AQUIFER THERMAL ENERGY STORAGE FOLLOWING UP ON THE TU DELFT GEOTHERMAL WELL

A study on how a low-temperature aquifer thermal energy storage system can cool and heat the campus in accordance with its climate goals by 2050

AES Bachelor Thesis
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9 July 2019

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Abstract

In 2020 TU Delft will build a geothermal well producing enough energy to power all its faculties and a number of buildings surrounding the campus. This is done to meet the climate goals the TU set itself: an energy neutral campus by 2040. Geothermal plants are designed to produce for 30 years. After this period, by 2050, the TU has to be energy-neutral without the geothermal heat flowing from deep underground. To prevent falling back to fossil fuels there is need for a new energy source. In this feasibility study one of the options is investigated, low temperature aquifer thermal energy storage (LT-ATES). This technology stores heat-energy produced during summertime in aquifers, during wintertime this water is used to heat the faculties. It was found that a LT-ATES system is viable. A 19 MW ATES system containing 23 cold and 23 warm wells to a depth of 180 meters is needed. Cooling during summertime is not sufficient to charge the system to meet the winter heating demand; therefore an additional solar thermal collector field of 35.000 m^2 is needed. Designing a strategy for 2050 means that there is a considerable amount of assumptions to be made. To optimize the LT-ATES-system, a more in-depth study should be performed.

Acknowledgements

I would like to thank my supervisors Dr. Phil Vardon and Dr. Ir. Martin Bloemendal for being there every week to answer my questions. Without their knowledge and patience I would not have been able to write this study. During a fieldtrip halfway this project I was allowed to visit two companies, Koppert Cress and Vogelaer Aardwarmte. I would like to thank them for the interesting and inspiring presentations.

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Abbreviations

ATES	aquifer thermal energy storage
CHP	combined heat & power
CRE	Campus Real Estate (TU Delft)
H/C	heating and cooling
CO_2	carbon dioxide
DAP	Delft aardwarmte project
DHW	domestic hot water
HVAC	heating, ventilation and air-conditioning
SodM	Staatstoezicht op de mijnen -> ‘State-supervision on the mines’
TU	University of Technology
KNMI	Royal Netherlands Meteorological Institute

1 Introduction

1.1 Problem: TU Delft needs to be energy neutral

The TUDelft has set ambitious targets for its future energy use, by 2020 the campus should use 40% less energy than it did in 2005 (TU Delft, n.d.). By 2040 the Executive board wants the TU to be fully energy neutral as far as energy provision is concerned.

To fulfil these targets there are advanced plans to drill a geothermal well, the DAP-well. This well is planned to heat the campus and its surrounding buildings, producing 76°C water from the 2300-meter-deep Delft sandstone (TU, 2017). Geothermal wells are generally planned to have a lifetime of 30 years and the same applies for this one. These years give the TU the opportunity to work on a long-term strategy to become or stay energy neutral.

Assuming that the TUDelft has to be energy neutral by 2050 and does not have the geothermal well to produce heat it has to invest in a campus that produces or saves its own energy. At the moment there are a number of ATES systems operating on campus, for instance under the library (TU Delft Library, n.d.). Newly constructed buildings such as TNW-Zuid are designed to be energy efficient and education building Pulse is completely energy neutral. The TUDelft is planning to invest up to 675M€ in its campus the coming decades (VSNU, 2016). The board has some important decisions to make steering the TU into an energy-neutral future. It is also possible to attempt to find a way of producing energy in such a manner that it does not contribute to the emission of greenhouse gasses. There are numerous different approaches to this problem, this study explores how this can be done utilizing a LT-ATES system.

1.2 Approach

The goal of this study is to investigate whether a LT-ATES system on the TUDelft can meet its campus heating and cooling demands. From a technical, financial and geological point of view. The following questions are answered to meet the goal of this study;

- What is the heating and cooling demand by 2050?
- Where does the excess heat and cold come from?
- Are there (enough) suitable formation(s) to store this amount of energy?

1.3 Assumptions

There are many uncertainties when researching cases 30 years in the future. To do proper research a number assumptions have to be made, they are stated Table 1. Some of them are averaged while others are there to keep this study manageable;

University size	No growth or decline. Staff and student numbers stay the same as in 2019.
Climate change	+ 1,7 °C; The Royal Netherlands Meteorological Institute (KNMI, 2015) has a number of climate models for 2030, 2050 and 2085. The four scenarios average into a rise of 1,7 °C by 2050 which is 0,05 °C/y.
H/C demand by 2050	15 % decrease in heating 35% increase in cooling (See 2.2.1)
Legislation	Municipality, SodM and government approve full size ATES and geothermal well
Energy production	Similar technologies, no major breakthrough in energy production.
Geothermal well end-of-life	2050
2019 H/C energy ratio	In Delft's climate the HVAC energy consumption is distributed as 95% heating and 5% cooling (Zangheri & Entranze, 2014). Assuming that Berlin and Delft have fairly comparable climates (Weather-averages, 2019)
DHW	Domestic Hot Water is added to heating energy as they are comparably produced
Groundwater flow	The effect of groundwater flow on ATES performance is not considered in this study

Table 1 assumptions

2 Background information

2.1 TUDelft campus

TUDelft has one of the largest university campuses in the world, accommodating about 27.000 people daily and stretching over 161 hectares. There are numerous buildings and faculties ranging in size from small office spaces to the EWI-skyscraper measuring almost 68.000 m^2. Most of the main faculties were built in the late 50's or early 60's as the TU moved from the historic centre of Delft to the current campus. The concentration of these buildings opens the door to a single energy source, and this is what the TU has been doing for some time. In paragraph 2.4 the current production will be further discussed.

The TU transparently shares its data via the Energy-Monitor, consumption data used in this study is retrieved from this online database. The E-monitor supplies information on the consumption of electricity, gas, heat, water and emissions of CO_2. To convert this data, it is assumed that the total consumption of heat and gas per faculty is the amount of energy used to heat the building. After the gas consumption is converted to kWh (Eq. 1) the cumulative of the two amounts to unit of energy in MWh.

$$\begin{gathered} 1\ kWh = 3{,}6\ MJ \\ 1\ m^3\ natural\ gas = 35{,}17\ MJ = 9{,}77\ kWh \end{gathered} \tag{1}$$

According to the numbers provided by itself the TUDelft consumes a total of 45 GWh annually to heat its buildings of which almost 80% is distributed via its heat network. As stated in Table 1 the total kWh consumed is multiplied by a factor 1,05 to estimate the total consumption including cooling. A common way to represent HVAC energy consumption is done by dividing the annual energy consumption over the total area in squared meters [kWh/m^2 y]. The buildings of which energy figures are available are listed in Table 2. The areas of building 26 and 28 are estimates.

