Cooling T.U. Delft by combining thermal energy from surface water and ATES.

By

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Abstract

T.U. Delft has set goals to severely reduce the CO_2 -emissions of the university by 2020. This report will investigate an option to reduce the CO_2-emissions for cooling the facilities of the university.

The possibilities of using surface water in combination with an ATES system will be discussed. In the winter, thermal energy from the surface water will be extracted and stored in the underground. This energy, in the form of cold water, can then be used in summer to cool the university's facilities.

It was found that the Delftse Schie can provide sufficient thermal energy to supply the cooling demand of the T.U. Delft and that this energy can be extracted efficiently by using a plate heat exchanger.

The cold well of the ATES system will deliver 4260000 kWh/year by supplying water at an average temperature of 4.94 ºC throughout the summer. This is done with a pump flow rate of 3381.8 m^3/day.

This report should serve as a preliminary overview which can be used as a starting point for future, more in depth, feasibility studies. Economical assessments are not considered in this report.

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1 Introduction

1.1 Problem Description

In 2014, the Executive Board of the Technical University of Delft has decided to severely reduce the CO_2 -emissions of the university by 2020. These plans consist of the following main points of attention:

1. 50% emission reduction compared to the 40 ktonnes/year of 2012
2. 25% sustainable generation of energy
3. 40% reduction of the primary energy demand per m^2

To reach these goals, the T.U. Delft has started several projects. The first target, 50% emission reduction, has already been met by buying green energy from Dutch origin. The reduction of gas usages for heating is a more difficult goal on which the Delft Aardwarmte Project focusses. This project aims on high temperature energy storage and the production of heat by using geothermal energy. This still leaves a gap for the energy that is required for cooling in summer. This report will go into the possibilities of using cold water from the river Delftse Schie in combination with Aquifer Thermal Energy Storage (ATES) systems to supply the cooling demand of the T.U. Delft. [1]

1.2 Goal

The goal of this report is to get a better understanding of the possibilities of using a modified ATES system to supply the cooling demand of the T.U. Delft and possibly also its surrounding buildings. This report should serve as a preliminary overview which can be used as a starting point for future, more in depth, feasibility studies.

1.3 Method of Approach

This report will consist of several parts which will lead to an end conclusion about the possibility of using an ATES system to provide the cooling demand of the T.U. Delft.

An overview of the proposed system will be provided in section 3.

In section 4, the amount of cooling energy that is required for T.U. Delft buildings will be estimated.

Section 5 eleborates on the amount of cold energy that can be extracted from the surrounding water during winter.

Section 6 will go into the efficiency of cooling with water. Different methods of cooling with water will be discussed.

In section 7, the local geology of the T.U. Delft area will be described and suitable aquifers will be discussed and compared.

Section 8 will describe an analytical model that is used to determine the volumes and temperatures of the ATES wells. The results of this model will be discussed and are used to draw conclusions about the feasibility of this project.

In section 9 the results of this report will be discussed and recommandations for further research will be given.

2 Background

2.1 T.U. Delft Campus and Surroundings

The T.U. Delft Campus covers 161 hectares and 27000 people reside on the campus on a daily basis. This includes students, scientists, visitors and employees of the university and on-campus companies. This makes the T.U. Delft campus one of the biggest university campuses of the world. [2]

The campus consists of over more than 30 buildings that all require heating and cooling. Only 3 of these buildings are already equipped with an ATES system, which leaves a gap for improvement.

The campus is surrounded by industry that could use more sustainable ways of cooling as well. This report will focus on the cooling of T.U. Delft buildings, but surrounding industry could be included in further stages of development.

Figure 1 gives an overview of the T.U. Delft campus and gives an impression of the location of the Delftse Schie relative to the campus.

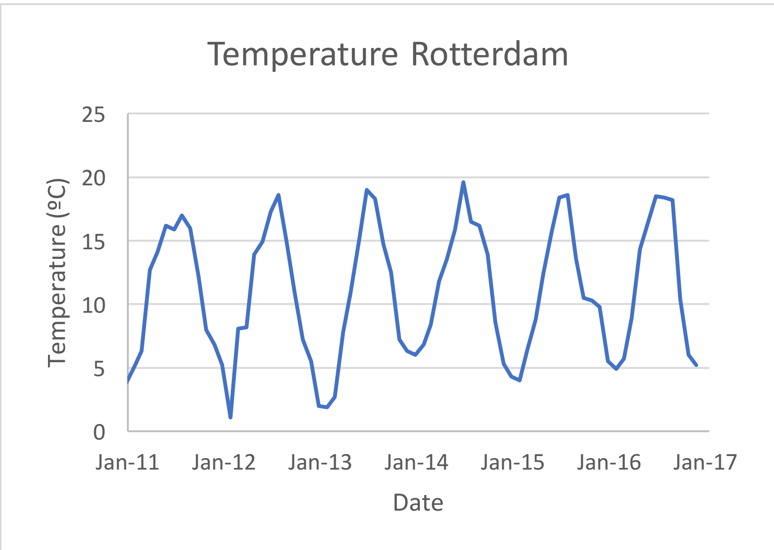


Figure 1: Temperature in Rotterdam (2011-2016).

2.2 Delft Climate

According to the Köppen system, the climate of the Netherlands can be described as an Oceanic climate. This means that the Netherlands has relatively mild winters and summers and that there is precipitation throughout the whole year. Figure 2 shows the temperature in Rotterdam, which is located 8 km southeast from Rotterdam, throughout 2011-2016. From this data it is concluded that on average June, July and Augusts are the three warmest months in Delft. During the rest of this this report it is assumed that there is a constant cooling demand during these three months and no cooling demand during the rest of the year.

According to the Royal Netherlands Meteorological Institute, it is predicted that the average temperatures in the Netherlands will have increased with 1 ºC to 6 ºC by 2100. This is an important change to take into account, which could cause a higher cooling demand in the future. [3]

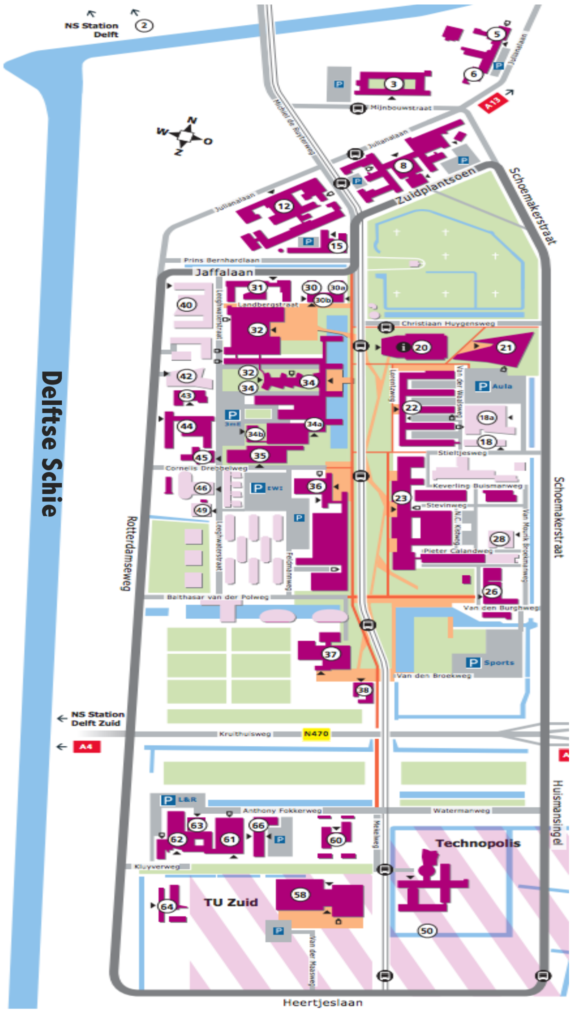


Figure 2:Overview of the T.U. Delft campus.

