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Concept of a HT-ATES system well design on the TU Delft campus

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Abstract

Geothermal energy is hot, TU Delft plans to drill a geothermal doublet to provide a sustainable heat source for its buildings. The main drawback of this system is the seasonal mismatch between supply and demand of heat. High Temperature Aquifer Thermal Energy Storage (HT-ATES) is a solution. In this research a concept well design for a HT-ATES system on the campus of the TU Delft is examined. The most important (geological) requirement for ATES is the availability of an aquifer. In this research the middle part of the van Oosterhout formation is used in the calculations of the well design. Two heat production scenarios of 165 TJ and 250 TJ are reviewed. With the heat production assumptions the capacity of the aquifer and the flow rate can be calculated. After these calculations it is clear how much energy needs to be stored and how much actually can be reused using a storage efficiency coefficient of $\eta_{\text{storage}} = 0.75$. Finally the amount of wells for all the scenarios are calculated and they are between 3 and 6 wells.

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1 Introduction

The world and the energy markets are changing. Initially this energy market was dominated by fossil fuels. Since the 1950's nuclear energy is also part of the energy market and later natural gas joined the market. The energy demand is growing and the energy sources are getting drained. The consumption of energy will be doubled in 2020.[1] One of the reasons is the enormous growth in population in the world and the shift of the population structure to the city. Further is the threat of climate change also a serious issue with traditional energy sources. That is why through innovation now renewable energy sources are a serious member of the energy market. Currently, the majority of the renewable energy production comes from hydroelectric power, solar power and wind power. An alternative is geothermal energy. The latter is also used for energy in the shape of heat. About 25 to 40 percent of all energy that we use in the Netherlands is used for heating and cooling our buildings.[2] The National Energy agenda [3] states that in 2050 natural gas cannot be used anymore for heating buildings.

1.1 Problem description

Geothermal energy is hot. Not only because the produced water is used for heating in industry [4] and urban environments [5], but it is seen as an alternative green energy source which might play an important role in the energy mix of the future. Although geothermal energy has a long history [7], it is now starting to gain more popularity in the Netherlands with an increase in projects. Geothermal energy is thermal energy generated in the earth. The temperature rises when we go deeper in the earth's crust. The natural present warm water is then pumped out of the subsurface, to then the heat is separated from the water and can be used for heating in industry, buildings and greenhouses. This method is very reliable because it is not dependent on the weather, wind or season like other green energies. The thermal energy supply is constant, that is why it is very predictable how much thermal energy we can produce. But the demand for thermal energy is not constant. And there is where we found a problem. In the summer the demand is very low but the production stays constant which creates a surplus. This surplus of heat could be used in the winter if it is saved properly, which will result to a reduction of energy consumption. Storage of heat is not a unknown area in the Netherlands and happens already [8] but there is still plenty of room to improve this technology to become more efficient. In this study the focus is on how this storage of heat can be developed and improved on the campus of TU Delft.

There are different methods for the temporary storage of heat (see table 1). Storage in the subsurface turns out to be a relative cheap option to save large amounts of heat. Further is the Netherlands a small country so storage in the subsurface saves us more space on the surface and there are more than enough suitable soil layers for this purpose.[9] With the use of the subsurface

for heat storage water with a higher temperature than the surrounding groundwater is injected via wells in aquifers and withdrawn when there is need for heat again. Two types of underground thermal energy storage can be distinguished: Low Temperature Aquifer Thermal Energy Storage (LT-ATES) which is often used [8] and High Temperature Aquifer Thermal Energy Storage (HT-ATES). The current thermal heat sources produce heat of 50 – 80 °C. Due to government ruling it is not allowed to store water higher than 25 °C in the subsurface, because of the dangers to the groundwater. That is why an additional heat pump is needed to meet the heat demand. The use of a heat pump can go up to 60 percent of the energy consumption. If we can store the water at 30 – 100 °C, then we do not need a heat pump to provide the buildings of heat. This makes the heat supply more sustainable. The other problems that we face in order to realize a HT-ATES on the campus of TU Delft are operational problems. For example we need to bring the energy flows and balance better in picture to determine what the heat demand is for the DAP well. Further we need to calculate what the predicted heat production can be by the DAP well, what is the precise mismatch between heat demand and production and what does the mismatch analysis mean for the exploitation. Other fields where we find problems for a HT-ATES on the campus are geological and economic issues. Where we need to know what the geological favourable conditions for HT-ATES are and do we have the suitable layers beneath the campus. And does the costs of developing and realizing a HT-ATES on the campus stay under the profits when it's done. Last but not least are the well design and completion problems. This study will concentrate on the latter.

Table 1: Properties different storage media for heat. [9]

	capaciteit [MWh]	vermogen [MW]	aanleg kosten [€/kWh]	efficiëntie [%]
phase change materials (PCM)	0,050 - 0,15	0,001 - 1	10 - 50	75 - 90
thermo chemical materials (TCM)	0,012 - 0,25	0,010 - 1	8 - 100	75 - 100
warmwateropties				
- bovengrondse buffertank	500 - 5.000	0,1 - 5	0,50 - 3	75 - 90
- ondergrondse buffertank	500 - 5.000	0,1 - 20	0,50 - 10	75 - 90
- open bodemenergie HTO	1.000 - 500.000	0,5 - 200	0,05 - 0,1	50 - 90
- open bodemenergie wko	10 - 100.000	0,2 - 40	0,10 - 0,4	75 - 95

1.2 Research Goal & Approach

The goal of this study is to develop a concept well design of a possible HT-ATES system on the campus of Delft University of Technology (TU Delft). Chapter 2 contains a literature survey to understand the different concepts of ATES systems followed by the requirements for HT-ATES systems. In chapter 3, the emphasis is put on the geological requirements which is finding a suitable aquifer. Thereafter, chapter 4 describes the steps to calculate the amount of wells. Subsequently, chapter 5 consists of an impact study in which risks influences are described. Finally a discussion and conclusion are given.

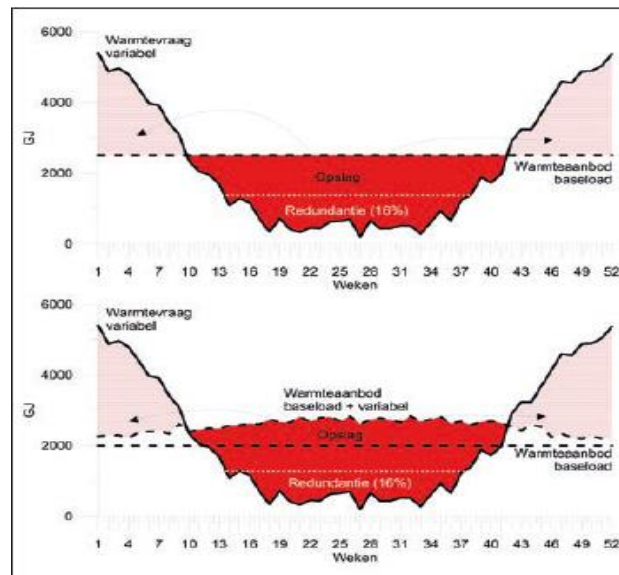


Figure 1.1: This graph shows the seasonal mismatch between demand and supply of heat.

2 Background information

There are various Aquifer Thermal Energy Storage (ATES) systems in the Netherlands. This chapter will present three different types of ATES systems. For these types it will be clear what the differences are, the benefits and the drawbacks. Further the requirements are explained for an HT-ATES system.

2.1 ATES systems

An Aquifer Thermal Energy Storage system can be a solution for the energy problem and climate discussion. With such a system, thermal energy, what is in abundance in the summer can be stored in the subsurface and reused when necessary in the winter. But not only heat can be stored. The cold water what is in excess during winter can also be stored and reused during the summer to cool buildings. Therefore a suitable aquifer is important where different thermal wells can be installed. The mono-wells, doublet and triplet ATES systems are the three systems that are known. The most common used are the doublet systems followed by the mono-wells. These are often used for LT-ATES, however for conserving energy of higher value for example water at 60 °C an extra well can be designed for medium temperature storage. This last system is called triplet and is better designed to the season in which the building needs to be heated. The first ATES systems that will be explained is the doublet system and the mono-well system, followed by the triplet system.

The *doublet systems* are the most popular because of the basic usage in comparison with the other two systems. These systems are mainly used for office buildings where the need for cooling is great. Two wells are drilled in the same aquifer about 100m apart that pump and inject groundwater from depths of 25m to 250m. The wells have different tasks, the cold well extracts cold water during the summer that was stored in the winter to cool the offices and other buildings. The water then logically heats up and is injected into the warm well. In the winter this process then continues but then the other way around. A schematic representation of ATES doublet system is shown in figure 2.1 alongside a mono-well system[14].

