUR/GJ$_{th}$ without policy impacts (gross LCOE), with all policy impacts (net LCOE) and the individual contribution of policies and regulations in the business-as-usual(BAU) and alternative(ALT) policy scenarios.*

	€ (BAU)	€ (ALT)
Gross LCOE	18,51	18,51
Contribution of EIA	-2,25	-3,03
Contribution of SDE$^+$	-14,74	-14,74
Net LCOE	1,52	0,74

Reference LCOE calculation

As construction of the thermal grid commences before the planned commissioning of the geothermal well, all heat will initially be delivered by the four natural gas boilers that will be employed as peak heat sources once the geothermal well is operational (see Appendix 4). The reference LCOE is therefore calculated with the capex and fixed opex of four boilers, even though not all four are required in the first few years following 2020, when demand is still relatively low. However, in the LCOE calculation the first years of heat supply are ignored and 2020 is assumed as the first year of operation. In Table 12 the key properties and assumptions of the boilers are listed. Financial parameters such as share of equity, discount rate, loan interest rate and inflation are equal to those for the HT-ATES LCOE calculation (Table 8).

Running the HT-ATES tool with the input of Table 8, Table 12, Table 13 and the tax rates listed in appendix 2 results in LCOE values of **23,91 EUR/GJ** (BAU) and **27,13 EUR/GJ** (ALT) (Table 14). Looking at the final natural gas price in Table 13, it already becomes apparent that the gas price alone is responsible for most of the levelized costs: the weighted average final natural gas prices are 18,45 EUR/GJ (BAU) and 21,04 EUR/GJ (ALT), which make up 77,13% and 77,55% of the LCOE respectively.

Table 12 *Overview of key parameters of the natural gas peak boilers that will be used in the Groningen district heating network. Where applicable, all parameters are displayed as combined(summed) values for four boilers.*

Parameter	Unit	Value
Manufacturer and type	-	FH Crone CLW 275 6 bar (no condenser)
Power	MW_{th}	42[a]
Capex	Euro	205.220[a]
Fixed maintenance costs	Euro/year	2052,2[b]
Economic lifetime	Years	15[c]
Thermal efficiency	%	88,2 (LHV)[d]

a: Parameter value taken from manufacturer quotation.

b: Estimated at 1% of capex based on communication with manufacturer F&H Crone (R. van Leeuwen, personal communication, June 20, 2016) and the assumptions in the Vesta spatial model (Leguijt & Schepers, 2014)

c: As the technical lifetime proved highly uncertain after literature research and contact with manufacturer F&H Crone (R. van Leeuwen, personal communication, June 20, 2016), an economic lifetime of 15 years is assumed

d: Parameter value taken from manufacturer's website (F&H Crone B.V., 2011). Due to the lack of a condenser on the boilers expected in the Groningen district heating network, the lower heating value(LHV) is used.

Table 13 *Calculation summary of the fuel costs of the four natural gas peak boilers in each year for the BAU and ALT policy scenarios. The final natural gas price represents the natural gas purchase costs per GJ_{th} of final energy. All calculations are performed assuming the caloric value of natural gas is 9,769 kWh/m^3 (0,035 GJ/m^3). An overview of energy taxes and levies is given in appendix 2.*

	2020	2021	2022	2023	2024	2025-2029	2030-2034
Natural gas price without tax (EUR/GJ)	11,51[a]	11,51	11,51	11,51	11,51	11,51	11,51
Heat demand (GJ)	383	2710	6560	7679	13384	15281	21498
Required natural gas (m^3)	13264	93744	226913	265649	462982	528616	743670
Gas in first tax bracket (m^3)	13264	93744	170000	170000	170000	170000	170000
Gas in second tax bracket (m^3)	0	0	56913	95649	292982	358616	573670
Total base costs natural gas (Euro)	5369	37947	91852	107532	187410	213978	301029
Total energy tax BAU (Euro)	3338	23594	46743	49437	63160	67724	82679
Total energy tax ALT (Euro)	6524	46110	87575	90269	103992	108556	123511
Total sustainable energy levy (Euro)	24	171	432	515	936	1076	1534
Final natural gas price BAU (EUR/GJ_{th})	22,77	22,77	21,19	20,51	18,79	18,50	17,92
Final natural gas price ALT (EUR/GJ_{th})	31,08	31,08	27,42	25,82	21,84	21,18	19,82

a: Projection of the European Commission (2014)

Table 14 *Overview of the levelized costs of energy(LCOE) in EUR/GJ for HT-ATES and gas boilers(reference) in two policy scenarios. The HT-ATES gross LCOE is the LCOE without taking into account the effects of policies and regulations(SDE$^+$; EIA), while in the net LCOE these policies and regulations are incorporated.*

	BAU		**ALT**	
	HT-ATES	**Reference**	**HT-ATES**	**Reference**
Gross LCOE	€ 18,51	n.a.	€ 18,51	n.a.
Contribution of EIA	€ -2,25	n.a.	€ -3,03	n.a.
Contribution of SDE$^+$	€ -14,74	n.a.	€ -14,74	n.a.
Net LCOE	€ 1,52	€ 23,91	€ 0,74	€ 27,13

LCOE comparison

An overview of all LCOE values for HT-ATES and its reference is given in Table 14 and visualized in Figure 16. It is clear that the net LCOE of HT-ATES is lower than the reference LCOE, both in the business-as-usual (-22,39 EUR/GJ) and alternative scenario (26,39 EUR/GJ). The large difference is mainly caused by the extra SDE^+ subsidy. The influence of the EIA on the HT-ATES LCOE is smaller. HT-ATES gross LCOE values (without SDE^+ and EIA) are also lower than the reference LCOE values, with a difference of -5,40 EUR/GJ(BAU) and -8,62 EUR/GJ(ALT).

Based (inter alia) on the demand and supply projections provided by Warmtebedrijf Groningen and the assumed parameters in Table 8 and Table 12, there is a viable business case for HT-ATES in 2020 in the Groningen district heating network. Uncertainty in assumptions, however, is a risk factor that could alter this outcome. The sensitivity analysis in section 5.3.3 will quantify the potential impact of this uncertainty on the outcome of the business case.

As there is a viable business case for HT-ATES in Groningen, this case study can be included in the HT-ATES market potential. With an expected total heat production during the 15 year lifetime of approximately 215 TJ, the natural gas savings potential amounts to approximately 7.424.000 m^3, equalling 15 kt of avoided direct CO_2-emissions from natural gas boilers[6]. After correcting for the emissions of the CHP, a savings potential of 14 kt of avoided direct CO_2-emissions in 15 years remains. Over the same period, approximately 2,35 million Euros are saved with HT-ATES and its CO_2 mitigation costs are circa -5,83 EUR/tCO_2 avoided[7].

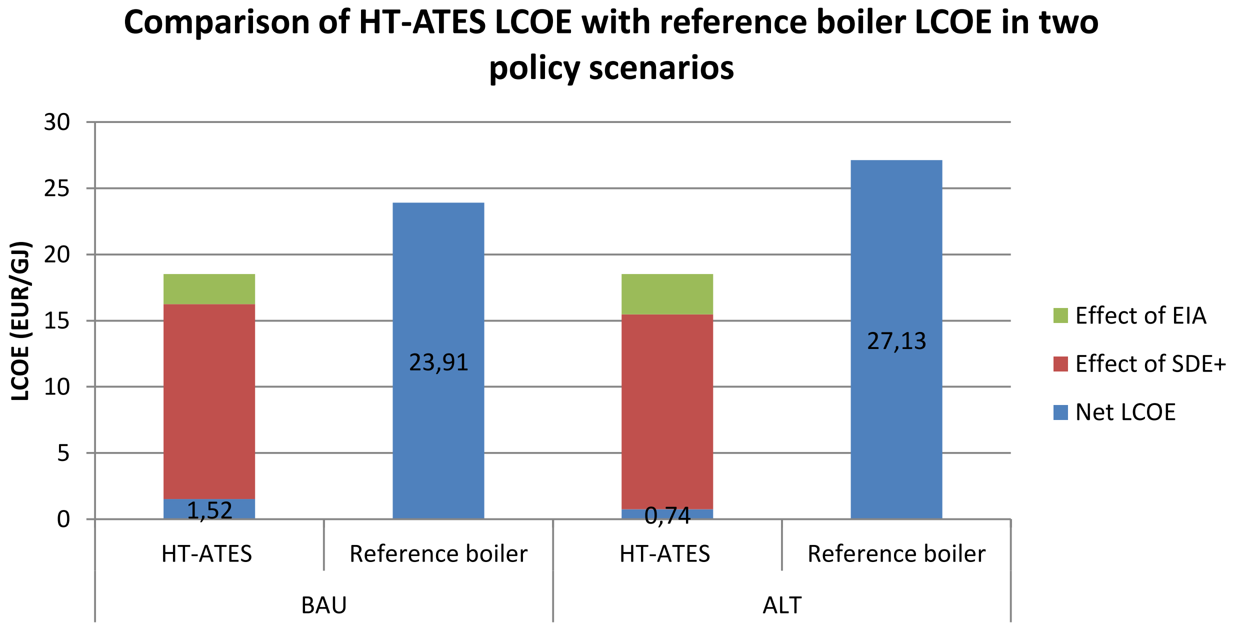


Figure 16 *Bar graph visually comparing the LCOE values of Table 14. The tops of the blue bars represent the net LCOE, which takes into account the effects of policies and regulations; the top of an entire bar (including the green and red parts) represents the gross LCOE.*

---

[6] Assuming a boiler efficiency of 88,2%, a natural gas caloric value of 0,03517 GJ/m^3 and a natural gas emission factor of 56,4 kg CO_2/GJ (Zijlema, 2013).

[7] Savings are calculated based on a comparison of the net present value(NPV) of HT-ATES and the NPV of the reference boilers. CO_2 mitigation costs are calculated by dividing the boiler NPV minus the HT-ATES NPV by the net(corrected) avoided CO_2-emissions.

5.3.3 Sensitivity analysis

Sensitivity analysis is conducted on parameters that have a high expected influence on the model output, and on parameters for which a value was chosen with a relatively high degree of uncertainty. For each parameter, the model is run with four different values. The first two values are the default value plus 10% and the default value minus 10%. By analysing all parameters with the same variation, their relative influence on the final outcome can be compared to see which factors are most dominant and if the influence is evenly or unevenly distributed over the different parameters. The other two parameter values in the sensitivity analysis are a *low* and *high* scenario. The low scenario represents the lowest parameter value that can reasonably be expected in 2020, while the high scenario represents the highest reasonable value in 2020. The default, low and high values are listed in Table 15 and Table 16. The full output of the sensitivity analysis is given in appendix 5.

Table 15 *Default values and values in the 'low' and 'high' scenarios of the sensitivity analysis for HT-ATES input parameters. The HT-ATES parameters analysed in the sensitivity analysis are not part of the policy scenarios and are thus equal for BAU and ALT.*

Variable	Unit	Default value	Low	High	Notes
Well depth[a]	M	312,5	226	399	Uncertainty range in Hellebrand et al. (2012)
Price geothermal heat	Euro/GJ	2	-	-	No *low* or *high* scenarios applied due to lack of insight in uncertainty range
Recovery Efficiency	%	72,5	50	90	Based on efficiencies mentioned in literature (see section 5.1.1)
Lifetime	Years	15	10	20	Range chosen considering the high uncertainty due to lack of recent successful pilots
Equity share	%	20	0	100	Range chosen to account for all investment scenarios
Electricity price	Euro/MWh	50	40	60	Range chosen considering the high uncertainty of the impact of renewables
Discount rate	%	6	3	15	Range chosen based on estimated minimum social discount rate(low) and a standard private discount rate
Demand size	MW	n/a*	-	-	No *low* or *high* scenarios applied due to limited insight in the most recent developments

a: Well depth is the parameter that has the strongest influence on the capital expenditure and also has the highest uncertainty. Therefore, it is used as a proxy for capex in the sensitivity analysis.

b: Demand size differs depending on the chosen year in the HT-ATES lifetime. Therefore, the default value is not listed here.

Table 16 *Default values and values in the 'low' and 'high' scenarios of the sensitivity analysis for the reference boiler input parameters. Only the energy tax differs between the BAU and ALT policy scenarios, and is therefore listed twice.*

Variable	Unit	Default value	Low	High	Notes
Lifetime	Years	15	10	25	Range according to supplier warranty(*low*) and highest figure in literature(*high*)
Gas price	Euro/GJ	11,51	6,51	16,51	Range chosen considering the high volatility of the price for this resource
Equity share	%	20	0	100	Range chosen to account for all investment scenarios
Energy tax (BAU)	Euro/m^3	0,26	-	-	No *low* or *high* scenarios applied as this parameter already varies between the BAU and ALT scenarios
Energy tax (ALT)	Euro/m^3	0,60	-	-	No *low* or *high* scenarios applied as this parameter already varies between the BAU and ALT scenarios
Discount rate	%	6	3	15	Range chosen based on estimated minimum social discount rate(low) and a standard private discount rate
Demand size	MW	n/a*	-	-	No *low* or *high* scenarios applied due to limited insight in the most recent developments
Boiler efficiency	%	82	-	-	No *low* or *high* scenarios applied due to the relatively high level of predictability of this parameter

*: Demand size is different for each year in the boiler's lifetime. Therefore, the default value is not listed here.

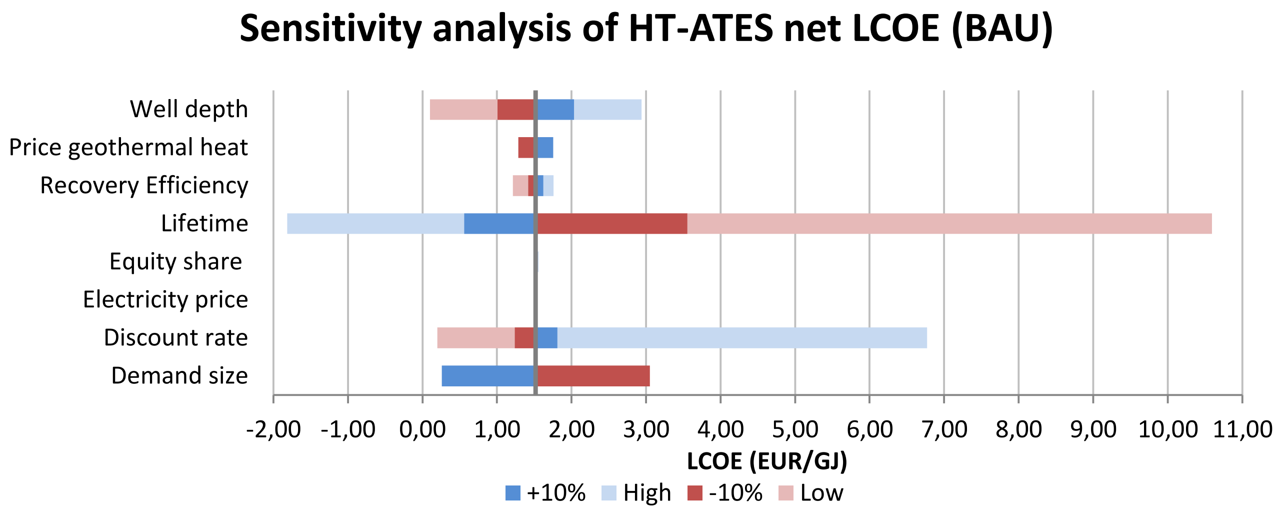


Figure 17 Sensitivity analysis of HT-ATES LCOE to selected input factors in the BAU policy scenario. The baseline is at 1,52 EUR/GJ.