2.3 Aquifer Thermal Energy Storage

Aquifer Thermal Energy Storage (ATES) systems are used to store large quantities of thermal energy in subsurface aquifers enabling the reduction of energy usage and emissions of the heating and cooling networks in buildings [4]. As approximately 40% of the global energy consumption is used in buildings, mostly to provide heating and cooling, large-scale application of ATES can contribute significantly to a more sustainable energy use in urban environments. [5] [6]

In general, an ATES system consist of two wells and has a seasonal operation cycles. Cold water is stored in one well and hot water is stored in the second well. The cold water is extracted from the aquifer in the summer and is passed through a heat exchanger to provide cooling. During the cooling process the water is heated up. This heated water is then injected into the warm storage well. In the winter this process is reversed to provide heating.

ATES systems are most suitable for heating and cooling of bigger utility buildings such as offices, hospitals, museums, universities and greenhouse.
A schematic representation of an ATES system is given in figure 3.

There are closed and open ATES systems. Figure 3 illustrates an open system. In this report, the focus will lay on open ATES systems and therefore closed systems will not be discussed. In general, there are three main types of ATES systems based on their purpose:

1: ATES systems for cooling
2: ATES systems for heating
3: ATES systems for both heating + cooling

The system that is investigated in this report will have cooling as its sole purpose and will therefore have a slightly different layout than the system displayed in figure 3. The exact layout of the proposed system will be discussed in section 3.
[7] [8] [9]

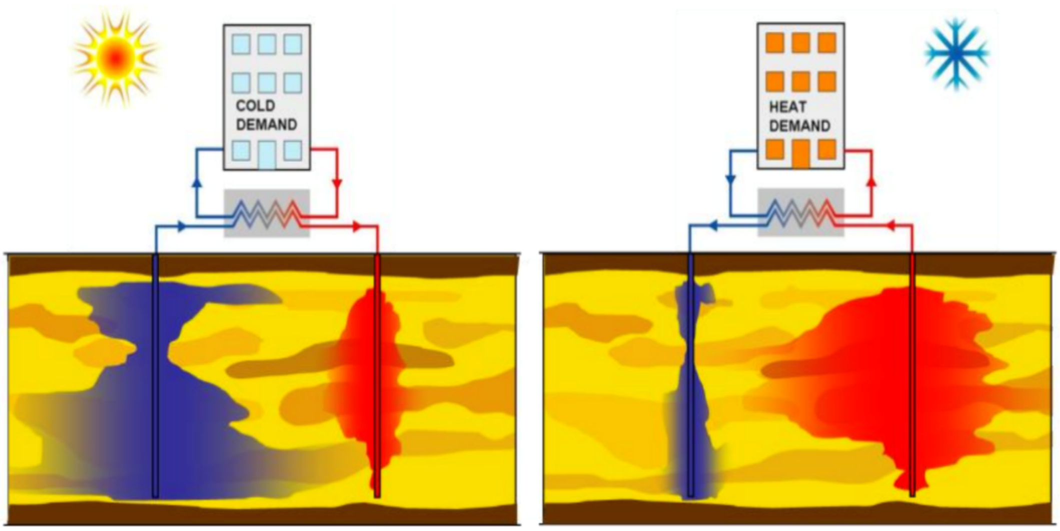


Figure 4: Schematic representation of an open ATES system.

3 Proposed ATES System Overview

Figure 4 gives an overview of the proposed ATES system. During winter, thermal energy, in the form of cold water, will be extracted from the Delftse Schie. The cold water will be stored in a cold aquifer until summer. The cold water will be extracted from the aquifer during summer. It is then pumped through the T.U. Delft buildings to deliver cooling. During this process, the temperature of the cooling water will rise. After cooling, the warm water will be stored in a warm aquifer until winter. In winter, this warm water will be extracted again to exchange thermal energy with the Delftse Schie.

4 Cooling Demand T.U. Delft (estimation)

4.1 Cooling demand

The cooling demand of the T.U. Delft is unfortunately not know at the moment. This is due to the use of many individual cooling units in each building of which the exact power usage is unknown. Therefore it is necessary to make an estimate of the yearly cooling demand of the T.U. Delft campus. This can then be used to predict whether the ATES is capable to deliver enough cooling energy for the campus.

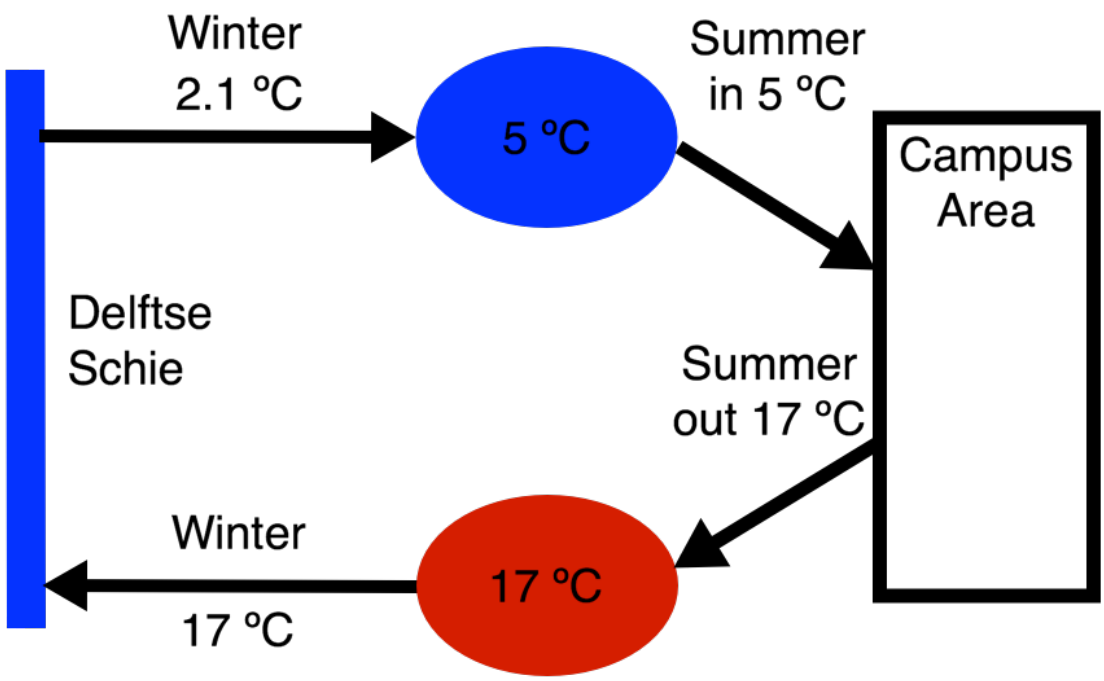


Figure 5: Schematic overview of the proposed ATES system.