A *mono-well system* is less used than the doublet because it has more requirements. The biggest difference is that a mono-well only drills one well in the subsurface. This means the cold and the warm water are transported through the same well. But for this system to be efficient the injection and extraction pipes for hot and cold storage are separated in the casing. The storage takes place in two separated screens where the warm water is stored above the cold water, figure 2.1 gives a schematic representation of this[14]. The positions are important because warm water tends to rise so it is recommended to store the warmer water above the cold water in order to not mix both. To minimize the risk of mixing the vertical distance between the two storage must be large enough. In some cases this is not possible then there must be an aquitard to keep the storages from mixing.

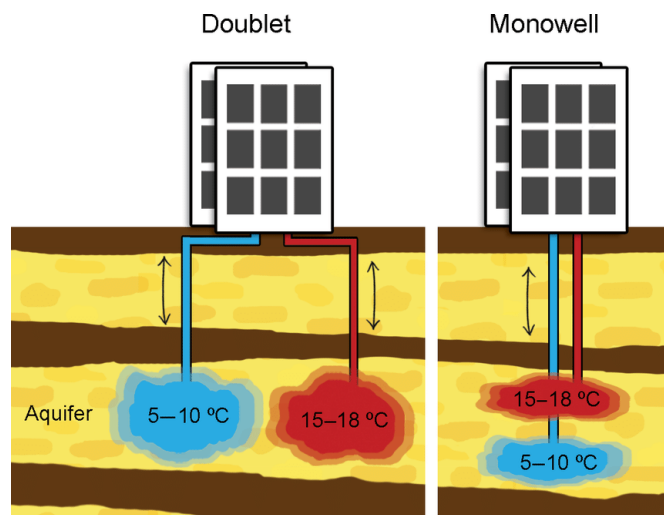


figure 2.1: A schematic representation of ATES doublet and mono-well system

The *triplet system* is the last ATES that will be discussed. Three wells form a triplet system as the name insinuates. This system has a third source, this buffer source stores water of medium temperature. With such a system we have water temperatures that are designed to the season that can heat or cool a building effectively. Depending on the outside temperature, there will be scenarios of excess of heat. These excesses of heat are preferred to be stored in order to be used later and are of medium temperature. So a third well with medium temperature comes in handy, this prevents the medium temperature water to influence the hot or cold well. In figure 2.2 [25] such a system is displayed. The best use of a triplet system is in spring and autumn.

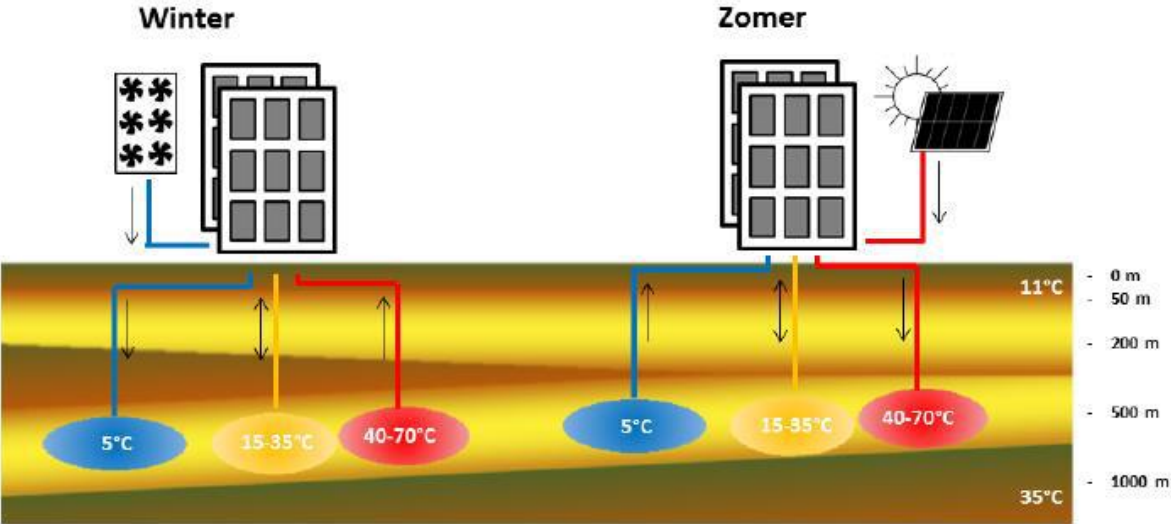


Figure 2.2: Functioning principal of a HT-ATES triplet by Hartog et al (2016)

2.2 Requirements for HT-ATES

HT-ATES systems are less used than LT-ATES this because of the risks it brings, the higher costs, government ruling and it has more difficult requirements. But the projects that realise such a system have been gaining and so there is more practical experience in this field. Different points of attention are discovered with this experience. A combination of these factors makes it difficult to implement a business case correctly. By setting up more HT-ATES research more answers are sought after to the various issues in order to arrive at a better estimation of whether HT-ATES is feasible at a specific location like TU Delft or not. In this paragraph the requirements for HT-ATES are discussed.

Sufficient residual heat

For a financially feasible project, *sufficient residual heat* must be available at the site at the lowest possible cost. Preferably the residual heat should be 'free'. With free residual heat is meant in this case that the costs to make the connection with the residual heat supplier are reimbursed, but that the supplied residual heat is free of charge. When it is necessary to pay for the residual heat, the financial feasibility decreases quickly.

Soil suitability

The soil at the project site must be suitable for high temperature storage. Whether an aquifer is suitable for the application of HT-ATES or not will be project dependent. A number of guidelines are:

- an aquifer of sufficient thickness (at least 10 m thick);
- a permeability of between 6 and 30 D at Average Temperature Storage;
- a permeability between 3 - 15 D at High Temperature Storage.[16]

Temperature levels

The temperature levels of the heat demand and the HT-ATES must be coordinated. The storage temperature must be higher than the temperature level of the heat demand, the so-called temperature jump. Only then can heat be supplied with the HT-ATES. The greater the temperature jump, the more heat can be supplied by the HT-ATES. In addition, at low storage temperatures the heat losses due to flow and convection are lower. The result is a higher storage efficiency than with high storage temperatures. The loss percentages also need to be taken into account and will be discussed later in the storage efficiency paragraph.

Permit

Depending on the depth, a permit is required in the context of the Water Act or within the context of the Mining Act. A license is required for the exploration for and production of minerals and geothermal energy and the storage of substances (Chapter 2, Mining Act[17]). An exploration, extraction or storage license gives the exclusive right to carry out these activities within a set area. There is an open round in the Netherlands for applying for permits, which means that an application can be submitted at any time.

Before actual extraction or storage can take place, there must be a recovery or storage plan approved by the Minister of Economic Affairs. In addition, additional permits are required, for example, to perform a drilling at a specific location and to build an installation for extraction.

Scale size

The scale size must be large enough. A thumb rule for the demand side is a thermal capacity of at least 6 MW and 2,500 operating hours per year[16]. From this size it is possible to recoup the relatively high investment costs (approximately 1.1 million euros at the mentioned values)

Storage efficiency

The storage efficiency is the ratio between the stored heat and the heat supplied. Hot water has a lower density than cold water. This creates density currents, in which hot water flows upwards and cold water is attracted. Some of the stored heat is lost. The storage efficiency of an 'average' HT-ATES system is between 50 and 70%[16].

Influence factors

The storage temperature and the permeability determine to a large extent the storage efficiency. All influencing factors and the qualitative influence on the storage efficiency are shown in the figure below. The bandwidth of the factors have been chosen in such a way that in practice there are opportunities for a feasible HT-ATES system. The calculations were performed with a simplified calculation model[16]. The results are indicative.

PARAMETER	EENHEID	BASIS	ONGUNSTIG	BASIS (72%)	GUNSTIG
VERTICALE PERMEABILITEIT	[D]	4	12	67% 	1
INJECTIETEMPERATUUR	[°C]	70	90	67% 	50
INJECTIEVOLUME	[m³]	300.000	100.000	67% 	500.000
HORIZONTALE PERMEABILITEIT	[D]	12	24	69% 	6
BODEMTEMPERATUUR	[°C]	20	10	71% 	30
DIKTE AQUIFER	[m]	40	60	71% 	20

Figure 2.3: Overview of influence factors[16]

3 Geology

In Chapter 2.2 various requirements are discussed for realising a HT-ATES. In this chapter the focus is on the geological requirements for a HT-ATES. The most important (geological) requirement for ATES is the availability of an aquifer [24]. After further discussing the appropriate geology for a HT-ATES the focus will be shifted to the underground of the campus of TU Delft. A narrow research will display all the available layers for a suitable aquifer under the campus.