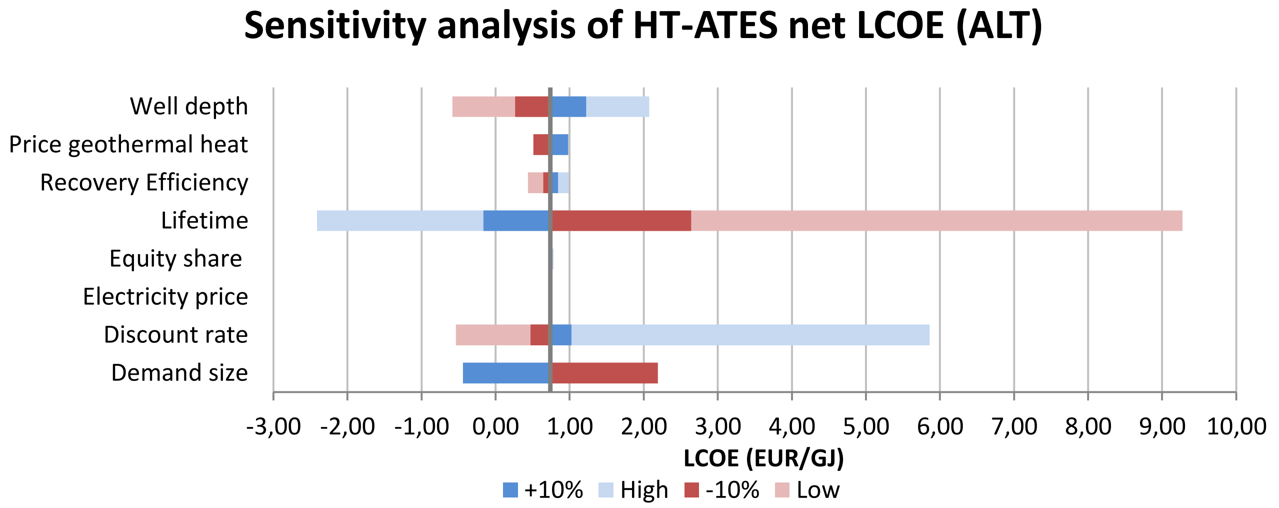


Figure 18 *Sensitivity analysis of HT-ATES LCOE to selected input factors in the ALT policy scenario. The baseline is at 0,74 EUR/GJ.*

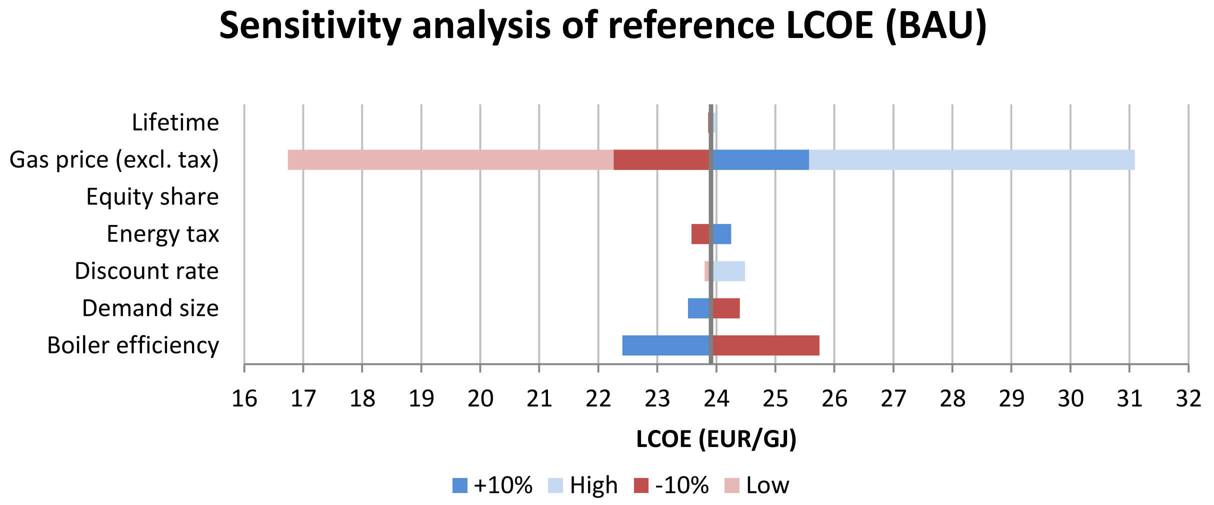


Figure 19 *Sensitivity analysis of the reference boiler LCOE to selected input factors in the BAU policy scenario. The baseline is at 23,91 EUR/GJ.*

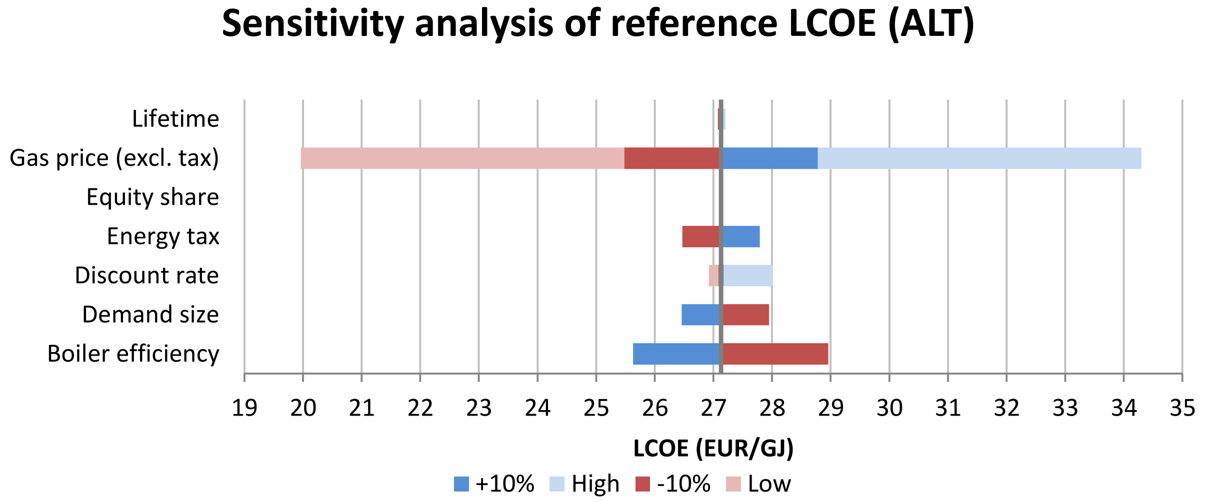


Figure 20 *Sensitivity analysis of the reference boiler LCOE to selected input factors in the ALT policy scenario. The baseline is at 27,13 EUR/GJ.*

Figure 17 and Figure 18 show that the HT-ATES LCOE is most strongly influenced by the lifetime and demand size. For instance, a 10% decrease in the economic lifetime results in an increase of the HT-ATES LCOE with a factor 2,34(BAU) and 3,57(ALT). The strong influence of these parameters on the LCOE can be explained by the fact that HT-ATES has very high capex and little opex. Lifetime and demand size each increase the number of full load hours to spread the capex over, either directly(lifetime) or indirectly(demand). Due to a high HT-ATES coefficient of performance of 132, changes in electricity price have a negligible influence on the model output.

A parameter that is excluded from the HT-ATES quantitative sentitivity analysis is the flow rate. Due to its dependence on local subsurface conditions such as transmissivity and hydrostatic pressure, this parameter is subject to a significant degree of uncertainty. Moreover, its influence on the LCOE is potentially large, as it is one of the two factors determining the HT-ATES thermal power, which in turn influences capex, opex and supply profile. The modifications made to the HT-ATES tool required the fixation of demand and supply profiles of each year. As a result, the influence of variations in the flow rate on the supply profile cannot be taken into account in the LCOE calculations. The qualitative influence of an increase in the flow rate is twofold: on one hand it increases the amount of heat that can be provided by HT-ATES and thus lowers the LCOE through a higher number of full load hours. On the other hand the increased thermal power results in higher capex and fixed opex, in particular due to the requirement of larger heat exchangers. A proxy for capex in the quantitative sensitivity analysis is *well depth*; a proxy for the supply profile is *heat demand*. The same holds for production temperature, which also detemines the HT-ATES thermal power. Contrary to the flow rate, the uncertainty in production temperature is relatively small. However, in addition to influencing capex, opex and supply profile in the same way as the flow rate, the production temperature determines the energy content of each liter of produced water. Consequently, it has a strong impact on the HT-ATES coefficient of performance(COP). A higher cop results in a lower LCOE.

Figure 19 and Figure 20 show that the opposite is the case for the reference boiler LCOE: operational costs dominate the model output while capex has a relatively small influence. For instance, a 10% decrease of the natural gas price without tax results in a 7,4%(BAU) and 6,5%(ALT) decrease of the model output. In the ALT scenario, the energy tax shows a significant influence on the output as well, while in the BAU scenario its role is smaller. Boiler efficiency is the most influencial factor, as it directly affects the amount of natural gas required to produce a GJ of final heat. If more gas is required, the costs for both natural gas and energy tax increase simultaneously. Another parameter that illustrates the capex dominance of HT-ATES and opex dominance of natural gas boilers is the discount rate. Varying the discount rate has little influence on the gas boilers as their investment costs are relatively low and it is assumed that no interest is paid on fuel costs. The HT-ATES LCOE significantly changes when the discount rate is varied, due to the high investment costs which are paid with a bank loan and equity.

Despite the wide uncertainty ranges of certain factors such as lifetime(HT-ATES) and natural gas price(reference boilers), the variety in the output(LCOE) that they cause is not sufficient to create overlap between the LCOE values of the HT-ATES and reference boilers in either policy scenario. This is largely the result of the effect of SDE^+ subsidy on the HT-ATES LCOE. Even the combined uncertainty in several parameters is unlikely to cancel the favourable business case determined in the previous section.

If HT-ATES projects are unable to receive SDE^+ and EIA, the reference LCOE has to be compared to the HT-ATES gross LCOE. In this scenario, the HT-ATES LCOE would approach the reference boiler LCOE. Considering the high uncertainty in the natural gas price in 2020, this could potentially jeopardize the viability of a business case for HT-ATES. To visualize the impact of a lower-than-projected natural gas price, the natural gas price (11,51 EUR/GJ in 2020) projected by the European Commission (2014) is replaced with the current average market price of natural gas in the Netherlands (7,96 EUR/GJ; Milieu Centraal, 2016). The resulting new reference LCOE value is represented by the grey bars in Figure 21. The reference LCOE decreases significantly with the lower natural gas price and is almost equal to the HT-ATES gross LCOE in the BAU policy scenario. There is still a viable HT-ATES business case without subsidies and at lower gas prices, although it is less distinct and therefore less certain. It is thus largely due to subsidies that the HT-ATES business case is highly certain and attractive.

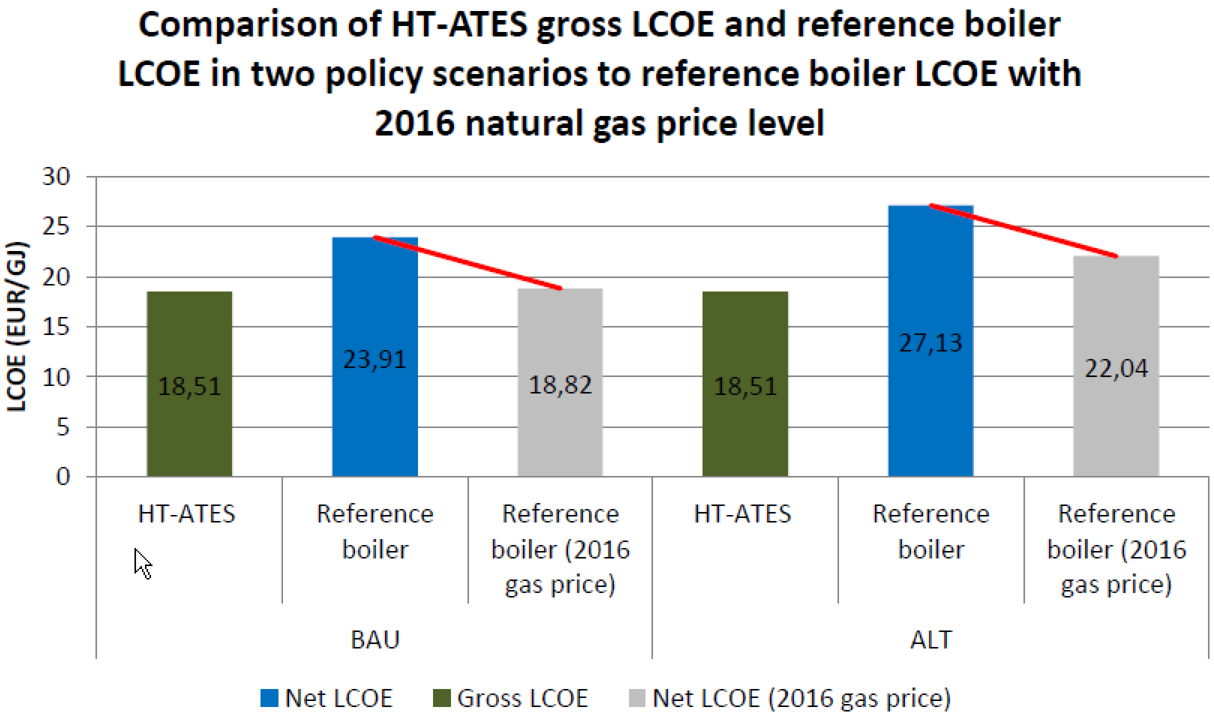


Figure 21 *Graph comparing the previously determined HT-ATES gross LCOE and reference boiler net LCOE values (section 5.3.2) with the reference boiler LCOE at 2016 natural gas price level (grey bars). Other parameters are kept at default values. The red lines indicate the reference boiler LCOE decrease as a result of using the 2016 instead of 2020 natural gas price level.*

5.4 Case study 2: Rotterdam

5.4.1 Background

The port of Rotterdam is the largest port of Europe and is home to many industrial processes as well as a waste incinerator. Consequently, a large amount of heat is produced every day and much of this heat is discharged to the surface water or atmosphere. On the other hand, there is a high demand for heat in the dense urban environment of Rotterdam, as well as in surrounding cities, horticultural areas and certain industries. Currently, this heat is predominantly produced with natural gas. The province of Zuid-Holland has therefore adopted the ambitious plan to build the infrastructure to connect heat demand hubs of the region to the port of Rotterdam and each other (Provincie Zuid-Holland, n.d.).

The Zuid-Holland heat roundabout

The so-called *heat roundabout* (*Warmterotonde*) will be an open network, i.e. additional suppliers or consumers of heat are allowed to connect in the future. This creates the potential advantages of enabling competition between heat suppliers, higher security of supply and the flexibility to integrate sustainable heat sources such as solar or geothermal heat in the future. Planned long-distance connections include cities such as Leiden, Dordrecht and Den Haag, the Heineken brewery in Zoeterwoude and horticultural areas such as Glasparel Zuidplaspolder (Warmtekoude Zuid-Holland, 2016a; Figure **22**). To provide the horticultural heat consumers with a viable business case to give up natural gas use, additional CO_2 infrastructure is planned as well (Gemeente Rotterdam, 2014).

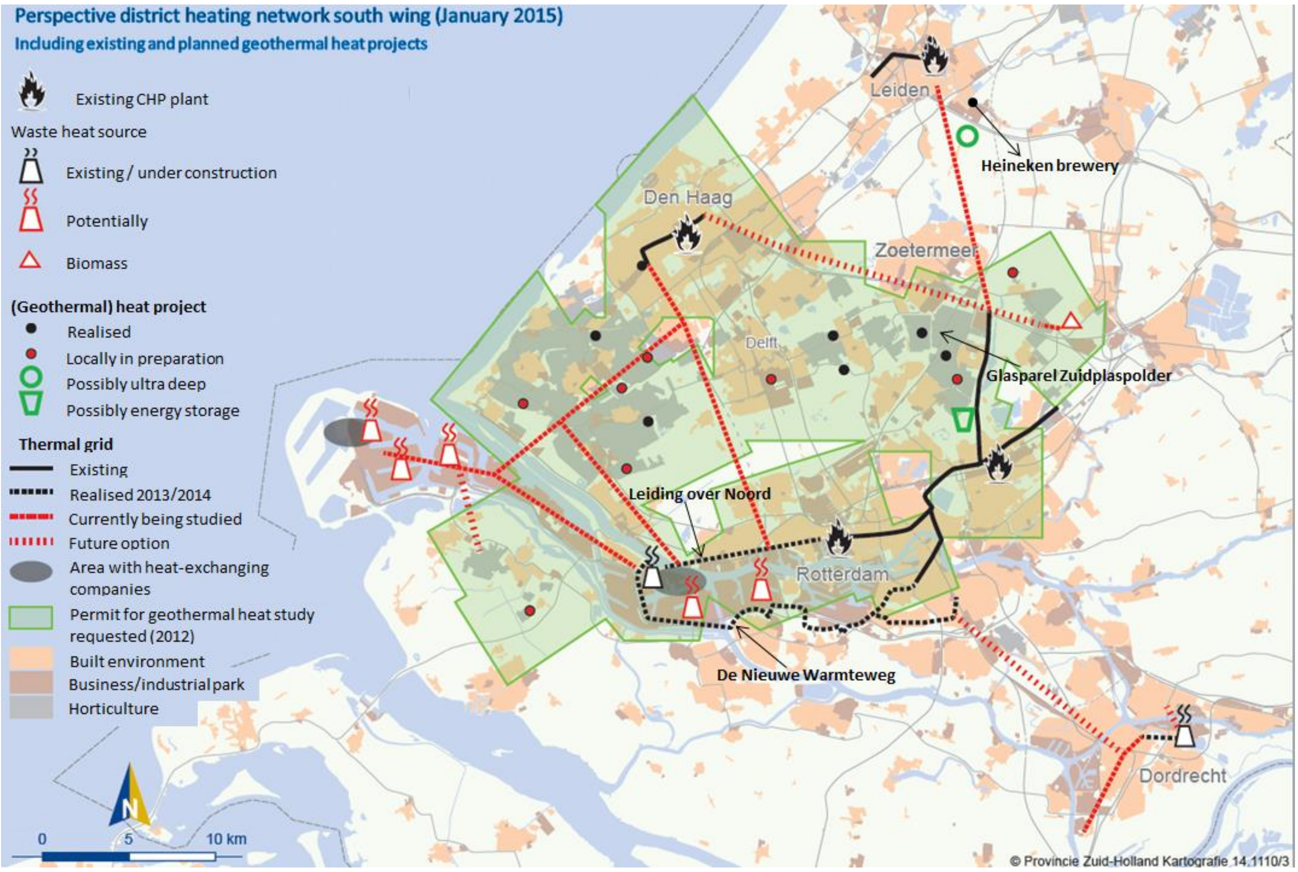


Figure 22 *Overview of planned and realised elements of the Zuid-Holland heat roundabout. Translated from: Provincie Zuid-Holland (2015)*

The first stage of this infrastructural project was to connect neighbourhoods in Rotterdam itself to the waste incineration plant of Afvalverwerking Rijnmond(AVR), located in the port. These neighbourhoods already have district heating networks, for which the heat was mainly supplied by natural gas-fired CHP plants until recently. A new 26 km-long underground pipe south of the New Meuse river – *De Nieuwe Warmteweg* - delivering heat to southern Rotterdam and Hoogvliet, was taken into use in 2013 (Figure 23). A year later, a 17 km-long underground pipe north of the New Meuse – *Leiding over Noord* – was taken into use to supply heat to the northern part of Rotterdam, as well as the cities of Vlaardingen and Schiedam (Figure 24). With both pipes finished, the entire Rotterdam district heating network is now using baseload heat from the port (Gemeente Rotterdam, 2014), complemented with heat from existing natural gas-fired CHP plants and peak boilers (Appendix 6). The AVR Rozenburg waste incineration plant in the port supplied approximately 4500 TJ of heat to the district heating networks in 2015(AVR, n.d.). Other potential heat suppliers in the port that may be connected to the network in the near future include the Pernis refinery of Shell and a coal-fired power plant of Uniper. Connection of especially the latter is highly uncertain as a result of an ongoing political and societal debate about closing coal-fired power plants (Botje, 2016; Liukku, 2016). Part of the ambitions articulated in the Green Deal in 2011 is to also include geothermal heat in the heat roundabout, which will predominantly be produced in the horticultural areas (Figure 22; Provincie Zuid-Holland, n.d.).