To predict the cooling demand of the T.U. Delft the latest Uniform Measure Build Environment of RVO (Rijks Dienst Voor Ondernemend Nederland) is used. This measure consists of average cooling demands for office buildings and is subdivided into different estimates for buildings within certain ranges of floor area. Only buildings of which accurate floor areas are know where included in the calculations. Buildings that already (partly) work with ATES systems are also left out of the calculations since they will not have much benefits of using a new system for cooling.

Table 1 displays the buildings that are included in the calculations, with their corresponding gross floor areas and current type of cooling systems.

Some of these 'buildings' actually consist of several separate buildings of which the separate floor areas are unknown. For now these buildings are considered as one building. [10]

These floor areas are then used to make an estimate of the cooling demand for each building. Table 2 displays the used cooling demand values in kWh/(m^2 * year).

*Table 2: Cooling demand values in kWh/(m^2 * year).*

Year of construction:	Up to 5000 m^2:	5000 m^2 and larger:
1994 - 2008	9.3	9.2
1990 - 1993	8.0	9.4
1977 - 1989	7.9	8.3
Earlier - 1976	7.5	12.4

Combining the above mentioned cooling demands per square meter and the floor areas mentioned in table 1, the total cooling demand in kWh/year can be calculated. This results in a cooling demand of 4260000 kWh/year. Since 1 kWh equals 3.6 MJ, the total energy required per year for cooling is estimated to be $1.534*10^7$ MJ. This is a rough estimate since in reality the cooling demand of a building is dependent on many factors that were not taken into account in this report.

Table 1: T.U. Delft buildings with their floor area, type of cooling and year of construction.

T.U. Delft Buildings:	Gross Floor Area (m^2)	Type of cooling	Year of Construction
Biotechnology + Chemical Engineering + Delft Reactor Institute + Applied Sciences	113800	Electric (air treatment system)	Unknown (1960s)
Architecture	46000	Electric (air treatment system)	1918
Aula Congress Centre	14040	Electric (air treatment system)	1965
Civil Engineering and Geosciences	70030	Electric (air treatment system)	1969 (2006)
OTB Research Institute	9240	Electric (air treatment system)	1961
Technology, Policy and Management	13290	Electric (cooling unit)	2001
Industrial Design + Data Centre	35050	Electric (air treatment system)	1973 (renovations 2000)
Sports Centre	5870	Electric (air treatment system)	1959
Aerospace Engineering + Structures and Materials Lab + The Fellowship + SIMONA + Aerodynamic Laboratory	37410	Electric (air treatment system)	1969 small one (1952)
Cultural Centre	2770	Electric (air treatment system)	1996

5 Energy Extraction From Delftse Schie

The cold energy that will be stored in the subsurface, first has to be extracted from the surroundings during winter time. This can be done by extracting cold energy from the air but another option is to extract cold energy from water in the vicinity which is a more efficient manner of extracting thermal energy. This report will focus on the energy extraction from water.

5.1 Water temperature

The needed cold energy can be extracted from cold water. The most suitable option for this case would be the river Delftse Schie which is close to university and big enough to deliver enough volume of cold water. Figure 5 displays the temperature of the Schie water. The horizontal line represents the 5 ºC boundary. This data is obtained and provided by the regional water authorities Delfland. The measurements were taken at the Beukelsbrug, which is a part of the Delftse Schie that is located more towards Rotterdam than Delft. This is the nearest location to the T.U. Delft with accurate data over a period of a full year. The data is considered to be a good enough representation of the Schie temperature for this report. Measurements were taken every 15 minutes throughout a full year cycle. Because the samples were taken this frequently the average temperatures that will be calculated from this data also take into account the difference in temperature between day and night. The exact location of the Beukelsbrug is displayed in Appendix 1.

From figure 5 it can be concluded that December, January and February are the months with the coldest temperatures. The average water temperature during these three months is calculated from the provided data and amounts to 2.07 ºC.

For the proposed ATES system it is important to understand that this average temperature is just based on the 2016-2017 winter due to lack of older data. It is recommended to collect more data in the coming years or use older data from comparable rivers to get a better understanding of the average temperatures throughout several years. A higher average water temperature will lead to an increase in the volume of water that needs to be pumped around. This will have impact on the size of the pumps, heat exchangers and the required aquifer volume.

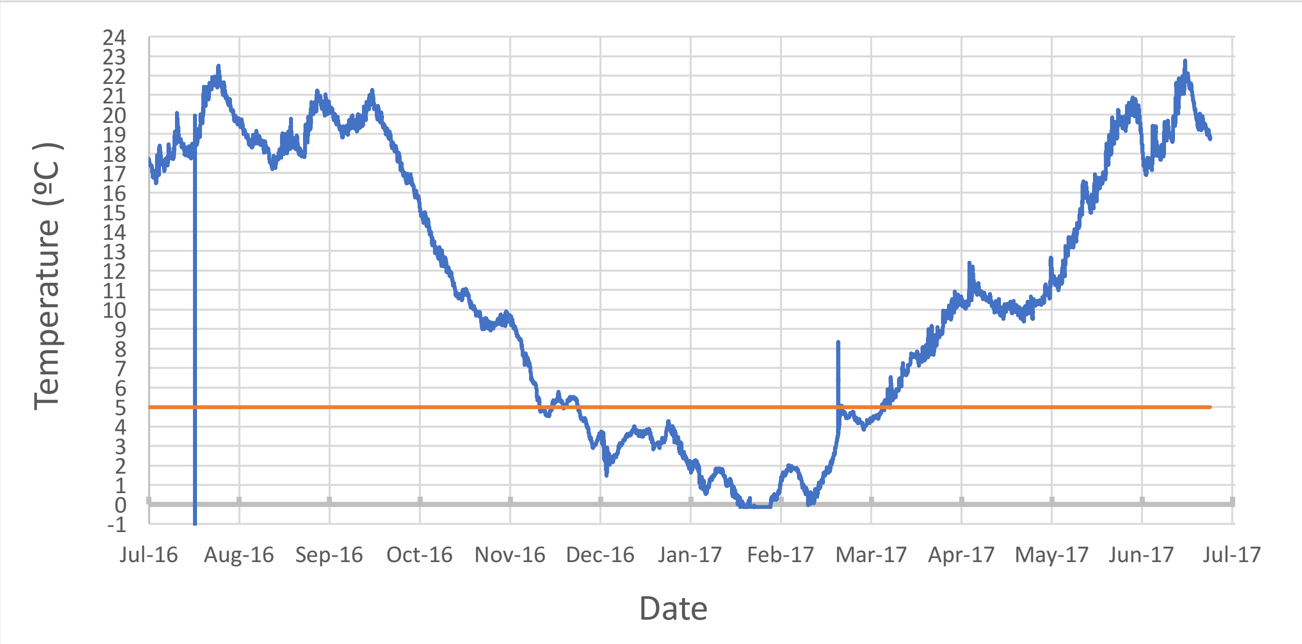


Figure 6: Water temperature of Delftse Schie.