	2018	Area in m^2	Annual kWh per m^2
Building 3	Science Centre Delft	13100	96,2
5	Biotechnology	13700	177,5
8	Architecture	47100	48,1
12	Chemistry building	28100	94,0
15	TNW - Physical and Chemical Technology	5100	111,0
20	Aula Conference Centre	14100	81,5
21	TU Delft Library	15100	101,3
22	Applied Physics	43100	133,0
23	Civil Engineering and Geosciences (CEG)	66600	98,3
26	Multi-tenant building	10000	141,8
28	TNO / EWI (EEMCS)	15000	31,5
30	International School Delft 30 True Colors Delft	9300	46,2
31	Technology, Policy and Management (TPM)	12400	73,2
32	Industrial Design Engineering (IDE)	34300	50,1
34	Mechanical, Maritime and Materials Engineering	47600	116,3
35	Education Building 35 (Drebbelweg)	5200	61,0
36	Electronic and Mechanical Support Division (EMSD)	67900	62,6
37	Unit Sports	11600	119,2
38	Unit Culture	3500	107,2
45	Composites laboratory / Inholland	3900	86,7
50	Reactor Institute Delft	16300	202,6
58	Applied Sciences (South building)	32000	0,5
61	Delft Aerospace Structures & Materials Laboratory	5100	127,6
62	Aerospace Engineering (AE)	21100	56,9
64	Aerodynamics Laboratory, Windtunnels	3200	127,0
66	The Fellowship	4800	98,7
	CAMPUS	**549200**	**86,1**

Table 2 annual energy consumption per analysed building

There are huge differences in the kilowatt-hours used to power the HVAC technology per faculty. The new Applied sciences building (#58) for instance is built to be energy neutral which results in an energy use of 0,5 kWh/m^2 y. Biotechnology (#5) on the other hand, one of the oldest faculties needs 177 kWh/m^2 y to power its HVAC installations. Applied physics (#22) stood out with a very high number of 271 kWh/m^2 y but this is most likely due to corrupted data in the last month of the year. When looking at past years there is a more consistent energy use in winter months which, when averaged, comes to about 133 kWh/m^2 y.

2.2 *Climate*

According to the Köppen classification Delft has an oceanic climate. All the climate related data that are used are obtained from the Royal Netherlands Meteorological Institute (KNMI) weather station at the Rotterdam-The Hague airport located 7 kilometres to the southwest. In Figure 1 the temperature range can be seen, the winter months December, January and February are the coldest. Woweer.nl states that there are is an annual average of 39 days where temperatures below 0 °C are measured.

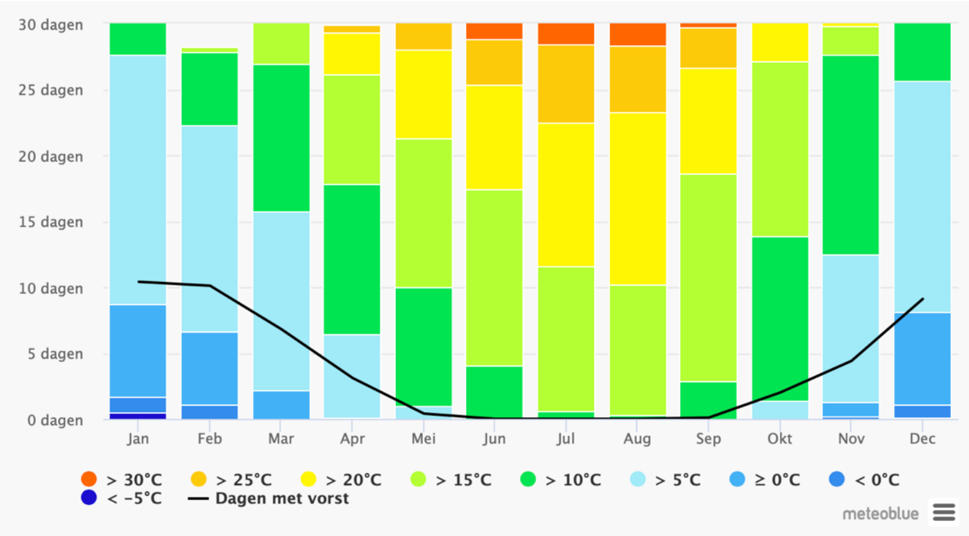


Figure 1 Daily temperatures Delft (Meteoblue.com)

2.2.1 *2050 climate*

In Figure 2 the average annual temperature at KNMI's Rotterdam weather station is displayed. The trendline shows a clear increase of temperature of about 0,5 °C per 10 years or about +1,5 °C by 2050. This coincides with the KNMI climate scenarios (KNMI, 2015b) in which they predict an average rise of 1,7 °C.

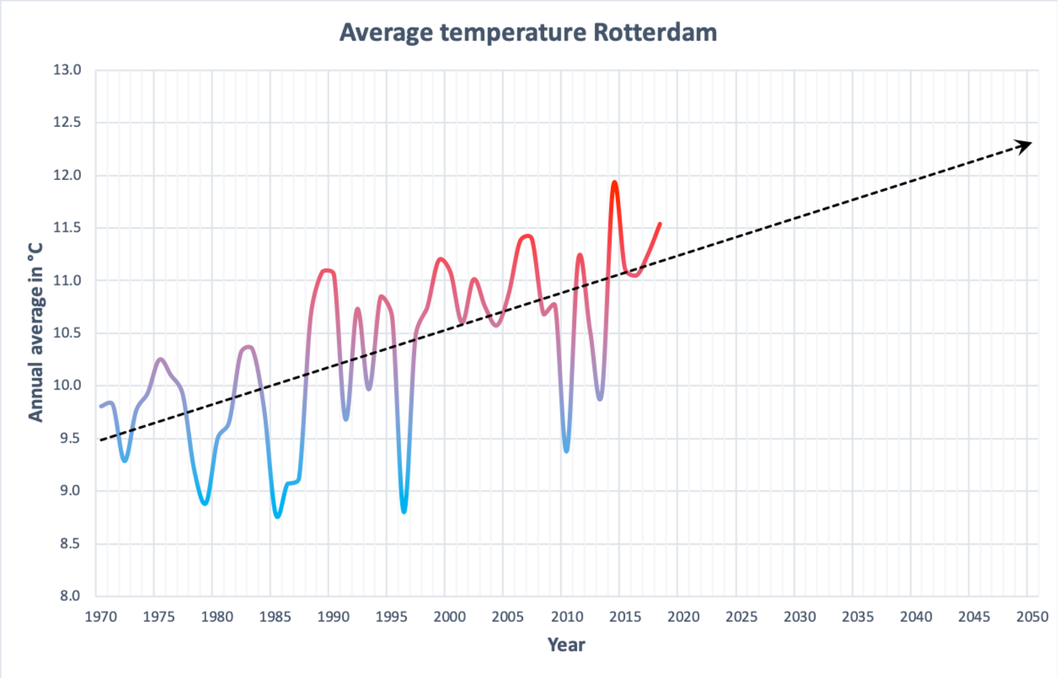


Figure 2 1970-2050 temperature range Rotterdam (Data: kwa.nl)

More significant for this research is the amount of heating and cooling that is needed by 2050. The data that is used to plot Figure 2 is provided by KWA, a consultancy that provides companies with technical advice on many aspects including sustainability (KWA Bedrijfsadviseurs, 2019). When companies invest money to improve their sustainability, they need a way to measure the progress. This progress however is hard to track as the year by year fluctuations in the weather prevent clear measurement. Therefore a way of accurately measuring the HVAC load during a period was developed. ‘Heating degree days’ (HDD) are used to measure the load on the heating by stating that below 18 °C the heating is activated. When the average day temperature is 12 °C that day counts as (18-12) 6 HDD. Similarly, there are ‘cooling degree days’ (CDD) that measure the degrees above 18. Using this technique, it is possible to represent the load on HVAC systems for a given year.