3.1 What is a suitable aquifer for HT-ATES?

Requirements of a suitable aquifer are briefly discussed in chapter 2 and in [11] and [23]. This section will give insight in what we are looking for in a suitable aquifer for HT-ATES. The requirements relate to three major factors, geology, economics and safety. Layer thickness, transmissivity and cap rock are all geological based factors, which influence the suitability of an aquifer layer. According to [12], the transmissivity should be above 100 m/D, and there should be an impermeable cap rock above the aquifer. Below the subsurface there are a lot of aquifers[11]. However, in this research we will limit the search of an aquifer between 150 and 500 meters depth. This is due to several reasons, if an aquifer less than 150 meters depth is chosen, there is chance of heating of the subsurface, contamination of fresh groundwater, and a low pumping rate due the a lower allowed pump pressure. Aquifers below 500 meters depth will cost more to drill, will generally have less permeability, will be subject to the unclear Mining law, i.e. the legislation is not clear about this subject and limited information is available through Dino loket, Nlog and thermogis.

3.2 Choosing a layer

[11] chose the top part of the Maassluis formation based on logs available from the nearby Pijnacker field and on REGIS II maps. The formation of Oosterhout is a semi-suitable layer according to Hacking. Based on the confined criteria the investigated area is narrowed down. A cross section is made via DINO loket and shown in figure 3.1.

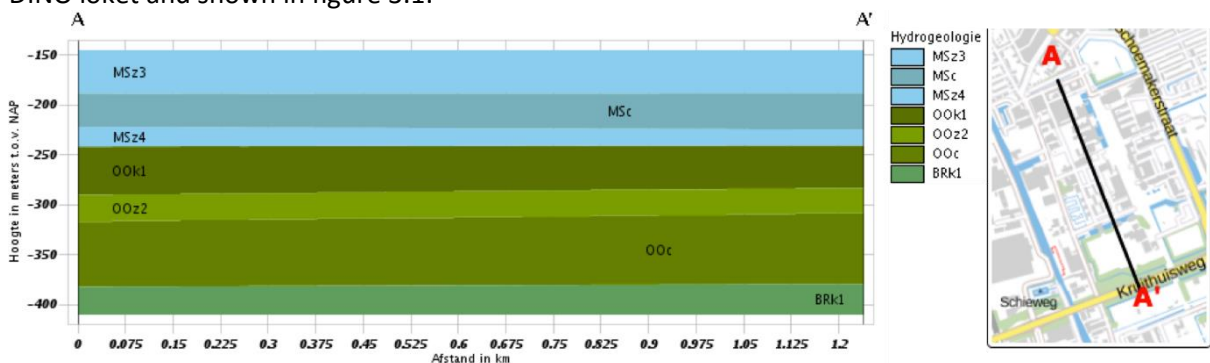


Figure 3.1 Cross-section of the subsurface of Delft

The blue layers on the top are from the Maassluis formation, below that the Oosterhout formation and underneath that is the Breda formation. Based on the REGIS II hydraulic information possible aquifers will be investigated. In figure 3.2, the result is given of a survey conducted near the campus of TU Delft.

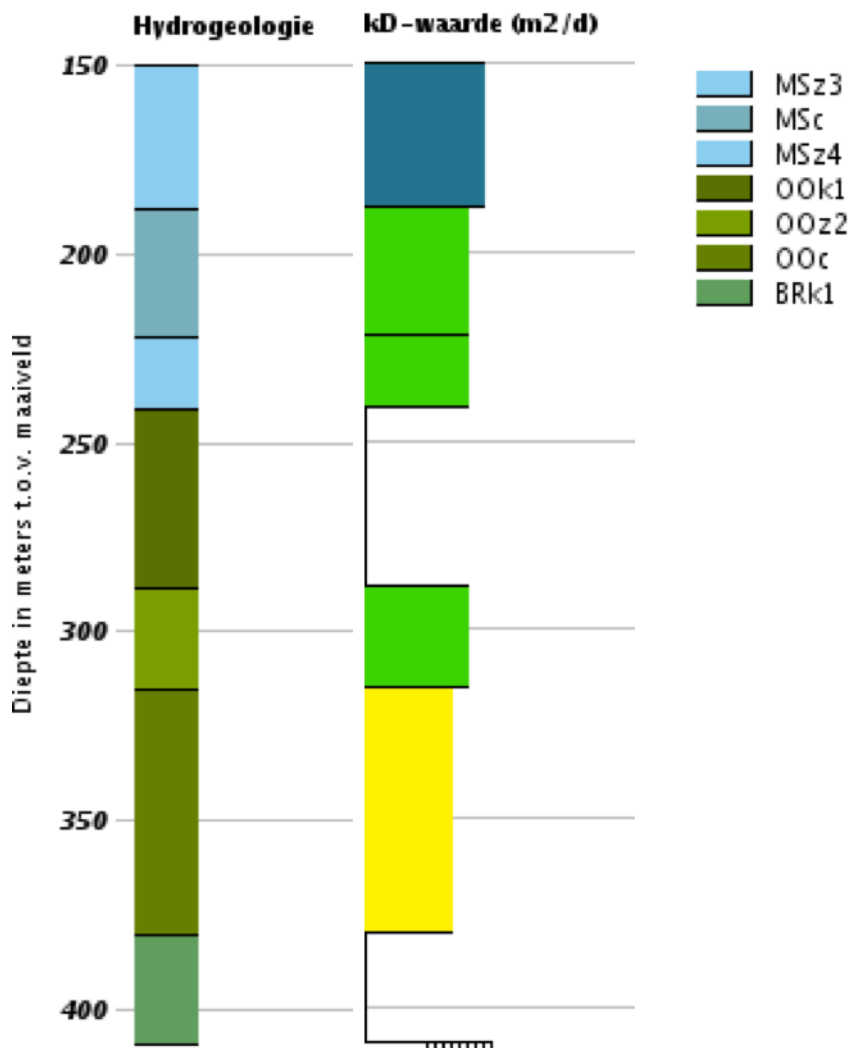


Figure 3.2 Transmissivity values of the different potential reservoir in the subsurface of Delft

Figure 3.2 shows that the Maassluis formation has the required transmissivity values, however, there are no cap rock shown. This will be a potential risk for groundwater contamination. The middle part of the Oosterhout formation shows reasonable transmissivity values. The cap rock present (OOk1) seals off the middle part of the Oosterhout formation. The thickness is around 25 to 30 meters (near the TU campus), which satisfies the requirement (figure 3.1). Therefore, in this research the middle part of the van Oosterhout formation will be used in the calculations of the well design in chapter 4. However, other layers should be subjected to further hydraulic research during the drilling of the DAPwell.

4 Well Design

In order to develop a well design for the campus of the TU Delft, certain conditions need to be discussed. In this chapter the energy demand of the campus will be displayed, this is important for the well design. With the energy demand in the picture, the amount of wells can be calculated. Initially when the energy demand is clearly displayed per building per month different production assumptions can be made for different scenarios. Then a more detailed estimation can be made for the flowrate, size and capacity needed from the HT-ATES. Finally, the amount and location of the wells is calculated and presented.

4.1 Energy demand campus TU Delft

Every day thousands of people come and visit the TU Delft campus: students, scientists, employees of the university and the companies on campus. The campus is over 161 hectares and is therefore larger than downtown Delft and one of the biggest university campuses in the world [13]. The campus of TU Delft consists of different buildings, with varying demands of energy. This paragraph shows how much each building needs of heating per month. In table A.1 all the buildings on the campus are displayed with its monthly heat demand. The numbers are from the last 12 months and are obtained from the energy monitor of TU Delft [13]. The units are in megawatt hours. In figure 4.1 the heat demand of all the buildings are added up and displayed per month for 2017/2018.