5.2 Extraction of energy from surface water

This section will go into the extraction of thermal energy from surface water. The cold water from the 'Delftse Schie' will not be injected into the aquifer directly to prevent pollution of the ground/river water. Water that is already in aquifer will be pumped up and cooled down to the desired temperature. This is done by passing both the aquifer water and Schie water through a heat exchanger in which the heat from the aquifer water can exchange to the Schie water.

5.2.1 Type of Heat Exchanger

There are many different types of heat exchanger than can be used for the proposed system. For this specific case it is chosen to use a plate heat exchanger for the following reasons [11]:

- Low approach temperatures can be used, as low as 1 ºC
- Plate heat exchangers are easy to maintain
- Extra plates can easily be added, which makes the plate heat exchanger flexible
- Significantly less fouling
- In general, plate heat exchangers have a higher temperature correction factor

Low approach temperatures and fouling are expected from the cold river water and therefore the plate heat exchanger is the most suitable options. The option of adding extra plates to the heat exchanger is also useful incase water temperatures or cooling demand are higher than expected.

5.2.2 Size and Output Temperature of Heat Exchanger

Heat transfer across a surface can be calculated by applying equation 1:

$$Q = UA\Delta T_m \quad [1]$$

Where:

Q = heat transferred per unit time, W
U = the overall heat transfer coefficient, W/m^2 ºC
A = heat-transfer area, m^2
ΔT_m = mean temperature difference, ºC

By using this equation, a rough estimate of the size of the heat exchanger at a certain output temperature and flowrate can be made. To do this the mean temperature difference (ΔT_m) has to be calculated. In the case of true co- or counter-current flow the logarithmic mean temperature difference can be used in equation 2. The logarithmic mean temperature difference is calculated as displayed in equation 2.

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad [2]$$

Where:

ΔT_{lm} = log mean temperature difference
T_1 = hot fluid temperature at inlet
T_2 = hot fluid temperature at outlet
t_1 = cold fluid temperature at inlet
t_2 = cold fluid temperature at outlet

In most heat exchangers the flow will not be true co- or counter-current but rather a mix of co-current, counter-current and cross flow. Therefore, the logarithmic mean temperature difference is not a realistic representation of the main temperature and a correction factor has to be applied to compensate for this. The true mean temperature difference can then be determined as follows in equation 3.

$$\Delta T_m = F_t \Delta T_{lm} \quad [3]$$

Where:

ΔT_m = corrected meant temperature difference, for use in equation …
F_t = temperature correction factor

To determine the temperature correction factor, the number of transfer units (NTU) have to be determined first. This is done by applying equation 4.

$$NTU = \frac{(t_0 - t_i)}{\Delta T_{lm}} \text{ [4]}$$

Where:

t_0 = stream outlet temperature, ºC
t_1 = stream inlet temperature, ºC

The NTU can then be used in combination with the flow arrangement type to determine the temperature correction factor. The simplest arrangements of plate heat exchangers are those where both fluid just make one single pass. These arrangements are labeled as 1-1 single-pass arrangements and exist in both countercurrent and cocurrent versions.

Single-pass arrangements make it easy to open the equipment for maintenance and cleaning without disturbing the pipework. Therefore this arrangement is chosen for the proposed ATES system. The U-arrangement is the most used single-pass design and is displayed in figure 7. [12]

With both the arrangement and the NTU known, the temperature correction factor (F_t) can be determined by using figure 6.

Now all variable of equation … are known, the area of the heat exchanger can be calculated. For this typical overall U values for a plate heat exchanger are used as well as typical fouling coefficients for river water. The used table can be found in Appendix 2. These values are sufficient for preliminary sizing of the heat exchanging equipment. [11] The corrected overall heat coefficient is than calculated as follows:

$$\frac{1}{U} = \frac{1}{U_u} + \frac{1}{F_f} \quad [5]$$

Where:

U = corrected overall heat transfer coefficient, W/m^2 ºC
U_u = uncorrected overall heat transfer coefficient, W/m^2 ºC
F_f = fouling factor coefficient, W/m^{2}ºC

The final results of the calculations described in this section are displayed in table 3.

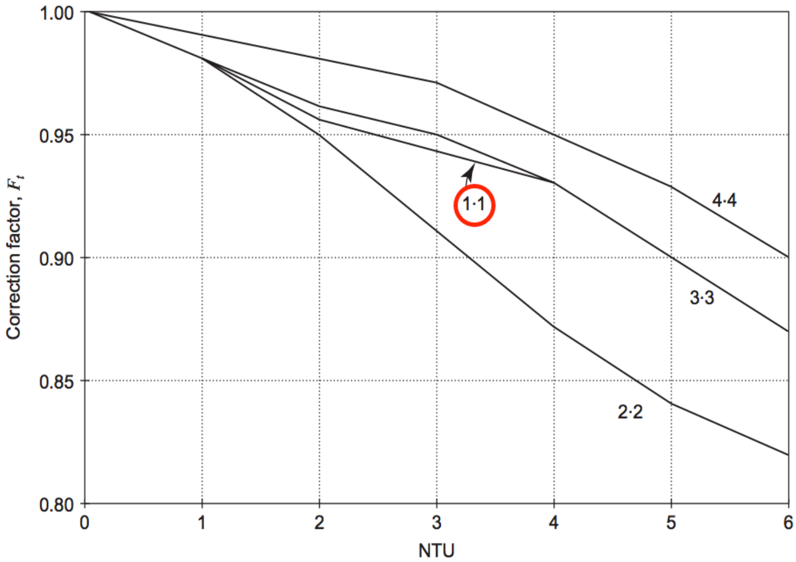


Figure 7: Temperature correction facter vs. NTU.

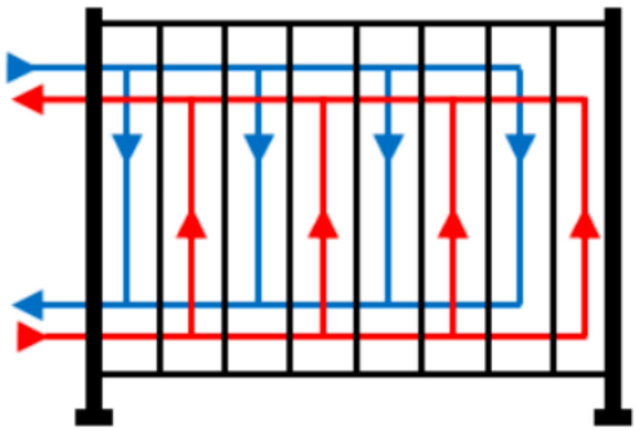


Figure 8: Single-pass U-arrangement of plate heat exchanger.

Table 3: Heat exchanger calculations.

T1	17	ºC	**ΔTlm**	2,90	ºC	**ΔTlm**	2,90	ºC	**U without fouling**	6000	W/m^2 ºC
T2	5	ºC	**ti**	17	ºC	**Ft (from graph)**	0,925	factor	**U with fouling factor**	3230,77	W/m^2 ºC
t1	2,1	ºC	**t0**	5	ºC				**Q**	1972736,6	Joule
t2	14,1	ºC							**ΔTm**	2,68	ºC
ΔTlm	**2,90**	ºC	**NTU**	**4,14**		**ΔTm**	**2,68**	ºC	**A**	**228**	**m^2**

In these calculations a fouling factor coefficient of 7000 W/m^2 ºC was applied, which is a typical fouling factor for river water.