In Figure 3 the data extracted from KWA is plotted per year including a trendline extended to 2050 to make a prediction. Concerning HDD the trendline shows a decrease of about 11 HDD per year. Notice that the average amount of HDD in 1970 was 3200. Currently the average number of HDD is 2650 and when this trendline is followed it is expected that by 2050 the average has dropped to 2300, a decrease of 15%. The cooling however shows an increase from 110 CDD in 2019 to an expected 150 by 2050, an increase of 35%.

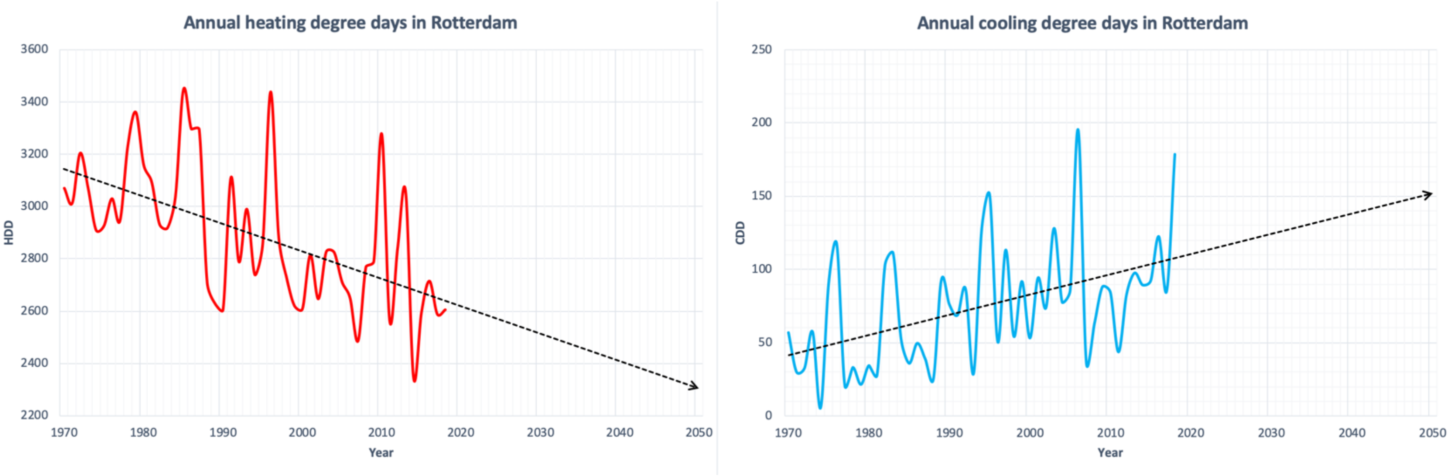


Figure 3 HDD & CDD in Rotterdam 1970-2050 (data: kwa.nl)

2.3 *Climate goals*

The TUDelft has set ambitious targets for its future energy use, namely;

- 2020: 40% primary energy saving (in comparison to 2005)
- 2020: 25% sustainable energy generation
- 2020: 50% reduction in CO_2 emissions (in comparison to 2005)
- 2040: no more gas-fired heating on campus (from 2035 onwards)
- 2040: fully energy neutral campus as far as energy provision is concerned

To achieve these goals there have been a number of changes to the campus. A contract was signed with Eneco, a Dutch energy producer, to deliver wind energy to the campus. On many of the campus' buildings a PV installation or photovoltaic system has been installed with a total capacity of 1,1 MW. In the coming decade the priority lies with demolition of older buildings to establish new, energy-efficient buildings. (TU Delft, n.d.)

2.4 *Energy production*

To reduce the CO_2-emissions of the campus a combined heat and power plant (CHP) was installed in 2011. Part of the heat demand of the faculties is supplied by this CHP via an underground heat network. The plant has a power output of 4 MWth (Megawatt thermal) and 4MWe (Megawatt electrical). A CHP uses superheated steam to power a generator just as an ordinary power plant does. After powering the generator, the partially cooled steam, sometimes referred to as 'waste heat' is used to heat buildings and produce DHW. This CHP delivers about 30% of the universities heat and electricity in an energy efficient way. For the same amount of energy conventional separate power production needs 60% more fuel. While operating a CHP is a step in the right direction the Executive Board has been planning ahead, these plans include the aforementioned geothermal well.

2.5 DAP-well

Since 2008 the Delft Aardwarmte Project Foundation (DAP) has been aiming to provide the TU Delft with a sustainable heat source by means of a geothermal well (Stichting DAP & TU Delft, 2019). Currently the Board of Delft University of Technology has made a decision-in-principle towards realising DAP-well. The university has taken over the project and is currently working on finalising the business case and administrative issues (TU Delft, 2019).

The well is planned to be drilled to 2300 meters depth. At this depth the expected aquifer temperature is 76 ºC which would give the power plant a thermal output of 14,5 MW. The expected duration of the project is comparable to most other geothermal projects, 30 years.

2.6 LT-ATES

A Low Temperature Aquifer Thermal Energy Storage uses the subsurface to store and recover thermal energy. During summertime groundwater (5-10 ºC) is extracted (Figure 4 flow 1) from the aquifer, this is used for cooling by extracting heat from the building. A heat exchanger is used in this process to prevent chemically complex groundwater from running through heating pipes.

Thereafter the slightly warmer water (15-20 ºC) is reinjected (flow 2) in another part of the reservoir/aquifer. Although no requirement, it is common that this reinjection takes place in the same layer. In wintertime the flow direction is reversed, water is pumped up from the warm reservoir (flow 4). At the surface a heat pump and heat exchanger increase the temperature to about 40-50 degrees Celsius to heat the building. When the warm water has given off its heat energy to its surroundings the heat pump lowers the pressure again, the water is cooled to 5-10 ºC and reinjected (flow 3).

