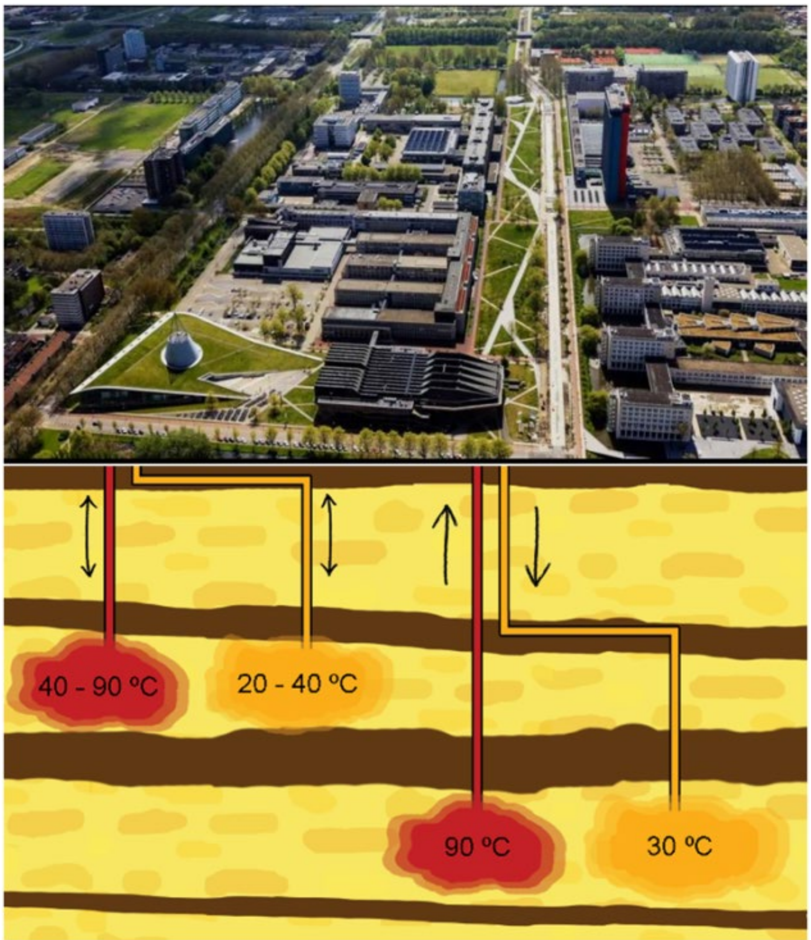
HT-ATES
at the TU Delft campus



TU Delft ENGIE

Feasibility study

HT-ATES at the TU Delft campus

Delft, October 2020

Delft University of Technology
ENGIE

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Executive Summary

The storage of heat from geothermal wells during the summer for use in the winter is an attractive option to increase the heat output from geothermal wells by increasing their full usage hours. To supply enough storage volume, storage in the subsurface, in aquifers, is the primary option. At present, the technology to do this is mature enough to carry out large-scale pilots, which can operate successfully, however careful monitoring is essential. It is also an opportunity to carry out further research and education on such systems, to answer applied scientific questions to enhance the state-of-the-art knowledge and engaged students will feed a developing industry with well-qualified personnel.

At TU Delft, a geothermal well (the DAPwell) is being developed, and this report has evaluated the potential to add a high-temperature aquifer thermal energy storage system (a so-called HT-ATES system) to the project. In addition, it is proposed to extend the city of Delft district heating network to the TU Delft campus to benefit from residual heat. Both of these scenarios have been evaluated in this report.

It is seen that adding an HT-ATES system to the DAPwell in all cases results in an improved NPV. Depending on the system setup, the improvement ranges from ~€5M to ~€9M. The SDE+ subsidy plays an important role here; exceeding subsidised heat supply limits results in a decreasing financial return. A substantial CO_2 saving can potentially be made, increasing with increased supply.

Summary table of financial performance and CO_2 reductions for the different scenarios assessed.

Cases	**NPV** *k€*		**CO_2 reduction** *tonnes/y*
	Maassluis	Ommelanden	
1 TUD (including DAPwell)	(11 801)	(11 801)	6 312
2 TUD + HT-ATES (Scenario 1)	(2 963)	(4 364)	11 235
3 TUD + City	1 992	1 992	15 149
4 TUD + City + HT-ATES (Scenario 2-I)	6 933	5 121	23 228

Two aquifers have been seen to be preferable to further develop technical solutions for (the Maassluis and the Ommelanden formations), however there are a further two aquifers which could be considered if needed. The Maassluis formation is at around 130-190m depth, whereas the Ommelanden is around 410-460m depth. The Maassluis is consequentially cheaper to install wells into, although has the highest chance of interfering with existing ATES systems in the Waalre formation above. The extents and properties of these formations can be further explored during the drilling of the DAPwell and associated monitoring wells.

HT-ATES systems can be allowed, but do not fit within the regular ATES policy, and therefore, have a route to obtain permits, as pilot projects. The location of TU Delft campus, ensures easy access for researchers to monitor in detail the operation, and will generate knowledge able to be used in the Netherlands and beyond.

An HT-ATES system offers additional advantages which have not been quantified in this report. For example, it can offer back-up heat production for planned or un-planned maintenance on the DAPwell and it can provide additional heat production to obtain unused subsidy from previous years (up to a limit). However, such a system also increases the complexity of the heat system and has several unknowns due to the properties of the aquifers. Another advantage is that the combination of a well monitored and researched geothermal and HT-ATES system will be a world-wide unique research and educational facility and will bring international esteem.

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List of definitions & Acronyms

ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BUM	Besluitvorming Uitvoerings Methode
CAPEX	Capital expenditure
CEG	Faculty of Civil Engineering and Geosciences
CHP	Combined heat and power plant
CRE	Campus Real Estate
DAPwell	TU Delft campus geothermal well
DHN	District heating network
DHW	Domestic hot water
DTS	Distributed temperature sensing
ESP	Electrical submersible pump
GHGs	Greenhouse gas emissions
GTD	GeoThermie Delft, the company owning and operating DAPwell
HT	High temperature
IEA	International Energy Agency
LT	Low temperature
OPEX	Operational expenditure
P50	50^{th} percentile
TNW	Faculty of Applied Sciences
TUD	Delft University of Technology / TU Delft

1 Rationale and goal

1.1 Large scale storage to optimally utilise DAPwell

To meet greenhouse gas emission reduction goals, it is key to decarbonise the heating and cooling demand of buildings, as heating and cooling makes up around 50% of the total energy consumption (e.g. de Jong, 2016). As heat can only be transported over relatively short distances, local solutions need to be found to provide space heating and cooling (Hoogervorst, 2017; Ministry of Economic Affairs, 2016). In moderate climates and industrialised areas both heating and cooling capacity is abundantly available, however there is generally a mismatch in time between availability and demand. Heat demand has a larger seasonal demand variation than electricity.

In Figure 1 (Hartog et al., 2017), the mismatch between heat supply and demand is demonstrated. Storage facilities can be used to overcome those discrepancies in time, which can be at individual building level as well as larger scale (e.g. Figure 1 shows the excess heat and excess demand can be balanced). There are various options for heat storage, but considering the required capacity and cost, aquifer thermal energy storage (ATES) is by far the cheapest and most feasible technology in areas where sandy layers with groundwater exist (IEA et al., 2013)[1]. Recent research showed that in the Dutch energy system without using gas, about 75% of the required heating and cooling needs to come from the subsurface (Naber et al., 2016), using both geothermal heat production as well as heat storage and recovery from the subsurface. With the construction of the geothermal well on the TU Delft campus (known as the DAPwell), TU Delft is building a research and operational geothermal projects, with a target of contributing to the widespread safe and efficient adoption of geothermal energy. However, also the DAPwell operation and business case can be optimised using inter-seasonal storage, by allowing the utilisation of the (excess) heat produced in summer during peak demand in winter.

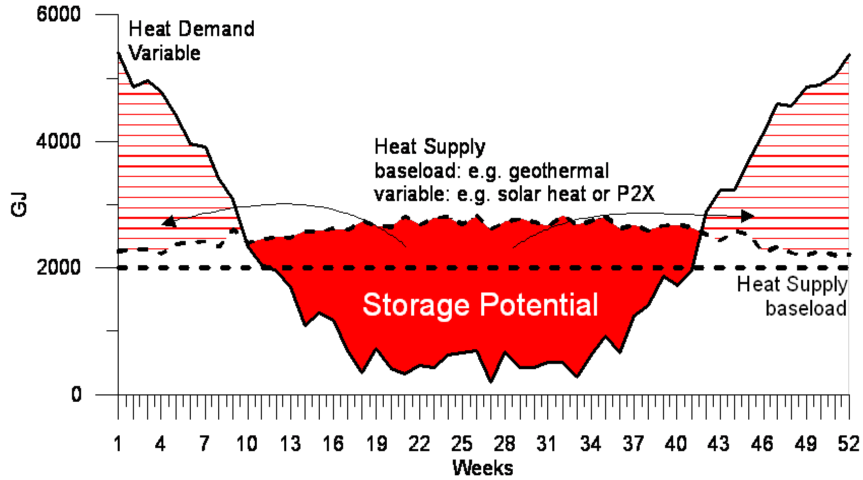


Figure 1: Example of waste heat and variable heat utilisation with heat storage (Hartog et al., 2016).

[1] Recently, NUON installed an €8M 'thermos' with a capacity of 20.000 m^3, enough to cover 2 days of heat delivery as a part of the Amsterdam district heating grid (Stam, S., 2016). A basic subsurface geothermal storage system, costing about €0.5M could utilise around 500.000 m^3 of storage space, with an additional advantage that such storage is in the subsurface and therefore, it is hidden from view and allows the use of valuable surface space another purpose.

1.2 TU Delft campus for research and development of geothermal energy

With research groups within the faculties of Architecture and the Built Environment, Civil Engineering and Geosciences, Electrical Engineering, Mathematics and Computer Sciences, and Mechanical Maritime and Materials Engineering and Technology Policy and Management TU Delft is the only research institute in the Netherlands to cover all fields required for the development and operation of heating and cooling systems in the built environment. This is currently coordinated in a TU Delft-wide platform called Thermo-X (https://www.tudelft.nl/thermo-x/).

Geothermal energy is one of the key technologies that will be used in the heat transition and beyond. Of the different geothermal technologies (Figure 2), each requires several fundamental research activities to allow and support the safe and efficient large scale and sustainable scale-up of the utilisation of subsurface resources. Therefore, a strategic theme / expertise centre exists and is under further development within the faculty of Civil Engineering and Geosciences (CEG).

HT-ATES is one of these technologies requiring considerable investigation and development before widespread adoption. However, in principle, all aspects are similar to low-temperature ATES and a small number of pilot projects have been or are being implemented. Therefore, a well-monitored HT-ATES pilot/research well will boost research and education on geothermal energy at TU Delft. In addition, this will be one of the first combinations of geothermal heat production with seasonal storage using ATES in the world, and including the envisioned monitoring and research of both systems, this will be a unique site in the world. The planned drilling of the DAPwell and surrounding monitoring wells offers a window of opportunity for sampling/coring of potential suitable formations for HT-ATES which are not yet well known.

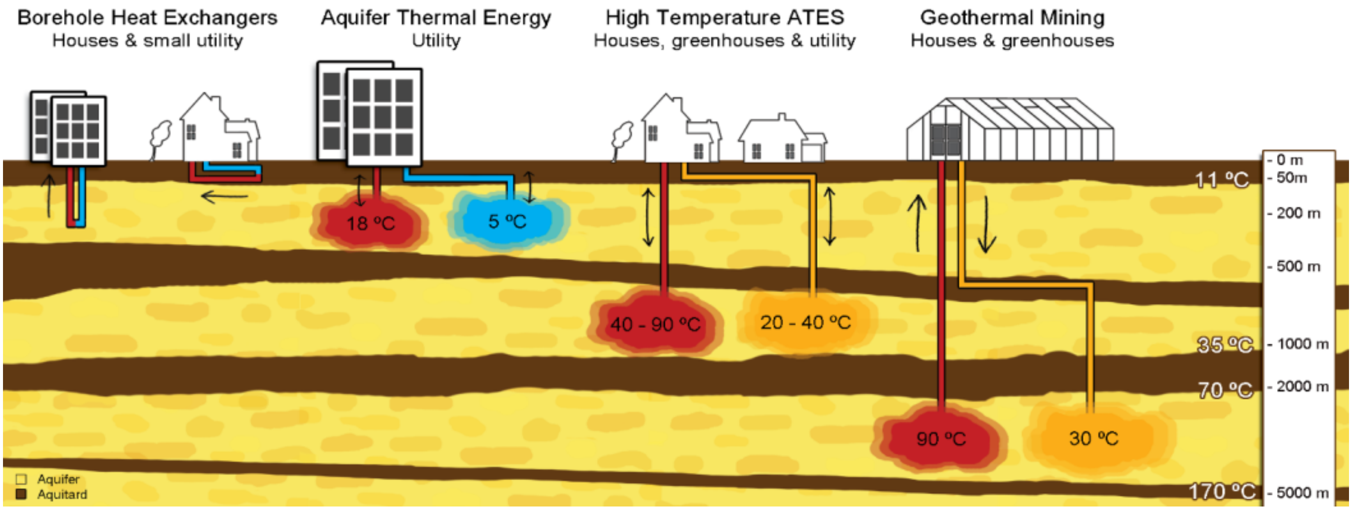


Figure 2: Overview of different geothermal technologies as applied in The Netherlands and the subject of research and education at TU Delft.