Warmte-Koude Zuid-Holland, the overarching alliance of 25 stakeholders in the plans for the heat roundabout, states that the goal is to supply 20 PJ of heat to diverse consumers in Zuid-Holland in 2020 (Warmtekoude Zuid-Holland, 2015). Part of the demand-side expansion required to achieve this goal, is the planned construction of a 43-kilometre underground pipeline from the port area to the cities of Leiden, Leiderdorp and Oegstgeest, as well as the Heineken brewery in Zoeterwoude, near Leiden (Figure **22**). The current boiler house of Heineken will be converted to a heat buffer and a back-up heat supplier for peak demand (Warmtekoude Zuid-Holland, 2016b). The connexion of horticulture to the heat roundabout is expected to decrease the temperature of the return flow, which enhances the energy efficiency of the entire district heating network (Appendix 6).

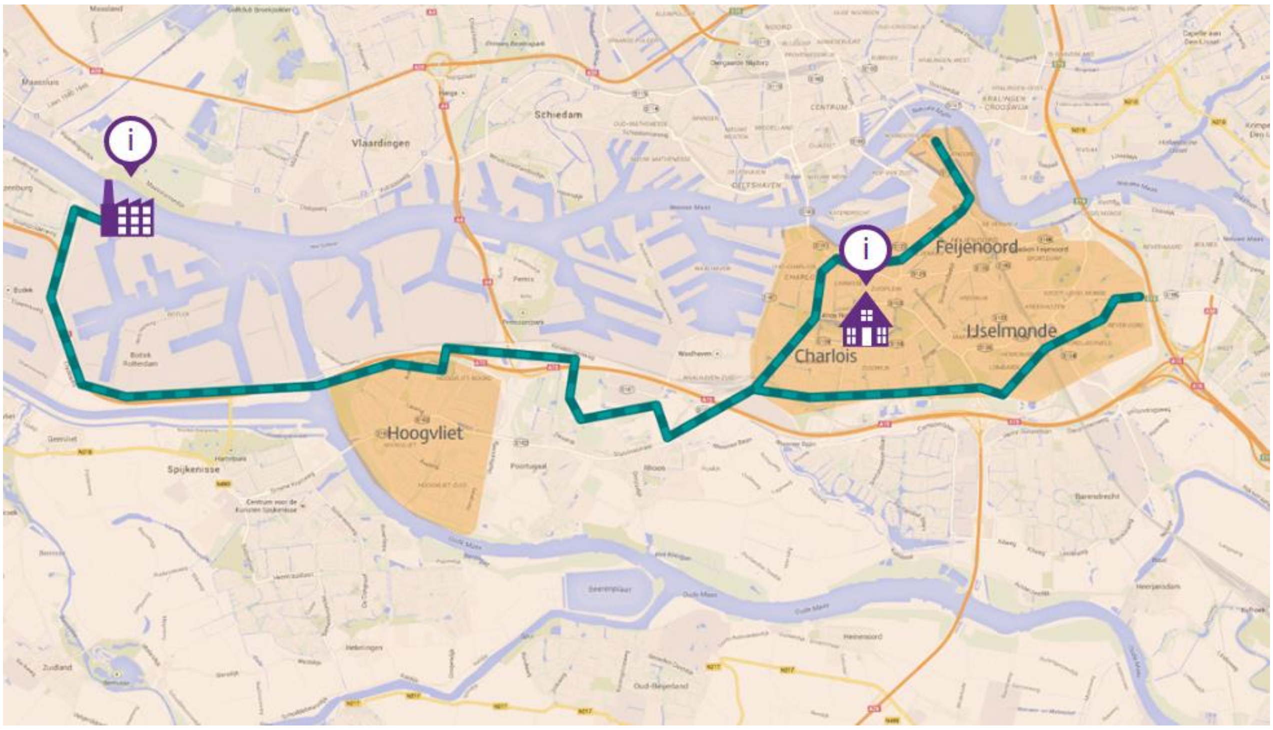


Figure 23 *Map showing the route of De Nieuwe Warmteweg. The purple factory building on the left represents the AVR waste incineration plant. Neighbourhoods with a district heating network connected to the main pipes of De Nieuwe Warmteweg are marked brown. From: Nuon (2015).*

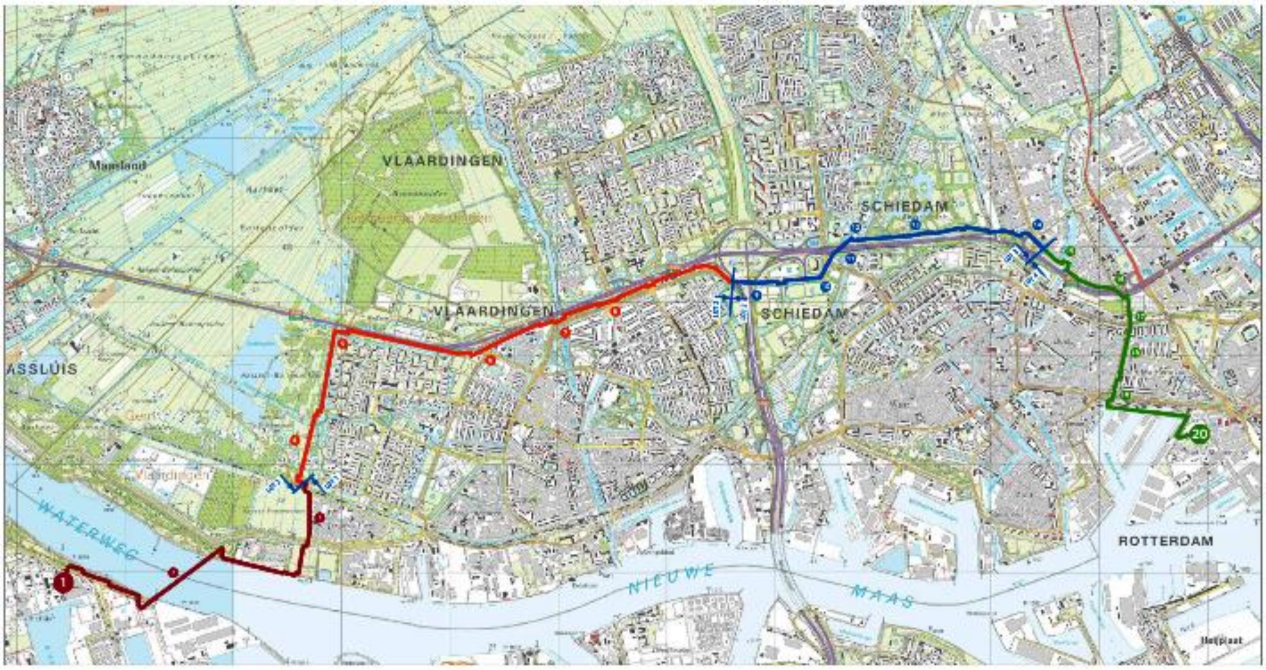


Figure 24 *Map showing the route of Leiding over Noord. Point 1 marks the AVR waste incineration plant. Point 20 marks heat station Galileïstraat, the former CHP plant now converted to transfer heat with the existing district heating network. From: Eneco (n.d.).*

Selecting the most likely proprietor

AVR is the only large heat supplier currently connected to the heat roundabout (i.e. the part of it that has been constructed to date), besides the remaining CHP plants in secondary networks[8]. Besides AVR, owners and operators of the primary (e.g. Warmtebedrijf Rotterdam) or secondary (Eneco and Nuon) grids as well as third parties are possible proprietors for HT-ATES. However, according to a preliminary investigation it is expected that the business case for AVR is most attractive. At least the following four benefits from investing in a HT-ATES system are expected for AVR:

1. **More heat can be sold throughout the year**
   Currently, part of the produced waste heat is discharged when demand from households, businesses and horticulture is low in summertime. In wintertime, however, peak demand exceeds the thermal power of the plant. Heat sources that are not owned by AVR supply this heat. If surplus summer heat can be sold in winter, these additional heat sources are not required and AVR can sell more heat throughout a year. AVR considers this as the primary advantage of HT-ATES (Appendix 6).

2. **Improved flexibility facilitates strategically varying electricity production**
   AVR currently has a limited flexibility in varying its ratio between electricity, steam and hot water production, as it has to supply a certain amount of baseload heat that is agreed upon with buyers in advance. Moreover, process steam has to be supplied to chemical company Emerald Kalama Chemical (EKC). The amount of electricity that is produced and supplied to the electricity grid, is fixed one day ahead. Heat and steam supply thus likely have priority over the amount of electricity produced, which can be determined relatively late. Having access to a large heat buffer partially uncouples heat demand and heat production. This allows AVR to produce more electricity and less heat when market prices for electricity are high, or on cold days when generation efficiency is higher (Kopac & Hilalci, 2007). When electricity prices and generation efficiency are low (e.g. in summer), it can potentially be attractive to

---

[8] The primary network consists of the large and long pipelines transporting heat from large baseload heat sources such as AVR to local distribution networks and large suppliers. The secondary networks are the local networks within urban areas that distribute heat among smaller users, such as individual dwellings.

produce and store a lot of heat while generating little electricity. With the ongoing growth of solar PV installed capacity, it is possible that electricity spot prices in summer further decrease. This can potentially increase the benefit of flexibility provided by HT-ATES (Appendix 6).

3. **Facilitation of AVR's function as a regulating heat hub**
   Many of the potential extra heat suppliers in the port area are industrial production processes, such as the Pernis refinery. If implemented, heat supply to a district heating network would be a secondary activity that has lower priority than the primary production process, e.g. petroleum refining. The activities in the primary production process therefore determine the amount of heat supplied at any given moment, rather than heat demand. For instance, if demand for the primary product suddenly decreases or maintenance of the primary production process is required, the supply of heat decreases or stops as well. These companies are unlikely to accept must-run contracts. Open networks therefore require a party that takes the responsibility to guarantee sufficient heat supply. AVR Rozenburg can act as a heat hub and provide a regulating role as heat supply is an important element in its business case and it can vary between electricity and heat production. By utilizing the steam return flow from EKC in the district heating water, AVR already acts as such a hub. This role can be scaled up with large heat buffers such as HT-ATES (Appendix 6).

4. **Increased cooling capacity**
   Waste is supplied to AVR Rozenburg from large parts of the Netherlands, as well as from other countries such as Ireland and Italy (AVR, n.d.). Depending on the type of waste, AVR is paid for its incineration. Therefore, incinerating more waste can potentially increase their revenues. However, the amount of waste that can be incinerated can potentially be limited by the plant's cooling capacity, or - if AVR's policy is to strive for minimizing heat discharge into surface water - by the demand for heat, steam and electricity. Although AVR Rozenburg has relatively good cooling facilities due to its location by a river, the cooling effect of heat demand from the district heating network decreases with a factor 2-3 during summer compared to winter (Appendix 6). A HT-ATES acts as an additional heat sink that increases the cooling capacity in summertime when it is charged. Investing in HT-ATES could thus potentially result in more income through handling more waste, if the cooling capacity is a limiting factor (J. Koornneef, personal communication, May 18, 2016).

Based on the benefits of HT-ATES of AVR described above, the proprietor perspective of AVR is chosen for the Rotterdam case study.

Technical background

Besides a household waste incinerator that produces steam and electricity, AVR has a biomass CHP plant and a wastewater treatment plant that produces waste heat. The combined thermal capacity of these three facilities is 559 MW_{th} (Figure 25). On average, 20% of the steam produced through the incineration of household waste is used for electricity generation, while 80% is thermal capacity employed for steam supply or district heating. 12% of this thermal capacity is transported to nearby chemical company EKC as steam at an average temperature of 380^{o}C. The steam in the return flow has a temperature of 180^{o}C. This thermal energy is transferred into the district heating network through a heat exchanger. 48% of the thermal capacity is directly transferred to the district heating system, provided that there is enough heat demand. Surplus heat is discharged in the surface water of the New Meuse river. AVR provides heat to the primary district heating network (i.e. the large pipes that transfer heat from the harbor to local district heating networks and large heat consumers) at 110^{o}C on average, while the return flow is 63^{o}C. Heat is supplied in blocks of heat that are agreed on in advance, making AVR a baseload heat supplier (Appendix 6; Figure 26; Eneco, n.d.).

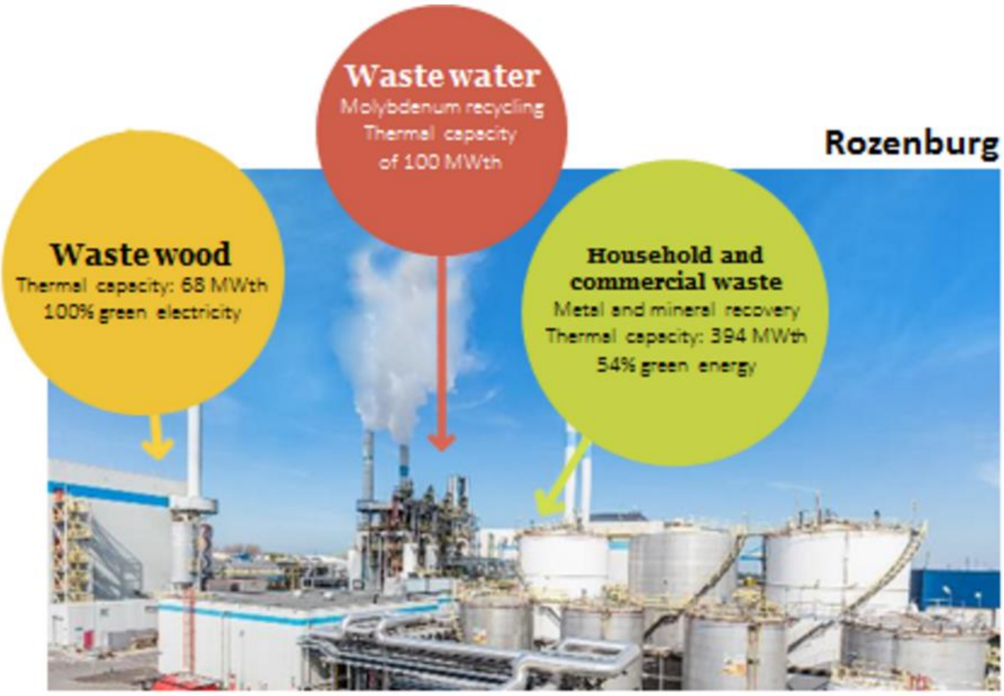


Figure 25 *An overview of the main facilities at AVR Rozenburg(Rotterdam) and their electric and thermal capacities. From:* AVR (2016b).

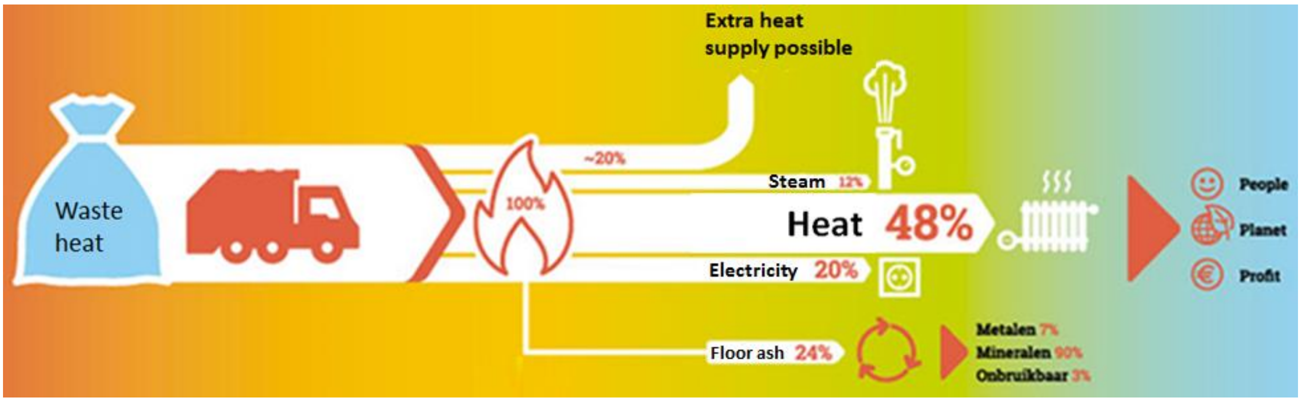


Figure 26 *Flow diagram of the energy streams of the waste incineration process at AVR Rozenburg. From: AVR (2016a).*

5.4.2 Market potential assessment

In the following market potential assessment only the potential benefit of the ability to sell more heat is quantitatively considered. The other benefits of HT-ATES for AVR (section 5.4.1) cannot be quantified due to lack of data and insight in AVR as a consequence of confidentiality.