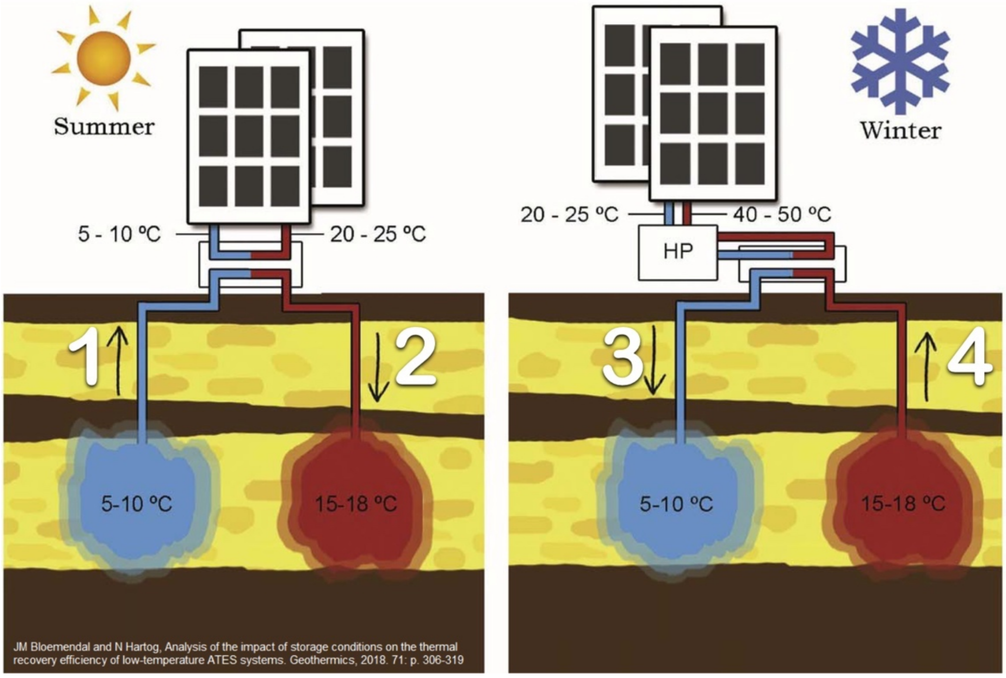


Figure 4 low temperature ATES system (source: (Bloemendal & Hartog, 2016)

3 Results

To operate a LT-ATES system successfully a number of requirements have to be met. A suitable aquifer has to be found, enough heat and cold have to be produced to meet demands, existing HVAC infrastructure has to be modified to operate under new circumstances.

3.1.1 Energy demand

As of today, the heat demand on campus is the sum of gas consumption and heat produced by CHP, that totals at 45 GWh. Cooling demand is derived from that consuming 2 GWh. Correcting for the expected HDD and CDD in 2050 these will respectively be 39 GWh and 3 GWh. An ATES system is designed to be able to supply heat or cold during peak demands. To estimate peak loads the 2016 data also used in designing the geothermal well is consulted. Total heat consumption that year was 169 Terajoules which converts to 47 GWh. Peak demand occurs on Monday the 18th of January at from 09:00 to 10:00 (TU, 2017). That hour 26,4 MWh is consumed, multiplied by 0,83 (factor 2016 -> 2050 = 39/47) the expected hour-peak load on the ATES system is 22MWh. Calculating the day-peak load the same way results in a 365 MWh demand or an hourly average of 15,2 MWh. The peak in the morning keeps returning in the figures delivered by TUDelft and Stedin, probably because that is the moment everyone enters its office and turns on their radiators. When the faculties are more evenly heated it might be possible to prevent this hourly-peak from occurring. Therefore, reducing the load on the ATES-system.

3.1.2 Aquifer

To store two different temperatures a suitable reservoir has to be found under the campus. There needs to be an aquifer (high permeability) and an aquitard (low permeability) top layer at reasonable depth. In the Netherlands the average temperature gradient is 31,3ºC/km with a surface temperature of 10,1ºC (Bonté, Van Wees, & Verweij, 2012). This low-temperature ATES system will be storing water at a maximum of 25 ºC which narrows the searching depth to a few hundred meters. Under current legislation it is not allowed to store water at a higher temperature (Article 6.11b AMvB Bodemenergiesystemen) . REGIS II is a hydrogeological model that uses the lithological information from boreholes and additional hydrological data such as hydraulic heads and pumping tests (DINOloket, 2019). The REGIS II-model of the first 400 meters under the campus is shown in Figure 5 including the horizontal and vertical permeabilities, for the legend please check the appendix. The red rectangle marks the Maassluis formation's 'third sandy unit', from now on 'Msz3', with the following properties;

Depth of top	130m
Thickness	>55m
Lithology	sandy unit, mainly consisting of medium and coarse sands
Horizontal hydraulic conductivity	10 – 25 m/d (avg. 17,5m/d)
Transmissivity	500 – 1000 m^2/d

Table 3 Msz3 properties

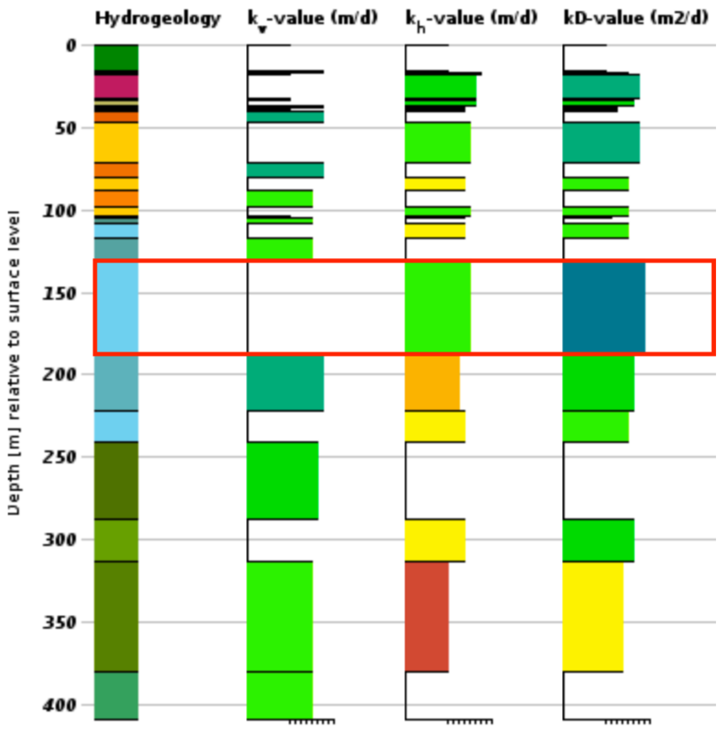


Figure 5 REGIS II hydrogeological model campus underground

On top of the ‘third sandy unit’ is the 13 m thick Maassluis formations ‘second clayey unit. This marine clay layer has a vertical hydraulic conductivity of 1-5 mm/d, preventing the injected water to mix with the groundwater above that layer. The Maassluis layer is suitable to store thermal energy, in the following paragraph borehole calculations are done.

3.1.3 Amount of wells

In paragraph 3.1.1 the peak power demand for one hour has been determined to be 15,2MW over the course of one day. The heat capacity of water is 0.00116 kWh/(kg*K) (USGS, 2019). The density of water at 10 ºC is 0,9997 kg/l and 0.99857 kg/l at 18 ºC, these differences are neglectable and density is assumed to be 1 kg/l from now on. When the water is stored at a temperature difference of 8ºC equation 2 follows;

$$Q_{max} = \frac{P_{max}}{Cp * \Delta T} = \frac{15,2\ MW}{0.00928\ \left(\frac{kWh}{l}\right)} = 1640\frac{m^3}{h} = 455\frac{l}{s} \tag{2}$$

The ATES-system needs to have a capacity of 1640 m^3 per hour. There is a maximum production rate a well can deliver, that depends on the permeability of the aquifer, the diameter and length of the screen. Equations 3 and 4 are needed to calculate the minimum screen area to produce or infiltrate;

$$V_{inflow} = 1000 * \left(\frac{k}{150}\right)^{0,6} \sqrt{\frac{v_{clog}}{2MFIu_{eq}}} \tag{3}$$

$$V_{extraction} = \frac{k}{12} \tag{4}$$

Paragraph 3.1.1 concludes that the heating demand exceeds the cooling demand. There will not be as much flow in flow 1 (Figure 4) as there will be in flow 3. That would result in the cold aquifer expanding every year and the warm reservoir not being replenished. To equal the amount of inflow and outflow, excess cold water needs to be siphoned to the warm reservoir during summertime. As this would cool the warm reservoir the siphoned water needs to be heated on its way, this will be dealt with in paragraph 3.1.6.