The river inlet temperature t_1, is 2, 1 ºC as discussed in section 5.1. T_1 is set to 17 ºC, which is equal to the temperature in the warm well. T_2 is set to the desired cold water temperature of 5 ºC. This results in a ΔT of 12 ºC (17-5) at 'hot' side of the heat exchanger. This same ΔT has to be achieved at the 'cold' side of the heat exchanger. Therefore, t_2 is set to 14.1 ºC which yields $t_2 - t_1 = 12$ ºC. An overview of these numbers is given in figure 8.

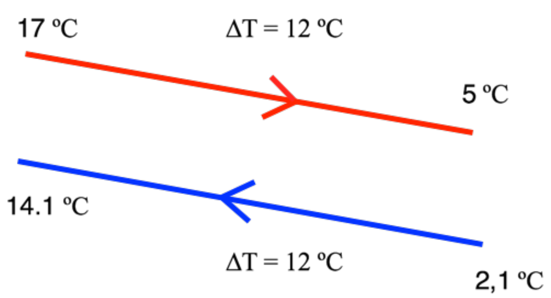


Figure 9: Overview of temperature differences in heat exchanger.

The result of all these calculations is a predicted area of the heat exchanger. In this case this area amounts to 228 m^2, which is a realistic/feasible value. An extra 15% surface area is added as a general safety margin. The total area will then be 262.2 m^2.

Using typical plate dimensions of 1.5 m by 0.5 m, this heat exchanger would require 350 plates. This is also a feasible value. From these numbers it can be concluded that it is possible to extract the required amount of cold energy from the 'Delftse Schie' with a plate heat exchanger

5.2.3 Pumping

To determine the exact pumping power that is required for the heat exchanger, a more detailed heat exchanger design has to be made. This goes beyond the scope of this report and therefore it can be assumed that the heat exchanger adds a hypothetical 15 meters to the water column of the ATES wells. This will translate into a higher required pumping power for the well and will hereby compensate for the required pumping power of the heat exchanger.

6 Efficiency of cooling with water

Cooling a building by using cold water as energy source, can be done in various ways. This section will go into some of the different options to use cold water for a cooling system. In general cooling with water works my passing the water through some sort of heat exchanger that will exchange the heat of the building with the cold of the water. This can be done directly, by pumping the water through areas of the building that need to be cooled. Another method of cooling with water is the more indirect approach of passing air passed the cold water and then using this cold air to cool the building. Below some of the different options for cooling with cold water are discussed.

6.1.1 Direct cooling

Cooling panels:

Cooling panels are aluminum plates through which the cold water flows. These plates transfer the heat from the air to the cold water, therefore cooling the room's temperature. The panels also cool the room's surfaces by low-temperature radiation.

Chilled beams:

Chilled beams cool the air in a room by natural convection from a finned heat exchanger. They can be combined with a fresh air supply stream, which often increases the cooling capacity.

6.1.2 Indirect cooling

Fan coil units:

Fan coil units can supply both heating and cooling. A fan passes air form the room through a heat exchanger that is supplied with cold (or hot) water from a central unit, hereby cooling the room's air temperature. These units can achieve high cooling requirement, but also has high noise levels.

Induction units:

These units make use of the supply of ventilation air to a room. The ventilation air is passed through a nozzle with high velocity, hereby inducing air from the room through a heat exchanger. This unit makes it possible to cool or heat a room with a single unit that does not use a fan. [13]

6.1.3 Assumed efficiency & pump flow rate

The method of cooling will be different for every building and depends on numerous design factors. Therefore, it is difficult to make detailed efficiency calculations in this stage. For the rest of this report the following assumptions are made:

- The incoming cold water is assumed to be at a constant temperature of 5 ºC
- It is assumed that cooling is initiated when building temperatures reach 25 ºC
- The warm water leaving the building is assumed to be at a constant temperature of 17 ºC

With these assumptions a pumping rate for the incoming cold water can be determined as follows:

$$Heat\ Capacity\ Water = 4200\ \frac{J}{kg * K}$$

$$Density\ of\ Water\ (5\ ºC) = 1000\ \frac{kg}{m_3}$$

Using the above mentioned properties of water, the required volume of water at 5 ºC can be determined. This results in a required volume of 304000 m^3. Dividing this number by the total amount of seconds in the three warmest months (June, July and August) yields an average pump flow rate of 0.0382 m^3/s. This equals to 3308 m^3/day.

7 Local geology and potential aquifers

This section will shortly go into the general geology of the T.U. Delft campus area, after which potential aquifers for the ATES system will be discussed and compared.

7.1 Local Geology

Drill hole data from two locations on the T.U. Delft campus is used to get a better understanding of the subsurface of the campus. The location of these drill holes are shown in Appendix 3. Both of these drill holes were drilled in order of the NAM. From these drill holes it is concluded that the North Sea Supergroup forms roughly the first 400 meters of the subsurface of Delft. This group consists of shallow-marine sediments, which are mainly deposited in the western Netherlands, and of terrestrial beds which have a fluvial, paralic and lacustrine origin. Glacigenic deposits occur in the upper part and the top of the layer is formed by the current land surface or sea floor. [14]

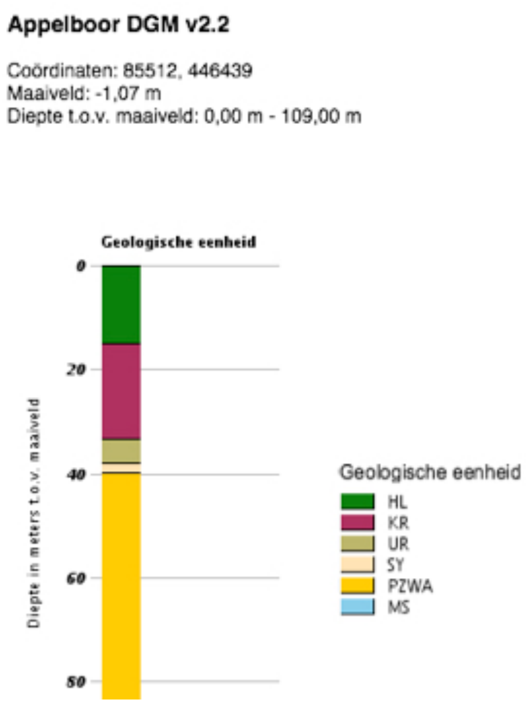
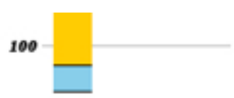


Figure 10:Geological section of the first 100 m of the NU.



Since the discussed ATES system will only store water at low temperatures, the storage will preferably be in shallow layers. This is due to cost considerations. Deeper storage is generally more expensive. Therefore only the upper 100 meters of the North Sea Supergroup (NU) will be discussed in this report. [15]

The upper 100 m of the NU consists of three main layers, which is displayed in figure 9. These layers are the Holocene Deposits, Formation of Kreftenheye and the Formation of Peize and of Waalre.