Subsurface assessment

Like in Groningen, the local data availability in the REGIS II database is insufficient to select an appropriate aquifer. Therefore, the subsurface assessment of Hellebrand et al. (2012) is used. Based on the overview of their assessment of the subsurface at AVR Rozenburg in Table 17, the Formation of Maassluis is the most appropriate aquifer for HT-ATES locally. This formation is the shallowest of the four (which keeps drilling costs low), is thickest (enhancing storage capacity and transmissivity) and has the highest expected flow rate. Taking the averages of the parameter value ranges given by Hellebrand et al. (2012) results in a depth of the base of the formation of 226m, a net thickness of 106m and a flowrate of 72,5 m^3/h. The top of the formation is between 81 and 159m below ground level, which is shallower than the minimum depth of 200m established in section 5.1.1. However, the fresh/salt water interface is shallower than the Formation of Maassluis at the site of AVR Rozenburg , i.e. the formation water is unsuitable as drinking water (Dufour, 1998). Therefore, the Formation of Maassluis is selected for this case study.

Table 17 *An overview of key subsurface parameters at the AVR Rozenburg site for four formations studied by Hellebrand et al. (2012).*

Parameter	Unit	Brussels Sand	Formation of Breda	Formation of Oosterhout	Formation of Maassluis
Depth of base	Meters	601-750	301-450	301-400	**201-250**
Net thickness	Meters	31-60	0-50	0-50	**91-120**
Flow rate	m^3/hour	1-15	n.d.	30-55	**50-95**

n.d. = no data available

Heat demand and supply profiles

The blue line in Figure 27 represents an estimation of the demand profile in 2020 assuming that the total annual heat demand in the heat roundabout is 20 PJ (Warmtekoude Zuid-Holland, 2015) and that 50% of this demand delegated to AVR Rozenburg[9]. The red line represents the share of thermal power available for the district heating network of the combined facilities at AVR (see Appendix 7 for calculations). The decrease in thermal power is caused by required annual maintenance of the facilities (Appendix 6; Appendix 7).

It can be observed in Figure 27 that there is a supply capacity surplus throughout most of the year, while only in weeks 1, 2, 8, 9 and 49-51 there is a supply capacity shortage. It can therefore already be concluded that the HT-ATES injection/production ratio will be significantly higher than the ideal value of 1,38 (recovery efficiency^{-1}).

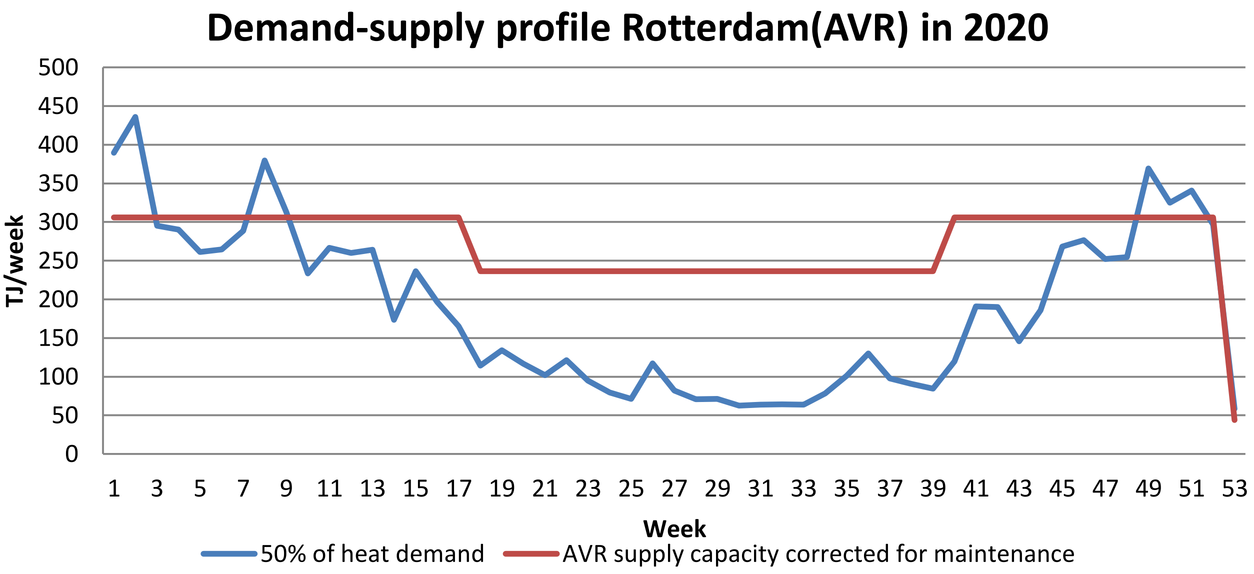


Figure 27 *Graph showing the distribution profile of the expected demand that is delegated to AVR and the estimated supply capacity profile of AVR.*

---

[9] AVR can theoretically provide almost 80% of 20 PJ in 2020 (see Appendix 7). However, a share of 50% is chosen because of the assumption that Warmtekoude Zuid-Holland is looking for more heat suppliers in the network to increase competition and security of supply (e.g. Liukku, 2016).

Table 18 An overview of the main parameter values used in the HT-ATES tool to calculate the LCOE of a HT-ATES.

Parameter	Unit	Value
Combined thermal power for district heating	MW_{th}	279,5[a]
Injection temperature HT-ATES	°C	140[b]
Cascaded final water temperature of return flow	°C	63
HT-ATES recovery efficiency	%	72,5
Maximum flowrate HT-ATES	m^3/hour	72,5
Depth of well	Meters below ground level	173
Economic lifetime	Years	15[c]
Capital expenditure	Euro	1.418.339[d]
Share of equity in investment	%	20[c]
Share of loan in investment	%	80[c]
Loan rate	%	8[c]
Loan term	Years	15[c]
Discount rate	%	15
Cost injected heat	EUR/GJ	0
Electricity price for pumps	EUR/MWh_e	50[c]
Maintenance costs per year	Euro	14.183[e]
Inflation	%	2,0065

a: See appendix 7.

b: Steam is produced at temperatures higher than 140°C (Appendix 6), so it is assumed that the injection temperature is not limited by AVR's facilities. 140°C is an optimal injection temperature for HT-ATES and results in a production temperature of roughly 100°C by the end of the production season (Joris Koornneef, personal communication, July 14, 2016). Through mixing with warmer water coming directly from the facilities of AVR, the appropriate temperature of 110°C can be realized.

c: Standard parameter value in HT-ATES tool.

d: Calculated by the HT-ATES tool based on temperatures, flow rate, depth and standard costs for drilling, pump, and heat exchanger (Pluymaekers et al., 2013)

e: 1% of capex

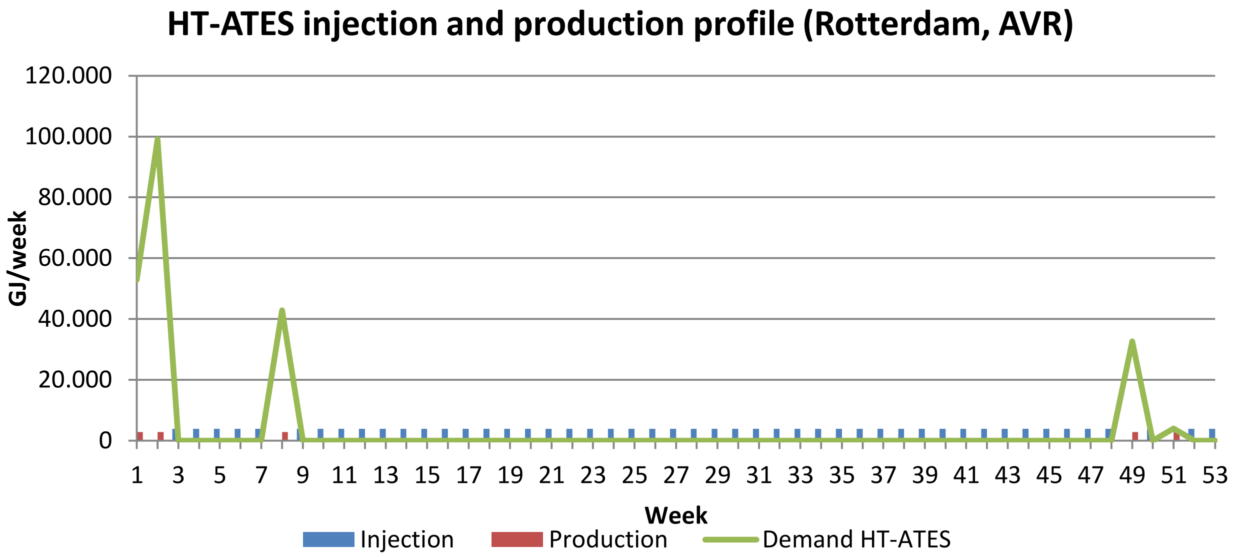


Figure 28 *Graph showing the heat that is available for injection into the HT-ATES(blue bars), heat produced by HT-ATES(red bars) and the demand for heat from HT-ATES.*

HT-ATES performance

Based on the data in Figure 27, profiles of the heat available for injection in HT-ATES and the demand for heat produced by HT-ATES are compiled. Figure 28 shows the HT-ATES injection and production profile calculated by the HT-ATES tool using these profiles and the parameters in Table 18. As expected, the heat available for injection is significantly greater than the amount of heat produced. At 8,87, the injection/production ratio is significantly higher than the ideal value of 1,38 (Table 19). The calculated heat supply-demand profiles in Figure 27 thus result in a HT-ATES that is operating inefficiently. Table 19 gives an overview of key operational indicators of the modeled HT-ATES system. The resulting LCOE values are listed in Table 20.

Table 19 *Overview of key operational indicators of the HT-ATES tool for the modelled year 2020. Constant heat demand and thermal capacity are assumed for the period 2020-2034, so these indicators apply to all years of the HT-ATES lifetime.*

	Unit	2020
Heat available for injection	GJ	176.421
Sum produced heat	GJ	19.896
Ratio injection:production	-	8,87:1
Power HT-ATES (injection)	MW_{th}	6,48
Power HT-ATES (production)	MW_{th}	4,70
Annual HT-ATES production capacity	GJ/year	148.208
Full load hours HT-ATES (production)	hours	1176

Comparison to the reference price and assessment of the impact of policies and regulations

AVR sells its heat to other companies who deliver it to the final heat consumers or act as an intermediate between AVR and these companies. Therefore, the reference is the weighted average selling price of heat (see section 4.2.1). This price is confidential and – inter alia due to the many parties and intermediates involved in the heat roundabout – cannot be accurately estimated. Therefore, the value of heat as determined in the ECN advice about SDE^{+} value corrections is assumed (Lensink & Van Zuijlen, 2016). The value of heat from large-scale suppliers is calculated based on the value of natural gas with the following formula:

*Value of heat = ICE-TTF market index * 0,7*

The ICE-TTF market index is a year-ahead market price index of natural gas. It is not yet available for 2020 as the index is only available up to two years ahead. Therefore, the 2018 index (*cal-18*) of 16,9 EUR/MWh (4,694 EUR/GJ) is used (ICE, 2016).

Table 20 gives an overview of the HT-ATES LCOE values and the reference price. The effect of EIA can easily be calculated, but this does not hold for other applicable policies, which are therefore qualitatively discussed. Of the policies and regulations listed in Table 4, only EIA, SDE^{+} and the heat discharge tax are applicable. The EU ETS is not applied on waste incineration plants in the Netherlands due to the way European legislation is interpreted. Therefore, the change in the heat law in the ALT scenario that allows passing on CO_2 tax to final heat consumers is also not applicable. Finally, the energy tax does not apply as no natural gas-fired boilers are used by AVR as alternative to HT-ATES.

From the applicable policies and regulations, only EIA can be quantified as it affects the HT-ATES capex. The capex depends on technical parameters such as ΔT and subsurface parameters such as depth and expected flow rate. Although there is considerable uncertainty in especially the subsurface parameters, they are available publicly. Data required to quantitatively assess the influence of SDE^{+} and a heat discharge tax, however, is confidential and insufficient public data is available to make assumptions.

SDE$^+$ subsidy is granted for each GJ of heat and electricity that is produced with the waste wood incinerator, as waste wood is biomass. However, it is unknown how much electricity and heat will be produced by the waste wood incinerator annually. Moreover, the internal merit order[10] of AVR is unknown. It is likely that the waste wood incinerator has high priority in the merit order as SDE$^+$ is received for each GJ of heat produced. Consequently, maximizing the full load hours results in more SDE+ subsidy. Other heat sources for which no SDE$^+$ is received, such as the household waste incinerator - likely have lower priority in the merit order and are therefore more likely to be used for the production of marginal heat for injection in HT-ATES. Although it is thus unlikely that extra SDE$^+$ subsidy is received because of HT-ATES, the potential effect of SDE$^+$ can be large, as is observed in the Groningen case study. As the HT-ATES gross LCOE in this case study is significantly lower than in the Groningen case study, extra SDE$^+$ acquired because of HT-ATES could potentially result in a negative LCOE. Negative LCOE in this context mean that the extra SDE$^+$ alone is higher than the lifetime costs of HT-ATES.

A heat discharge tax could be applicable to the HT-ATES business case, as a limited amount of heat is discharged at AVR (Appendix 6). This discharge is a consequence of the fact that – contrary to the geothermal well in the Groningen district heating system (section 5.3.2) - AVR has other tasks than producing heat, such as incinerating waste and biomass, recycling waste water and producing electricity. However, it is unknown how much heat is discharged annually and how much of the heat that would be injected in HT-ATES is waste heat. The effect of the waste discharge tax is an increase in operational expenditure for AVR. As HT-ATES can potentially reduce or even eliminate the payable heat discharge tax, these savings (divided by the amount of heat produced by HT-ATES) can be deducted from the HT-ATES gross LCOE.

SDE$^+$, IEA and the heat discharge tax have the potential to increase the viability of a business case for HT-ATES. Based on the assumed parameter values there is neither a viable business case without any policies and regulations, nor with the effect of EIA included (Table 20 and Figure 29). Assumptions that were made to calculate the HT-ATES LCOE and the reference price are highly uncertain, however. Particularly a higher share of AVR in the total heat supply to the heat roundabout or a lower than calculated thermal capacity, can potentially change the outcome of the business case by lowering the injection/production ratio towards the ideal value of 1,38. To assess how robust the outcome is to variations in these and other input parameter values, sensitivity and uncertainty analysis are required.

Table 20 *Overview of the levelized costs of energy(LCOE) in EUR/GJ and the reference price (an assumed weighted average price for sold heat) in two policy scenarios. The HT-ATES gross LCOE is the LCOE without taking into account the effects of policies and regulations.*

	BAU	ALT
HT-ATES gross LCOE	€ 11,10	€ 11,10
HT-ATES net LCOE (+ effect EIA)	€ 9,78	€ 9,32
Reference price	€ 4,69	€ 4,69

---

[10] The internal merit order of AVR is a ranking of which of their heat producing assets are employed first. Assets with the lowest marginal costs are employed before assets with higher marginal costs.

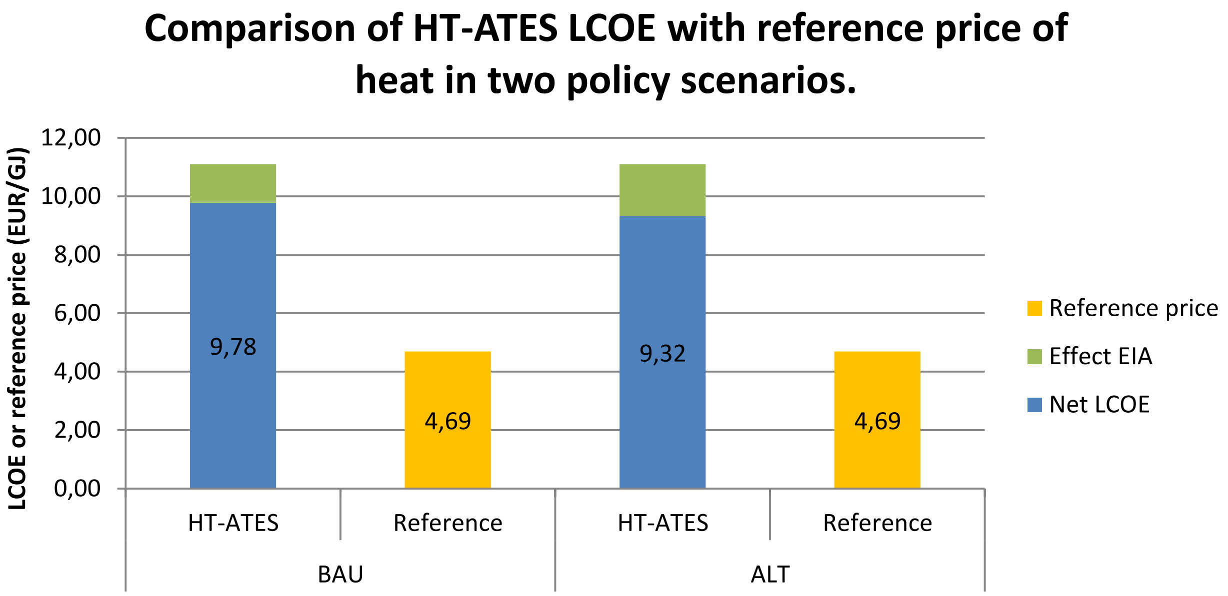


Figure 29 *Bar graph visually comparing the LCOE values of Table 20. The sum of the green and dark blue bar represents the gross LCOE. The net LCOE is the gross LCOE plus the effect of EIA. The reference price is the assumed weighed average price of sold heat.*

5.4.3 Sensitivity analysis

Due to time restrictions, sensitivity analysis is only conducted on the two input parameters for HT-ATES LCOE calculation that are expected to be most influential and uncertain:

- The share of AVR in the heat supply to the heat roundabout in 2020-2034
- The thermal capacity of AVR that is available for the heat roundabout

Like in the sensitivity analysis of the Groningen case study, a *low* and *high* scenario as well as -10% and +10% variations in the input values are applied (Table 21). Sensitivity analysis is conducted on the HT-ATES net LCOE, i.e. the HT-ATES gross LCOE plus the effect of EIA.