The variables in Eq.3 the following; [V_{inf}] is the flow velocity at the borehole wall in m/h; [k] is the permeability in m/d, between 10-25 for Msz3, averaged to 17,5 m/d from now on; [v_{clog}] is the clogging speed, assumed to be 0,1 m/j; [MFI] is the membrane filter index, assumed to be 2 and [u_{eq}] is the number of equivalent full load hours in h/year, which is 2600 (39GWh/15,2MWh) (Bodemenergie.nl, 2019). The borehole wall diameter is the result of dividing the flow rate by the V_{inf} or V_{ext}. The screen length is equal to the Msz3-layer thickness, 55 meters.

	V_{inf}	V_{ext}
Flow velocity borehole wall	**0,85 m/h**	1,45 m/h
Minimum area borehole wall	1929 m^2	1131 m^2
Minimum area / screen length	35 m	20,6 m

Table 4 infiltration and extraction rates

As the V_{inf} results in a bigger minimum area that figure is leading in determining the number of wells. (Schüppler, Fleuchaus, & Blum, 2019) describe an ATES-well with a diameter of 0,8 meter which is large compared to the usual 0,3m Bodemenergie.nl describes. Schüppler's system however operates at very shallow depths reducing the effect pressure has on the casing. The ATES system on TU Delft's campus will be one of the larger if not the largest system in the Netherlands and will need big wells. (Devon & EPA, n.d.) mention that pressure/casing diameter and casing thickness influence its strength and capability to resist pressure. To be on the safe side the well diameter of the TU ATES system will be 0,5m resulting in a circumference of 1,57 meter. The minimum number of wells after this calculation will be 35/1,57 = 23 wells.

The amount of water needed to store 39 GWh is 4,2 million m^3 at a ΔT of 8 ºC. Assuming a porosity of 0,33 the share of groundwater/soil would be 1/3 groundwater, 2/3 soil. The total infiltrated volume would become 4.200.000 m^3 / 0,33 = 12,6 million m^3. The Msz3 layer is 55 meters thick, the total area of the infiltration zone is 12,6M m^3 / 55 m = 229.000 m^2. Divided over 23 wells that would result in an area of 10.000 m^2 or a hydraulic radius of 56 m. The cylinder influenced by each well will have a volume of about 540.000 m^3

3.1.4 Hydraulic and thermal radius

When water of a different temperature is injected it transfers heat energy to the sand and water already present in the aquifer. As can be seen in Figure 6, the hydraulic radius expands further than the thermal radius and contains injected water that transferred its heat to its surroundings. Thermal radius ($R_{thermal}$) is defined as the maximum distance of the thermal front from the injection well, also known as the thermally affected area (Sommer, 2015). There are different methods to calculate the hydraulic and thermal radius of an injected aquifer, in this paragraph two will be highlighted;

With Bodemenergie's formula's (Eq. 5 & 6), when variables are unknown for the campus subsoil assumed variables by Bodemenergie are used as shown in Table 5;

Subsoil temperature	10	°C
Infiltration water temperature	18	°C
Temperature difference	8	°C
Volume of infiltrated water (Q)	183.000	m^3
Heat capacity water (C_w)	4,2	MJ / (m^3 K)
Heat capacity sand	1,65	MJ / (m^3 K)
Porosity (n)	0,33	-
Heat capacity aquifer (C_a)	2,5	MJ / (m^3 K)

Table 5 variables campus subsoil

$$R_{hydraulic} = \sqrt{\frac{Q}{nh\pi}} = 56{,}6m \qquad (5)$$

$$R_{thermal} = \sqrt{\frac{C_w Q}{C_a h \pi}} = 42{,}2m \tag{6}$$

Hartog & Bloemendal use the same formula to estimate the hydraulic radius, the thermal radius however can be approached; $0{,}66R_H = R_T$. Using the Hartog-approach the thermal radius would 37,4m.

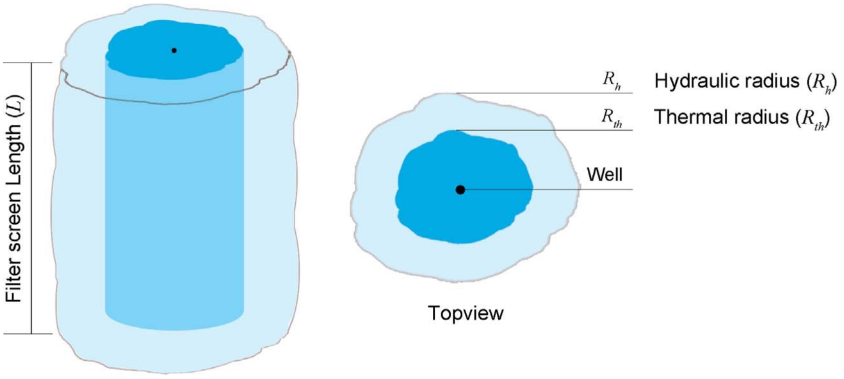


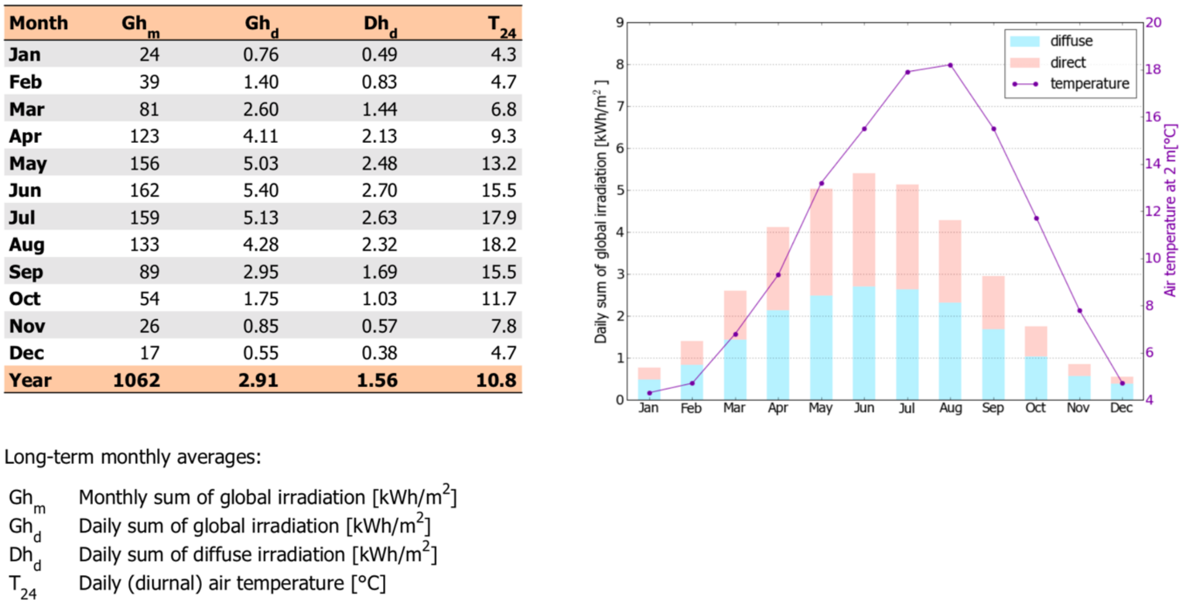
Figure 6 hydraulic and thermal radius (source: Bloemendal, Hartog)