1.3 HT-ATES

In moderate climates such as found in the Netherlands, during winter months there is a large heat demand, while in the summer months there is a net heat surplus. During the summer months excess energy is available, e.g. from wind, solar, cooling, geothermal energy or residual heat from industries. There is a considerably greater seasonal mismatch in thermal energy than for electricity. To not let the excess thermal energy go to waste, this heat can be stored and used in the winter months where there is demand for this heat. Aquifers provide space to store large amounts of heat in systems called aquifer thermal energy storage (ATES) systems. ATES systems are commonly applied in the Netherlands, with over 2 700 systems installed, and are typically installed in buildings with a cooling demand in the summer and a heating demand in the winter.

The general principle of ATES systems is that excess energy is stored as thermal energy in the groundwater, i.e. by increasing the temperature of the groundwater. The excess energy is mostly available in summer months where heat demand is low. When the heat demand is high, mostly in the winter months the heat extracted and used. Storage temperatures vary depending on project-specific heat supply and demand, but for commonly applied ATES systems are limited by permitting to a maximum of 25°C.

For geothermal systems (and several other sources of excess heat) a higher temperature is required to be stored (and is more efficient), these systems are known as high-temperature (HT)-ATES systems (e.g. Kallesøe and Vangkilde-Pedersen, 2019; Drijver et al., 2019). Temperatures vary by project, but are limited by the temperature at which the water would be liquid. At the present time, provinces are granting pilot licences for projects, to test the wider applicability (SIKB, 2015).

1.3.1 Advantages and disadvantages of HT-ATES

There are several potential advantages of HT-ATES systems but also potential disadvantages. Table 1 gives an overview of these pro and cons.

Table 1: Overview of advantages and disadvantages of HT-ATES systems.

Advantages	Disadvantages
Reduction of energy cost	Possible impact on groundwater quality
Positive climate effect (reduction of CO_2 emissions)	Feasible only for large capacity storage
Little space needed at the surface	Feasible only for certain energy systems
Efficient use of heat sources	

1.4 Goal of this report

An HT-ATES system at the campus could provide both a demonstration of this technology integrated in a heat network with a geothermal well, as well as a site for fundamental research to answer key outstanding questions which need to be answered for development of this novel technology. The approach is to use the organisation of the DAPwell as an example, where there are operational and research programmes associated with the same system.

The goal of this study is to evaluate whether it would be feasible to have a HT-ATES system on the TU Delft campus, and to provisionally estimate under what conditions this could take place. An evaluation of the current design and operational conditions of the DAPwell, the potential subsurface formations which could be used for HT-ATES, the potential thermal changes in the subsurface, the business case and potential scientific activities will be undertaken. The current plans of the geothermal well (June 2020), and subsurface properties available in literature form limits to the scope of this work. These would be several implementation challenges, including integration in the TU Delft heating system, which have been addressed here in a limited manner, and would require further detailing.

1.5 Consortium TU Delft - ENGIE

This study has been carried out by TU Delft and ENGIE. Following a series of exploratory meetings held between Delft University of Technology (TU Delft) and ENGIE Energy Solutions (ENGIE), it was agreed to work together on HT-ATES systems, with a focus on a pilot project on the TU Delft campus. The collaboration between ENGIE and TU Delft brings together two established partners, with substantial and mutually beneficial expertise and experience. Specifically, ENGIE has substantial practical/applied experience in ATES projects and sustainable district heating, including project management, economics, engineering, building and exploiting such systems. ENGIE has involvement in many international and national projects and is able to benchmark projects and should be able to rapidly implement research findings and provide solutions to society. TU Delft is a strong knowledge partner for knowledge of the subsurface and has a strong research track record straddling the scientific and applied arenas. TU Delft focuses on investigating and understanding fundamental processes and mechanisms occurring and applies them to practical applications; this often results in computational tools informed by experimental activities. TU Delft has an existing heat grid and is planning a geothermal well and therefore offers a realistic case study. Due to the substantial heat and cooling demand and complexity of the current and future energy system, TU Delft is also a potential customer for several of ENGIE's services.

2 Technical Feasibility I: Heat demand and availability

In this chapter, the first part of the technical feasibility is presented: the current and future demand and availability of heat at the TU Delft campus and Delft city. Two scenarios are evaluated, which represent a different composition of consumers, connected to the TU Delft district heating network:

- Scenario 1: Heat is only delivered to TU Delft.
- Scenario 2: Heat is delivered to TU Delft (TUD) and the city of Delft (city).

A HT-ATES system is beneficial when there is a seasonal mismatch in availability and demand for heat. Therefore, both demand for heat (Section 2.1), the heating network which distributes available heat (Section 2.2) and the availability of heat sources (Section 2.3) are evaluated, followed by an evaluation of the need for storage (Section 2.4).

All values here are estimations made for feasibility purposes and no rights can be claimed with respect to contractual agreements.

2.1 Demand for heat

2.1.1 TU Delft heat demand

About 27 000 people work on the TU Delft campus every day: students, scientists, visitors, and employees of the university and the companies on campus. The heating of the majority of the buildings used by these people is delivered from the central production plant via boilers and a combined heat and power plant (CHP). The DAPwell will connect to the current heat distribution network from this location. The district heating network (DHN) stretches out around the campus in four branches, as shown in Figure 3. Due to the high quality of insulation, limited network length, the large average building size and subsurface concrete ducts in which the pipes are installed, the heat losses in the heat network are limited to a maximum of 10%**.**

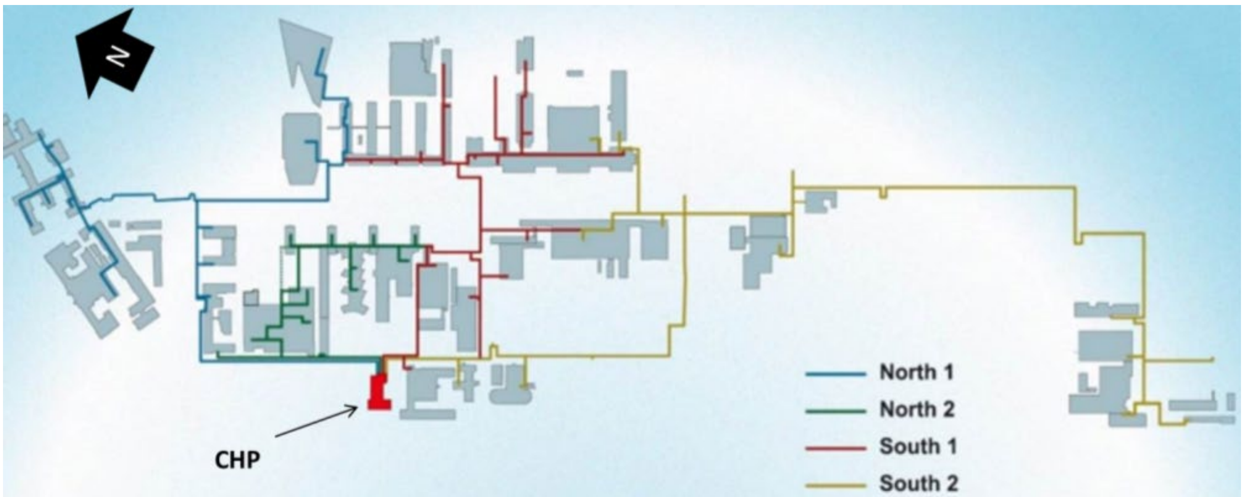


Figure 3. Overview of the district heating network tracks at the TU Delft campus, including the combined heat and power plant (CHP) location.

There are various developments planned for the TU Delft campus, including the expansion of the campus with new buildings and renovation of existing buildings. Some of the new buildings will be connected to the existing heat network of TU Delft. This implies an increase of the heat demand of the campus. In addition, existing buildings that are located on the campus but are not property of TU Delft (e.g. inHolland and the student housing of DUWO) are planned to be connected to the heat network of TU Delft (the so-called track 5 development). On the other hand, there are plans to improve the insulation of the existing buildings which will decrease the peak load and total energy demand. For this study, it is assumed that these two developments will cancel each other out and the current energy use of TU Delft is representative for the future heat demand. This is thought to be a conservative estimate, as the total energy demand is more likely to increase. However, this must be evaluated in more detail in future studies.

The total heat demand of TU Delft has been derived from measured hourly demand and translated to an average expected energy use for a reference year (NEN5060), reflecting average heating demand. The result of this analysis is presented in Figure 4. The following key points are noted (Techniplan, 2020; Medema, 2020):

- During the months July and August, the heating system is switched off. There is no heat demand in these two months.
- The current working temperatures of the TU Delft DHN are supply of 130 - 110 °C depending on demand, and a return of approximately 70 °C. During the summer of 2020, various changes have been implemented allowing supply temperatures of 90 - 75 °C and target return temperatures of 55 °C which is compatible with temperatures from the DAPwell delivering heat to the TU Delft DHN. The higher input temperature is needed during negative external temperatures.
- The total heat demand of the TU Delft campus (for both scenarios) is **200 TJ/y**. This includes a 10% heat loss in the heat distribution network.
- The maximum required capacity is **27 MW** (which is predicted to grow to 35 MW when track 5 is connected). CRE is considering peak shaving strategies in the buildings that will reduce the peak capacity and peak boilers (Stoelinga, 2016), and as a consequence will increase the (potential) supply from the HT-ATES. Hence, the business case will further improve with these peak shaving strategies in place.

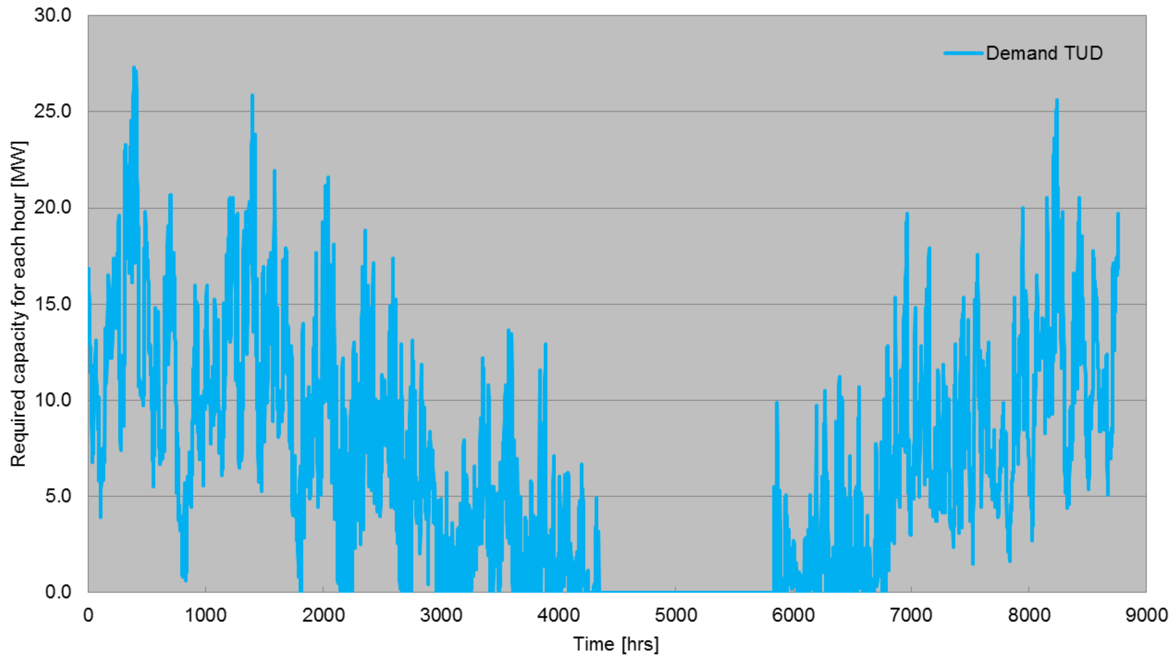


Figure 4: Current demand profile of the TU Delft campus (excluding the planned track 5).