Table 21 *Default values and values in the 'low' and 'high' scenarios of the sensitivity analysis for HT-ATES input parameters. The HT-ATES parameters analysed in the sensitivity analysis are not part of the policy scenarios and are thus equal for BAU and ALT.*

Variable	Unit	Default value	Low	High
Thermal capacity	MW_{th}	306	200	400[a]
Share in heat supply	%	50	40[b]	80

a: If thermal capacity >436 MW_{th}, demand is lower than thermal capacity in every week. Consequently, no HT-ATES production occurs and no LCOE can be calculated.

b: If share of AVR in the heat roundabout’s heat supply <36%, demand is lower than thermal capacity in every week. Consequently, no HT-ATES production occurs and no LCOE can be calculated.

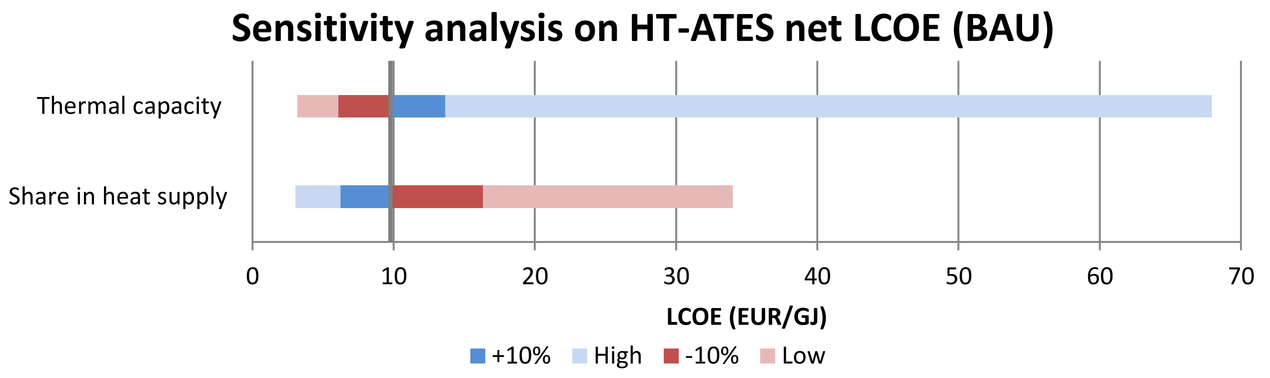


Figure 30 *Sensitivity analysis of HT-ATES net LCOE to selected input factors in the BAU policy scenario. The baseline is at 9,78 EUR/GJ.*

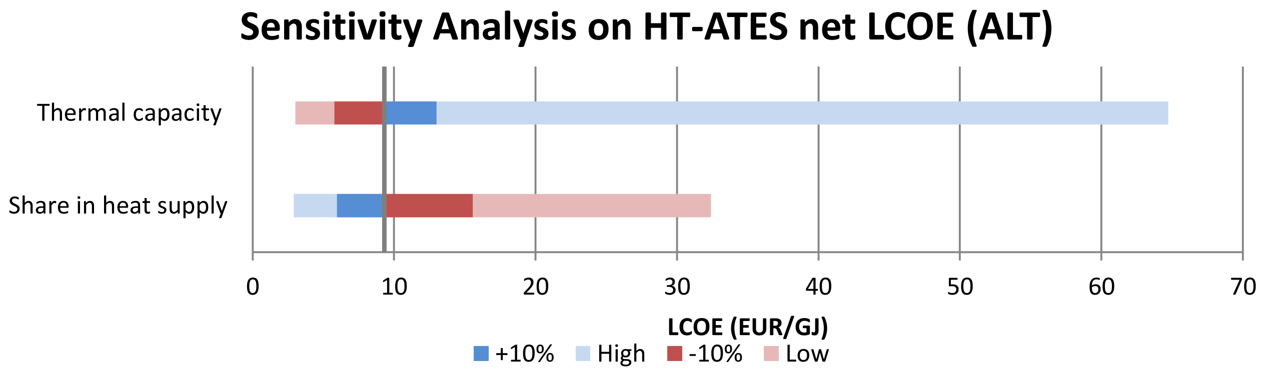


Figure 31 *Sensitivity analysis of HT-ATES net LCOE to selected input factors in the ALT policy scenario. The baseline is at 9,32 EUR/GJ.*

Figure 30 and Figure 31 show that the HT-ATES net LCOE has a significant sensitivity to both input parameter values, as expected. The strongest influence on the output is exerted by the share of heat in the roundabout that is supplied by AVR. In the output tables in appendix 5 it can be seen that if this share is 80%(*high* scenario), the HT-ATES net LCOE decreases to 3,04 EUR/GJ(BAU) and 2,90 EUR/GJ(ALT) respectively. Both values are lower than the reference price of 4,69 EUR/GJ, i.e. there is a viable business case in this scenario. Similarly, if the thermal capacity of AVR is 200 MW_{th}(*low* scenario), the HT-ATES net LCOE decreases to 3,17 EUR/GJ(BAU) and 3,02 EUR/GJ(ALT) respectively. This scenario therefore also results in a viable business case for HT-ATES in Rotterdam.

6 Discussion

In the next section(6.1), the results are interpreted and their theoretical, societal and political implications are explained. This is followed by a critical reflection on the uncertainties and limitations of this study. Finally, recommendations for further research are given.

6.1 Results and implications

Potential frameworks

To determine theoretical and technical potentials of HT-ATES, boundaries must be determined and the physical and technical factors that limit the potentials must be mapped. Key parameters and formulas were mapped and parameter values were proposed that – together with the proposed boundaries - can be used as a standard in further research. The frameworks made based on the parameters, formulas and boundaries are the starting point for future quantification of the theoretical and technical potentials of HT-ATES in the Netherlands. The basic step-by-step approach of the frameworks can also be applied in other countries or regions, although that requires the revision of some of the parameters to comply with local conditions.

The market potential of HT-ATES is restricted not only by physical and technical factors, but also by economic, political and social factors. Besides providing the methodology for market potential assessment in future research, the acquired insight in relevant conditions, drivers and barriers contributes to the general understanding of the embeddedness of HT-ATES in energy systems. Special attention was given to how current policies and regulations influence HT-ATES business cases, which improvements can be made to increase their stimulatory influence on HT-ATES business cases and which new policies and regulations could be added to the policy package in 2020. Future case studies conducted with the developed market potential assessment framework can further assess the effectivity of proposed changes in policies and regulations, as well as identify possible flaws or side-effects.

Case studies

Due to the use of geothermal heat in the Groningen district heating network, only two policies and regulations are applicable besides energy tax for the reference boilers: EIA and SDE$^+$. The EIA significantly lowers the HT-ATES LCOE through decreasing its dominant capital expenditure. A higher EIA percentage therefore proved to be an effective measure to further stimulate the HT-ATES business case. The influence of extra SDE$^+$ subsidy on geothermal heat injected in the HT-ATES, however, was significantly higher. At 12,5 EUR/GJ, SDE$^+$ subsidy exceeds the marginal costs of geothermal heat by 10,5 EUR/GJ. As the annual SDE$^+$ cash flow reduces the amount of money acquired through loans or equity (and thus reduces the absolute amount of interest paid), it lowers the gross HT-ATES LCOE by 14,75 EUR/GJ. The resulting low LCOE and subsequently attractive HT-ATES business case are a clear indication of the good prospects for HT-ATES in combination with geothermal heat in the Netherlands. However, if the annual heat demand in a district heating network is larger than in Groningen and approaches the annual capacity of its geothermal well, the maximum SDE$^+$ full load hours in the BAU policy scenario may be approached or exceeded. In such a scenario, the SDE$^+$ subsidy that can be accredited to the HT-ATES business case would decrease or disappear entirely. Without the dominant influence of SDE$^+$ there is still a viable business case for HT-ATES in Groningen, but the uncertainty in several model input values make this business case less irrefutable.

In the case study of Rotterdam, the HT-ATES heat originates from a waste incineration plant and would at least partially be discharged in the surface water without HT-ATES. The SDE$^+$ subsidy that makes the business case in Groningen particularly attractive, does not apply here. The HT-ATES LCOE calculated with the effect of EIA included is higher than the reference price, yet sensitivity analysis showed that other values of two highly uncertain input parameters can change this, even without SDE$^+$. This is a result of the large heat demand coming from the provincial heat roundabout, that – depending on which share of this demand is delegated to AVR – can potentially result in a near-optimal HT-ATES injection/production ratio. The HT-ATES business case for AVR Rozenburg therefore largely depends on which other heat suppliers will connect to the heat roundabout. In Groningen an optimal injection/production ratio is not possible in the 2020-2034 period due to the limited heat demand in its small district heating network.

While HT-ATES facilitates both environmental and financial benefits in Groningen and Rotterdam, financial incentives can potentially prevail or even be the only reason to invest in HT-ATES in other settings. Natural gas-fired CHP plants supplying heat to district heating networks are an example of such a setting. Without HT-ATES, these power plants often operate in must-run conditions to ensure the supply of heat to the district heating network, even when heat demand is very low. As their flexibility in terms of the ratio between electricity and heat production is limited (Christidis et al., 2012), this potentially means that more heat than required is produced and/or electricity is produced even when the marginal costs are higher than the electricity spot price. This situation mainly occurs during summer and can potentially occur more frequently when natural gas prices increase beyond current prices, which – combined with low electricity prices - already make many natural gas-fired plants in the Netherlands unprofitable (Tennet, 2015). Connecting gas-fired CHP plants to HT-ATES increases the flexibility of the plant by allowing it to produce less or more heat than is demanded at a given moment. Consequently, more electricity can be produced when spot prices are high (Fragaki et al., 2008). When electricity spot prices are low, more heat can be produced to charge the HT-ATES or the plant can be turned off. The latter could potentially be done for extended periods in summertime when heat demand is so low that the HT-ATES alone can supply all heat. This can potentially decrease the operational costs. However, this strategy involves burning more natural gas to produce heat for HT-ATES injection. Considering the assumed average recovery efficiency of 72,5%, HT-ATES in this setting could potentially have a negative effect on the energy efficiency of the entire district heating system.

The HT-ATES potential assessment frameworks constructed in this thesis facilitate future research that can contribute to the development of the integrated assessment of HT-ATES. Moreover, this is the first time that conditions, drivers and barriers of HT-ATES as well as its potential applications were investigated. The overview of relevant policies and regulations, economic and technical factors, as well as their demonstration in a quantitative case study not only is a valuable source of information for potential investors, but also brings new arguments into the scientific debate about space heating in a wider context. For instance, there is an ongoing trend towards lower temperatures in district heating networks (Lund et al., 2014), but HT-ATES brings new counterarguments into the discussion that require reconsideration and further investigation of this development. Moreover, the suggestions for new policies and regulations as well as the assessment of the influence of existing policies, can be a starting point for the development of an improved policy package to stimulate HT-ATES deployment.

6.2 Critical reflection and limitations

Throughout this study, assumptions have been made that each have a degree of uncertainty. For other parameters, methods or boundaries, no suitable assumptions could be made at all. An example of the latter occurred in the theoretical potential framework, where no suitable boundaries could be defined to distinguish between ATES, MT-ATES and HT-ATES. This is the result of a lack of consensus on definitions and boundaries in literature.

Most assumptions were made in the quantitative case studies. The lack of REGIS II data in the appropriate depth range on the expected location of the HT-ATES, necessitated the use of a less detailed data source (Hellebrand et al., 2012) for subsurface assessment. Consequently, it is unknown if there is an impermeable layer that meets the established requirements(see section 5.1.1) above the formation used for the case study. Furthermore, the maps of Hellebrand et al. (2012) are based on extrapolation from unevenly distributed well logs and have a relatively higher uncertainty in Groningen due to strong salt tectonics. Certain assumptions required for their flowrate calculations, such as pump pressure, are not given at all.

For the reference boiler LCOE calculations the 2016 energy tax and sustainable energy levy rates were used, as projections of their future development are lacking. However, there has been a trend of increasing natural gas energy tax rates between 2009 and 2016 (Belastingdienst, 2016b). Therefore, energy tax rates in 2020 and beyond are likely to be higher in reality and could potentially even exceed the values assumed in the ALT scenario. Moreover, increasing shares of variable renewable energy sources in the energy system may result in higher sustainable energy levy rates, as has already happened between 2013 and 2016 (Belastingdienst, 2016b). The base prices of natural gas that were used for 2020 and 2016 were average prices for Europe and the Netherlands respectively. In reality, companies like Warmtestad Groningen that consume large quantities of natural gas, may pay a lower price than average. However, HT-ATES or the reference natural gas peak boilers provide heat when demand is highest, and natural gas demand in the Netherlands follows approximately the same profile as heat demand in a district heating network. With reducing domestic natural gas production (Rijksoverheid, 2016), more natural gas must be imported in the future. As this gas is more expensive, it will likely be provided during peak demand. Therefore, it can be assumed that the reference boilers mainly use imported natural gas with a higher marginal price, which is closer to the national or (higher) European average price (Joris Koornneef, personal communication, July 6, 2016).

Another parameter in the Groningen case study with high uncertainty is demand size. As the district heating network will be newly constructed and the process of contracting heat consumers is still ongoing (Appendix 4), the projections of Greenvis are inherently uncertain. This is further aggravated by global climate change, which may alter the local climate and subsequently the heat demand profile.

To deal with the uncertainty described in the previous paragraphs as well as other uncertainties in Groningen, a sensitivity analysis was conducted on the HT-ATES LCOE and the reference boiler LCOE. This sensitivity analysis proved that no single parameter could change the outcome of the business case. However, to validate that also the combined uncertainty of all parameters simultaneously cannot change the outcome, an uncertainty analysis such as stochastic Monte-Carlo analysis is required (Ou, Thilakaratne, Brown, & Wright, 2015). Based on the results of the simple sensitivity analysis, and given time restrictions and the large difference between the HT-ATES LCOE and reference LCOE, this was omitted.

Two notable limitations of the case studies remain. HT-ATES systems have relatively low recovery efficiencies during the first years of operation. The efficiency increases as injected heat increases the aquifer ambient temperature (Schout et al., 2014). Therefore, the first years can be considered as the charging phase. These heat losses were not taken into account, as a constant recovery efficiency of 72,5% was assumed. Future market potential assessments can incorporate the costs associated with the charging phase(mainly heat purchase costs) into capital expenditure or use a variable recovery efficiency. The second limitation concerns the operational strategy of the HT-ATES. It was assumed that the (hypothetical) operator has perfect foresight, i.e. it is known exactly how much heat will be demanded on each day of every winter season. Consequently, the amount of injected heat (with a cost of 2 EUR/GJ in the Groningen case study) perfectly matches heat demand, after correcting for the assumed recovery efficiency. In reality it is unknown how large heat demand will be in the next winter season, so operators are likely to inject more heat in summer than is required in an average winter. Any injected heat that is not used in the first subsequent winter season can be considered as lost.

An overarching limitation of this study appeared during the Rotterdam case study. The private companies involved in the district heating network were not able to share heat production and demand profiles for reasons of confidentiality. It can be expected that this problem will be encountered at other case studies as well, when using the market potential framework. Unfortunately, no viable alternative was found that does not require heat production profiles. For heat demand and several other parameters, public data and standard assumptions can be used more easily than for heat supply.

In the Rotterdam case study, bold assumption were made as a result of the need to work with public data. Particularly the 50% share of heat demand delegated to AVR is highly uncertain as no information is available to make an accurate assumption for this parameter. On top of this, the assumed constant total heat demand in the heat roundabout of 20 PJ in the 2020-2034 period is a simplification. Again, lack of more accurate data necessitated this assumption. Finally, the used demand distribution profile of Groningen is unlikely to represent the real distribution in Rotterdam, as a significant share of heat demand comes from industry and horticulture in addition to households (which is expected to somewhat flatten out the demand profile). The connection of additional heat suppliers can also potentially alter the profile of heat demand that is delegated to AVR.

A simplification and uncertain factor in the calculation of the reference price for AVR is the ICE TTF index. This index was not yet available for the years 2020-2034 due to the unpredictability of natural gas prices. Consequently the 2018 index was used, which likely results in an underestimation of the selling price of heat (i.e. the reference price) considering the expected long-term rising trend of the natural gas price (e.g. European Commission, 2014). This uncertainty comes on top of the uncertainty resulting from the use of a general estimation of the value of heat by ECN.

6.3 Recommendations for future research

Several of the uncertainties and limitations described in section 6.2 are the result of the low number of studies about HT-ATES and the lack of pilots projects. Pilot projects are required to improve the understanding of highly uncertain parameter values such as HT-ATES lifetime, which has the strongest influence on the HT-ATES LCOE. Moreover, pilots can provide the required data to include the charging phase and more realistic operational behaviour in future HT-ATES market potential assessments. Finally, pilot projects can potentially play a role in studies of the societal factors that influence the HT-ATES market potential. Further research on the influence of societal factors is an indispensable part of HT-ATES market potential assessments.