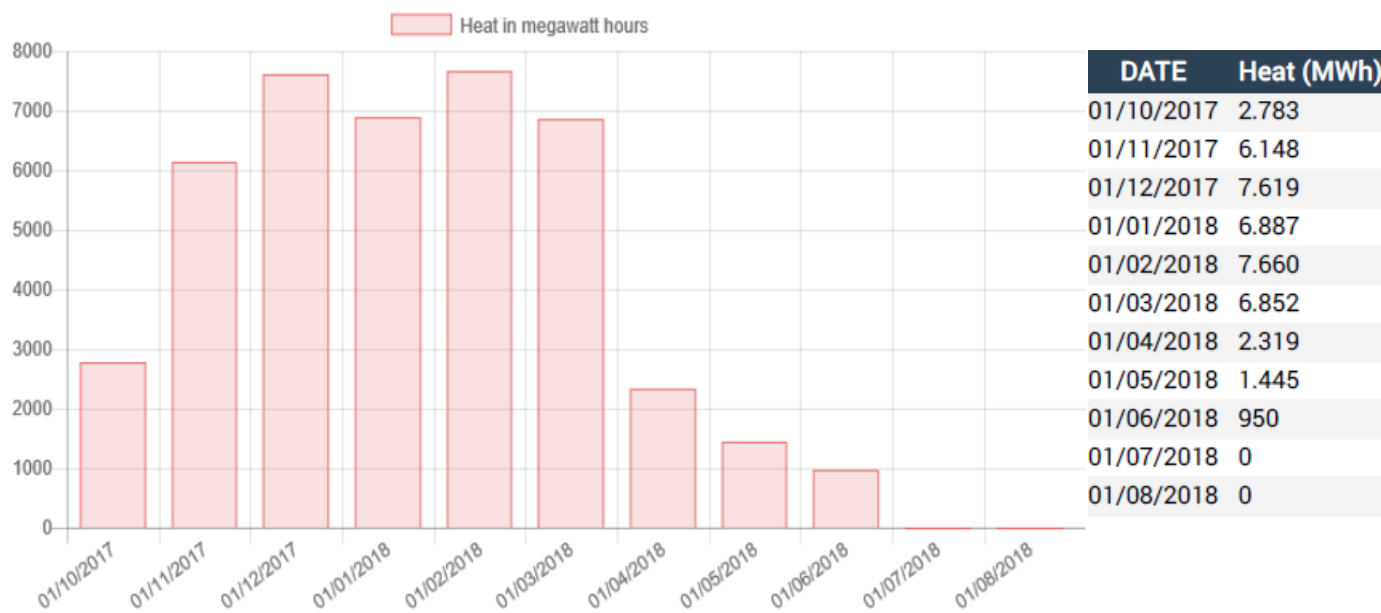


Figure 4.1: Energy demand per month in MWh [13].

4.2 Production rate and Capacity of the HT-ATES

The next step is to estimate the size of the ATES and the capacity. The total heat demand per month is used for the estimation of the size and capacity of the ATES. One of the benefits of geothermal energy is that the production can be constant. But the energy demand is not constant every month, see figure 4.1. In the process of realizing a HT-ATES it is important to take into account that there are different scenarios possible based on the geothermal heat production. In this research two scenarios will be discussed. The first one is when the geothermal source produces 165 TJ of heat per year and the second scenario is when the geothermal source can produce 250 TJ per year [19].

The monthly geothermal heat production is calculated by dividing the total energy that can be produced per year by 12 months. Figure 4.1, shows the constant monthly geothermal heat production and the figure clearly displays which months the heat produced is not enough and which months there is bycatch (Oct, Apr, May, Jun, Jul, Aug, Sep). The bycatch is the only heat that needs to be stored with HT-ATES so it can be used later in the months where we don't produce enough heat. A similar graph is displayed in figure 4.2. In the appendix figures A.1 till A.4 show the effect of the HT-ATES by comparing the scenarios with and without HT-ATES.

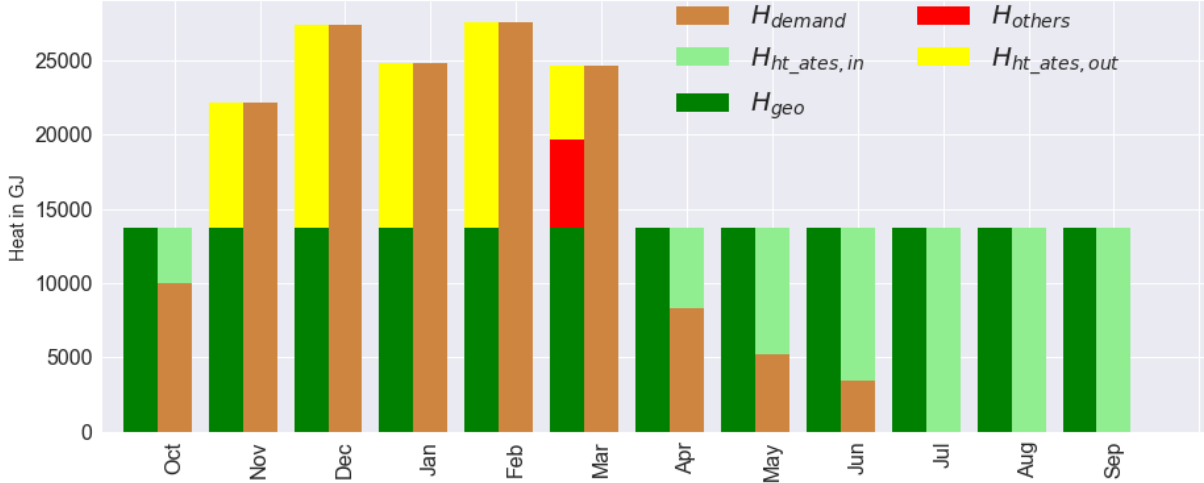


Figure 4.2: Scenario 1 with HT-ATES

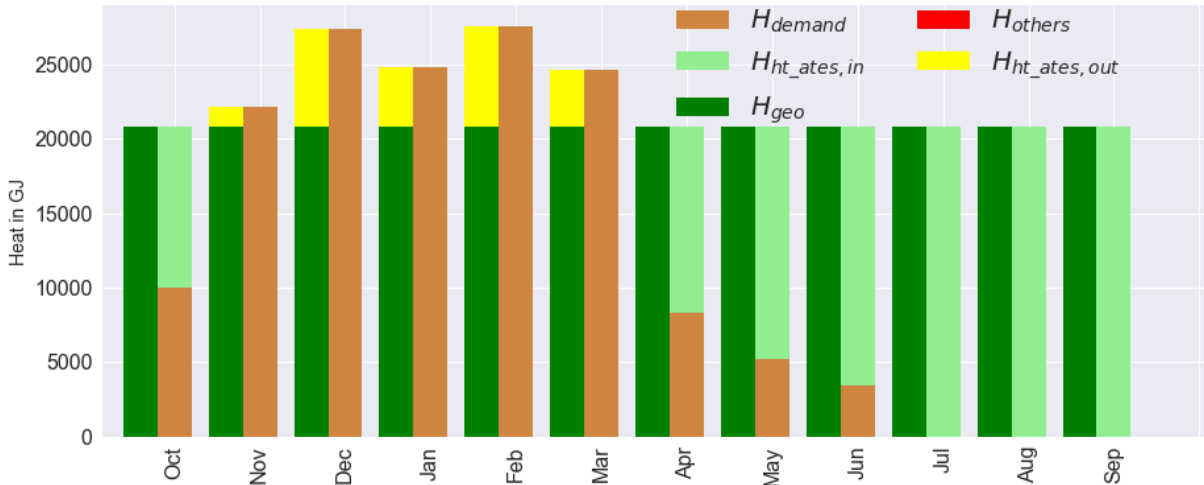


Figure 4.3: Scenario 2 with HT-ATES

Now that the amount of heat that needs to be stored is known, the size of the HT-ATES in thermal energy is also clear. The storage needs to be able to save an amount of 69 TJ for scenario 1 and 119 TJ for scenario 2. The equivalent volume of water is calculated with,

$$V = \frac{E_Q}{c\Delta T}, \quad (4.1)$$

where E_Q is the amount of heat in joules, c is the volumetric heat capacity of 4.18 MJ/m³, V is the Volume in m³ and ΔT the difference in injection and production Temperature in °C (assumption made: min. 15 °C, max. 25 °C). To calculate the flow rate, i.e. the pumping rate Q , equation 4.1 is divided on both sides with t ,

$$\frac{V}{t} = \frac{\frac{E_Q}{c\Delta T}}{t} = \frac{E_Q}{t c\Delta T}, \quad (4.2)$$

where the flow rate is defined as,

$$Q = \frac{V}{t}, \quad (4.3)$$

with the peak power defined as,

$$P_{peak} = \frac{E_Q}{t}, \quad (4.4)$$

which leads to the equation where the flow rate can be calculated based on the peak power and equation 4.1,

$$Q = \frac{P_{peak}}{c\Delta T}, \quad (4.5)$$

where the P_{peak} is 2.4 MW [11].