2.1.2 City of Delft heat demand

TU Delft and the municipality of Delft signed an agreement that the city will use residual heat from the TU Delft campus supply. Delivery of residual heat from the TU Delft campus to the city of Delft will take place when a city DHN is installed. The expected starting date of heat delivery at the city DHN is the end of 2023. It is possible that it will take some years before this is the case, however it could also be developed at the same time as the DAPwell. In Scenario 2, it is assumed that the heat will be delivered to the city via a supply and return temperature of about 55/35 °C because only new, well insulated buildings will be connected. The minimum and maximum capacity of the transport line to the city is assumed to be 5 and 25 MW respectively. The demand profiles of the city of Delft will differ from the TU Delft campus as a result of the following differences:

- The TU Delft campus mostly contains office buildings while Delft city is mostly residential.
- For residential areas there is a baseload (continuous demand) required for Domestic Hot Water (DHW), sanitation and cooking, which is a significant fraction (40 – 50%) of the total heat demand in new buildings.
- Peak demands are in the evenings and weekend for newly built residential areas, while in office buildings this is in the morning and during weekdays.

These differences in demand profile result in the fact that the residual heat of the TU Delft campus cannot always be immediately discharged to Delft city and a short-term storage of the residual heat is needed at the return flow from the TU Delft campus. Following the working conditions of the TU Delft DHN, it will be indicated within which ranges heat can be delivered to the city. The short-term storage at 55 °C temperature range is not considered in this study. This needs to be further specified following the expected heating demand of the city of Delft to be supplied.

2.2 Capacity and limitations of the DHN

The district heating network has the following characteristics (Techniplan, 2020):

- The maximum flow capacity is 855 m^3/h.
- The temperature range of the TU Delft DHN (after modifications in summer 2020) is a 90-75°C supply and 55-65°C return, depending on the external air temperature (see Figure 5).

The required supply temperatures in Figure 5 are worst-case as they are established from a capacity test in the network and worse-case return temperatures at different outside-air temperatures (Techniplan, 2020). These temperatures are likely to be lower in practice and are likely reduce when buildings are refurbished.

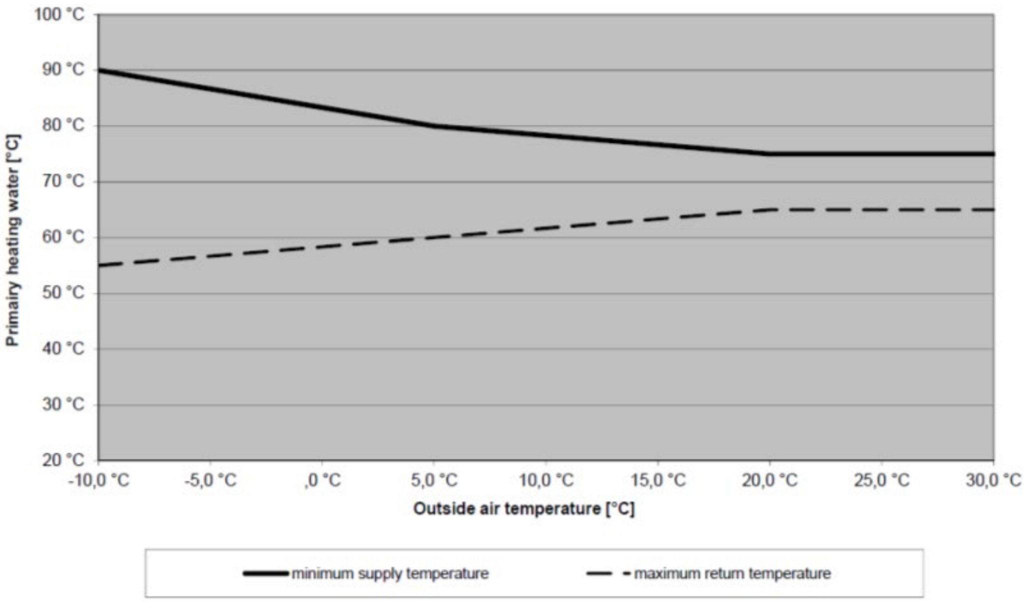


Figure 5. Worst-case supply and return temperatures required at different outside air temperatures in the TU Delft DHN (Techniplan, 2020).

2.3 Sources of Heat

2.3.1 Current heat producers: Boilers and CHP

The campus is equipped with a set of boilers and a CHP, which supply heat to the heating network of the campus. The CHP produces a baseload of the heat for the TU Delft campus, while natural gas fired boilers[2] supply the peaks. To reduce the CO_2 footprint of the campus, a new CHP unit was installed in 2011, consisting of two gas engines, with an electrical capacity of 4 MW and a thermal capacity of 4 MW. , i.e. when heat is required. They provide approximately 20% of the current TU Delft demand for electricity and almost 50% of the demand for heat. The total capacity of the boilers is about 65 MW. The capacity of the CHP is based on a temperature increase (ΔT) of 25°C of the flow provided to the CHP.

2.3.2 Geothermal well: DAPwell

The TU Delft campus geothermal wells or “Delft Aardwarmte Project” wells (DAPwell) will replace the CHP and boilers as the primary heat source for the campus district heating network and thus the main source to load an HT-ATES system. The DAPwell is planned to be drilled by the end 2021 and will deliver heat mid-2022. The well can produce heat during the whole year, with a

[2] Some buildings have their own gas fired boilers or a LT-ATES with a heat pump.

predicted maximum flow capacity of 320 m^3/h (P50 value), at an approximate temperature range of 75-55 °C in Scenario 1 and 75-35 °C in Scenario 2, resulting in a thermal capacity of 7.4 and 14.8 MW, respectively[3]. During low demand, heat production can be reduced, but not more than the minimum flow rate (80 m^3/h) designed for the DAPwell pumps.

Due to the required minimum 75 °C in the TU Delft DHN, a heat pump will be placed between the DAPwell and the DHN, which will increase the supply temperature to the DHN to about 82°C.

2.3.3 Total heat available

Table 2 shows the overview of the total capacity and amounts of heat available from the different sources.

Table 2: Overview availability of heat, approximate numbers, the numbers change for Scenario 2 because the ΔT of the heat delivery is increased by 20°C.

Property	Boiler		CHP		DAPwell		Heat pump	Unit
Scenario	*1*	*2*	*1*	*2*	*1*	*2*	1 & 2	
Production temperature	105	105	+25†	+25†	75	75	82	*°C*
Max. capacity	65	117*	4	4	7.4	14.8	2	*MW*
Min heat delivery	0	0	0	0	154	308	41	*TJ/y*
Max heat delivery	n.a*		125	125	235	470	63	*TJ/y*

†They add 25°C to any incoming temperature.
*in this study it is assumed no heat produced from gas is delivered to the city. This may change if the city DHN does not have any peak capacity source in their system, or that it is more (cost)effective that TU Delft supplies more than only their residual heat from the geothermal/HT-ATES plant. By lowering the return temperature as done in Scenario 2, the available is heat is better utilised and the actual power and heat available from the DAPwell and CHP and boiler is significantly increased.

2.4 Integration: match demand and availability of heat

2.4.1 Scenario 1: heat for TU Delft campus

To explore how HT-ATES can contribute to maximise the use of the geothermal well, the potential for heat storage is derived from the heat demand profile and DAPwell capacity. Figure 6 presents the hourly heat demand and geothermal heat production at maximum and minimum capacity, indicating the potential for storage. The HT-ATES system needs to store the heat that is not directly used by TU Delft and deliver this heat when the hourly heat demand exceeds the hourly heat production of the geothermal well. Please note that when only the DAPwell is used, it is only possible to directly use 100TJ/y or lower, because the DAPwell cannot quickly change pumping rate. As a result, DAPwell will only produce at maximum capacity during winter months and run at a lower constant flow during spring and autumn. However during these period there will still be 'peaks' exceeding the supply capacity at which the DAPwell is then running. Therefore, the higher amount (135 TJ/y), shown in Figure 6, can be directly used if an HT-ATES system is installed. This is because the DAPwell would not need to reduce pumping rates when the HT-ATES is in place as any excess heat supplied can be stored. These 'peaks' in time periods with a low overall demand could then be supplied directly, which is attributable to the installation of the HT-ATES system.

[3] The formation gas produced by the DAPwell as a by-product, will be injected in to the gas grid and is not considered an extra source of heat. If this changes, and the formation gas is directly used in the CHP or boiler the capacity and total heat availability increases with about 2 MW and 57 TJ, see Appendix I.

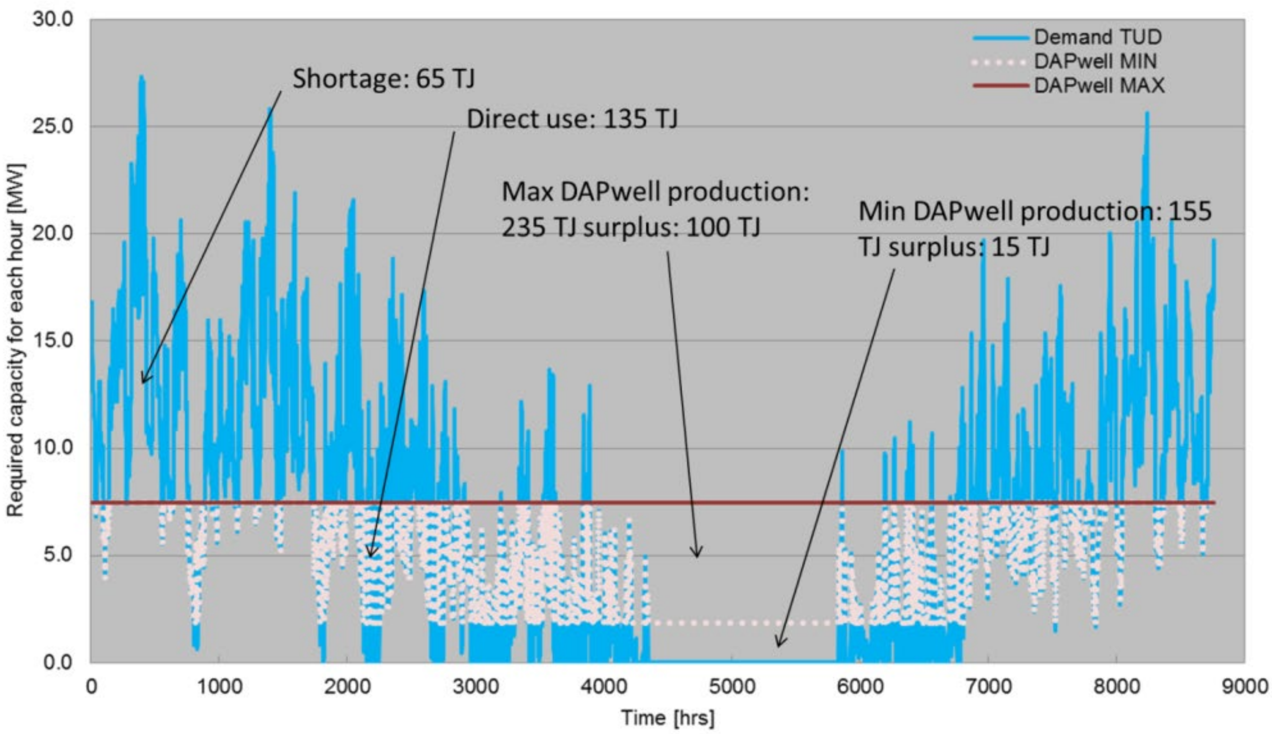


Figure 6: Heat demand campus and geothermal production (rounded numbers).