An important topic for future theoretical research is the definitions of ATES, MT-ATES and HT-ATES. The clear boundaries that are required to prevent overlap between their potentials depend on these definitions. How these definitions can potentially change when the legislation that partially determines them (the 25-30°C temperature limit in the water law) is revised, and what the arguments and counterarguments are for integrating the potentials of ATES, MT-ATES and HT-ATES into a single potential, are also an important issue for further research. Finally, the potential interference of other activities that exploit the subsurface, such as carbon capture and storage and (natural) gas storage, are an issue that has yet to be addressed.

In this study, a number of changes and additions to the policy package were proposed to stimulate HT-ATES deployment. However, further research is required to increase insight in their effectiveness and potential spin-off consequences. As for the policies that are incorporated in the market potential assessment framework, an important part of this further research consists of conducting more market potential assessments of case studies to acquire quantitative insights. Different HT-ATES settings are ideally assessed in these case studies. Additional research is required to assess the feasibility of an information programme and explore the options for policies to implement a heat ladder.

One proposed policy change requires further research in particular: the levelling of energy tax on natural gas with energy tax on electricity. When the tax brackets of natural gas and electricity are converted to the same energy units, it can be observed that the first tax bracket for electricity is significantly smaller than the first tax bracket of natural gas. This raises the question of whether levelling the current first tax brackets is appropriate. Besides identifying ways to deal with this issue, potential side-effects of increasing the energy tax on natural gas need to be mapped in further research.

Although policies and regulations can play an important role in stimulating HT-ATES deployment, they can also be used unethically. This particularly holds for SDE$^+$ subsidy on geothermal heat. If a HT-ATES injects geothermal heat, extra SDE$^+$ can potentially be received for each injected GJ. However, over a quarter of the injected energy is lost before it reaches its final consumers, mainly due to subsurface losses. This share can further increase when HT-ATES is used purely as a tool for profit maximization of a geothermal well, in which case as much geothermal heat as necessary to reach the maximum number of SDE$^+$ full load hours is injected into a HT-ATES. It would therefore be more ethical to only receive extra SDE$^+$ for the geothermal heat that is produced by the HT-ATES. Research is required to alter the conditions for SDE$^+$ subsidy to prevent unethical use.

A possible HT-ATES business case that has not been addressed in the 2020 market potential assessment framework, is its potential role in the flexibility of the future energy system. Further research is required on the applications of HT-ATES combined with P2H technology, as well as the business cases that come with it. However, before expansion of HT-ATES applications, life cycle assessments(LCA) in different settings must be conducted to verify that HT-ATES contributes to a more sustainable energy system. An LCA for HT-ATES combined with geothermal heat and waste incineration heat is currently being conducted at TNO. Further research is needed on HT-ATES combined with other heat sources and P2H.

7 Conclusion

The goal of this thesis is to contribute to the methodological development on the integrated assessment of HT-ATES by developing a framework for the theoretical, technical and market potential assessment of HT-ATES in the Netherlands, as well as to identify the main conditions, barriers and drivers of HT-ATES implementation.

Through literature and document research, complemented with brainstorm sessions with experts, the parameters relevant for HT-ATES potentials were mapped and classified in the appropriate type of potential. Parameter values, formulas and boundaries were proposed and a methodology for the assessment of the theoretical, technical and market potential of HT-ATES was developed. Together with relevant data sources for potential assessment in the Dutch context, this resulted in frameworks for the assessment of these potentials. These step-by-step frameworks provide a methodology that can be used in future research as a guideline to fully quantify HT-ATES potentials in the Netherlands as well as in other parts of the world. Together with the HT-ATES definition that was further specified during the development of the frameworks, these quantified potentials can further enhance insights into the role that HT-ATES can fulfil in the development of future smart energy systems.

Using the developed market potential assessment framework, a quantitative market potential assessment was conducted of a to-be built district heating network in the Dutch city of Groningen as well as a planned provincial district heating network in Zuid-Holland using primarily waste heat from the port of Rotterdam. A viable business case for HT-ATES was defined in Groningen, with a potential to abate 14 kt of CO_2-emissions within its 15-year economic lifetime. This case study revealed the potentially good prospects for HT-ATES in combination with geothermal heat in the Netherlands, which is largely the result of SDE^+ subsidy. No viable business case was defined in Rotterdam based on the assumptions that were made, but a large potential for HT-ATES under slightly different conditions was identified. The business case of HT-ATES in Rotterdam proved to be highly dependent on the assumed ratio between heat surplus in summer and heat shortage in winter.

The development of the market potential assessment framework as well as its application on two case studies also revealed several shortcomings and weaknesses in the existing policy package in the Netherlands. Recommendations were made for further research on these policies, in order to enhance their effectiveness and limit options to exploit them unethically.

8 Bibliography

AVR. (n.d.). AVR Rozenburg. Retrieved May 27, 2016, from http://www.avr.nl/over-avr/onze-locaties/avr-rozenburg/

AVR. (2016a). 100% waardevol. Retrieved July 14, 2016, from http://www.avr.nl/nl/100-waardevol

AVR. (2016b). Flexible and adaptive. Retrieved July 19, 2016, from http://www.avr.nl/en/flexible-and-adaptive

Belastingdienst. (2016a). Handboek Milieubelastingen 2016. Belastingdienst. Retrieved from http://download.belastingdienst.nl/belastingdienst/docs/handboek_milieubelastingen_ml0301z61fd.pdf

Belastingdienst. (2016b). Tabellen tarieven milieubelastingen. Retrieved June 21, 2016, from http://www.belastingdienst.nl/wps/wcm/connect/bldcontentnl/belastingdienst/zakelijk/overige_belastingen/belastingen_op_milieugrondslag/tarieven_milieubelastingen/tabellen_tarieven_milieubelastingen?projectid=6750bae7-383b-4c97-bc7a-802790bd1110

Bioregional. (2015). Why can't we get district heating right in the UK? Retrieved May 20, 2016, from http://www.bioregional.com/district-heating-uk/

Bloemendal, M., Olsthoorn, T., & Boons, F. (2014). How to achieve optimal and sustainable use of the subsurface for Aquifer Thermal Energy Storage. *Energy Policy*, *66*, 104–114. http://doi.org/10.1016/j.enpol.2013.11.034

Bloemendal, M., Olsthoorn, T., & Van de Ven, F. (2015). Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. *The Science of the Total Environment*, *538*, 621–33. http://doi.org/10.1016/j.scitotenv.2015.07.084

Botje, H. E. (2016). Protest of geen protest, Kamp blijft vol inzetten op kolencentrales. *Vrij Nederland*. Retrieved from https://www.vn.nl/protest-kamp-kolencentrales/

Botje, H. E., & Broer, T. (2014, July 27). Voorbij de gasdroom: onze ongezonde relatie met Rusland. *Vrij Nederland*. Retrieved from https://www.vn.nl/voorbij-de-gasdroom-onze-ongezonde-relatie-met-rusland/

Böttger, D., Götz, M., Lehr, N., Kondziella, H., & Bruckner, T. (2014). Potential of the Power-to-Heat Technology in District Heating Grids in Germany. *Energy Procedia*, *46*, 246–253. http://doi.org/10.1016/j.egypro.2014.01.179

Bragadóttir, H., Magnusson, R., Seppänen, S., Sundén, D., & Yliheljo, E. (2016). *Sectoral expansion of the EU ETS: - A Nordic perspective on barriers and solutions to include new sectors in the EU ETS with special focus on road transport*. Copenhagen, Denmark: Nordic Council of Ministers.

CBS. (2014). *Hernieuwbare energie in Nederland 2013*. *Centraal Bureau voor de Statistiek*. Retrieved from https://www.cbs.nl/nl-nl/.../b6819c84be2845dea0c8902ab631935f.ashx

CBS. (2015). CBS: Lagere uitstoot broeikasgassen in warm 2014. Retrieved February 16, 2016, from http://www.cbs.nl/nl-NL/menu/themas/natuur-milieu/publicaties/artikelen/archief/2015/lagere-uitstoot-broeikasgassen-in-warm-2014.htm

CBS. (2016). Inflatie; CPI, vanaf 1963. *StatLine*. Centraal Bureau voor de Statistiek. Retrieved from http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=70936NED&D1=0&D2=(l-34)-l&HD=081020-1258&HDR=T&STB=G1

Christidis, A., Koch, C., Pottel, L., & Tsatsaronis, G. (2012). The contribution of heat storage to the profitable operation of combined heat and power plants in liberalized electricity markets. *Energy*, *41*(1), 75–82. http://doi.org/10.1016/j.energy.2011.06.048

De Beer, J., Slingerland, E., & Meindertsma, W. (2014). *Warmteladder - Afwegingskader warmtebronnen voor warmtenetten*. Retrieved from www.ecofys.com/files/files/ecofys-2014-warmteladder.pdf

De Zwart, B. (2009). *Haalbaarheidsonderzoek warmteopslag glastuinbouw Vierpolders, MEC-V fase 2a*. Retrieved from http://www.agrimaco.nl/sites/default/files/redactie/bestanden/pdf/090528 mecv rapport def 2a.pdf

Den Ouden, B., Hoeksema, L. H., & Graafland, P. (2015). *Verduurzaming gebouwde omgeving door open warmtenetten*. Retrieved from https://www.allianderdgo.nl/wp-content/uploads/2015/07/Rapportage-Verduurzaming-gebouwde-omgeving-door-open-warmtenetten.pdf

Drijver, B. (2012). *Meer met Bodemenergie: Rapport 6 - Hogetemperatuuropslag. Kennisoverzicht en praktijkmetingen rondom hogetemperatuuropslagsystemen*. Retrieved from http://soilpedia.nl/Bikiwiki documenten/Meer met Bodemenergie/Rapport 6 Hogetemperatuuropslag Meer met Bodemenergie.pdf

Drijver, B., Aarssen, M. Van, & Zwart, B. De. (2012). High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. *Paper Presented at InnoStock 2012, Catalonia, Spain*.

Dufour, F. C. (1998). *Grondwater in Nederland - Onzichtbaar water waarop wij lopen*. Retrieved from http://publications.tno.nl/publication/34617052/1FNeOl/dufour-1998-grondwater.pdf

Eneco. (n.d.). Waar ligt Leiding over Noord? Retrieved May 27, 2016, from http://projecten.eneco.nl/leiding-over-noord/projectgegevens/trace/

Eneco. (2016). Warmte stroomt onder de grond. Retrieved July 18, 2016, from http://projecten.eneco.nl/leiding-over-noord/projectgegevens/warmtetransportnet/

Energy Valley Top Club. (2015). WarmteStad. Retrieved June 29, 2016, from http://www.evtc.nl/nieuws/warmtestad/

European Commission. (2014). *TRENDS TO 2050 - REFERENCE SCENARIO 2013*. Luxemburg: Publications Office of the European Union. http://doi.org/10.2833/17897

F&H Crone B.V. (2011). FAQ - VEELGESTELDE VRAGEN. Retrieved June 20, 2016, from http://www.fhcrone.eu/index.php?option=com_content&view=article&id=130&Itemid=53&lang=nl

Fragaki, A., Andersen, A. N., & Toke, D. (2008). Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. *Energy*, *33*(11), 1659–1670. http://doi.org/10.1016/j.energy.2008.05.011

Gemeente Rotterdam. (2014). Eerste stap gezet voor Warmterotonde. Retrieved May 30, 2016, from http://www.persberichtenrotterdam.nl/bericht/444/Eerste-stap-gezet-voor-Warmterotonde/

Gustavsson, L., Dodoo, A., Truong, N. L., & Danielski, I. (2011). Primary energy implications of end-use energy efficiency measures in district heated buildings. *Energy and Buildings*, *43*(1), 38–48. http://doi.org/10.1016/j.enbuild.2010.07.029

Hellebrand, K., Post, R. J., & In 't Groen, B. (2012). *Kansen voor Ondiepe Geothermie voor de glastuinbouw*. Retrieved from http://www.soilpedia.nl/Bikiwiki documenten/SKB Projecten/2145 Kansen voor ondiepe geothermie in de glastuinbouw/2145 Kansen voor ondiepe geothermie in de glastuinbouw.pdf

Huismans, M. (2016). *The potential contribution of geothermal heat to regional heat distribution networks in the Netherlands (bachelor's thesis)*. Utrecht University, Utrecht, the Netherlands.

ICE. (2016). DUTCH TTF GAS FUTURES. Retrieved July 15, 2016, from https://www.theice.com/products/27996665/Dutch-TTF-Gas-Futures/data

IEAGHG. (2011). *Potential for Biomass and Carbon Dioxide Capture and Storage*. Retrieved from http://www.ieaghg.org/docs/General_Docs/Reports/2011-06.pdf

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Jeon, J.-S., Lee, S.-R., Pasquinelli, L., & Fabricius, I. L. (2015). Sensitivity analysis of recovery efficiency in high-temperature aquifer thermal energy storage with single well. *Energy*, *90*, 1349–1359. http://doi.org/10.1016/j.energy.2015.06.079

Kamp, H. G. J. (2015). Kamerbrief Warmtevisie. Ministerie van Economische Zaken. Retrieved from https://www.rijksoverheid.nl/documenten/kamerstukken/2015/04/02/kamerbrief-warmtevisie

KNMI. (2000). *Handboek Waarnemingen*. Retrieved from http://projects.knmi.nl/hawa/download.html

Koornneef, J. (2016). Presentatie Hoge temperatuur opslag. Retrieved June 26, 2016, from http://www.slideshare.net/AmsterdamEconomicBoard/presentatie-hoge-temperatuur-opslag

Koornneef, J., Griffioen, J., Pluymaekers, M., & Boxem, T. (2015). *Technische en Juridische belemmeringen Hoge Temperatuuropslag (HTO) (Unpublished)*.

Kopac, M., & Hilalci, A. (2007). Effect of ambient temperature on the efficiency of the regenerative and reheat Çatalağzı power plant in Turkey. *Applied Thermal Engineering*, *27*(8-9), 1377–1385. http://doi.org/10.1016/j.applthermaleng.2006.10.029

Kramers, L., Van Wees, J. D., Pluymaekers, M. P. D., Kronimus, A., & Boxem, T. (2012). Direct heat resource assessment and subsurface information systems for geothermal aquifers; The Dutch perspective. *Geologie En Mijnbouw/Netherlands Journal of Geosciences*, *91*(4), 637–649. http://doi.org/10.1017/S0016774600000421

Leguijt, C., & Schepers, B. (2014). *Functioneel ontwerp Vesta 2.0*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/pbl-2014-ce-delft-functioneel-ontwerp-vesta-2.0.pdf

Lensink, S. M., & Van Zuijlen, C. L. (2016). *Aanvullend onderzoek correctiebedragen SDE+-regeling*. Retrieved from https://www.ecn.nl/publicaties/ECN-E--15-070

Liukku, A. (2016). Shell Pernis sluit alsnog aan op Rotterdams warmtenet. *Algemeen Dagblad*. Retrieved from http://www.ad.nl/rotterdam/shell-pernis-sluit-alsnog-aan-op-rotterdams-warmtenet~aecb4326/

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH) - Integrating smart thermal grids into future sustainable energy systems. *Energy*, *68*, 1–11. http://doi.org/10.1016/j.energy.2014.02.089

Milieu Centraal. (2016). Energieprijzen. Retrieved June 23, 2016, from https://www.milieucentraal.nl/energie-besparen/snel-besparen/grip-op-je-energierekening/energieprijzen/

Nuon. (2015). CO2 - Reductierapport 2015 - Rotterdam. Retrieved May 27, 2016, from http://co2-reductierapporten.nuon.com/rotterdam

Ou, L., Thilakaratne, R., Brown, R. C., & Wright, M. M. (2015). Techno-economic analysis of transportation fuels from defatted microalgae via hydrothermal liquefaction and hydroprocessing, *72*, 45–54. http://doi.org/10.1016/j.biombioe.2014.11.018

Pawel, I. (2014). The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy (LCOE) and Applications to Renewable Energy Generation. *Energy Procedia*, *46*, 68–77. http://doi.org/10.1016/j.egypro.2014.01.159

Platform Geothermie. (2013). Aardwarmte Den Haag. Retrieved June 29, 2016, from http://geothermie.nl/geothermie-aardwarmte/projecten/aardwarmte-den-haag/

Pluymaekers, M., Van Wees, J.-D., Van der Kuip, M., & Vandeweijer, V. (2013). *HTO - Hoge temperatuur opslag in de ondiepe ondergrond*. Retrieved from http://www.nlog.nl/resources/Geothermie/2013 R11694 HTO - Hoge temperatuur opslag in de ondiepe ondergrond.pdf

Provincie Zuid Holland. (2012). *Voorstel voor besluitvorming aan gedeputeerde staten: pilot opslag warmte met hoge temperatuur GeoMec-4P in gemeente Brielle (Unpublished)* (No. Besluitnummer PZH-2012-338558306 (DOS-2011-0010880)).

Provincie Zuid-Holland. (n.d.). Warmte - Warmterotonde. Retrieved May 27, 2016, from http://www.zuid-holland.nl/onderwerpen/energie/warmte-warmterotonde/

Provincie Zuid-Holland. (2015). Perspectief warmtenet Zuidvleugel. Retrieved July 16, 2016, from www.zuid-holland.nl/publish/pages/9387/kaart_warmtenet.pdf

Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., & Haas, R. (2008). Potentials and prospects for renewable energies at global scale. *Energy Policy*, *36*(11), 4048–4056. http://doi.org/10.1016/j.enpol.2008.06.029

Réveillère, A., Hamm, V., Lesueur, H., Cordier, E., & Goblet, P. (2013). Geothermal contribution to the energy mix of a heating network when using Aquifer Thermal Energy Storage: Modeling and application to the Paris basin. *Geothermics*, *47*, 69–79. http://doi.org/10.1016/j.geothermics.2013.02.005

Rijksoverheid. (2016). Gaswinning Groningen verlaagd tot 24 miljard kubieke meter. Retrieved July

5, 2016, from https://www.rijksoverheid.nl/actueel/nieuws/2016/06/24/gaswinning-groningen

RVO. (2016a). Energie-investeringsaftrek (EIA). Retrieved May 11, 2016, from http://www.rvo.nl/subsidies-regelingen/energie-investeringsaftrek-eia

RVO. (2016b). Stimulering Duurzame Energieproductie (SDE+). Retrieved May 11, 2016, from http://www.rvo.nl/subsidies-regelingen/stimulering-duurzame-energieproductie-sde

Sanner, B., & Knoblich, K. (1999). Advantages and problems of high temperature underground thermal energy storage. *Bulletin d'Hydrogéologie*, (17), 341–348.