Below the calculations for the volume and pumping rate of the two scenarios as discussed earlier are done. The two scenarios differ in the fact that they have another total production of heat. The pumping rate is for both scenarios the same, this is because of Equation 4.5, where pumping rate only depends on P_{peak} , c , and ΔT .

Scenario 1

ΔT	Total heat storage (GJ)	Volume (m ³)	Pumping rate (m ³ /s)
15 °C	69262	1.1*10 ⁶	0.038
25 °C	69262	6.6*10 ⁵	0.023

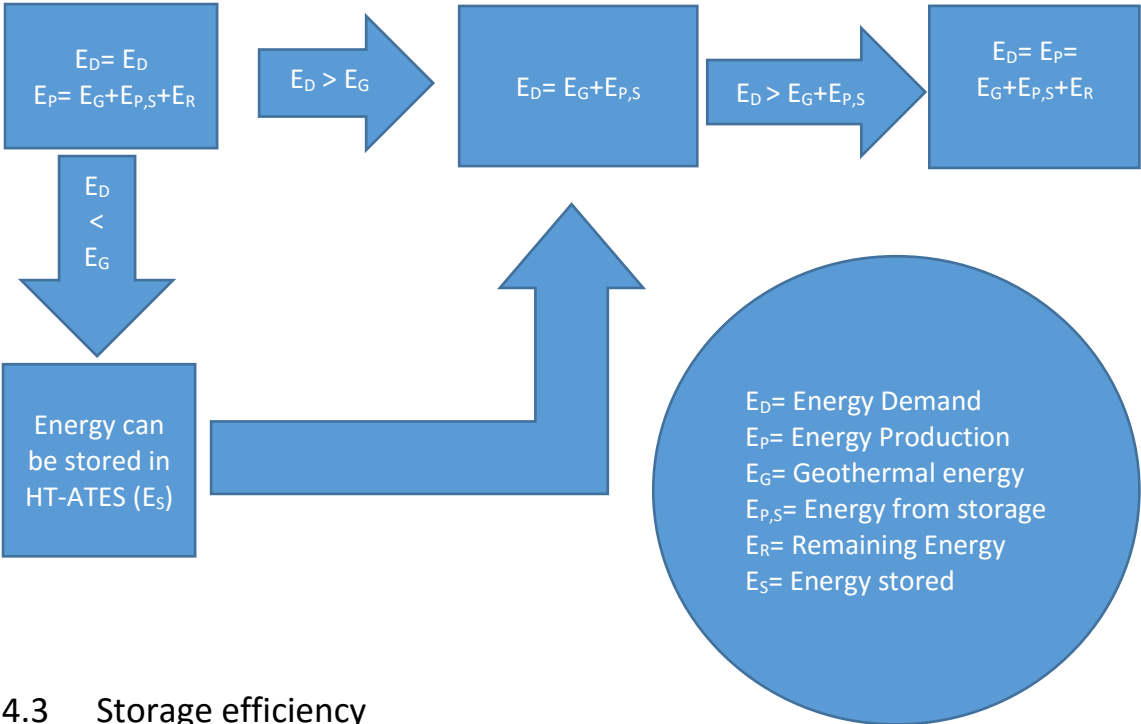
Scenario 2

ΔT	Total heat storage (GJ)	Volume (m ³)	Pumping rate (m ³ /s)
15 °C	118845	1.9*10 ⁶	0.038
25 °C	118845	1.1*10 ⁶	0.023

Table 4.1: Calculations of HT-ATES capacity and pumping rate.

However, these calculations for the capacity of the aquifer where done without considering loss percentages of the heat during storage. It is important to understand when energy is stored, when it is reused and how much of the stored energy can be reused. After researching what the energy demand is, it is important to determine how this demand can be satisfied. Further when the geothermal energy production is larger than the energy demand, the energy that is in abundance can be stored. When the energy demand is larger than the geothermal energy production we must fill the gaps. First we try to fill the gaps with the geothermal energy that is stored in the HT-ATES, when

this is not sufficient other energy sources like gas are used to fulfil the remaining energy demand. Below a block diagram shows the situation clearly.



4.3 Storage efficiency

The amount of heat that is in abundance and needs to be stored cannot all be reused. There will be always some loss of energy in the aquifer. So the storage efficiency also needs to be taken into account. The storage efficiency is the ratio between the stored heat and the heat supplied. Hot water has a lower density than cold water. This creates density currents, in which hot water flows upwards and cold water is attracted. Some of the stored heat is then lost. It has been shown that the groundwater flow, the heat capacity of the soil, heat conduction, dispersion and any short-circuit flows are also decisive for the heat transfer in the soil and for losses of stored cold or heat[12].

By taking these thermal aspects into account, you can determine how much heat in the soil should be stored to the heat demand, taking into account the temperature levels that have been imposed by the aboveground system. If the losses are large, more warm water must be stored than the heat energy demand.

The efficiency of the system per season cycle is assumed to be 75% [18]. This means that the energy that is stored must be multiplied with a storage efficiency coefficient of $\eta_{storage} = 0.75$ to obtain the right number of energy that can be reused.

Scenario 1:

ΔT	Total heat storage (GJ)	Volume (m ³)	Reusable energy (GJ)
15 °C	69.262	1.1*10 ⁶	51947
25 °C	69.262	6.6*10 ⁵	51947

Scenario 2:

ΔT	Total heat storage (GJ)	Volume (m ³)	Reusable energy (GJ)
15 °C	69.262	1.9*10 ⁶	89134
25 °C	69.262	1.1*10 ⁶	89134

Table 4.2: Calculation of reusable energy with storage efficiency taking into account.

4.4 Amount of wells

Now that the energy demand of the TU Delft campus is clear and the capacity of the HT-ATES is known, the amount of wells needs to be calculated that can provide this demand.

An ATES consists of one or more extraction sources and infiltration sources. Within the HT-ATES research it was examined which design standards apply to HT-ATES. The design standard contains guidelines for the maximum speed on the borehole wall. With high temperature storage the design speed is up to two times higher than with regular open soil energy systems. The properties of water change at high temperatures. As a result, a higher speed can be applied at HT-ATES without clogging the sources or delivering sand.

From 4.3 we got the required pumping rate Q to satisfy the peak demand of heat which will be needed. The total velocity v is defined by,

$$v = \frac{Q}{A}, \quad (4.6)$$

where area A in m^2 is given by,

$$A = 2\pi r_{well} h, \quad (4.7)$$

with the radius of the well r_{well} in meters and the height of the well inside of the aquifer h in meters. The radius of r_{well} is assumed to be 0.3 meter. The height h of the Oosterhout formation is 27 meters defined in chapter 3. The total velocity calculated with equation 4.6 is without considering technical limitations. The design velocity v_d in m/h is defined by [12]:

$$v_d = 1000 \left(\frac{k}{150} \right)^{0.6} \sqrt{\frac{v_v}{2MFI_{mea} u_{eq}}}, \quad (4.8)$$

where k is the permeability in m/d, v_v is the specific blockage speed of 0.1 m/a, MFI_{mea} is the modified fouling index of 2 and u_{eq} is the amount of full load hours of 1600. These numbers are assumed using [12].

By inserting the total pumping rate Q_{tot} in equation 4.6,

$$v_{tot} = \frac{Q_{tot}}{A}, \quad (4.9)$$

The total amount of wells N_{well} is determined by dividing v_{tot} (equation 4.9) by the design velocity v_d (equation 4.8)

$$N_{well} = \frac{v_{tot}}{v_d}$$

ΔT ($^{\circ}C$)	k (m/d)	N_{well}
15 _{Scenario 1}	5	6
25 _{Scenario 1}	5	4
15 _{Scenario 2}	10	4
25 _{Scenario 2}	10	3

Table 4.3: Calculations of amount of wells with different scenarios.

In the calculation for the amount of wells the permeability of the layer is important. In chapter 3 we found that our layer had a permeability between 5 and 10. Further two different scenarios are discussed in this chapter, that is why table 4.3 has four different calculations for the amount of wells.

4.5 Location

In this paragraph a convenient location is chosen for the HT-ATES on the campus. In figure 4.4 a Kick-off point where all the wells come to the surface is indicated. From this point there will be drilled with certain angles and orientations to multiple targets. The advantages of this technique is that no aboveground pipes are needed to the HT-ATES, the drill platform does not need to be moved and when pumping, the heat from all the wells is immediately at the combined heat and power plant. This is only one scenario where three wells are needed to satisfy the energy demand.