As seen in Figure 6, the maximum capacity missing during peak demand is about 20 MW. The total amount of heat the DAPwell cannot deliver (when heat demand exceeds the DAPwell capacity of 7.4 MW) is 65 TJ annually. Instead, surplus heat from the DAPwell during times of low heat demand can be stored and used during peak demand. Running the DAPwell at minimum and maximum capacity gives a produced surplus of 15 and 100 TJ, respectively. Taking account of heat losses in the HT-ATES system, the 100 TJ surplus has potential to substantially contribute to the missing 65 TJ. Note, that a summer shutdown period of 6 weeks is possible for the R&D programme of the DAPwell, which is not taken into account here.

Figure 7. Dominant heat flows and temperatures of the TU Delft campus heating system including the DAPwell with HT-ATESillustrates the different modes of operation in this scenario:

- **No heating demand (upper sub-figure):** In this mode of operation the HT-ATES is charged at full capacity.
- **Low heating demand (not shown):** In this mode of operation part of the DAPwell capacity is used to supply the heat demand of TU Delft and the remainder is used to charge the HT-ATES.
- **Medium heating demand (lower sub-figure):** In this mode of operation the geothermal well is delivering directly to the TU Delft campus at full capacity and the HT-ATES well is delivering at partial load to the campus.
- **Peak demand (lower sub-figure):** In this mode of operation both the geothermal well and the HT-ATES well are delivering heat at full capacity. And if needed also the CHP and boiler also supply any requiring capacity.

Preconditions for heat delivery:

- DAPwell production temperature is predicted to be 75 °C. When considering heat loss in the transport network and through the heat exchangers, it is assumed that both the heat pump and the hot well of the HT-ATES system are provided with a temperature of 73 °C.
- The HT-ATES system needs two wells, a hot well for storing heat produced in summer at 73 °C and a warm well at 60 °C. The expected return temperature of the DHN during heat delivery when the HT-ATES is also providing heat is expected to be 58°C or lower. Other arrangements are possible, including a heat pump immediately connected to the HT-ATES. This would have the effect of lowering the temperature of the warm well, reducing the return temperature to the DAPwell while charging and reduce the use of the boilers/CHP; however this would require a large flow rate heat pump, representing a large capital investment. The selected arrangement has been chosen as it is compatible with staged development towards Scenario 2. This should be further explored in next steps when this scenario is further elaborated/assessed.

These temperatures take account for a 2 °C change in temperature due to the use of heat exchangers.

During the summer when there is no heating demand, the HT-ATES capacity should be the same as the DAPwell to allow full capacity charging of the HT-ATES system, this is the minimum required capacity. This capacity is however not sufficient to also supply the peaks in winter, in order to meet the remaining 65 TJ. This would require an HT-ATES well capacity of about 20 MW, resulting in a much larger flow capacity of the HT-ATES system. The HT-ATES capacity can be enlarged by adding well capacity, however, more HT-ATES wells also cost more and every well added will have lower running hours, because the peaks occur less frequently.

Next to flow capacity of the wells, the capacity of the HT-ATES also depends on the ΔT between warm and hot wells during charging and heat delivery. Due to losses in the subsurface, the ΔT is

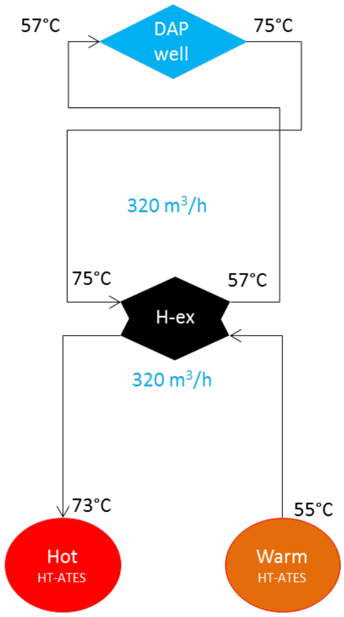
A) not the same during charging and discharging heat to/from the HT-ATES wells, and
B) not constant during the charging and discharging period.

Both HT-ATES wells will lose heat because the surrounding ambient groundwater temperature is about 12-20°C depending on depth of storage aquifer. Due to changes in density of the water, buoyancy flow will potentially result in larger losses in the hot wells. However, these can be limited by placing the warm wells around the hot wells. For the extraction temperatures of the HT-ATES wells, it is for now assumed that both wells have a cut-off at 10°C lower than the injection temperature. Following this assumption, the calculations are carried out using the expected average extraction temperature of 5°C lower than the injected temperature (see Chapter 4 for more details on this assumption). Resulting in an average operational ΔT of 8 °C during heat delivery from the HT-ATES and 18 °C during charging.

The presented modes of operation and associated temperature levels and flowrates are schematically provided in Figure 7. Due to the low ΔT during charging and discharging of the HT-ATES wells, the recovery efficiency could be low. To prevent this, a heat exchanger should be used that allows for different flow rates to be used simultaneously at both sides of the heat pump.

Please note that TU Delft considers a lower minimum direct use from the DAPwell (100TJ/y or lower), whereas here a higher amount can be directly used as excess heat supplied can be stored, so peaks in time periods with a low overall demand can be supplied directly. At the present time, no contractual agreements have been made.

Scenario 1: No heating demand (Charging of the HT-ATES)



Scenario 1: Heating demand

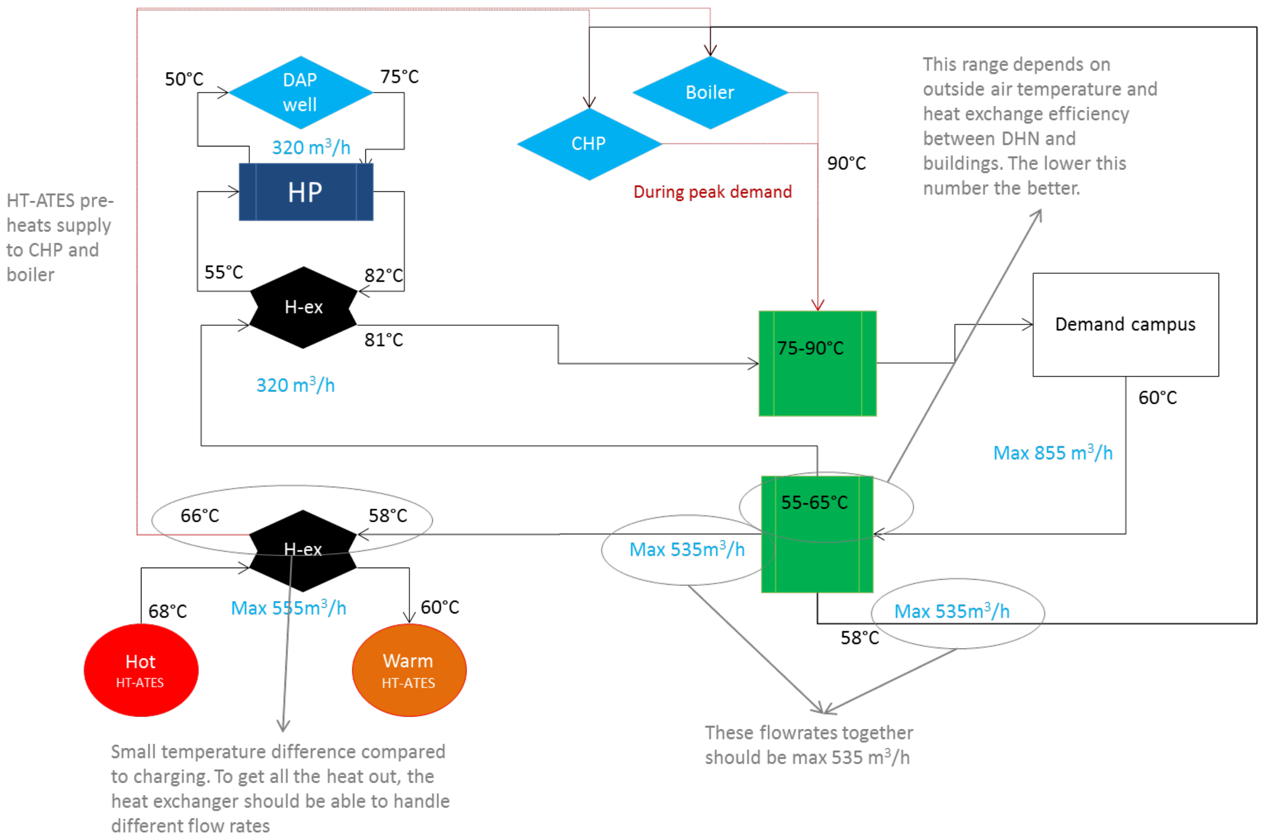


Figure 7. Dominant heat flows and temperatures of the TU Delft campus heating system including the DAPwell with HT-ATES.

Figure 8 shows the calculated relation between the HT-ATES thermal capacity and the required maximum flow rate of the HT-ATES wells together with the total amount of heat the HT-ATES can deliver. This shows that at the minimum flowrate installed for charging the HT-ATES (320 m^3/h), about 30 TJ can be supplied by the HT-ATES. Increasing HT-ATES capacity, strongly increases total heat contribution until about 10 MW. At 10 MW the required flow rate is about 1 000 m^3/h. Beyond this, the additional energy supplied reduces considerably because the largest peaks only occur very few hours per year. Table 3 shows the various options, also indicating estimate recovery efficiencies. Due to the large difference in storage and extraction ΔT the approximated recovery efficiencies are very poor.

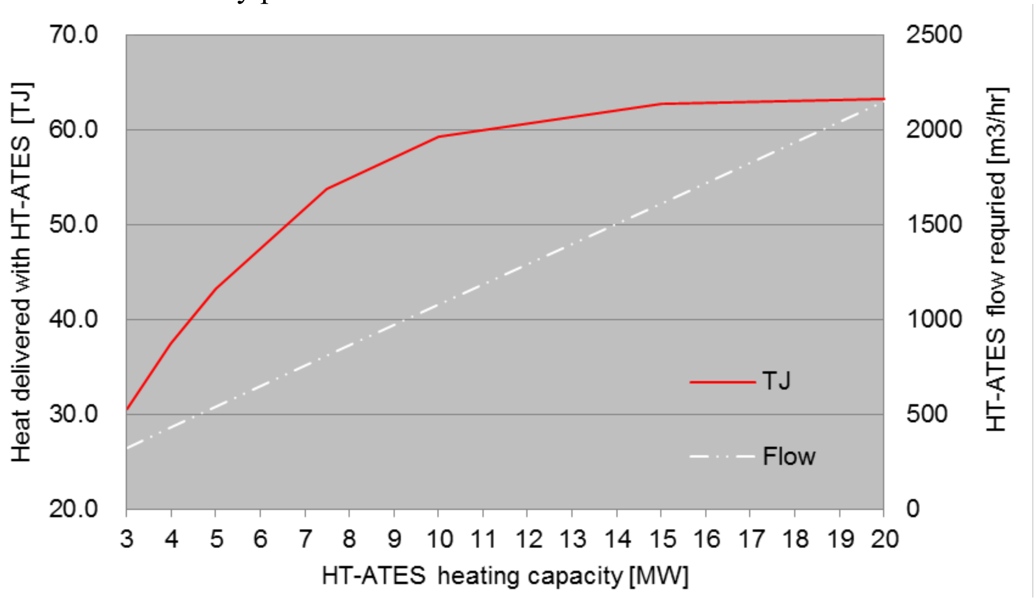


Figure 8. The amount of heat that can be delivered, required well flow as a function of HT-ATES well capacity.

Table 3. HT-ATES charging and discharging characteristics at different HT-ATES well capacities.

	Charging		**Discharging**		*Unit*
Capacity HT-ATES	6.7	3	5	10	*MW*
Total heat HT-ATES	100	31	43	59	*TJ/y*
Max. flow capacity	320	320	535	1 071	*m^3/h*
Volume	1.06	0.91	1.29	1.76	*Mm^3/y*
Approximate efficiency*	-	31%[4]	43%	59%	-

*Solely based on the anticipated storage and extraction heat flows, no groundwater model simulations.

Depending on geohydrological conditions, the best HT-ATES well capacity can be identified, to be optimised for number wells and drilling costs. The following points should be further elaborated on when further detailing the HT-ATES design:

- The exact infiltration and extraction temperatures depend on the losses that occur during storage. However, they have a large effect on HT-ATES capacity and with that on the overall feasibility.
- Linked to the temperature difference is the water balance for charging and discharging the heat to/from the HT-ATES. These seasonal pumping volumes cannot differ too much to prevent short-circuit flow between the hot and warm HT-ATES wells.