7.1.1 Holocene Deposits (HL)

The Holocene Deposits were deposited over the last 12000 years. In the T.U. Delft area it roughly makes up the first 15 meters of the subsurface. This layer mainly consists of clay sand and peat. These are not ideal soils for an ATES system, so this layer will not be used for the storage of water. [16] [14]

7.1.2 Formation Kreftenheye (KR)

This layer has a thickness of about 15-20 meters at the T.U. Delft location. It is dominantly consists of course sands and gravel, which makes it a good aquifer with high permeability. Due to the low depth and good permeability and porosity, this layer is a good option for the suggested ATES system. The layer is relatively thin and close to the surface water, which are two important point that have to be considered before selecting this layer of the ATES system. [16] [14]

7.1.3 Formation of Peize and Waalre (PZWA)

The formation of Peize and of Waalre is thicker layer. At the T.U. Delft location it has an approximate thickness of 60 meters. The Peize formation is the upper part of this formation and consist predominantly out of course to medium grained sand layers and some clay and silt layers.

The Waalre formation is located below the Peize formation. At the T.U. Delft area this layer starts from about 70/75 meters onwards but the exact boundary between these two formations needs to be further investigated. The Waalre formation consist mainly out of clay and silt layers. This causes a lower vertical and horizontal permeability in the layer, which makes this lower part of the formation less suitable for an ATES aquifer. [16] [14]

7.2 Potential Aquifers

In this section the properties of the possible aquifers in the subsurface of the T.U. Delft campus will be discussed and compared.

As discussed in the previous section, the Formation Kreftenheye and the Formation of Peize are the most suitable shallow aquifers in this case. In figure … two drill sample profiles of drillings at the campus are displayed. From these profiles and the above discussed formations, two possible aquifers are found. These are further discussed in the following sections. Both options are indicated in figure 10.

7.2.1 Option 1

From the drill hole data this aquifer seems to have an inconsistent thickness in the two profiles. The thickness is 23 meters in drilling B37E0581 and 18 meters with some interruptions in drilling B37E0583. The layer has very high (K≥100 m/day) horizontal and vertical conductivity. Especially the high horizontal conductivity is a must for ATES systems. High vertical conductivity is not considered as a problem since the proposed ATES system is a low temperature system and therefore thermal convection is no threat to the system.

The aquifer consists of both medium and coarse grained sand. This also indicates high permeability and a good porosity. Based on literature values, the effective porosity for this layer is assumed to be 0.30. [17]

In the B37E0583 drilling, the layer has a small interruption by a clay layer. This clay layer has low K values and is therefore undesirable.

7.2.2 Option 2

Aquifer option 2 has a more consistent thickness throughout the 2 drill holes. It has a thickness of 26 meters in drilling B37E0581 and a thickness of 23 meters in drilling B37E0583.

This layer also has very high horizontal and vertical K values, within the same range as option 1.

Aquifer option 2 mainly consists of medium grained sand and has some courser grained sand layers. On average this aquifer has finer grained sand than option 1 and therefore the effective porosity is estimated to be slightly higher; 0.32.

This aquifer does not show any interruptions by clay layers.

7.2.3 Chosen Aquifer

Based on the different properties discussed in section 7.2.1 and 7.2.2, aquifer option 2 is chosen as the preferred aquifer option for the proposed ATES system. The most important reason for this conclusion are displayed below:

- Option 2 has a larger and more consistent thickness than option 1
- Option 2 does not show any interruptions by impermeable layers, which option 1 does
- Option 1 and 2 have similar horizontal and vertical K values
- Option 2 has a slightly higher assumed porosity

The most important aquifer properties of option 2 are summarized in table 4.

Table 4: Aquifer properties of option 2.

Average Thickness	24.5 m
Horizontal Conductivity	≥100 m/day
Vertical Conductivity	≥100 m/day
Porosity	0.32
Average Upper Boundary	46.5 m
Average Lower Boundary w.r.t. surface level	71 m

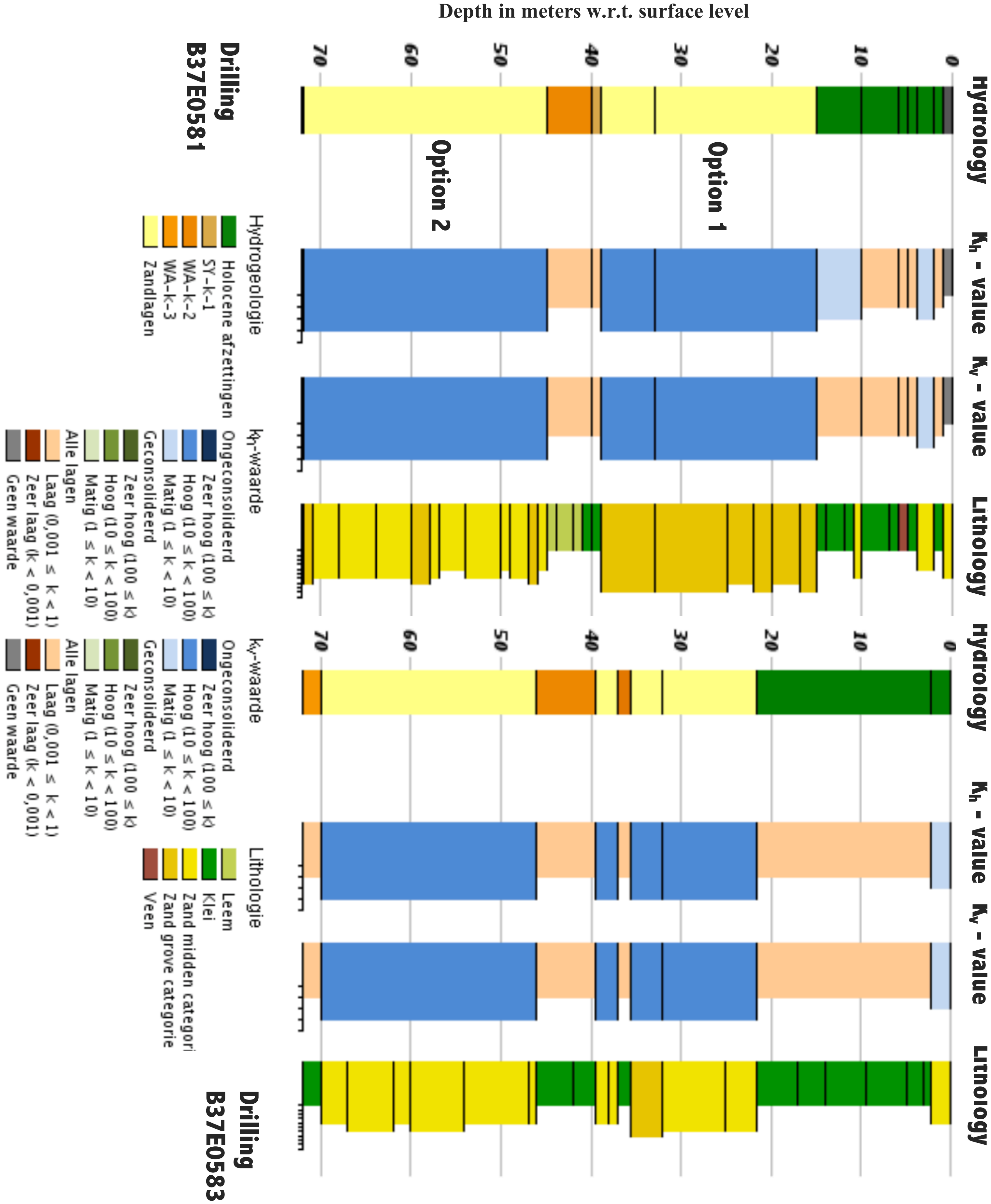


Figure 11: Overview of potential aquifer.