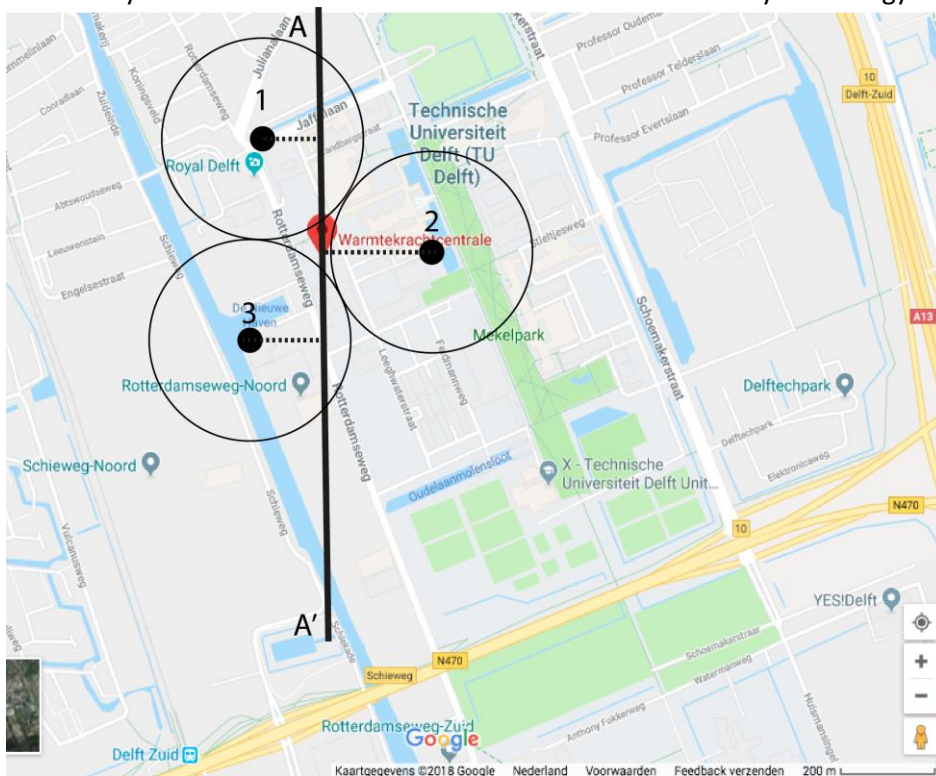


Figure 4.4: Chosen location for HT-ATES

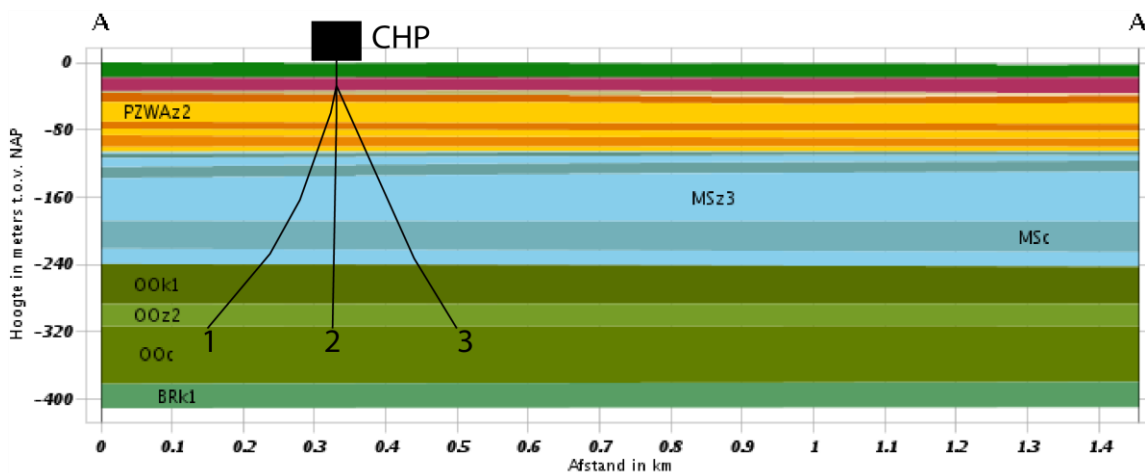


Figure 4.5: Cross section of the location for HT-ATES

5 What are the risks of a HT-ATES system

The use of groundwater for energy storage has consequences for the groundwater. The consequences mainly consist of changes in head heights, groundwater level changes, settlements, temperature changes and clogging of the source. Furthermore HT-ATES can influence the microbiology of the area, groundwater quality and possible water composition changes. If the project in question is licensed under the Groundwater Act, the permit application must be accompanied by an impact study in which these influences are quantified and described. In this chapter these risks will be discussed.

5.1 Hydrological effects

Rise height changes, groundwater level changes and flow changes (seepage / sideways et cetera) are counted among the hydrological effects. The rise heights drops around the source of extraction and rises around the infiltration source. Depending on the soil structure, flow rate, duration, etc., this change can continue to the shallow groundwater. The extraction and infiltration can also lead to changes in the extent of seepage or inaction. Such hydrological effects can be calculated using models such as Modflow, MicroFEM, MLPU, MLAEM etcetera. The groundwater and hydraulic head changes must be presented on a topographic surface[20].

The degree of elevation depends on the flow rate with which the injection is made and on the permeability of the aquifer. With a large capacity the increase will be less than with a small capacity (assuming the same flow rate). The hydraulic head change for a doublet can be calculated using the following formula[12],

$$\Delta h = \left(\frac{24q_v}{2\pi kH}\right)\ln\left(\frac{L}{r_b}\right), \quad (5.1)$$

where Δh the head height increase is in meters, q_v is the flowrate in m^3/h , k is the permeability of the aquifer in m/d , H is the filter length, L is the source distance and r_b is the radius of the borehole.

During the design, the head height increase must be taken into account. At too high an increase the so-called burst pressure can be exceeded, causing cleavage of the soil around the sources. A good design prevents overrun of the burst pressure..

In summary, it can be stated that an increase in the temperature in sand layers leads to an increase in volume and in clay layers to a decrease in volume. For example, a 50 m thick layer of sand that is heated to 75 ° C and an increase in the thickness of the sand layer by 7.5 cm is expected. If a 10 m thick layer of clay is present above the 50 m thick sand layer and this clay layer warms up to 30 ° C on average, then a decrease in thickness of 6.0 cm is to be expected. The net effect under the influence of the temperature changes would then result in an increase of the thickness by 1.5 cm. At the same time, settling can also occur due to the resulting hydraulic head changes, which result in a decrease in the thickness of the soil layers[20].

5.2 Clogging effects & Water treatment

The precipitation of carbonates is specific for high temperature heat storage. This problem is known from daily practice: scale in the whistling kettle and limescale at the heating element of the washing machine. Energy is required to dissolve most minerals (such as gypsum or quartz) in water. These minerals therefore dissolve better at higher temperatures [21]. Carbonates are an exception to this. The solubility of lime (calcium carbonate: CaCO_3) actually decreases with increasing temperature (see Figure 5.1)[20].

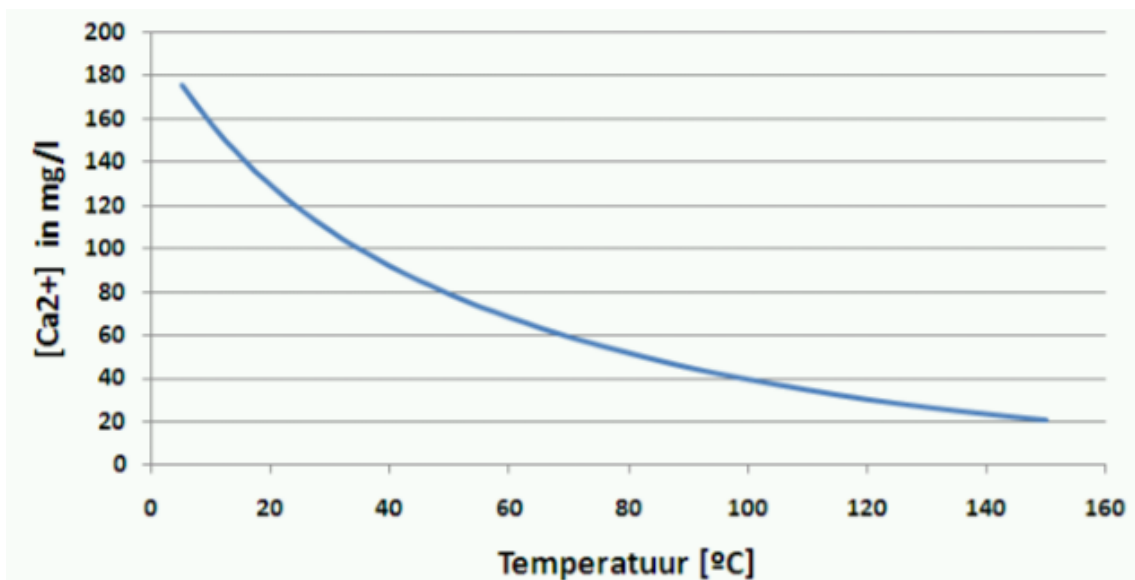


Figure 5.1: Temperature of the concentration of calcium in the groundwater in equilibrium with calcite at a pH of 7 [20]

The clogging of the source results to that the groundwater insufficient flows in the formation. Various causes are indicated in the literature for clogging sources[12].