3.1.5 Area to volume ratio

The efficiency of ATES systems depends on a lot of factors. (Bloemendal & Hartog, 2017) conclude that the ratio between area and volume (A/V) and ambient groundwater flow greatly affect the thermal efficiency. Figure 6 illustrates the shape of the influenced zone, the hydraulic radius always reaches further than the thermal radius. The contact-area of a cylinder with a base of 10.000 m^2 and height of 55 meters is 39.000 m^2, the A/V-ratio 0,072. With this ratio and an assumed groundwater flow of 0 m/y the expected efficiency can be up to 80% (Bloemendal, Hartog, 2017 figure 13). To compensate for this thermal energy loss in the aquifer the output of the system needs to be raised. By raising the ΔT from 8 to 10 ºC the amount of throughput can be maintained. The final input comes to 49GWh while the output stays 39GWh.

3.1.6 External heat supply

The cooling to heating ratio at TU Delft's campus is in no way balanced. The changing climate creates more cooling demand but there still is thirteen times more heating demand than cooling. To ensure a steady supply of warm water from the ATES system an additional heat source is desirable. A solar thermal collector heats water by absorbing sunlight. Solargis is a company that allows members to calculate solar radiation at desired locations. When simulated for Delft Figure 7 is the result. The daily global horizontal irradiation totals at 2,91 kWh/m^2 and the diffuse irradiation 1,56 kWh/m^2. Summed that is 4,47 kWh/m^2, annually 1630 kWh/m^2.



Month	Gh_m	Gh_d	Dh_d	T_{24}
Jan	24	0.76	0.49	4.3
Feb	39	1.40	0.83	4.7
Mar	81	2.60	1.44	6.8
Apr	123	4.11	2.13	9.3
May	156	5.03	2.48	13.2
Jun	162	5.40	2.70	15.5
Jul	159	5.13	2.63	17.9
Aug	133	4.28	2.32	18.2
Sep	89	2.95	1.69	15.5
Oct	54	1.75	1.03	11.7
Nov	26	0.85	0.57	7.8
Dec	17	0.55	0.38	4.7
Year	**1062**	**2.91**	**1.56**	**10.8**

Long-term monthly averages:

Gh_m	Monthly sum of global irradiation [kWh/m^2]
Gh_d	Daily sum of global irradiation [kWh/m^2]
Dh_d	Daily sum of diffuse irradiation [kWh/m^2]
T_{24}	Daily (diurnal) air temperature [°C]

Figure 7 Delft's solar irradiation (source: Solargis.info)

Low temperature solar thermal collectors can have efficiency's up to 80% (Fan et al., 2009). That would make the yield 1300 kWh/m^2 annually. To produce 46GWh a solar thermal collector field of 35.000 m^2 is needed. In Figure 8 the location of an empty field on the campus is highlighted. The area of this lot is 40.000 m^2 which would fit the solar thermal plant. Another option would be to fit all roofs of the campus buildings with collectors. The floor area of 570.000 m^2 divided by a guessed average of 6 to 7 floors totals the roof area at 70- to 90-thousand square meters.

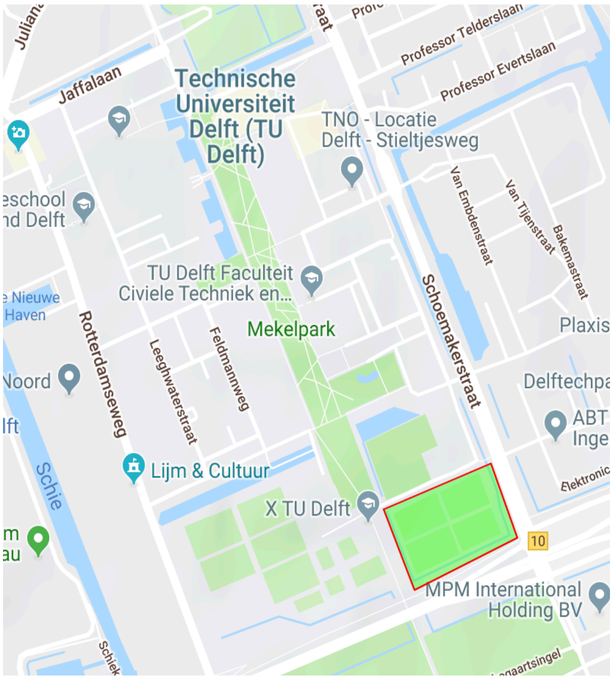


Figure 8 potential location collector-field

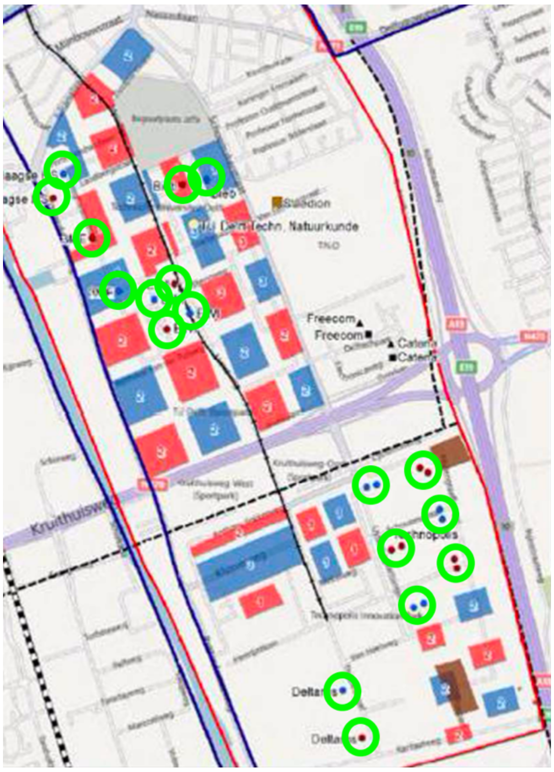


Figure 9 2018 location ATES-wells + well plan (Edited, original: Bloemendal, Jaxa-Rozen, & Olsthoorn, 2018)

3.1.7 Distance between wells and well-plan

There are a number of ATES-systems active on the campus, Figure 9 shows a map of the current campus with the active wells circled green. The blue and red areas are potential locations for thermal energy storage selected by Bloemendal et al.. When an ATES system is designed it is always required to take the (past) underground activity into account. It is however impossible to say how much of the campus underground is exploited by then.