8 ATES Model

An analytical ATES model is used to predict the volumes, temperatures and thermal radius of the wells throughout multiple years. This model is based on the model described in (A Control-Oriented Model For Combined Building Climate Comfort and Aquifer Thermal Energy Storage Systems, Vahab Rostampour, Martin Bloemendal, Marc Jaxa-Rozen, and Tamas Kevickzy) The model is mainly control oriented but also takes thermal losses and ground parameters into account. For the depth of this initial report, on the possibilities of a cold ATES system at the T.U. Delft campus, this is considered a sufficient model. The following sections will elaborate on the buildup of the model and the obtained results.

8.1 Model Input Values

Table 5 gives an overview of the input variables used in the model.

Table 5: Input values of analytical model.

L	20 m	Fixed filter screen lenght, based on aquifer thickness.
T_{amb}	13.0 ºC	Ambient water temperature.
Tc_{in}	2.1 ºC	Temperature of injected cold water. Based on section 5.1.
Tw_{in}	17 ºC	Temperature of injected warm water. Based on section 6.1.3.
D	210 m	Distance between warm and cold well. Based on at least 2xRth and best output temperature.
Pr	3381.8 m^3/day	Pump flow rate. Based on cooling demand. Same calculations as in section 6.1.3 but then divided by the amount of winter days (90).
c_w	4200 J/kg*K	Heat capacity of water.
c_{aq}	2800 J/kg*K	Heat capacity of the saturated porous medium.

8.2 Model Formulas

The first step in modeling the ATES system is to define formulas for the volume of both the cold and warm well over time. See equation 6 and 7.

$$Vc(k) = Vc(k-1) + (PD * Pr) \quad [6]$$

$$Vw(k) = Vw(k-1) + ((-1 * PD) * Pr) \quad [7]$$

Where:

V_c = Aquifer storage volume cold well (m^3)

V_w = Aquifer storage volume warm well (m^3)

Pr = Pump flow rate (m^3/d)

PD = Pumping direction: 1 when pumping from warm well to cold well, - 1 for pumping from cold well to warm well and 0 when not pumping

After the well volumes are defined, the thermal radius of both wells can be determined over time as well. This is done by applying equation 8 and 9.

$$R_{thc} = \sqrt{\frac{c_w V_c}{c_{aq} \pi L}} \quad [8]$$

$$R_{thw} = \sqrt{\frac{c_w V_w}{c_{aq} \pi L}} \quad [9]$$

Where:

R_{thc} = Thermal radius cold well (m)

R_{thw} = Thermal radius warm well (m)

c_w = Specific heat capacity of water (J/kg*K)

c_{aq} = Specific heat capacity of saturated porous medium (J/kg*K)

L = Filter screen length (m)

The temperature in both warm and cold well throughout the pumping cycles can now be calculated with the following first-order difference equations:

$$Tc(k) = Tc(k-1) * \frac{Vc(k-1)}{Vc(k)} + Tc_{in} * \frac{PD*Pr}{Vc(k)} - \alpha c(k) * (Tc(k-1) - Tamb) * \left(1 - \frac{Vc(k)}{Vc(k-1)}\right)$$

[10]

$$Tw(k) = Tw(k-1) * \frac{Vw(k-1)}{Vw(k)} + Tw_{in} * \frac{PD*Pr}{Vw(k)} - \alpha w(k) * (Tw(k-1) - Tamb) * \left(1 - \frac{Vw(k)}{Vw(k-1)}\right) \quad [11]$$

In these equations αc and αw are the rates of convergence that determine the rate at which thermal losses occur. [18] These α values are dependent on system characteristics such as L, D and storage volume. A relation has to be found between these system characteristics and the values, which is done in [18]. This relation is created by executing the following steps:

- Determine α for a large number of simulations with a wide range of system characteristics
- Evaluate α with respect to the system characteristics to verify the existence of a relationship between α and one or more system characteristics
- Implement the found relation in the analytical model and verify its behaviour

This resulted in the relation displayed in figure 11, provided by Martin Bloemendal. From this relation, equation 12 and 13 are defined.

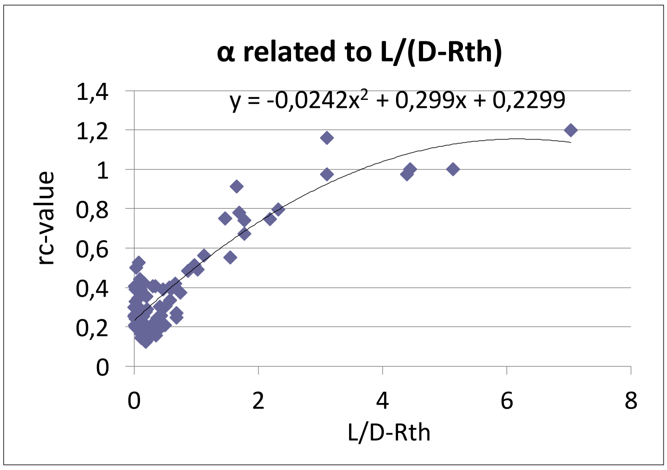


Figure 12: α value related to L/(D-Rth).

$$\alpha w(k) = A * \left(\frac{L}{D-Rthw(k)}\right)^2 + B * \left(\frac{L}{D-Rthw(k)}\right) + C \quad [12]$$

$$\alpha c(k) = A * \left(\frac{L}{D-Rthc(k)}\right)^2 + B * \left(\frac{L}{D-Rthc(k)}\right) + C \quad [13]$$

Where:

A = -0.0242

B = 0,299

C = 0,2299

With these values the model is completed and can be used to create the results displayed in the following section. [19] [7]

8.3 Model Results

In this section the results of the model described in sections 8.1 and 8.2, will be displayed and discussed.

Figure 12 shows the volume of both warm and cold well over time. The simulation is started at the beginning of January and therefore starts with pumping from the warm well to the cold well. It is chosen to never completely empty the cold well for improved efficiency. When the cold well is completely emptied, its temperature increases too rapidly during pumping. This causes a to high overall output temperature from the cold well. The warm well is almost emptied completely since in this case the output temperature is not that important.

Figure 13 displays the thermal radius of warm and cold well. In this figure it is also clearly visible that the warm well is pumped towards a more empty state than the cold well. The thermal radius of the warm well starts to decrease ever more rapidly when the well moves towards its empty state.

Figure 14 shows the temperature over time, for both the cold and warm well. The initial temperature of both the cold and warm well is set to the ambient temperature of 13.0 ºC. Since the simulation is started at the beginning of January, the cold well does not reach its desired temperature of 2.1 ºC in the first year.