[4] For this scenario the DAPwell heat production can be reduced during summer, which will increase the efficiency.

- The yearly energy amounts mentioned in this section are an indication based on the reference year used for climate installation design. In practice the actual heating demand will vary over the years and deviate from the demand calculated with the reference year.

2.4.2 Scenario 2: heat for TU Delft and city of Delft

The second scenario comprises the heat demand not only the TU Delft campus, but also the city of Delft. Both users will be supplied with heat from the DAPwell and the HT-ATES system. At this stage, the yearly required heat and capacity is uncertain. Based on preliminary studies for the development of the city district heat network, it is assumed that heat will be supplied at a temperature level of 55 °C and return at 35 °C. The demand profiles of the TU Delft campus and city of Delft will be different due to the difference in type of buildings. The TU Delft campus mostly contains office buildings causing peaks in the morning on week days, while the city of Delft is mostly residential, causing peak demands in evening and weekends. In the residential areas there is a baseload required for Domestic Hot Water (DHW) sanitation and cooking, also during summer.

Case I: City demand follows campus demand

The most simple configuration considered is that heat supply to the city follows heat demand of the campus. The return flow from the campus to the HT-ATES system and DAPwell[5] is used for heat delivery to the city. In this case the modes of operation are the same as in Scenario 1. Only the temperature levels change, as seen in Figure 9. Assuming similar temperature losses, the temperature difference between the wells for the DAPwell becomes 45 °C and for charging and discharging the HT-ATES 45 and 35 °C, respectively, resulting in available total heat/year and capacities presented in Table 4. Due to the much larger temperature differences, especially during discharging, much lower flow rates are needed from the HT-ATES system to achieve the same energy output.

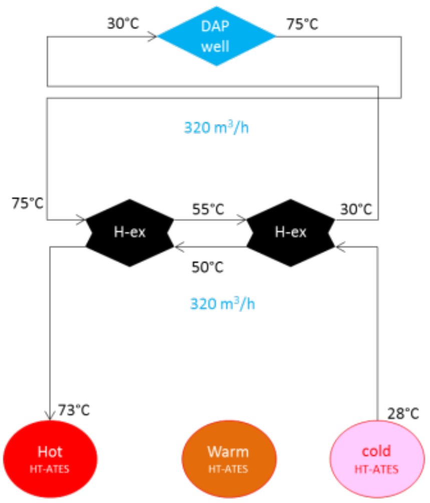
Table 4: HT-ATES and DAPwell characteristics with heat delivery to city of Delft in Scenario 2 (numbers for Scenario 1 from Table 3), well capacity and storage volume are the same as in Scenario 1.

	Charging	Discharging			Unit
Capacity	16.7 (6.7)	13 (3)	22 (5)	43 (10)	*MW*
Total HT-ATES	210 (100)	65 (31)	93 (43)	125 (59)	*TJ/y*
Approximate efficiency*	-	31%	44%	60%	-
Additional to Scenario 1					
DAPwell heat to city	*112*	136	136	136	*TJ/y*
HT-ATES to city		35	49	68	*TJ/y*

*Solely based on the anticipated storage and extraction heat flows, no groundwater model simulations.

[5] Not the full return flow during peak demand, otherwise TU Delft CHP and boiler are then also heating the city of Delft.

Scenario 2: No heating demand



Scenario 2: Heating demand (TU and city energy demand coupled)

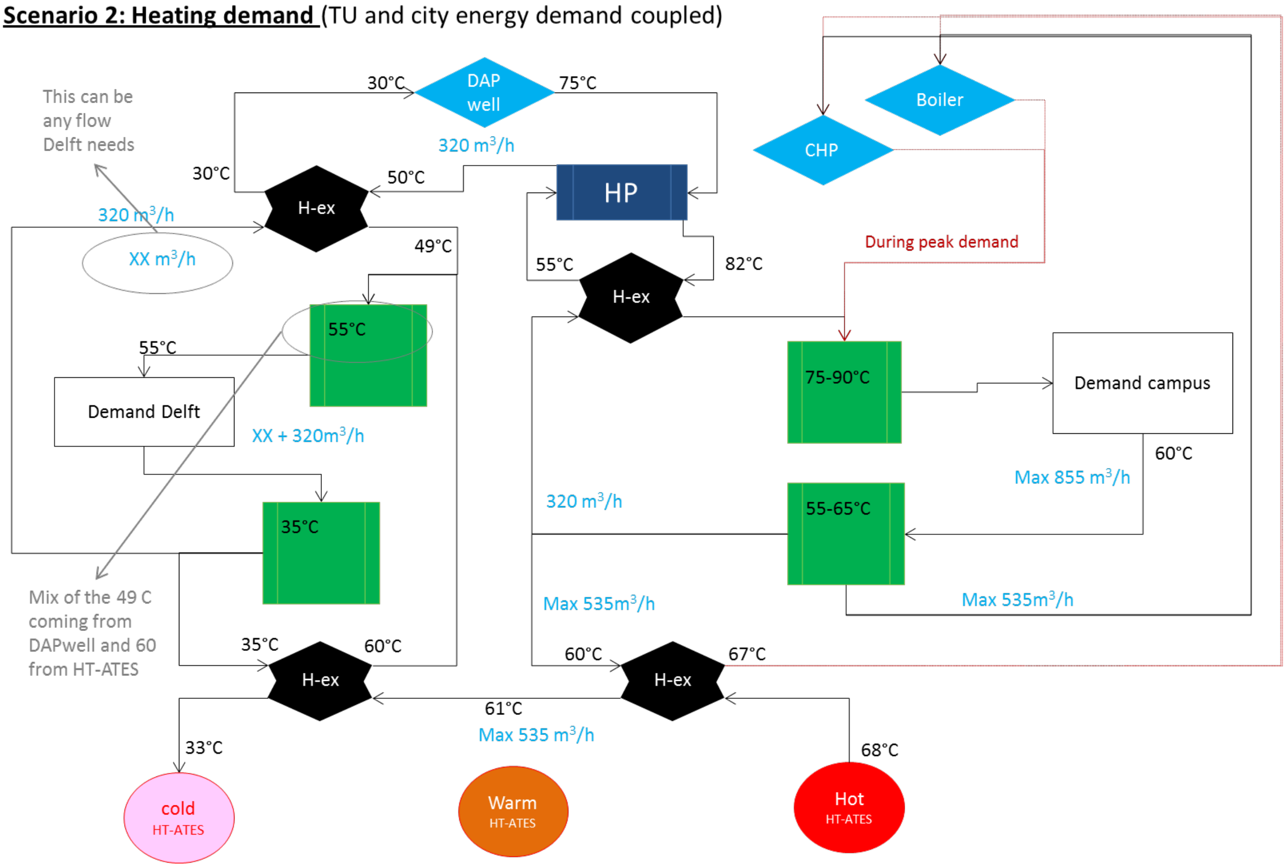


Figure 9. Preliminary heat flows DAP well with HT-ATES with approximate temperature levels for Scenario 2-Case I.

Case II: Realistic demand for City of Delft

In practice, the demand profiles will not match, and therefore the residual heat of the TU Delft campus will not be able to be directly discharged to Delft city. This results in a need for additional heat storage, at ~60 °C. This could be provided by an additional HT-ATES well at this temperature level or another system. An additional HT-ATES well (see Figure 10), on the one hand complicates things with respect to costs, and control and optimisation during operation, while on the other hand it also offers more flexibility and opportunity to utilise more sources of (waste/residual) heat.

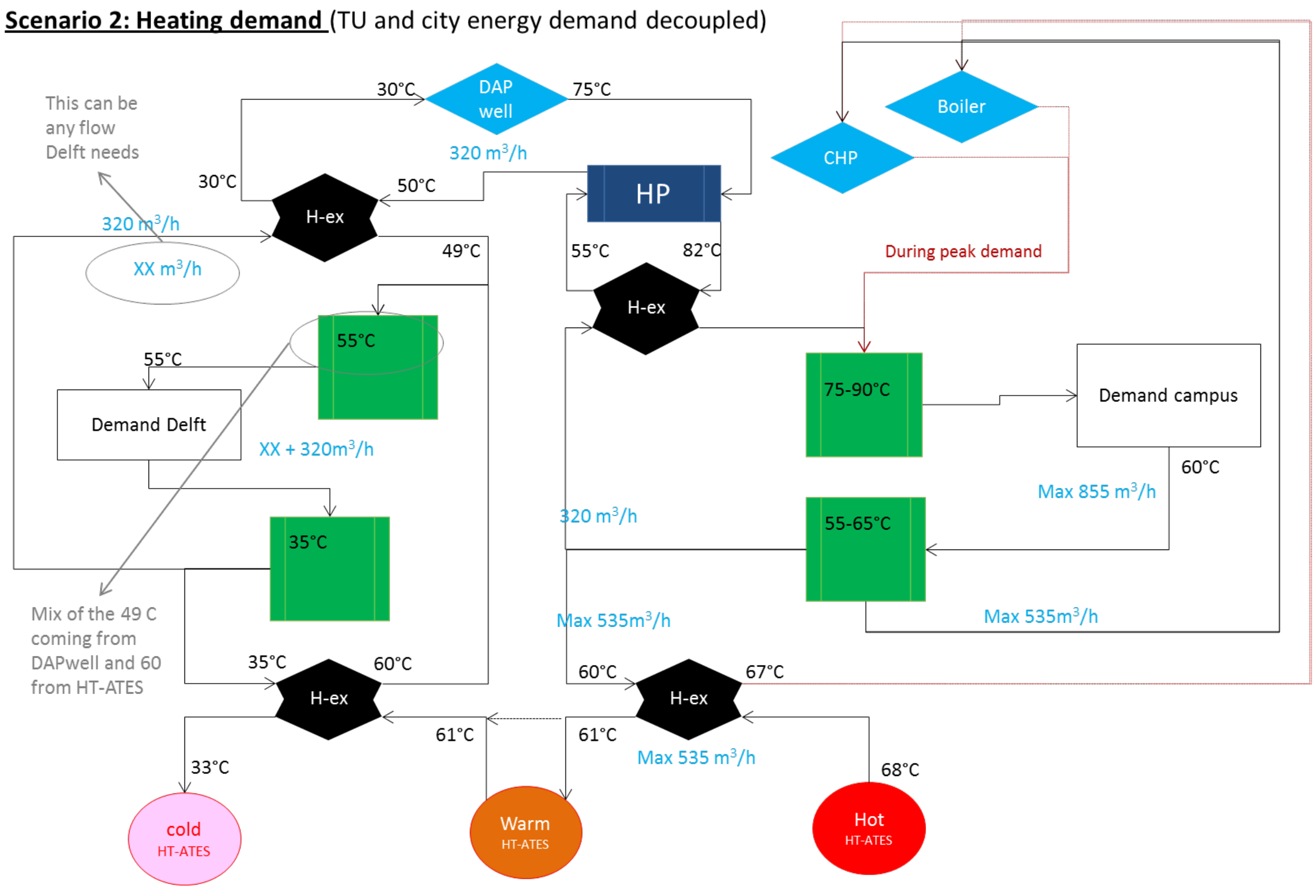


Figure 10. Example heat flow schematic for decoupled energy delivery to TU Delft and city and delivery to both from HT-ATES.

However, there are many uncertainties identifying a more realistic energy demand profile for the city. Therefore, this case can only be further elaborated when there is more clarity/certainty about the heating demand characteristics of the city of Delft. For this situation, a simpler configuration with the HT-ATES solely supplying heat to the city may be beneficial. The total amounts of heat would not change, only the CO_2 reductions for the campus heat would be lower (and possible higher reductions for the city supply). The advantage would be a somewhat more straightforward control of heat storage and recovery to/from the three different temperature level wells.

2.5 Conclusion: Heat demand and availability

Considering the heat demand and supply profiles and quantities, it is concluded that there is considerable potential for an HT-ATES system to contribute to the sustainable heat delivery of the TU Delft campus and city of Delft. Table 5 provides an overview of the main benefits and characteristics of an HT-ATES connected to the DAPwell in Scenarios 1 and 2. With a flow capacity of about 535 m^3/h (i.e. the 5 MW in Scenario 1) around 89% of the TU Delft campus heating demand can be delivered from sustainable resources (in comparison with between 50 to 68% with only the DAPwell). In Scenario 2-Case I, the same capacity system would deliver another 50 TJ of heat to the city of Delft from the HT-ATES (DAPwell would deliver 140 TJ directly to the city, and 50 TJ via the HT-ATES, in total 190 TJ).