- floating (suspended) particles of all kinds, which accumulate around the source;
- gas, for example air bubbles or methane;
- chemical precipitation in the aquifer by reaction between different water types;
- growth of bacteria and the formation of biological deposits in the source, the collapse and the first cm's of the aquifer package;
- change in the structure of the grain skeleton (porosity) under the influence of the flow.

Water treatment

The do's and don'ts of water treatment were investigated within MMB[21]. At high temperatures the solubility of lime decreases and lime precipitates when no countermeasures are taken. To prevent clog up of the sources, water treatment is therefore necessary. Four water treatment techniques are described below.

HYDROCHLORIC ACID DOSAGE

Addition of acid to water reduces the pH-value and ensures a higher solubility of carbon benefits. This prevents lime deposits. The technique has been applied in practice in the Netherlands. The dosage can be controlled well so that it has proved to be a good method to prevent lime deposits. By adding hydrochloric acid, the chloride content in the groundwater will increase, but in practice it has been found that the effect in salt groundwater is relatively small.

CO² DOSAGE

The addition of CO², like hydrochloric acid, lowers the pH-value of the groundwater. CO² dosing is also well-controlled. The technique has been applied in experiments in Germany and Switzerland, but as far as is known not yet applied on a project.

ION EXCHANGE

In this technique, groundwater is led through a vessel filled with negatively charged resin granules. By equilibrating the resin beads with a NaCl solution, Na⁺ is bound to the granules. If ground water is then passed through the exchanger, then through cation exchange Na⁺ is added to the water and other cations, such as Ca²⁺, are withdrawn from the water. The technique has been applied in the Netherlands. Major drawbacks of this technique are high salt consumption, labor intensive and clogging risks with too much and too little treatment.

INHIBITORS

Inhibitors are chemicals and have an inhibiting effect on chemical processes. Known inhibitors to prevent carbonate precipitation are phosphates, acrylates and natural inhibitors. Recently, inhibitors have been developed that consist of polymers. The use of inhibitors could be interesting, but has not yet been investigated.

5.3 Groundwater Quality

The high temperatures of an HT-ATES system have a heavier impact on the chemistry and microbiology of the groundwater than with LT-ATES.

Influence on groundwater chemistry

The water treatment methods as described in 5.2 also come with certain risks. To date, only two water treatment methods have been applied to project scale, namely ion exchange and hydrochloric acid dosing[23]. Ion exchange, however, has a number of important drawbacks, it involves high salt consumption, it is labor-intensive and there are clogging risks in too much and too little treatment.

An indirect consequence of the high temperatures may be that deeper groundwater is attracted as a result of the caused density flow. Influence on groundwater quality can then occur if the deeper groundwater has a different composition (e.g. saltwater).[23]

Influence on microbiology

The microbiological risks of ATES are often thought to be pathogens (pathogens), in particular as a risk factor for the drinking water extraction. The possible risks depend on two aspects, first the influence of thermal storage on the presence and growth of pathogens and secondly the risks of spreading pathogens in the subsoil.

It is concluded that on the basis of current knowledge no growth of pathogens due to high temperature storage can be expected. Within MMB[21] specific research has been done into the effects on pathogens that can naturally occur in the groundwater, such as Clostridia. No significant numbers of pathogens were found in the sampled sites with elevated temperatures, with the maximum temperature in the measurements being 40 °C. A point for discussion is that HT-ATES involves higher temperature.

6 Discussion and recommendations

The assumptions made in chapter three concerning the energy demand are based on information of October 2017 till September 2018. These assumptions will not be correct for future years. The summers are getting stretched due to global warming, the population is also changing in amount and efficiency. Further shall the amount of buildings change with the demolition of the EWI tower and the construction of other buildings on the TU Delft campus. These are all affairs that will adjust the demand for heat and are not taking into account in this research. Besides that the energy demand will change in the future is there also an uncertainty in the current energy demand used in this research. The amount of energy demand is taken from the e-monitor[13] of TU Delft, however this source is debatable because of the inconsistency it shows. It is possible to look up the energy demand per month of the campus and also per building per month. Summing up the energy demand of all the buildings should give you the same amount of energy as the energy demand of the campus, but it does not. Therefore the numbers of the energy demand per month for the whole campus is used as this was larger than when the energy demand of the buildings were summed up.

In Chapter four the amount of wells is calculated and always rounded up. However in some cases it is wiser to round down. For example in the last scenario with $\Delta T = 25$ the calculated amount of wells was 2.07 and was rounded up to three. For economic reasons it is better to use two wells with a larger radius to satisfy the energy demand. Another more efficient option than drilling an extra well for such a small amount of energy is to use alternative energy to satisfy the remaining energy demand. Furthermore like indicated earlier two different scenarios are discussed in this research concerning the amount of energy that can be produced from a HT-ATES under the campus. In the second scenario there is a surplus of energy even after satisfying all the energy demand. This energy can be very useful and needs a purpose. An option is heating the football fields of the sport centre during winter so that the games will not be cancelled. Another option is to use the heat available to grow vegetable garden roofs. The ground is threatened in urban areas, but there is sufficient roof surface than be used for 'green' purposes.

For a complete well design concept of a HT-ATES one must also take the well completion into account. In the Netherlands there are many ATES systems active[8], however these are mainly for lower temperature. With higher temperatures there are other risks like chapter five describes. Therefore solutions must be found and some can be found in the material that is used. The use of composite materials in the borehole wall (the 'casing') would be a completely new application. Composites have several advantages over traditional steel casings, such as a much lower weight and insensitivity to corrosion[22]. Other problems that can be solved through well completion and is not discussed is the noise disturbance that a HT-ATES system can produce where a campus of a university often needs silence. Lastly if the project in question is licensed under the Groundwater Act, the permit application must be accompanied by an impact study in which risks influences are quantified and described. In this research the risks are only described and not quantified specifically for the campus of TU Delft.

Other recommendations could be to carry out further research into design standards for poorly permeable aquifer packages and possibilities to increase the flowrate per well. And investigate the feasibility of optimizing the storage efficiency (whereby a comparable return can be achieved when using soil layers with a higher permeability).

7 Conclusion

This thesis goal is to develop a concept well design for a High Temperature Aquifer Thermal Energy Storage system on the campus of the TU Delft. For a well design several topics must be discussed. Such as that there are various Aquifer Thermal Energy (ATES) Storage systems in the Netherlands and the doublet system seems to be the most suitable for this case. This research has explained clearly what the requirements are for an HT-ATES system are and found it to be possible to continue realizing a HT-ATES on the campus. The most important (geological) requirement for ATES is the availability of an aquifer. After further discussing the appropriate geology for a HT-ATES the focus is shifted to the underground of the campus of TU Delft. A narrow research displayed all the available layers for a suitable aquifer under the campus. As a result, in this research the middle part of the van Oosterhout formation is used in the calculations of the well design.

Then the well designing can begin with the energy demand per month clearly in the picture. Two different geothermal heat production assumptions are made and used to calculate the capacity of the HT-ATES. One of 165 TJ and the other of 250 TJ. The pumping rate is for both scenarios the same, this is because of Equation 4.5, where pumping rate only depends on P_{peak} , c , and ΔT . Afterwards the energy that can be stored is used to calculate how much of that energy actually can be reused. Then it is clear that for scenario 1 other energy sources still are necessary in very small amount and in scenario 2 we even have enough energy saved for other usage than heating the buildings of the campus. Finally the amount of wells for all the scenarios are calculated and they are between 3 and 6 wells.