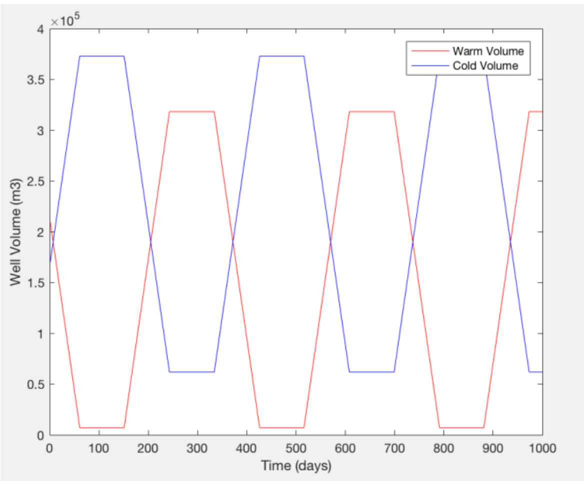


Figure 14: Volumes of cold and warm well.

The difference in volume between the cold and warm well can be recognized again. The warm well is almost completely emptied and therefore its temperature rises to 17.0 ºC almost immediately when injection starts. The warm well is not emptied completely and therefore it takes some more injection volume before the overall temperature of the well reaches its desired temperature of 2.1 ºC.

The average output temperature of the cold well during summer time is calculated to be 4.94 ºC. This is a little bit lower than the desired cooling water temperature of 5 ºC and therefore a positive result.

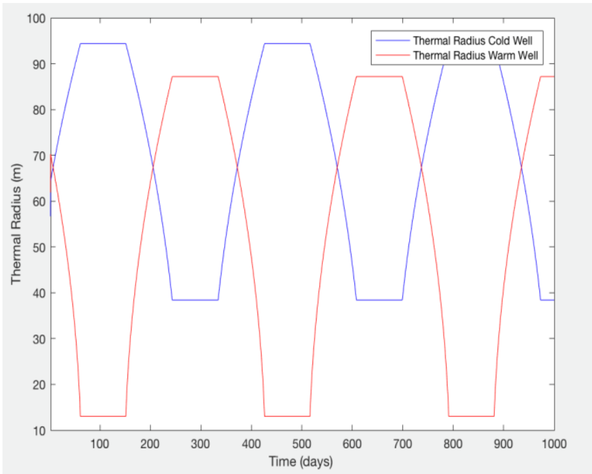


Figure 15: Thermal radius of cold and warm well.

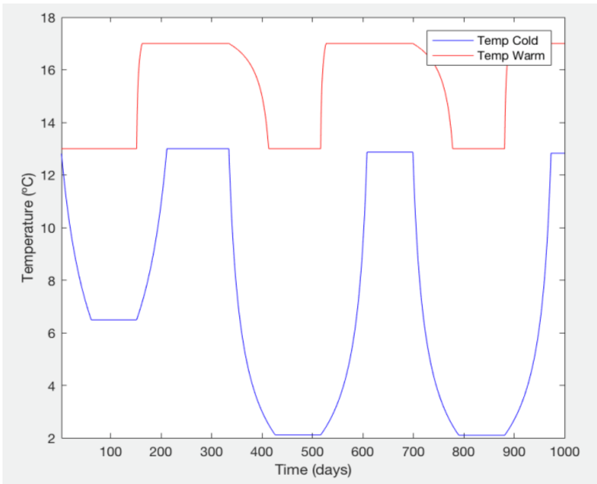


Figure 13: Temperature of cold and warm well.

9 Discussion

The goal of this report is to serve as a preliminary overview which can be used as a starting point for future, more in depth, feasibility studies. As stated in the goal, this does leave some gaps and points of improvement for further research. The most important ‘gaps’, uncertainties and points of improvement are listed below:

Economics:

This report did not focus on the economicall aspects of the proposed ATES system. It was chosen not to do this due to the lack of detailed information. Because of this many assumptions will have to be made during the economical calculations which will lead to an unpredictable result. Nevertheless, economics remains one of the main descision criteria for sush a project and will therefore have to be investigated further. To do this, a more detailed plan with specific equipment selection has to be created.

Subsurface Data:

The amount of subsurface data that was available is not sufficient for detailed predictions. Some of the parameters, such as porosity, conductivity and permeability, that are now used had to be estimated or assumed. Other parameters, such as groundwater flow rates were not taken into account. This all amounts to high uncertainties that have to be reduced in future works.

Accuracy of Model:

A more accurate model of the ATES system has to be created to get a better understanding of the exact thermal losses during storage of the cold water. This can have a big influence on the feasibility and efficiency of the whole project.

Total Efficiency:

The total efficiency of the project is not calculated in this report. It was chosen not to do this, due to lack of accuracy of the current data and information.

To create reliable efficiency calculations, detailed information about building design, campus infrastructure and piping, heat exchangers and energy demand has to be obtained. In this stage this is not the case, and therefore efficiency calculations would not be accurate and could thereby be the cause of wrong conclusions.

10 Conclusion

Investing in the proposed ATES system can help the T.U. Delft in achieving its sustainability goals for 2020. This system could severely reduce the universities energy demands for cooling and would be a perfect example of using new technologies to make the T.U. Delft more sustainable.

From this report, it can be concluded that the Delftse Schie is a suitable source of thermal energy that can supply enough energy to cool the campus facilities. With current heat exchanger technologies, enough energy can be extracted from this water.

The subsurface of the T.U. Delft area offers enough possibilities for suitable aquifers that can be used for the ATES wells.

Summarizing, the proposed ATES system could extract and store the desired 4260000 kWh/year by delivering an average cooling water temperature of 4.94 ºC at a pump flow rate of 3381.8 m^3/day.

11 References

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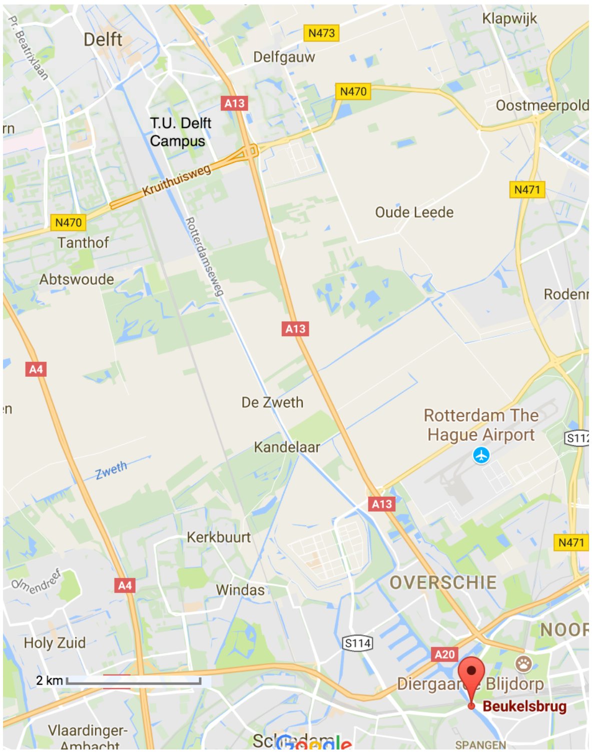
12 Appendix 1



13 Appendix 2

Table 19.2 Fouling Factors (Coefficients), Typical Values

Fluid	**Coefficient (W/m^2°C)**	**Factor (Resistance) (m^2°C/W)**
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Town water (soft)	3000–5000	0.0003–0.0002
Town water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapors	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

14 Appendix 3