Table 5: Overview HT-ATES characteristics.

	Scenario 1	Scenario 2-Case I	*Unit*
Total heat DAPwell and HT-ATES	178	368	*TJ/y*
Directly by DAPwell	135	275	*TJ/y*
HT-ATES			
Total available heat for injection*	100	210	*TJ/y*
Total heat extraction	43	93	*TJ/y*
Storage volume	1	1	*Mm^3/y*
Flow capacity	535	535	*m^3/h*
Thermal capacity	5	22	*MW*
Hot well temperature	73/63	73/63	*°C*
Warm well temperature	60/50	n.a.	*°C*
Cold well temperature	n.a.	33/23	*°C*

* Maximum potential heat to be stored. Can be reduced if needed to better match demand. A summer shutdown period of 6 weeks is possible for the R&D programme of the DAPwell, which is not taken into account here.

Please note that the numbers provided are yearly averaged expected numbers. It is assumed heat is stored at maximum rate from DAPwell, further detailed studies should identify if this can be reduced, following simulated efficiencies. In Scenario 2, this is also the case but much more heat can be delivered to the city if we "disconnect" the city from TU Delft demand. In future detailed design, these numbers should be optimised. Heat demand for the TU Delft campus is likely to increase due to an additional track of the DHN. This higher heat demand would generally increase the requirement for storage, but this may also include more residential buildings, which may have the effect of decreasing the proportional seasonal imbalance.

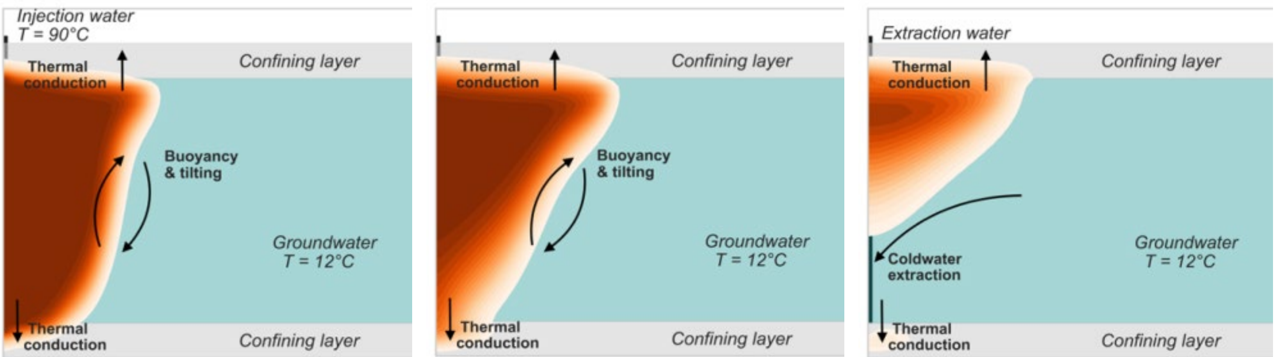
3 Technical Feasibility II: Subsurface conditions

In this chapter, the subsurface conditions at the TU Delft campus are analysed for the potential for a HT-ATES system.

3.1 Criteria for suitable aquifers

The geohydrological conditions play an important role in the performance of an HT-ATES system. The thermal recovery efficiency and extraction temperature are the main indicators of the performance of an HT-ATES system. The efficiency is defined by the total extracted energy over the total injected energy during one recovery cycle. The amount of energy that can be extracted after storage is influenced by the losses that occur during storage.

The main geohydrological properties that affect heat loss in an HT-ATES system are: the vertical/horizontal hydraulic conductivity, and the depth and thickness, because they determine the shape of the heat bubble in the aquifer and with that the conduction losses. The aquifer thickness and hydraulic conductivity affect the losses due to buoyancy flow, triggered by the large differences in temperature, as schematically shown in Figure 11. In addition to heat losses, legal and financial considerations affect the suitability of a layer.



a) After injection b) After storage c) After extraction

Figure 11. Buoyancy flow affecting extraction temperature of an HT-ATES system.

3.1.1 Thickness

The thickness of the aquifer strongly affects the flow capacity of a well but also has effect on the thermal losses of the system. Thermal losses occur at the boundaries of the hot water volume in the form of conduction and dispersion. A thin layer, results in a 'pancake' shaped thermal plume in the aquifer, resulting in large conduction losses to the confining layers. On the other hand, thick layers result in 'candy cane' shaped heat plumes, causing conduction losses to the aquifer and more buoyancy losses. These losses can be minimised by using a screen length that results in the smallest surface area (A) of the heat bubble for a given storage volume (V). Figure 12 shows the well optimal screen length/aquifer thickness (L) for different storage volumes, to minimise conduction losses (minimise A/V). It shows that for a storage volume of 1 000 000 m^3 (approximately what is needed for the HT-ATES of TU Delft, see Table 5) there is a 'flat' optimum at about 115 m, i.e. it is relatively insensitive to reasonable changes. Due to buoyancy losses it is better to have a smaller aquifer thickness, therefore a limiting value of about 45 m is selected to prevent large conduction losses.

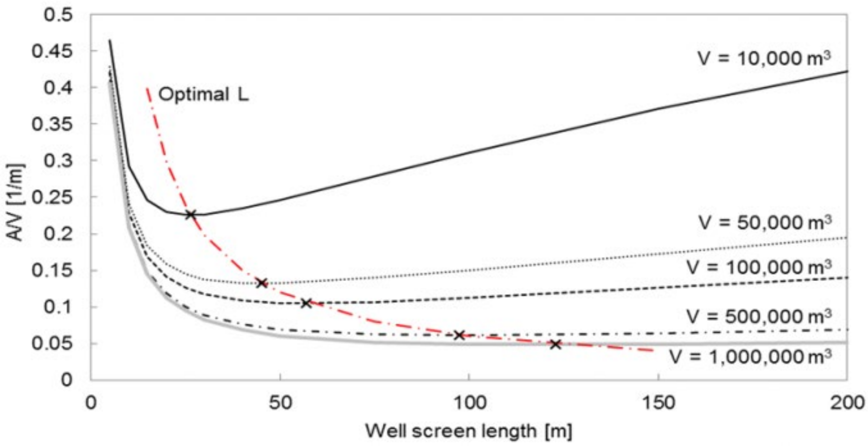


Figure 12. Optimum well screen length for given injection volumes, to minimise conduction losses (Bloemendal and Hartog, 2018).

3.1.2 **Hydraulic conductivity**

The hydraulic conductivity determines how easy water can flow in an aquifer. It depends on the intrinsic permeability, porosity, density of the water and viscosity, of which the latter two depend on temperature. A distinction is made between the vertical and horizontal hydraulic conductivity. To limit buoyancy losses, a small vertical hydraulic conductivity is preferred. The horizontal hydraulic conductivity determines the flow capacity of a well, thus a high horizontal conductivity is preferred to limit the number of wells, therefore also the drilling costs. Usually, the vertical hydraulic conductivity is lower than the horizontal, the ratio between the two is called the anisotropy factor. Usually it is the case that the deeper the aquifer, the larger the anisotropy and the smaller the absolute values are for the hydraulic conductivity.

Heterogeneity in the form of small clay layers in the aquifer, negatively affects the average aquifer hydraulic conductivity. However, small clay layers also limit buoyancy flow, and can thus result in a better overall performance of an HT-ATES system. It is also more complex to properly install the well screens at the required depth in such conditions.

3.1.3 **Geochemistry / microbiology**

HT-ATES induced changes in the chemical composition of the groundwater and/or microbiological activity may result in clogging of wells or groundwater quality deterioration. Temperature changes and/or mixing of groundwater may trigger biological activity, chemical reactions and/or mobilisation of components. A known compound is calcium carbonate which can precipitate and clog the wells or the formation. The extent to which such processes occur depends strongly on the local geohydrological and geochemical conditions, and the storage temperature.

3.1.4 **Depth**

When drilling deeper than 500m in the Netherlands, the Mining Law drilling guidelines are effective, requiring significant safety measures, strongly increasing the drilling costs (Wiebes, 2020, see Section 7.1 for more details). Therefore, the aquifer depth is preferably shallower than 500m.

The groundwater temperature increases with depth, by approximately 30°C each 1000m in the Netherlands. With an ambient temperature of 10 °C at very shallow depths (~10 m below surface), at 500m depth the ambient groundwater will have a temperature of around 25°C. This will decrease the losses due to conductions and buoyancy flow.

Table 6 provides an overview of pros and cons for application in shallow and deep

Table 6. Overview of pros and cons for application of HT-ATES in shallow and deep aquifers.

	Shallow	**Deep**
Pro	+cheap drilling +well known layers +high capacity	+Higher ambient groundwater temperature, fewer losses +Less impact to other groundwater users +Low hydraulic conductivity, limiting buoyancy flow +less change for microbiological effects
con	-potential negative impact to other groundwater users -more heat losses -change for microbiological activity	-Low hydraulic conductivity, limiting capacity, increasing costs -Extra regulations concerning the Mining law. -Higher drilling costs -more uncertainties about characteristics

3.2 Local Geohydrology

For integration in the heating system, the HT-ATES system can best be located near the CHP and DAPwell. Subsurface data for this location is gathered from nearby drillings and subsurface model REGIS (TNO, 2017) provide insight in the local geohydrology. The inventory is carried out to a total depth of 1000m. The main datasets and models that were used for this projection are listed below and presented in Figure 13. Overview of the subsurface data. Left: Delft-07 SP log and formation interpretation. Top right: REGIS II model. Middle right: Location of data sources. Drillings at the Technopolis and train station are not depicted in this figure but were used for interpretation.:

A. Drilling at TU campus (Technopolis) and Delft NS station: Detailed insight to a depth of 240m
B. REGIS II Model: general subsurface condition to a depth of 420m
C. SP-Logging at Jaffalaan (DELFT-07): rough indication of various layers up to 1 000m depth

The Delft-07 logging shows the logged Spontaneous Potential results and the lithology of the subsurface on the left hand side of the figure. The yellow layers bars represent the possible aquifers. The local geohydrology is heterogeneous as a result of the deposition by rivers and deltas, but lacks any major faults in the near lateral environment. Comparing the drillings at Technopolis and the train station indicate that confining layers are less defined towards the city of Delft. The following possible suitable formations are identified:

- **Waalre (45m-70m)**: Pros: Low drilling cost, high hydraulic conductivity. Cons: Close to surface (environmental impact), permits difficult due to other systems present in this layer.
- **Maassluis (130m-190m):** Pros: thick, layered, not deep, high conductivity. Cons: other ATES systems present.
- **Oosterhout (285m-310m)**: Pros: high conductivity, no other systems. Cons: Small thickness, uncertainty about characteristics (Conflicting information about the thickness.

According to REGIS model 30m but log data suggests 40m. This can be the result of the "complex" bottom confining layer.)

- **Ommelanden (410m-460m)**: Pros: High conductivity, thick, no other functions. Cons: Geochemistry (dissolution of calcium carbonate), uncertainty about characteristics: possible karstified material which could have an effect on efficiency.
- **Boven Holland Mergel (725m-775m)**: Pros: Thick enough, small environmental impact, fewer losses. Cons: Low conductivity, mining law applicable, formation gas, uncertainty about characteristics.
- **Midden Holland Kleisteen (815m-860m)**: Pros: Thick enough, fewer losses, no other functions. Cons: Low conductivity, mining law applicable, formation gas, large uncertainties about suitability/presence of aquifer.
- **Holland Groenzand (940m-975m)**: Pro: Fewer losses, no other functions. Con: Low conductivity, mining law applicable, formation gas, exact depth uncertain.

The 3 deepest layers do not have a large potential, there are too many uncertainties and there are no apparent benefits that would justify the higher drilling costs (due to the Mining law regulations and higher depth). Therefore, the Waalre, Maassluis, Oosterhout and Ommelanden formations are taken into further consideration. The table in Appendix II provides detailed information about the characteristics obtained from REGIS and the local drillings.

3.3 Identification of suitable layers and locations

To try to discriminate between the identified layers a multi-criteria analysis has been used. The four layers are evaluated following criteria affecting: A) the expected performance, B) the cost of the system, and C) possible impact to other subsurface users. See Table 7 for the detailed criteria and scoring.

Table 7. Criteria for evaluation of suitable layers.