Lastly the use of groundwater for energy storage has consequences for the groundwater. The consequences mainly consist of changes in head heights, groundwater level changes, settlements, temperature changes and clogging of the source. Furthermore HT-ATES can influence the microbiology of the area, groundwater quality and possible water composition changes. If the project in question will be licensed under the Groundwater Act, the permit application must be accompanied by an impact study in which these influences are quantified and described.

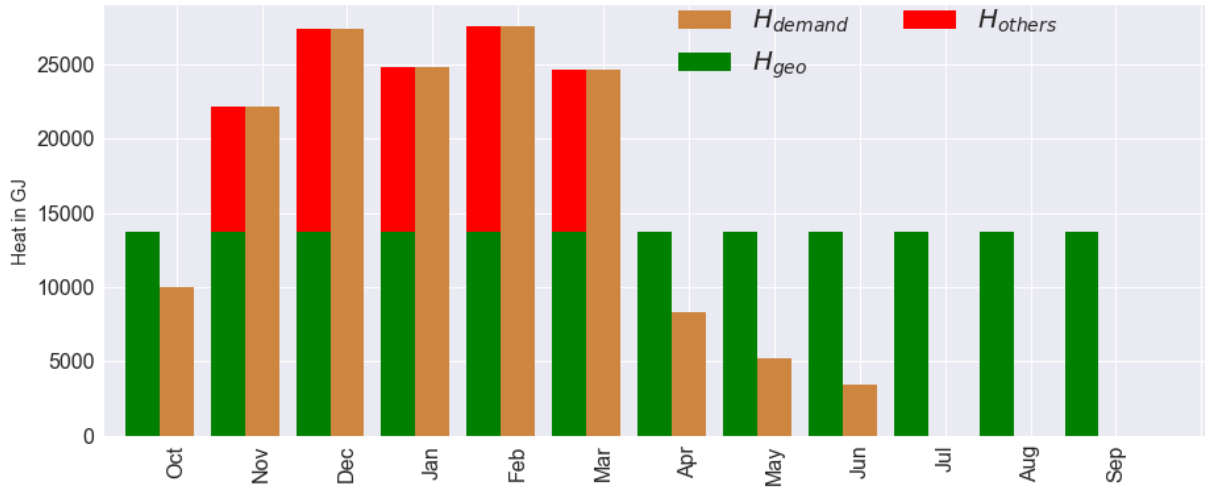


Figure A.1: Scenario 1 without HT-ATES

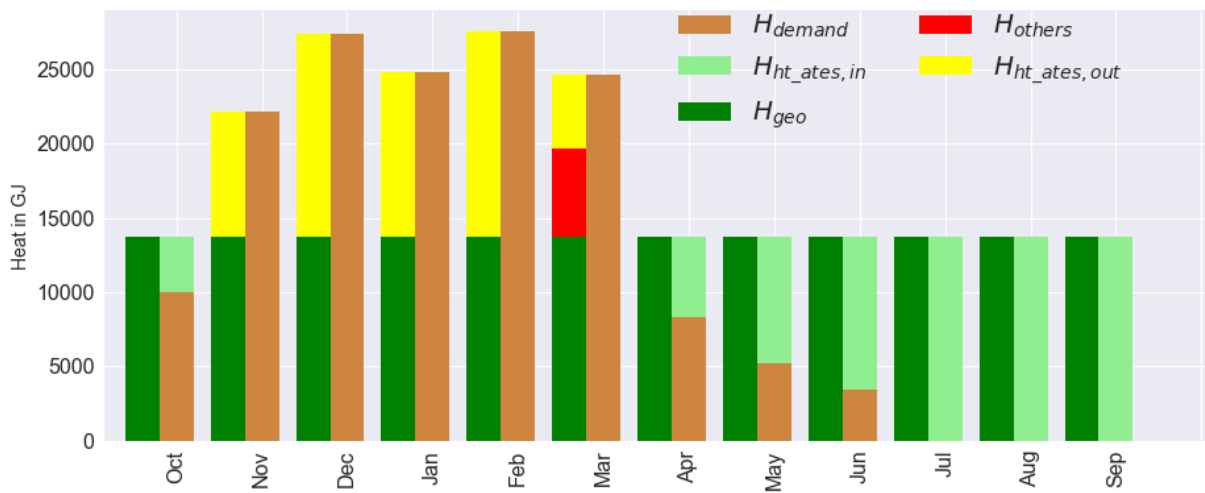


Figure A.2: Scenario 1 with HT-ATES

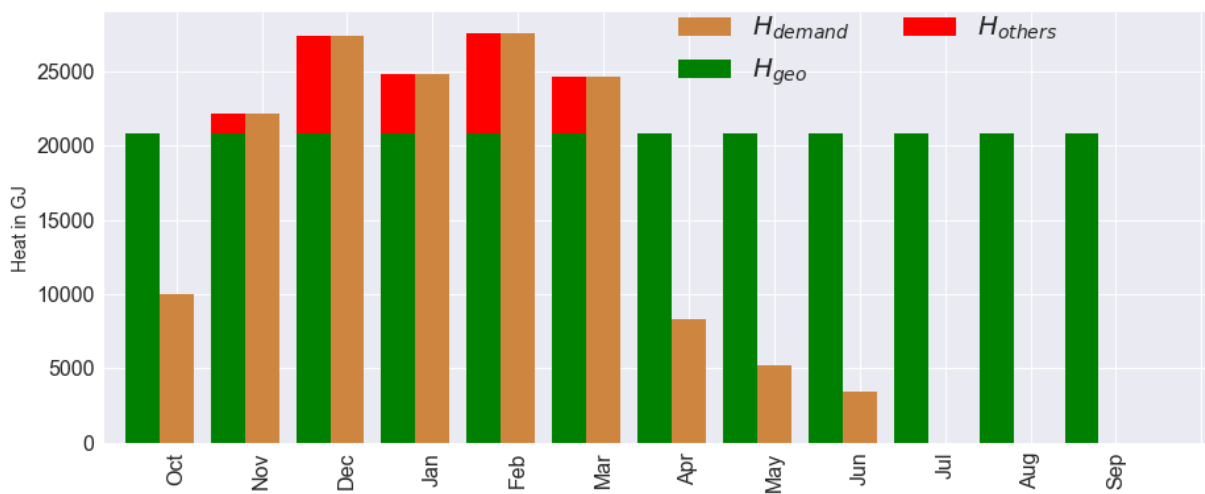


Figure A.3: Scenario 2 without HT-ATES

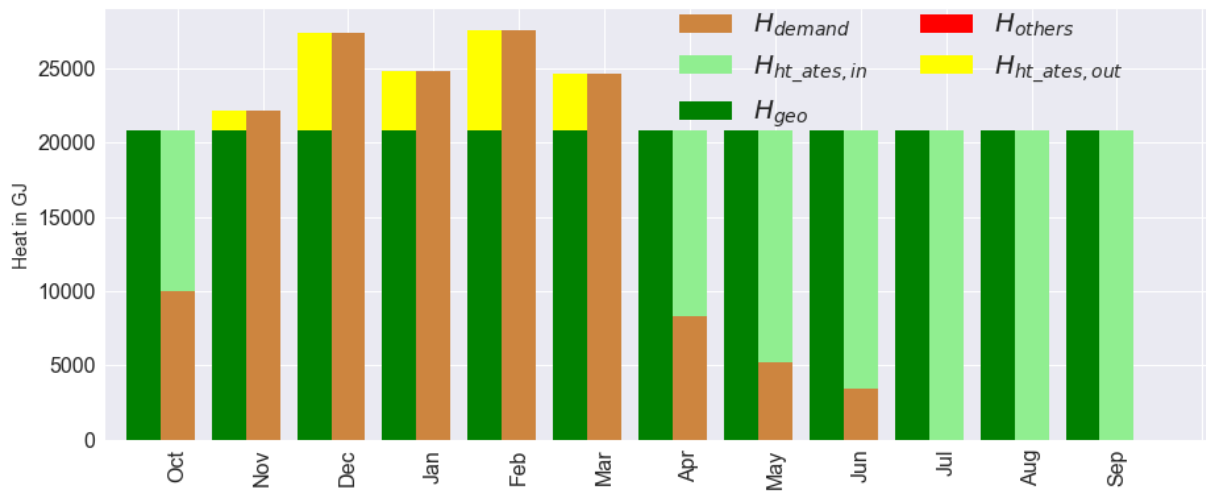


Figure A.4: Scenario 2 with HT-ATES

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