The distance between two wells should be 2,25x the hydraulic radius or 3x the thermal radius (Bodemenergie.nl, 2019). The hydraulic radius per well has been determined to be 56,6 meters, the distance between wells should therefore be at least 130m. In Figure 10 two possible configurations are shown, the black bar on the right side represents 500 meters. Each well has a hydraulic radius of 56,6 meters, and therefore a diameter of 113,2m. The black edge around every red or blue circle represents is an extra 12,5% that should not touch the margin of another circle (112,5% + 112,5% = 2,25x). The lay-out on the left alternates between five cold wells and five warm wells in a north/south-direction. The left well-plan 23 warm and 23 cold wells. This could be a viable option when groundwater flow is in an east-west direction. The lay-out on the right concentrates the warm and cold wells with each other. The yellow box on top of the aquifers represents the location and size of the potential solar thermal collector field.

Figure 10 potential well-plan TU campus

3.1.8 Heat pump

It is impossible to heat a building with the 18 ºC water that is pumped up (Figure 4 / 4). A heat pump is needed to increase the temperature to about 45 ºC which is, after adjustment, sufficient to feed the central heating. These heat pump's consume energy, the rate at which they do is measured using a COP (Coefficient of Performance). When one unit of energy is put in to extract two units of heat from the water, the COP is 2. In Eq. 7 this is expressed, where h_h = heat produced and h_e = equivalent electric energy input (EngineeringToolbox, n.d.).

$$COP = \frac{h_h}{h_e} \tag{7}$$

The theoretical maximum achievable COP for a heating process is (Eq. 8) where T_h is the temperature of the hot side in K (Kelvin) and T_c the temperature of the cold side in K. The maximum COP is also known as the 'Carnot efficiency'.

$$COP_{heat} = \frac{T_h}{T_h - T_c} \tag{8}$$

In this case the hot side is preferred to be 45 ºC and the cold side is 18 ºC. Therefore, the maximum achievable COP_{heat} is 11,8. Return temperatures are expected to be 20 ºC and need to be cooled to 8 ºC. The achievable COP-formula is comparable (Eq. 9) and results in a COP_{cool} of 23,4.

$$COP_{cool} = \frac{T_c}{T_h - T_c} \tag{9}$$

Heat pump efficiencies have been modelled and tested. With Todorov's model a heat pump would be able to reach a COP of 6 using T_c =18 ºC and T_h = 45 ºC, about 50% of the Carnot efficiency (Todorov, 2018). The Global CCS Institute observed that the average COP of geothermal heat pumps linearly raised from 3 to 5 from 1990 to 2020, a 66% increase (Global CCS Institute, 2013). Assuming that these heat pumps keep being improved in another 30 years the COP of the campus heat pump can be up to 10. Using a slightly less optimistic number and assuming the heat pump has a COP of 9 by 2050, the electricity needed to transfer 39GWh of heat is 4,3 GWh of electricity.

3.1.9 Heat pump electricity

This 4,3GWh needs to be produced in an emission free manner to cope with the climate goals. A 2 MW (19/9 [MW/COP]) solar powerplant could be an option. In paragraph 3.1.6 an annual irradiation of 1630 kWh/m^2 is calculated. (Fraunhofer Institute, 2019) states that in labs efficiencies of up to 46% are achieved, it is reasonable to assume that these solar technologies are on the market by 2050. The total amount of square meters of photovoltaic panels would be 5.750 m^2. The problem with solar power is that when the production is the highest, daytime in summer, the heat pump is most likely not active. The electricity is needed in wintertime. By that time there might be a way to store this energy as well but that is outside the scope of this research.

3.1.10 Costs

The total capacity of power of the ATES system will be 19MW, the 15,2MW calculated in paragraph 3.1.1 increased to compensate for the efficiency of the system (15,2/0,8). The total power output of the solar thermal field will be 35 MW as it will almost never function at full load and only works during daytime. The solar installation to power the heat pump would have capacity of 2 MW. To estimate the costs a calculation model by KWA is consulted;

Installation	Investment costs per kW	Investment costs
Wells	€450	€8.550.000, -
Solar collector	€600	€21.000.000, -
Heat pump	€195	€3.705.000, -
Central heating adjustments	€50	€950.000, -
PV electricity	€750 (CO2CRC, 2017)	€1.500.00, -
		€35.705.000, -

Table 6 estimated costs LT-ATES system

The total costs of constructing the ATES-system are estimated to be approximately €36 million.

4 Conclusion

When the geothermal well would be terminated by 2050 the campus HVAC systems could be powered using a LT-ATES-system. When following the assumptions made in this study that would entail a 19 MW ATES system, annually moving 4,2M m^3 of water between 23 cold wells and 23 warm wells. The temperature difference between the reservoirs would be 10 °C making the total amount stored energy 176 TJ. To provide in additional heat a 35.000 m^2 solar thermal collector field needs to be constructed. Additionally, a 5750 m^2 field of solar panels can be constructed to power the heat pumps. There might however be options to produce this electricity in a more practical way.

5 Discussion and recommendations

There are of course numerous ways to approach a net-zero campus by 2050. Two other scenarios have been explored for this study. In future studies the these can be investigated more thoroughly;

5.1 Total rebuilding of campus

This approach focusses on lowering the campus energy use to a minimum. Instead of investing in ways to produce cleaner energy, the TU invests purely in reducing the consumption of its faculties. One great example of how this can be realised are the new net-zero buildings Pulse and Echo (under construction).

This implies that most of the current faculties will no longer be suitable as they are. The 2018 energy consumed totals 126 Terajoules (TJ) resulting in 17 $ktCO_2$ emissions (Campus Real Estate TU Delft, 2019). The average energy consumed per square meter by HVAC at TUDelft its faculties is equivalent to 13,4 m^3 of gas. According to the EIB (Dutch Economic Institute for Building) that would place the campus at energy label [D] on a scale from [G – most polluting] to [A++++ - least polluting] (EIB, 2016). When an office building uses less than 6 (m^3/m^2y) it is, among other requirements, categorized as an energy-label [A] building (ECN & CBS, 2017). For this approach however it is crucial to lower the amount of energy used to a minimum. In this case the coming 31 years the faculties need to be rebuild one by one to a standard comparable to Pulse and Echo. Pulse is equipped with several types of equipment that contribute to its energy-neutrality. On its roof lie 750 m^2 of solar panels with an annual yield of 150 MWh, it is fitted with super insulating glass and an ATES system.

Over a period of 30 years a total of 500.900 m^2 needs to be reconstructed. Numbers on the total construction costs of either Pulse or TNW are not publicly available so it is difficult to give a €/m^2. The RVO (Netherlands Enterprise Agency) published a study on the construction costs of six energy-neutral schools in the Netherlands (AHB consultancy & RVO, 2014). The total expenditure of constructing a high school probably is lower than that of academic buildings. The vast number of square meters that need to be constructed does mean that the TU can benefit from economies of scale. Expensive academic equipment is already part of the inventory and will not add to this price. Therefore, the best estimate of the price in euro per square meter is was €2.060, -/m^2 as stated by RVO. The rebuild of 500.900 m^2 campus to completely energy-neutral is guessed at over a billion euro.

5.2 Partial rebuilding of campus

The TU is currently rebuilding parts of its campus corresponding with its campus vision (CRE TU Delft, 2019b). TNW (#58) is a new faculty with a net-zero energy use. Over the years the TU will replace its faculties that consume the most. When, for instance, the boundary is put at 100 kWh per m^2 per year. Faculties that consume more energy than this number can be replaced. That will entail buildings numbers; 5, 15, 21, 22, 26, 34, 37, 38, 61 and 64. As plans to replace EWI (#36) are already in an advanced stage (Van Uffelen & Delta, 2018) this building is also assumed to be rebuild despite its consumption of 62 kWh/m^2year. Building #50, Reactor Institute Delft, will in all probability not be rebuild. In the calculations for this scenario the energy consumption by building 50 will only be adjusted for climate change.