A) Performance	*Thickness* 1. <40 or >60 m 2. - 3. 40-60 m	*Vertical conductivity* 1. 10-20 m/d 2. 5-10 m/d 3. 1-5 m/d	*Confining layers* 1. Poor 2. Medium 3. Good	
B) Cost	*Thickness* 1. <40 m 2. 40-60 m 3. >60 m	*Horizontal conductivity* 1. 1-5 m/d 2. 5-10 m/d 3. 10-20 m/d	*Risk of Clogging* 1. High 2. Medium 3. Low	*Depth* 1. > 500 m 2. 250-500 m 3. 0-250 m
C) Impact on environment or other subsurface systems	*Depth* 1. 0-250 m 2. 250-500 m 3. >500 m			

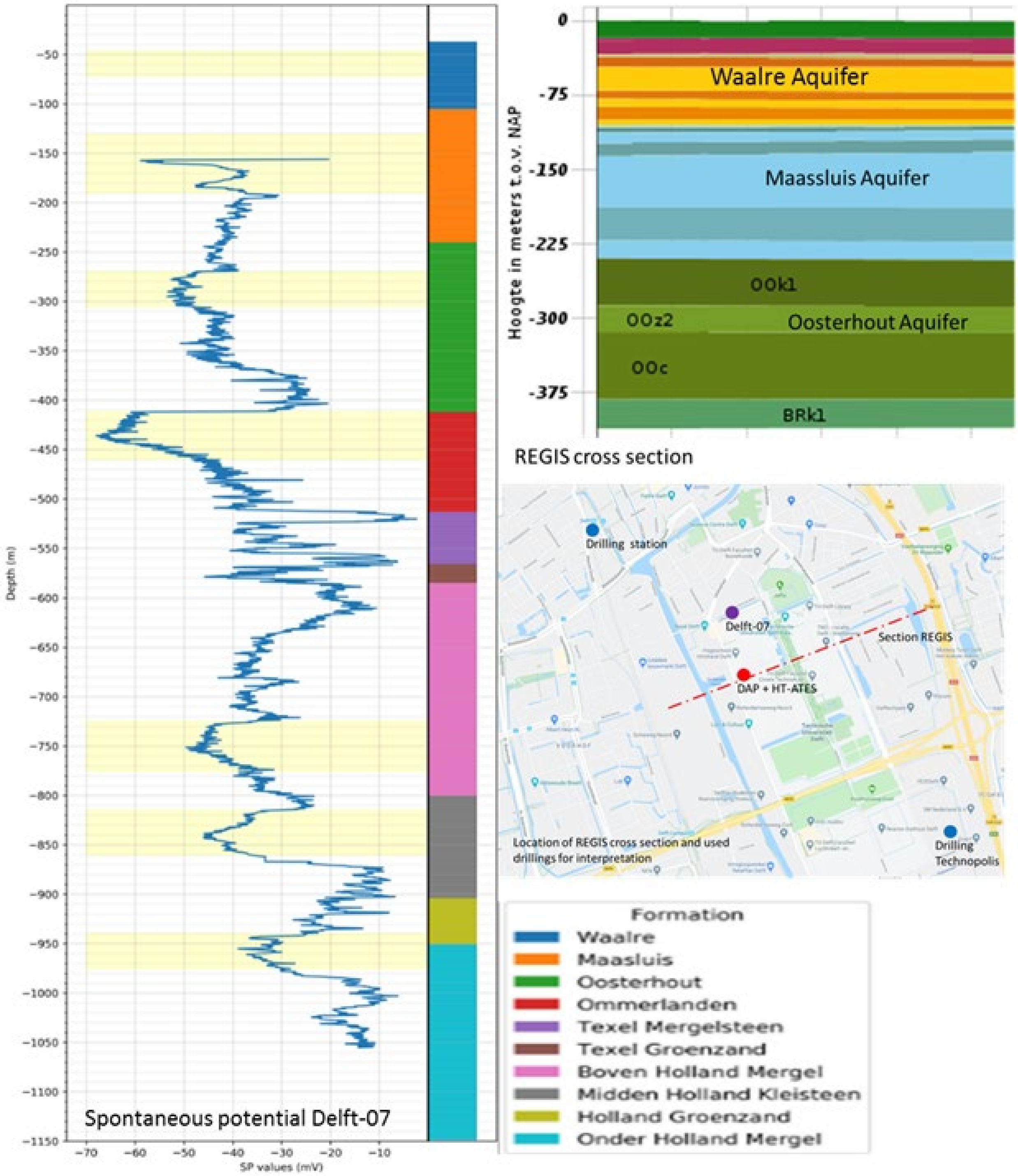


Figure 13. Overview of the subsurface data. Left: Delft-07 SP log and formation interpretation. Top right: REGIS II model. Middle right: Location of data sources. Drillings at the Technopolis and train station are not depicted in this figure but were used for interpretation.

The four aquifers (Waalre, Maassluis, Oosterhout and Ommelanden) have been ranked following their characteristics, whereby the score of each of the main criteria is equal. The results are presented in Table 8. This overview shows that Waalre formation is least favourable, and Maassluis and Ommelanden are most favourable. The differences between Maassluis, Oosterhout and Ommelanden are small, partly due to some characteristics having conflicting evaluation results. Changing the weights for the main criteria does not change the results much, only when costs criteria weight is increased the Maassluis outperforms the Ommelanden, and significantly outperforms the Oosterhout.

Beside the sandy aquifer in the Maassluis and Oosterhout formation, there are indications of a highly permeable chalk layer in the Ommelanden formation. The logging and general information about this formation indicate that this layer has sufficient thickness and hydraulic conductivity, also suitable for HT-ATES. Compared to the Maassluis formation, the higher vertical hydraulic conductivity will result in more heat loss in the Ommelanden formation due to buoyancy flow, which may be compensated for by a reduction in conduction losses due to the higher ambient temperature. The Oosterhout has a lower score for cost than Ommelanden, despite the shallower depth, this layer may need more wells than is the case in the Ommelanden formation. For now Maassluis and Ommelanden are proposed for further investigation, however, the Oosterhout formation should still remain "in the picture" for the situation both Maassluis and Ommelanden appear to be not feasible.

Table 8. Results of MCA for different aquifers.

	Weight	**Waalre**	**Maassluis**	**Oosterhout**	**Ommelanden**
Thickness	*1.33*	1	3	1	3
Hydraulic conductivity k_v	*1.33*	2	3	3	2
Confining layers	*1.33*	1	2	2	3
TOTAL for losses	**1.0**	**5.3**	**9.3**	**8.0**	**9.3**
Thickness	*1.00*	1	3	1	2
Hydraulic conductivity k_h	*1.00*	3	2	2	3
Risk of clogging	*1.00*	1	2	2	1
Depth	*1.00*	3	3	2	2
TOTAL for costs	**1.0**	**8.0**	**10.0**	**7.0**	**8.0**
Environmental impact	*4.00*	1	1	2	2
TOTAL for env. impact	**1.0**	**4.0**	**4.0**	**8.0**	**8.0**
Total score		**17.3**	**24.7**	**23.0**	**26.7**
Percentage of maximum score		48%	69%	64%	74%

3.4 Conclusion: Subsurface conditions

Multiple subsurface layers at the TU Delft show strong potential for the application HT-ATES systems, but that the Ommelanden and Maassluis formations are most suitable.

The information on the Oosterhout and especially the Ommelanden formations are very uncertain. These aquifers should be further investigated during the drilling of the DAPwell, to confirm their properties.

4 Technical Feasibility III: Preliminary design

4.1 Design principles of HT-ATES system

In order to meet the required characteristics of the HT-ATES, the system must be designed in a way that efficiently utilises the heat supply from the DAPwell and the subsurface conditions in an optimal way, as well as allowing for the required heat offtake in peak demand moments. Following the heat demand and availability as described in Chapter 2 and the subsurface conditions as described in Chapter 3, the HT-ATES preliminary design will be elaborated in this chapter. The focus is on the Ommelanden and Maassluis formations as these were indicated to be the most suitable. The system characteristics for Scenarios 1 and 2-I are presented in Table 9. It is assumed well diameters of about 1 m are used, which is a regularly used diameter for low temperature (LT)-ATES wells.

Table 9. Design principles for the Maassluis and Ommelanden aquifers.

	Maassluis	**Ommelanden**	*Unit*
Thickness / screen length	50	50	*m*
Hydraulic conductivity k_h	10	15	*m/d*
Hydraulic conductivity k_v	2	5	*m/d*
Depth	130	410	*m*
Flow capacity – heat delivery	535	535	*m^3/hr*
Flow capacity – loading	320	320	*m^3/hr*
Storage volume	1	1	*Mm^3/y*
Thermal radius	95	94	*m*

4.2 Operating modes

4.2.1 Heat storage - Loading of the HT-ATES system

Considering the maximum expected DAPwell heat output with a flowrate of 320m^3/h, the hot wells infiltration capacity must reach 320m^3/h in total to ensure that all available heat in low demand/ loading moments can be stored for future use. At the same time extraction capacity at warm wells has to reach 320 m^3/h total for system equilibrium.

Both formations need 4 hot wells which results in an infiltration capacity of 80m^3/h per well. The hot wells could realistically infiltrate the required ~80 m^3/h, especially as the high temperatures increase infiltration due to lower water viscosity and higher hydraulic conductivity of the layer.

4.2.2 Heat delivery – Unloading of the HT-ATES system

In order to reach the thermal capacity of 5 and 22 MW (Scenario 1 and Scenario 2), the system must be able to reach 535m^3/h extraction flowrate of hot water from the hot wells. This means that the infiltration capacity of the cooled water into the warm wells has to reach a total of 535 m^3/h for system equilibrium. This means that for the warm wells where cooled water is stored, the infiltration capacity per well must be much larger - 535m^3/h - than hot wells that infiltrate 320 m^3/h during peak loading hours. It can be concluded that the infiltration capacity of cooled water into the warm wells is the limiting factor of the total system.

The Maassluis formation needs 8 warm wells to accommodate the 535m^3/h infiltration capacity, i.e. around 67 m^3/h per well. This number is based on the Dutch design standards for Dutch ATES wells (NVOE, 2006) and practical experience in the Maassluis formation in the Delft region (ATES systems on campus, e.g. TNW-Zuid). One of the limiting factors of the infiltration capacity in the Maassluis formation is the presence of mineral Glauconite and the fine sand/clay composition of the layer. Enlarging the capacity by increasing infiltration pressure increases the risk of structural damage to the well.

For the Ommelanden formation it is estimated that 6 warm wells can provide the 535m^3/h infiltration capacity, i.e. a little under 90 m^3/h per well. This figure is based in the indication of a highly permeable chalk layer in the Ommelanden formation with sufficient thickness and hydraulic conductivity. The Ommelanden formation characteristics will be further investigated during DAPwell drilling (as discussed in Section 3.4).

4.3 HT-ATES well design

4.3.1 Well numbers and the required capacities

An overview of the number of wells and the required capacities, for both the Maassluis and the Ommelanden formation, can be seen in Table 10.

Table 10. Wells and the required capacities for the Maassluis and Ommelanden aquifers.