Schoots, K., & Hammingh, P. (2015). *Nationale Energieverkenning 2015*. Retrieved from https://www.ecn.nl/publicaties/ECN-O--15-033

Schout, G., Drijver, B., Gutierrez-Neri, M., & Schotting, R. (2014). Analysis of recovery efficiency in high-temperature aquifer thermal energy storage: A Rayleigh-based method. *Hydrogeology Journal*, *22*, 281–291. http://doi.org/10.1007/s10040-013-1050-8

Siemer, L., Schöpfer, F., & Kleinhans, D. (2016). Cost-optimal operation of energy storage units: Benefits of a problem-specific approach. *Journal of Energy Storage*, *6*, 11–21. http://doi.org/10.1016/j.est.2016.01.005

skb. (2013). Position paper hogetemperatuuropslag. skb duurzame ontwikkeling ondergrond. Retrieved from http://www.soilpedia.nl/Bikiwiki documenten/SKB Projecten/2068 Hogetemperatuuropslag in de bodem/7751 SKB HTO.pdf

Stork, M., Blinde, P., & Borkent, B. (2013). *Warmtestromen binnen het EU-ETS*. Retrieved from https://www.rvo.nl/sites/default/files/2014/01/Warmtestromen binnen het EU ETS.PDF

Taskforce WKO. (2009). *Groen licht voor Bodemenergie*. Retrieved from https://www.rijksoverheid.nl/documenten/brochures/2009/03/01/groen-licht-voor-bodemenergie-advies-taskforce-wko

Tennet. (2015). Elektriciteitsprijzen in Nederland gedaald met ruim 20 procent in 2014. Retrieved July 5, 2016, from http://www.tennet.eu/nl/nl/nieuws/article/elektriciteitsprijzen-in-nederland-gedaald-met-ruim-20-procent-in-2014.html

Tigchelaar, C. (2015). Showstoppers & gamechangers - Beleid voor gasloze woningen. ECN. Retrieved from https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-L--16-020

TNO. (n.d.). Digitaal Geologisch Model: DGM-diep. DINOloket 2016. Utrecht.

TNO. (2005). REGIS II - Landelijk hydrogeologisch model. DINOloket 2016. Utrecht.

TUM. (2014). Seasonal High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Bavarian Malm. Retrieved July 4, 2016, from https://www.hydro.geo.tum.de/projects/aquifer-thermal-energy-storage/

Van den Wijngaart, R., Folkert, R., & Elzenga, H. (2015). *Naar een duurzamere warmtevoorziening van de gebouwde omgeving in 2050*. Retrieved from http://www.pbl.nl/sites/default/files/cms/publicaties/PBL-2012-Duurzamere warmtevoorziening-500264002.pdf

Van der Doelen, F. C. (1998). The "give-and-take" packaging of policy instruments: optimizing legitimacy and effectiveness. In *Carrots, sticks and sermons - Policy instruments and their evaluation* (pp. 129–146). New Brunswick, NJ, USA: Transaction Publishers.

Van der Krogt, R. (2011). *Energie uit de Ondergrond: Potenties en kartering*. Retrieved from http://www.rvo.nl/sites/default/files/2014/10/Energie uit de ondergrond, potenties en kartering.pdf

Van Heekeren, V., & Bakema, G. (2015). The Netherlands Country Update on Geothermal Energy. In *Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April*.

Van Huissteden, E. (2015). Kader en plankrediet Geothermie en warmtenet Noordwest. Retrieved from http://www.selwerd.info/index.php?option=com_content&view=article&id=608:raadsvoorstel-kader-en-plankrediet-geothermie-en-warmtenet-noordwest&catid=35&Itemid=150

Vedung, E., Bemelmans-Videc, M. L., & Rist, R. C. (1998). Policy instruments: typologies and their evaluation. In *Carrots, sticks, and sermons: Policy instruments and their evaluation* (pp. 21–58). New Brunswick, NJ, USA: Transaction Publishers.

Verbruggen, A., Fischedick, M., Moomaw, W., Weir, T., Nadaï, A., Nilsson, L. J., … Sathaye, J. (2010). Renewable energy costs, potentials, barriers: Conceptual issues. *Energy Policy*, *38*(2), 850–861. http://doi.org/10.1016/j.enpol.2009.10.036

Warmtekoude Zuid-Holland. (2015). Over het programma. Retrieved July 14, 2016, from http://warmopweg.nl/programma/

Warmtekoude Zuid-Holland. (2016a). Glasparel Zuidplaspolder in 2018 ook voorzien van Rotterdamse restwarmte. Retrieved July 17, 2016, from http://warmopweg.nl/glasparel-zuidplaspolder-2018-ook-voorzien-rotterdamse-restwarmte/

Warmtekoude Zuid-Holland. (2016b). Warmtelevering in Leidse regio stap dichterbij, ambitieverklaring getekend. Retrieved July 14, 2016, from http://warmopweg.nl/warmtelevering-leidse-regio-stap-dichterbij-ambitieverklaring-getekend/

Willemsen, G. (2010). Hoge temperatuur warmteopslag; Stand van zaken in NL [PowerPoint slides]. IF Technology. Retrieved from http://www.boersmatuinbouwadvies.nl/IF.pdf

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. http://doi.org/10.1016/j.enpol.2006.12.001

Zeghici, R. M., Oude Essink, G. H. P., Hartog, N., & Sommer, W. (2015). Integrated assessment of variable density-viscosity groundwater flow for a high temperature mono-well aquifer thermal energy storage (HT-ATES) system in a geothermal reservoir. *Geothermics*, *55*, 58–68. http://doi.org/10.1016/j.geothermics.2014.12.006

Zijlema, P. J. (2013). *Berekening van de standaard CO2-emissiefactor aardgas t.b.v. nationale monitoring 2014 en emissiehandel 2014*. Retrieved from http://www.rvo.nl/sites/default/files/2014/08/Zijlema 2013 Berekening CO2-emissiefactor aardgas jaar 2014.pdf

9 Appendix 1: Overview of parameters in the HT-ATES tool

Technical parameters

Parameter	Parameter value
Surface temperature	10°C
Pump pressure	4,5 bar
Pump efficiency	63%
HT-ATES recovery efficiency	72,5%
Heat capacity formation water	4,01 $J/g*K^{-1}$
Density formation water	958 kg/m^3

Economic parameters

Parameter	Parameter value
Economic lifetime HT-ATES	15 years
Economic lifetime natural gas-fired peak boiler	15 years
Costs of drilling	1000 EUR/m
Price of pump	100.000
Lifetime pump	5 years
Surface investment costs (i.a. heat exchanger)	150.000 EUR/MW_{th}
Fixed operation and maintenance costs	1% of capex
Electricity price for pumps	50 EUR/MWh
Inflation	2,0065%
Loan interest rate	8%
Required return on equity	6% (Groningen); 15% (Rotterdam)
Equity share in investment	20%
Loan share in investment	80%
Tax rate	25,5%
Loan term	15 years
Depreciation period	15 years
Percentage of capex for EIA	58%(BAU); 78% (ALT)

10 Appendix 2: Overview of natural gas taxes and levies

For the conversion of natural gas taxes and levies from EUR/m³ to EUR/GJ, a caloric value of 9,769 kWh/m³ (0,035 GJ/m³) is assumed.

Energy tax:

Tax brackets		BAU tax rates		ALT tax rates	
Gas (m^3/year)	**Electricity (MWh/year)**	**Gas (EUR/GJ)**	**Electricity (EUR/GJ)**	**Gas (EUR/GJ)**	**Electricity (EUR/GJ)**
0-170.000	0-10	7,156	27,972	13,986	27,972
170-1.000.000	10-50	1,977	13,878	1,977	13,878
1.000.000-10.000.000	50-10.000	0,721	3,697	0,721	3,697
>10.000.000 (private)	>10.000 (private)	0,345	0,297	0,345	0,297
>10.000.000 (business)	>10.000 (business)	0,345	0,147	0,345	0,147

Sustainable energy levy (*Opslag duurzame energie*):

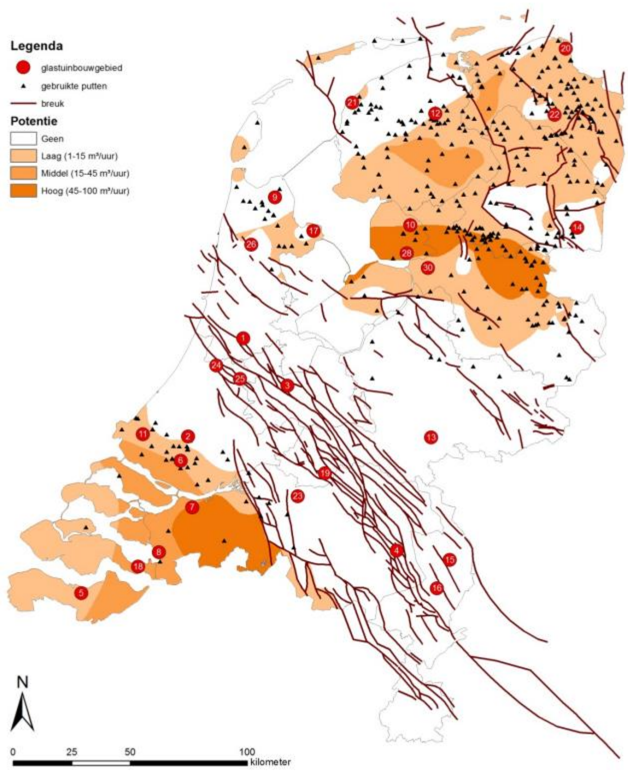
Tax brackets		Levies[b]	
Gas (m^3/year)	**Electricity (MWh/year)**	**Gas (EUR/GJ)**	**Electricity (EUR/GJ)**
0-170.000	0-10	0,05	1,56E-06
170-1.000.000	10-50	0,06	1,94E-06
1.000.000-10.000.000	50-10.000	0,04	5,28E-07
>10.000.000 (private)	>10.000 (private)	0,03	2,33E-08
>10.000.000 (business)	>10.000 (business)	0,03	2,33E-08

b: Sustainable energy levies are equal in both policy scenarios

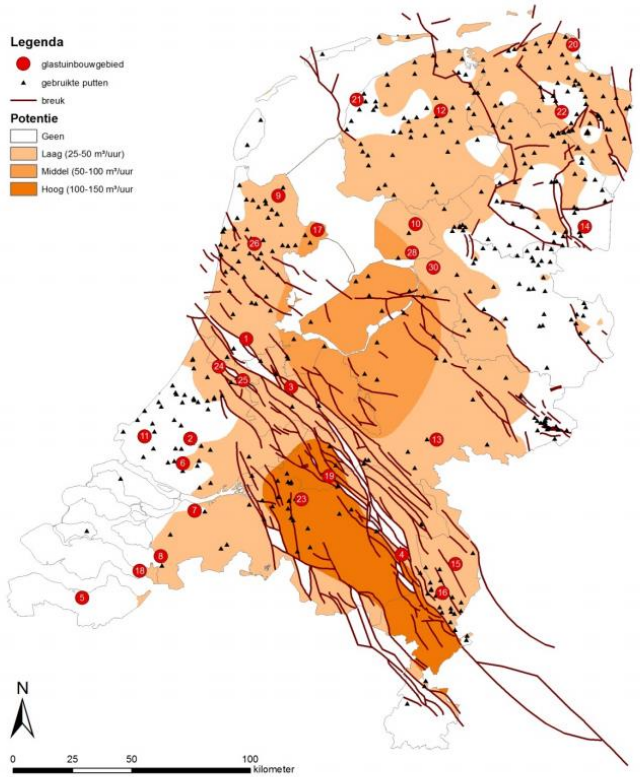
11 Appendix 3: Potential maps of several geological formations

The following maps show estimations of the flow rates that can be expected from a specific formation at different locations in the Netherlands, according to Hellebrand, Post, & In ’t Groen (2012). The values are only a preliminary indication.

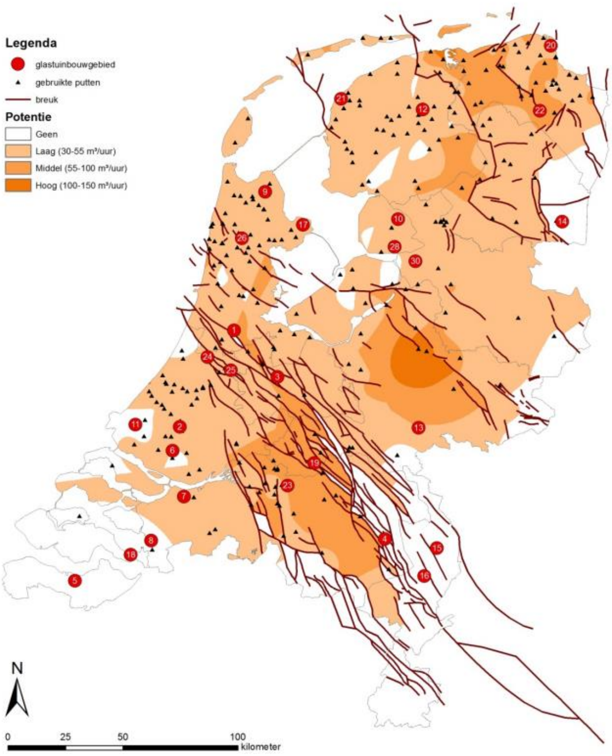
Brussels sand



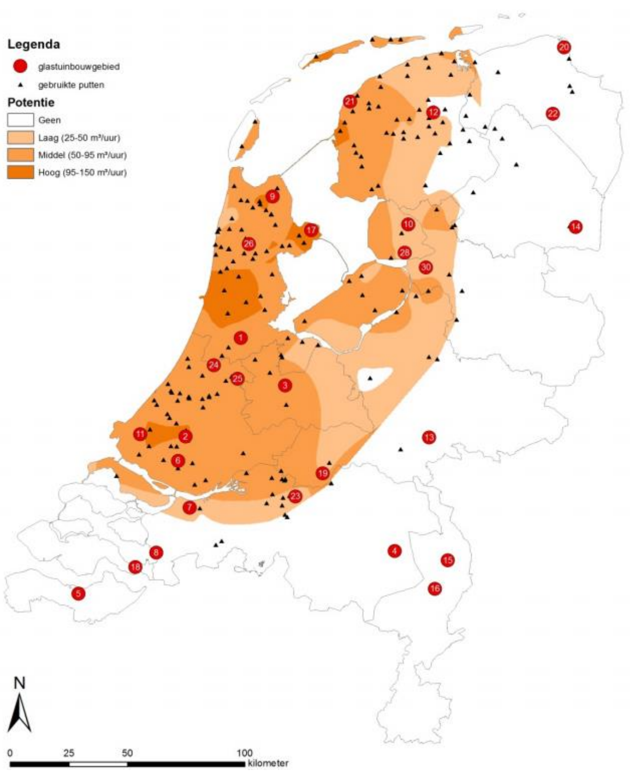
Formation of Breda



Formation of Oosterhout



Formation of Maassluis



12 Appendix 4: Interview Warmtestad Groningen

Interviewee: Sander-Luc Visser, Assistant Project Leader geothermal energy

May 31, 2016. TNO Utrecht, Princetonlaan 6.

The interview transcription below is a translation and summary of those parts of the interview that are deemed relevant for this thesis by its author. Text in italic between brackets – [example] – is added by the author to elucidate the statements of the interviewee. Extensive data was provided by e-mail following the interview

Has the drilling of the geothermal well started yet?
No, we hope to start drilling after the summer of 2017.

Your current SDE$^+$ ascription has already expired by then, hasn't it?
That is true, however we received a new SDE$^+$ permit last week for deeper geothermal heat, as we plan to drill slightly deeper than 3500 meters. This means we will get a higher SDE$^+$ subsidy per GJ than in the previous ascription.

What is the maximum number of full load hours for which you will receive SDE$^+$?
I cannot find that at the moment, I will inform you by email.

Is it true that Warmtestad Groningen will be responsible for the entire chain from production of heat to transport, delivery and customer contact?
Yes, that is what we plan to do.

Will the entire district heating network be newly constructed, or are there existing grids to which you will connect?
Yes, by the end of 2016 we will construct the first part of the grid. Before drilling the geothermal well we expect that 10-20 MW worth of heat demand has already been connected to the grid. It is our strategy to realize (part of) the grid before drilling the well on purpose, because of what happened in The Hague. A geothermal well was drilled there that was supposed to supply heat into a new grid connected to newly built households. However, the housing corporation responsible for building the houses went bankrupt, leaving the already drilled geothermal well without heat demand. By connecting to existing houses and building the grid before drilling a well, we are guaranteed to have demand for heat when the well is ready.

Will the natural gas infrastructure be removed in the neighbourhoods that get connections to the heat grid?
No, that infrastructure will stay in place. We will first connect the low hanging fruit: buildings with central gas boilers.