The total floor area of the faculties that will be replaced is 225.900 m^2 or about 40% of the total campus. For the remainder of the buildings a 10% efficiency improvement can be added to the 2050 scenario. The EIA (US Energy Information Association) researched that educational buildings reduced their total energy use by about 10% over a period of 10 years (EIA, 2012). It can be assumed that over the coming 30 years a comparable improvement can be achieved with little effort. These newly build faculties are likely to be fitted with ATES systems as Pulse and Echo are. This would make the ATES system less centralised than the system proposed in this study. It can be investigated whether the original, non-reconstructed, faculties can be connected to a main, centralised, ATES-system.

This study focusses on a case 31 years from now in an industry that is subject to huge developments. It is therefore hard to make an actual prediction of the techniques by 2050. If the implementation of an LT-ATES-system is considered by TU Delft or another consumer it is possible that assumptions appear to be inaccurate.

It is expected that with improving isolation, heat produced by computers, desktops and humans will contribute more to the temperature inside buildings. This effect has not been researched in this study and could add significant heat, decreasing the need for heating.

Some climate models of KNMI predict up to 6,5% more solar radiation by 2050. This is probably due to a decrease in cloud coverage. The yield of the thermal and photovoltaic panels is influenced by this increase.

In this study the ambient groundwater flow is assumed to be zero. If there is a flow direction, which is to be expected, this should be taken into account when drawing a well-plan to prevent warm and cold storage water mixing.

Temperature differences in the injected reservoirs are relatively low, up to a maximum of 10 °C. It has not been researched what influence buoyance flow has at these temperatures.

Energylabel A++++ is dependent on a lot of factors. In this study only the energy used for heating and cooling per m^2 is looked into. The improvement of this energy use does not mean the building is eligible for an A++++-label.

In this study the costs of actual energy have not been calculated, only the investment costs are considered. A reduction in energy use often means a lower energy bill. Operation and maintenance of an ATES-system are a yearly expense of 4% of the investment costs (KWA, 2018)

This study focuses on low-temperature ATES systems. The law states that ATES systems can store water to a maximum of 25 ºC (Article 6.11b AMvB Bodemenergiesystemen). It is plausible that this law is reviewed before 2050. A study on a high-temperature ATES system on campus is done by T. Hacking ('The Suitability of a High Temperature Aquifer Thermal Energy Storage on the TU-Delft Campus', 2017).

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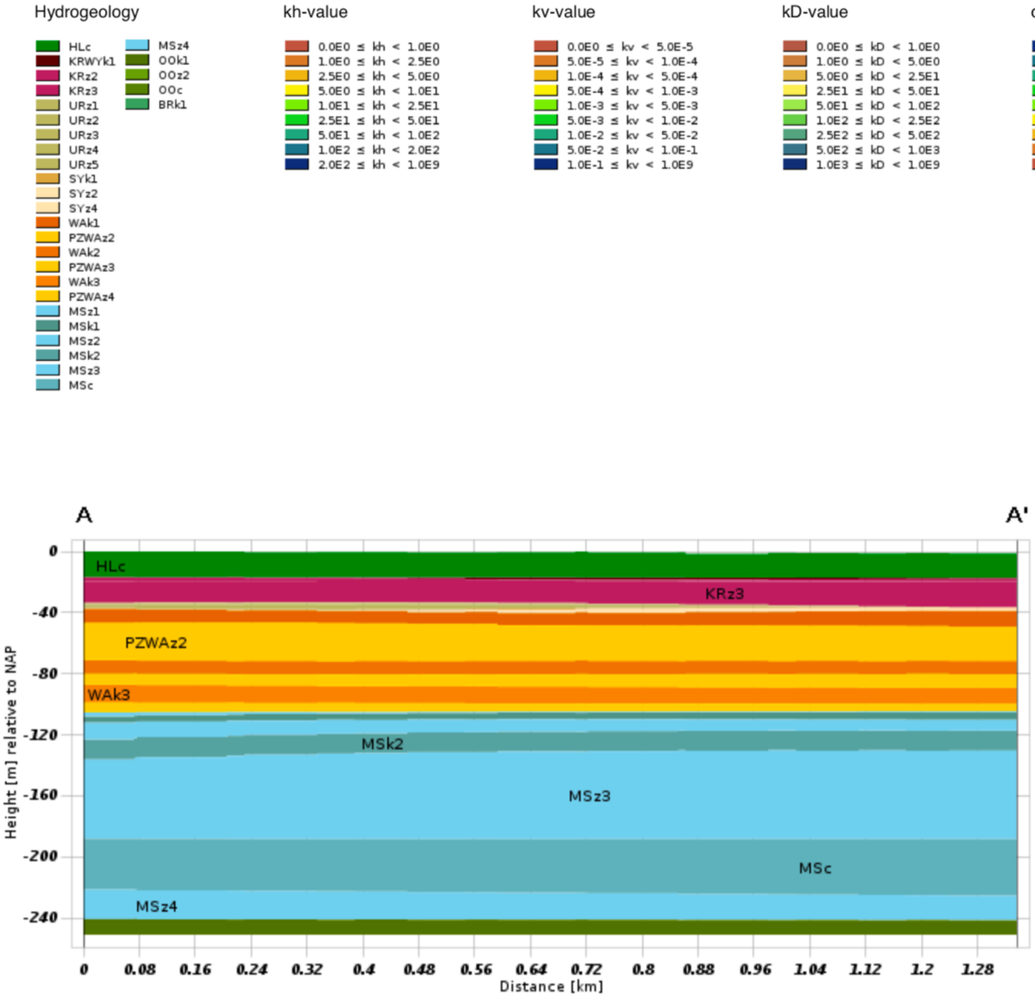
Appendix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KRz3
URz1
URz2
URz3
URz4
URz5
SYk1
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WAk1
PZWAz2
WAk2
PZWAz3
WAk3
PZWAz4
MSz1
MSk1
MSz2
MSk2
MSz3
MSc
MSz4
OOk1
OOz2
OOc
BRk1
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2.5E0 ≤ kh < 5.0E0
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1.0E3 ≤ kD < 1.0E9
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1.0E2 ≤ c < 5.0E2
5.0E2 ≤ c < 1.0E3
1.0E3 ≤ c < 5.0E3
5.0E3 ≤ c < 1.0E4
1.0E4 ≤ c < 1.0E5
1.0E5 ≤ c < 1.0E6
1.0E6 ≤ c < 1.0E9
A
A'
HLc
KRz3
PZWAz2
WAk3
MSk2
MSz3
MSc
MSz4
Height [m] relative to NAP
0
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-80
-120
-160
-200
-240
0
0.08
0.16
0.24
0.32
0.4
0.48
0.56
0.64
0.72
0.8
0.88
0.96
1.04
1.12
1.2
1.28
Distance [km]


A
A'
hoemakersstraat
Kruithuisweg