Is it true that in the first two deployment phases only buildings of education institutes will be connected?
No, dwellings will be connected too. Mostly dwellings actually, mainly old flat buildings with collective boilers and heating operating at temperature ranges of 90-70 degrees Celsius.

Which business cases of adding a HT-ATES system to the Groningen grid do you foresee, besides reducing natural gas consumption of peak boilers?
The geothermal well preferably operates at a flow rate of at least 90 m^3/hour, but on hot summer days the demand for heat drops to below 20 m^3/hour, even with 10.000 household equivalents connected. The surplus of heat *[i.e. 90-20=70 m^3/hour]* would have to be pumped back into the ground for example. It would be very valuable for us to keep a stable high flow rate during the whole summer. That allows us to sell more GJ of geothermal heat. The submersible pump is very expensive and has a short lifetime, so we want to utilize it as much as possible.

We also looked at Ecovat, an alternative underground heat storage technology that uses a concrete tank. But this solution turned out to be rather expensive per unit of energy stored, compared to HT-ATES. The advantage may be a slightly higher flow rate or thermal power, but the storage capacity is much smaller. A HT-ATES cannot fill the gap between the maximum flow rate of the geothermal well – 200 m^3/h– and the peak heat demand on a very cold, windy day - 800 m^3/h – as its maximum hourly output is much lower than 600 m^3.

I read online that Warmtestad also considers the option of using summer surplus heat for absorption cooling. Is that a realistic competitor for HT-ATES?
It is a realistic option to apply, but at about 15.000 GJ per summer season the cooling demand is by far not sufficient to let the geothermal well produce 200 m^3/hour *[i.e. its maximum flowrate]* all summer. So enough surplus capacity in summer remains to implement HT-ATES.

The cold will be stored in the ATES system of the university, which has a cold shortage. The connection will amount to 2,5 MW.

Will this ATES be a part of the district heating network, or is it a separate storage merely benefiting from it?
It will be an isolated storage system that does not serve as a buffer for the district heating system. So it will not supply heat to the grid in winter, but only consume some heat in summer.

Will the grid's pipelines be put in the ditch banks?
That was the plan originally, but we found that the banks are already full of other infrastructure. The ditch itself is not suitable as it complicates maintenance and timely repairs in case of malfunctioning. We now found a suitable route under a bicycle lane.

Do you plan to make this a closed district heating network with only the geothermal heat as a baseload heat supplier, or are third parties also welcome?
We did discuss a biomass plant, but decided to initially only use the geothermal well. There is still room for expanding the demand side.

How will the grid look by 2020? Which supply and demand elements will be realized by then?
According to the current plans, 40 MW(phase 1) of demand will be connected within 5 years. Subsequently, we can continue with the second phase. But the process is a very uncertain and political one. There are many flats with collective boilers in Groningen, but it remains uncertain which want to connect to our grid. The housing corporations are not very cooperative, despite the fact that we can offer them quite a lot of benefits. We can offer them heat below the costs of heating with natural gas and they do not really need to invest for that. The corporations probably find it risky to cooperate with a new heat supplier.

The demand and supply profiles that I will email you are representative for the demand situation in 2022-2025, according to the latest planning. However, if the performance of the geothermal well proves to be as expected or even better, everything can suddenly speed up and pipeline connections can be realized much faster. At this moment we also have a number of interested potential investors, so that is a plus as well. These are mainly public bodies from within the province Groningen, as well as banks. For commercial investors, geothermal heat is still too uncertain.

Are the payback times of projects like this also too long to be attractive for market parties?
The payback time indeed is rather long. But, even without subsidy, there is a healthy business case. Compared to sustainable energy sources such as solar or wind power, it is relatively attractive. However, the initial investment and the risks are quite large.

Which buffers and peak heat supplies do you expect to be operating in 2020, besides potentially a HT-ATES?

I will email you detailed documents about this. We at least plan to have two above-ground tanks of 650 m^3 each as well as four peak boilers that together have 42MW of thermal power. The buffers will be installed in the early stages to allow the geothermal well to operate at an acceptable flow rate even when few households are connected. The submersible pumps have a lifetime of only 5-7 years so we want to use them as much as possible during those years.

What is roughly the ratio in demand composition of office/education buildings, horticulture and dwellings?
I do not know the exact ratio, I will send you a list of the power of buildings that will be connected. I do know we expect to realize a return temperature of roughly 50 degrees Celsius. This might increase after a few years as older flat buildings *[which require relatively hot water in their radiators]* will be connected later. Horticulture will not be connected to the grid, there hardly is any in Groningen. Besides, we do not want to inject the return flow back into the deep aquifer at temperatures below 50^oC, because of the risk of scaling/thermos-elasticity.

What is the expected coefficient of performance(COP) of the geothermal well?
This is very uncertain because we do not know enough about the extent of pressure depletion - due to the extensive natural gas production in the area – locally. The pump pressure we can apply is limited because high pressures could induce earthquakes. Although natural gas production is the main cause of those earthquakes, the pressure we apply could be a final trigger inducing them. Disputes about the cause of earthquakes is the last thing we want.

If there is very high pressure depletion of say 150 bar, the COP could be as low as 4 or 5. Without pressure depletion it could be 52. Based on our latest expectations, I recommend you assume a COP of 48.

The advantage of pressure depletion, by the way, is that re-injection of the water is easier. This is often difficult in geothermal wells. Energetically, however, it is obviously a disadvantage. Economically the COP is partially improved by the value of natural gas that comes up with the water.

Will there be a series set-up that allows cascading heat?
Yes, the modern buildings will be connected to the return flow, while the old buildings use the higher temperatures of the initial flow.

What is the expected heat loss in the entire grid?
We expect losses between 12-15%. In summer the losses are slightly lower due to lower supply temperatures and a higher ambient temperature of the ground.

What is the efficiency of the peak boilers?
We currently assume 98%. The CHP plant using the natural gas that is produced together with hot water has a 52% thermal efficiency and 40% electric efficiency.

What is the price that you can charge the consumers of your heat, considering the Warmtewet?
We will provide our heat at roughly 18 EUR/GJ, while the price cap in the Warmtewet is about 22 EU/GJ. This difference is partially due to negotiations of housing corporations.

What is the LCOE of the peak boilers?
I will send you information from the manufacturer by email.

What is the price that Warmtestad will pay for natural gas in the peak boilers?
Approximately 0,20 EUR/m^3 including all taxes.

Which discount rate for investments such as HT-ATES does Warmtestad pursue?
I do not know this, but you should consider that the funding comes from public parties such as the municipality, as well as banks. So you should assume social rather than private discount rates.

What are the costs per GJ of heat of the geothermal well within the full load hours limit (thus receiving SDE$^+$), and what are the marginal costs when this full load hours limit is surpassed?
The marginal costs are mainly the costs of electricity and amount to about 2EUR/GJ. I do not know the LCOE with SDE$^+$.

13 Appendix 5: Results of sensitivity analysis

13.1 Groningen

HT-ATES (BAU)

Parameter	Unit	Low	-10%	+10%	High	Default
Demand size	EUR/GJ	-	3,05	0,26	-	1,52
Discount rate	EUR/GJ	0,20	1,24	1,81	6,77	1,52
Electricity price	EUR/GJ	1,50	1,51	1,53	1,54	1,52
Equity share	EUR/GJ	1,51	1,52	1,52	1,56	1,52
Lifetime	EUR/GJ	10,59	3,55	0,56	-1,82	1,52
Recovery Efficiency	EUR/GJ	1,21	1,42	1,62	1,76	1,52
Price geothermal heat	EUR/GJ	-	1,28	1,76	-	
Well depth	EUR/GJ	0,10	1,01	2,03	2,94	1,52

HT-ATES (ALT)

Parameter	Unit	Low	-10%	+10%	High	Default
Demand size	EUR/GJ	-	2,19	-0,44	-	0,74
Discount rate	EUR/GJ	-0,54	0,47	1,03	5,86	0,74
Electricity price	EUR/GJ	0,73	0,74	0,75	0,76	0,74
Equity share	EUR/GJ	0,74	0,74	0,75	0,78	0,74
Lifetime	EUR/GJ	9,28	2,64	-0,16	-2,41	0,74
Recovery Efficiency	EUR/GJ	0,44	0,64	0,84	0,98	0,74
Price geothermal heat	EUR/GJ		0,51	0,98		
Well depth	EUR/GJ	-0,59	0,26	1,22	2,07	0,74

Reference boiler (BAU)

Parameter	Unit	Low	-10%	+10%	High	Default
Boiler efficiency	EUR/GJ	-	25,75	22,41	-	23,91
Demand size	EUR/GJ	-	24,40	23,52	-	23,91
Discount rate	EUR/GJ	23,80	23,89	23,94	24,49	23,91
Energy tax	EUR/GJ	-	23,58	24,25	-	23,91
Equity share	EUR/GJ	23,91	23,91	23,91	23,92	23,91
Gas price (excl. tax)	EUR/GJ	16,74	22,26	25,57	31,09	23,91
Lifetime	EUR/GJ	23,87	23,86	23,90	23,99	23,91

Reference boiler (ALT)

Parameter	Unit	Low	-10%	+10%	High	Default
Boiler efficiency	EUR/GJ	-	28,96	25,63	-	27,13
Demand size	EUR/GJ	-	27,95	26,46	-	27,13
Discount rate	EUR/GJ	26,92	27,08	27,18	28,02	27,13
Energy tax	EUR/GJ	-	26,47	27,79	-	27,13
Equity share	EUR/GJ	27,13	27,13	27,13	27,13	27,13
Gas price (excl. tax)	EUR/GJ	19,96	25,48	28,78	34,30	27,13
Lifetime	EUR/GJ	27,08	27,08	27,11	27,21	27,13

13.2 Rotterdam

HT-ATES (BAU)

Parameter	Unit	Low	-10%	+10%	High	Default
Share in heat supply	EUR/GJ	34,01	16,33	6,25	3,04	9,78
Thermal capacity	EUR/GJ	3,17	6,07	13,66	67,93	9,78

HT-ATES (ALT)

Parameter	Unit	Low	-10%	+10%	High	Default
Share in heat supply	EUR/GJ	32,41	15,56	5,96	2,9	9,32
Thermal capacity	EUR/GJ	3,02	5,78	13,01	64,73	9,32

14 Appendix 6: Interview AVR

Interviewee: Hans Wassenaar, Senior Project manager

June 21, 2016. By telephone

The interview transcription below is a translation and summary of those parts of the interview that are deemed relevant for this thesis. Text in italic between brackets – [example] – is added by the author to elucidate the statements of the interviewee.

Are there any restrictions or obligations relating how much electricity you produce at any given moment?
We hand in our program a day ahead, but other than that we are free.

The website of AVR states that there is a total of 559 MW of thermal power at AVR Rozenburg, generated from household waste, water recycling and wood waste. How are the electricity and steam production affected if all of this thermal power is used for district heating?
559 MW is the thermal power with which we generate steam. This steam can be delivered to customers directly, or can be converted to low-pressure steam to warm up water in the district heating network.

What is the temperature of the high-pressure steam?
The steam we sell to industries has a standard temperature between 360 and 400°C. The district heating water is heated to 100-120°C.

The company that we sell steam to is called Emerald Kalama Chemicals(EKC), which produces E-numbers. The return flow from EKC is a very hot condensate of 180°C. We further utilize this return flow by warming the district heating water with it, so basically we transfer industrial waste heat into the district heating system. This makes us a heat hub, especially since we can regulate energy flows by varying between electricity and heat production. A chemical factory cannot do this, they will never accept must-run conditions like e.g. CHP plants do. If demand for their primary product (E-numbers) stops, the factory will be shut down. So in open district heating networks like the heat roundabout that has multiple heat suppliers, there is always a need for a party which takes responsibility to guarantee adequate heat supply. Matching supply with demand, especially in winter, is an expensive task. HT-ATES can help reduce natural gas consumption by increasing the baseload's share in peak heat supply. This is the main reason for HT-ATES in Rotterdam.

To what extent does the amount of waste limit the amount of heat that AVR can deliver? In other words, is there currently a heat surplus that has to be discharged into the surface water, or would you need more waste if you wanted to produce more heat, steam or electricity?
Our biomass plant currently produces 100% electricity, but we will convert it so it can also deliver heat for the district heating network. There is little room to manoeuvre with household waste.

By the way, we do not provide all the heat demand in Rotterdam. Part of the heat demand is provided by natural gas-fired CHP plants. On top of that there are natural gas-fired peak boilers in the network. We do not have enough thermal power to always provide all heat demand. In summer, heat demand is much lower so then we produce more electricity. That results in condensation losses to the surface water [*the New Meuse*]. In wintertime we produce heat at full capacity and there is no need to discharge heat to the surface water.

AVR Duiven has expressed interest in HT-ATES, but AVR Rozenburg has not. Could you explain this difference?
In Duiven, AVR delivers the entire demand for heat except for a small share that is produced with peak boilers. Consequently, the demand profile is sharper, i.e. the difference in heat demand between summer

and winter is greater. In Rotterdam the heat demand is so large that we cannot provide the peak heat demand. Therefore, we provide a sort of baseload heat, which results in a less sharp demand profile. In Duiven the difference between heat demand in winter and summer is roughly a factor 8, in Rotterdam this is a factor 2-3.

During which time of a year is it most attractive for AVR Rozenburg to produce electricity?
In Duiven AVR has the advantage of lower temperatures in winter, which enhances the efficiency of electricity production. In Rotterdam we cool with surface water, which has a relatively constant temperature. Therefore, the efficiency is also more constant throughout the year.
I belief that the market value of electricity is a bit lower in summer than in winter, and I expect that this difference will increase due to an increasingly dominant role of solar PV.

I recommend you not to focus your HT-ATES research too much on the electricity markets. The ability to exploit the baseload heat sources more, is our main advantage of HT-ATES.

Do you expect any changes in the baseload thermal capacity that you will be able to deliver between now and 2034?
Besides converting the biomass plant, we hope to lower the temperature of the return flow in the district heating network. However, for that we depend on our customers, inter alia in the horticultural sector. A lower temperature of the return flow means that we can recover more waste heat from e.g. exhaust fumes.

By acting as an additional independent heat source, HT-ATES can increase the security of supply. Does this extra security of supply potentially increase the value per GJ of heat that AVR sells?
I do not see a lot of prospects for that, particularly in Rotterdam. We have 7 grate furnaces, 4 vortex furnaces and the bio-energy plant. That is a total of 12 assets. If one of those assets malfunctions, the impact is quite limited. Nevertheless, there is always a risk of clogging when waste is used as a fuel, as it can contain large parts.

Imagine your heat supply were completely independent of heat demand. How would your supply profile look in such a scenario, taking into account electricity and steam sales?
In summertime the thermal production is lower due to maintenance. In winter we cannot perform maintenance. All ovens require maintenance for 4-6 weeks per year, starting in May or June.

15 Appendix 6: Calculation of AVR Rozenburg heat supply capacity

Calculation of AVR thermal power for district heating network

AVR Rozenburg has a total installed thermal capacity of 559 MT_{th}, which consists of wastewater recycling(100MW), waste wood incineration(68MW) and household and commercial waste incineration(394 MW) (Figure 25). This thermal capacity is used to produce steam for nearby chemical plant EKC and heat for the district heating network (Appendix 6). On top of this, there is electric capacity for power generation. Assuming that the ratio of energy flows in Figure 26 is identical to the ratio of installed capacities, that these ratios are representative of all assets at AVR Rozenburg in 2020 together, and that the 20% capacity for extra energy production is thermal capacity, the installed thermal capacity is 80% of the total capacity. Multiplying 559 MW by the share in the thermal capacity of each incineration product gives the thermal capacities for each stream in the table below.

Process steam going from AVR to EKC has an average temperature of 380°C. The return flow going back to AVR has a temperature of 180°C and is used in for the district heating network. The return flow of the district heating network has an average temperature of 63°C. The share of the energy contained by the process steam that eventually ends up in the district heating network is therefore $\frac{180-63}{380-63}$ =36,91%. Consequently, AVR's thermal capacity that can be used for the district heating network is 506 MW (see table), i.e. 306 TJ/week or 15.960 TJ per year(79,8% of the expected annual heat demand in the heat roundabout in 2020). These capacities can only be supplied if enough waste, biomass and recyclable water are available.

Incineration product	% of total incineration energy	% of thermal capacity	Thermal capacity (total: 559 MW_{th})	Thermal capacity for district heating
Electric capacity (20%)				
Electricity	20%	n.a.	n.a.	n.a.
Thermal capacity (80%)				
Process steam	12%	15%	83,85 MW	30,95 MW
Heat	48%	60%	335,4 MW	335,4 MW
Unused energy	20%	25%	139,75 MW	139,75 MW
		Total thermal capacity for district heating:		**506 MW**

Maintenance

In 2020, AVR is expected to have 12 heat producing assets that each require 4-6 weeks maintenance per year (Appendix 6). On average, each asset that is in maintenance reduces the thermal capacity for district heating by 506/12=42,17 MW. Assuming an average of 5 weeks of maintenance per asset, the heat supply capacity is reduced with 128 TJ (42,17*5*7*24*3,6) per asset per year, i.e. 1530 TJ per year for all 12 assets. Maintenance can take place when the difference between heat demand and supply capacity is large enough to shut down 1/12th of the supply capacity. The weeks 18-39 (22 weeks) are chosen for maintenance as heat demand is relatively constant and low during this period. Dividing the annual capacity reduction due to maintenance by the 22 weeks in which maintenance occurs results in a capacity reduction of 70 TJ per week in the maintenance period (see Figure 27).