	Maassluis		Ommelanden		*Unit*
	Warm	Hot	Warm	Hot	
Number of wells	8	4	6	4	#
Infiltration capacity	535 (8×67)	320 (4×80)	535 (6×90)	320 (4×80)	*m^3/hr*
Extraction capacity	320 (8×40)	535 (4×134)	320 (6×54)	535 (4×134)	*m^3/hr*

4.3.2 Generic design rules

The well location selection follows the generic rules presented in

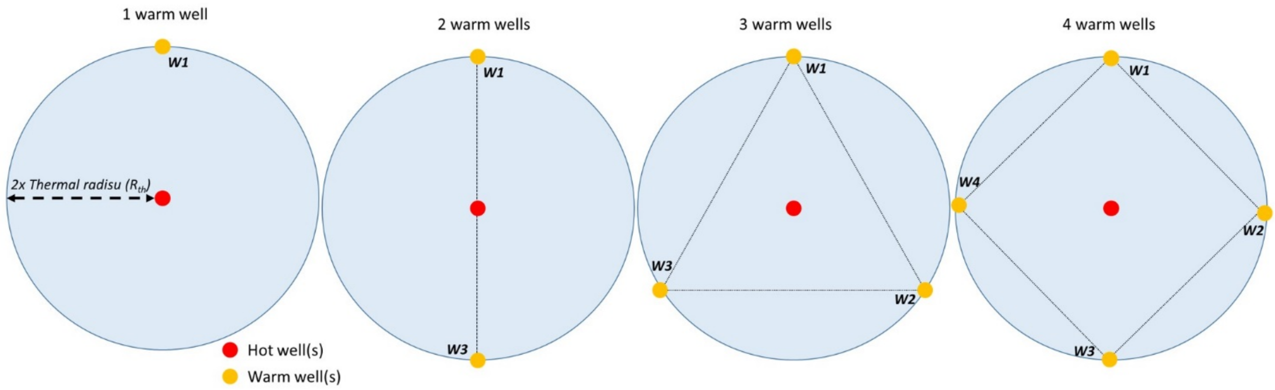


Figure 14. All the hot wells should be clustered to create one large hot zone in order to prevent heat losses. The warm wells can also be clustered or spread around the hot zone, to shield the hot wells from interaction with the much colder ambient groundwater. The distance between the hot and warm wells should be around 2 times the thermal radius of the wells (when thermal radii are not the same

the average of the two is used). The distance between the hot and warm wells can be optimised in a next phase for optimal heat recovery of both warm and hot wells. For the preliminary design the warm wells are spread around the hot wells. In a next stage, the actual drilling location may be altered complying to

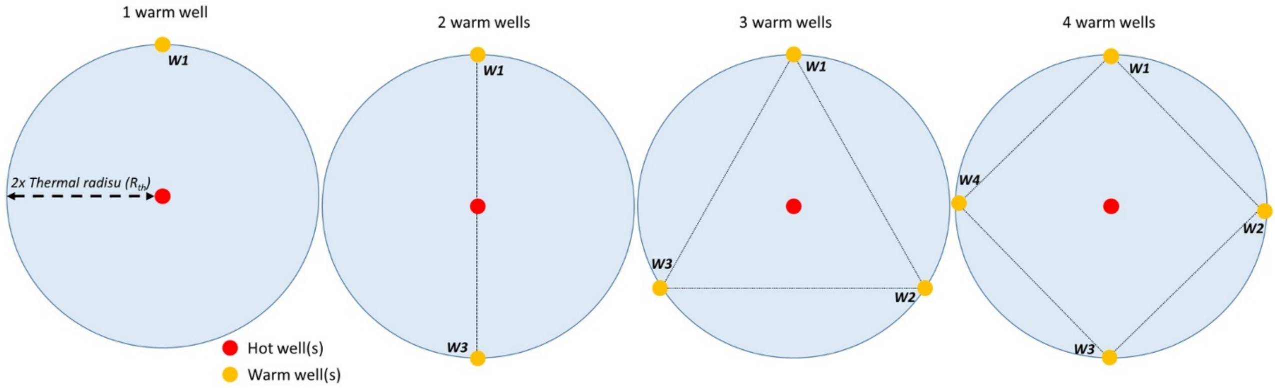


Figure 14.

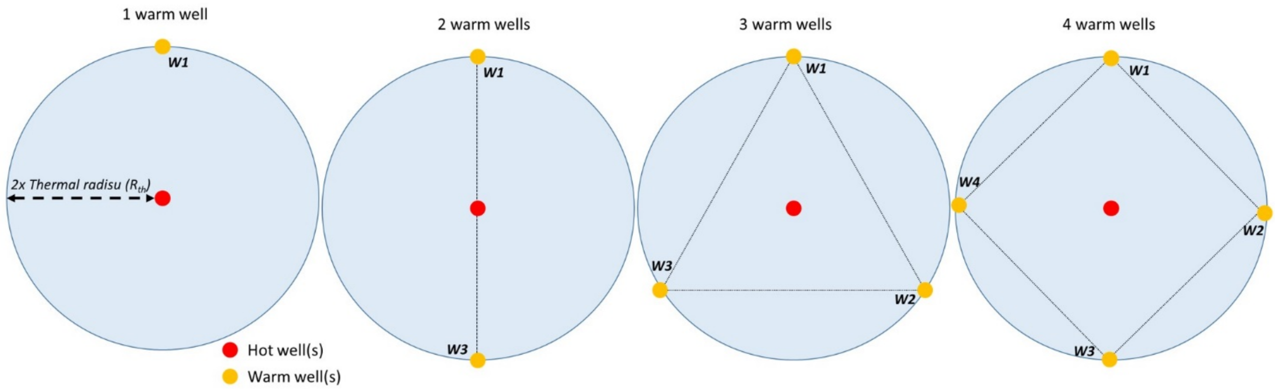


Figure 14. Placement rules for HT-ATES wells. An individual dot in these scenarios can consist of multiple clustered wells of the same type.

4.3.3 Design of the wells location

Specific system requirements for both the Maassluis and Ommelanden formations are discussed in this section and listed in Table 11. For optimal performance, the four hot wells of the system should have at least 40 m distance between each other to avoid possible hydraulic interference during operation. 40 m is based on experience of similar installations and can be seen as a conservative distance which will be further detailed out in the next phase.

Table 11. HT-ATES well configuration requirements for the Maassluis and Ommelanden formations.

	Maassluis	**Ommelanden**	*Unit*
Thickness / screen length	50	50	*m*
Number of hot wells	4	4	#
Number of warm wells	8	6	#
Storage volume	1	1	*Mm^3/y*
Storage volume / well	0.25	0.25	*Mm^3/y*
Thermal radius Hot well	100	100	*m*

Distance between hot wells	40	40	*m*
Required distance between wells	150	150	*m*

The HT-ATES system is proposed to be located on the TU Delft campus. All heat sources are concentrated between Leeghwaterstraat and the Rotterdamseweg. The HT-ATES system will be connected to the geothermal well and the distribution network of starting at the CHP. Keeping close to these installations would be preferable in order to reduce transport loses and infrastructure investments.

In Figure 15 and Figure 16, possible locations for the HT-ATES wells for two different target layers are indicated. The systems shown would (in either case) be as close as possible to geothermal well planned, as well as abide by recommendations of HT-ATES design regarding distances between wells and design of system as shown in Table 11.

Figure 15. Sketch of possible HT-ATES system for the Maassluis formation (12 total wells) in immediate area of DAPwell. Red and blue dots are hot and cold wells, respectively, brown circle is the maximum thermal zone.

Figure 16. Sketch of possible HT-ATES system for the Ommelanden formation (10 total wells) locations in immediate area of DAPwell. Red and blue dots are hot and cold wells, respectively, brown circle is the maximum thermal zone.

One of the core aspects of the location choice for planned systems (Figure 15 and Figure 16) is the proximity to the expected DAPwell location. As described in Table 11, The warm wells and closest hot wells should be located at least 150 meters away from each other, in order to sustain optimal thermal zone and to keep losses of stored heat to a minimum. Ensuring that distances between wells are kept to a minimum, infrastructure and development costs are kept as low as possible. The required distance between the hot and warm wells is based on the expected storage volume of the system (1 Mm^3/y), as well as the expected porosity of the aquifer. The required minimum distance between wells ensures optimal thermal storage and reduces the chance of heat losses, as lower than necessary distance between wells could actively cool down stored water/ warm up cold water. Figure 15 and Figure 16 show the estimated thermal zone with a diameter of ~340m (brown circles), indicating the minimal optimal distance to ensure sufficient HT-ATES system performance. Optimisation of the size of the thermal zone of the HT-ATES installation, as well as other core design aspects which should be further investigated or that can be implemented to improve system performance, are further discussed in Section 4.3.4.

Based on the DAPwell design, land ownership, legislative requirements and interactions with other ATES systems, the locations of the HT-ATES wells will be further investigated in the next stage and, as a result, could be adjusted.

4.3.4 Consideration for further design development

To achieve optimal system performance, various aspects of HT-ATES system can be adjusted in the design stage. An adjustment in the design for increased performance could be (for example) an application of segments in the filter of the wells, so that the thermal zone could be controlled more accurately. There are many more detailed design choices to be made in further stages of the system design, in order to achieve best possible results.

Analysis should be done between switching frequencies to determine most suitable choice (e.g. short-cycle/ long-cycle) for the system, based on expected heat demands during various times of year. Such choice of switching cycle frequencies and are increasingly important during autumn/spring season, where different utilisations of all available wells are required on a short-term basis. Different extraction and injection configurations (depending on situation) could also be developed, allowing for e.g. one extraction well and three injection wells to operate at once, with changes happening based on algorithms and needs of the complete system. For surface installation and well locations and design, further analysis into possible locations of installation need to be performed, as well as operation specifics.

Such considerations (and more), investigated prior to installing the HT-ATES system, will allow the system to perform better, be more flexible and responsive to loading and extraction of heat from the system. However, these might result in increases in operational or investment costs. The impact of various design decisions has to be determined in further project stages in more detail to ensure balance between optimal cost and performance of the HT-ATES system.

Modular development needs to be carefully considered. The DAPwell could be seen as an exploration well that brings a huge amount of information from the targeted reservoirs which will be used for optimising the design. If necessary, additional information could be obtained by staged realisation (i.e drill one warm well first, then one hot well, prior to the full system) in order to exactly understand the subsurface properties to be able to further optimise the design of the whole system.

4.3.5 Exploratory simulations

Goal and approach

In this section, the behaviour of the HT-ATES system is explored by simulations in an axisymmetric and 3D numerical model (SEAWAT), see Appendix III for further details. The goal of these simulations is to get insight into:

1. The environmental impact: What is the temperature distribution in the subsurface after 50 years of operation?
2. The performance of the well: how much of the injected energy can be extracted after storage?
3. The thermal quality of the extracted water: What is the extraction temperature?

The simulations are carried out for the Maassluis and the Ommelanden aquifers. The hourly required flow rates to and from the HT-ATES system are aggregated into monthly values, as the model uses monthly time steps. The flow in the wells is enforced following the yearly calculated required volume and the assumed ΔT between the wells. A cut-off temperature, below which extraction is stopped, is used for extraction of heat from the hot well: 63°C for the only campus case and 43°C for the situation including Delft city. The main indicator for the performance of an HT-ATES well is the thermal recovery efficiency. This is calculated by the total extracted energy divided by the total injected energy over the evaluation period.

Two different simulation sets have been carried out:

- Axisymmetric simulations (AXI) – which simulate the effect of a single well, and have a better computational performance so more analyses can be carried out.
- 3D simulations (3D) – which simulate the whole HT-ATES system, and therefore allow an analysis of the interaction between the thermal plume from wells. These analyses take much longer and therefore only few can be carried out.

Results

Figure 17 shows the temperature distribution around a hot well and in confining layers after 50 years of operation of the HT-ATES for the axisymmetric analyses. This is especially important when the well is placed in an aquifer alongside low temperature ATES systems (such as the Maassluis formation), which would be adversely affected if they heat up. Figure 17 shows that above a radius of 300m no influence is experienced in terms of temperature increase as a result of an operating HT-ATES well for 50 years. The impact of density driven flow can be seen with the heat plume having a larger radius at the top of the formation than at the bottom.

Figure 18. HT-ATES well extraction temperatures. Top: AXI, only campus, Middle: AXI, campus and city of Delft, Bottom: 3D model Maassluis TU Delft campus and city of Delft. shows the injection/extraction temperatures over time. The top and middle sub-figures show results from the axisymmetric analyses for the campus only (Scenario 1) and the campus and city of Delft (Scenario 2-Case 1), respectively. They all show that the extraction temperatures generally increase each year. The extraction temperatures are slightly higher when the well is located in the Maassluis aquifer. This is most likely due to losses due to density difference being smaller as the vertical hydraulic conductivity is lower, and that the conduction losses are smaller as the A/V ratio in this case is closer to the optimum.

The yearly thermal recovery efficiency (Equation [1], Appendix III) of the hot well is around 80% for both the Maassluis and Ommelanden formations and for both energy delivery scenario (Figure 18. HT-ATES well extraction temperatures. Top: AXI, only campus, Middle: AXI, campus and city of Delft, Bottom: 3D model Maassluis TU Delft campus and city of Delft., top and middle). The Maassluis formation gives the best performance for the hot well. The step changes in efficiency observed are due to the cut-off in previous years. When it is activated later, more production occurs, which causes more losses in the following year(s). The overall efficiency is around 7% higher for the Maassluis formation, due to the lower losses.

The overall efficiency (warm and hot well combined) is much better (around 20% higher) in the scenario with a lower warm well temperature (Scenario 2). In this situation the warm well loses much less heat, due to the lower temperature difference between the well and the surrounding aquifer, and due to the larger temperature differences between the wells, any losses contribute less strongly to efficiency changes.

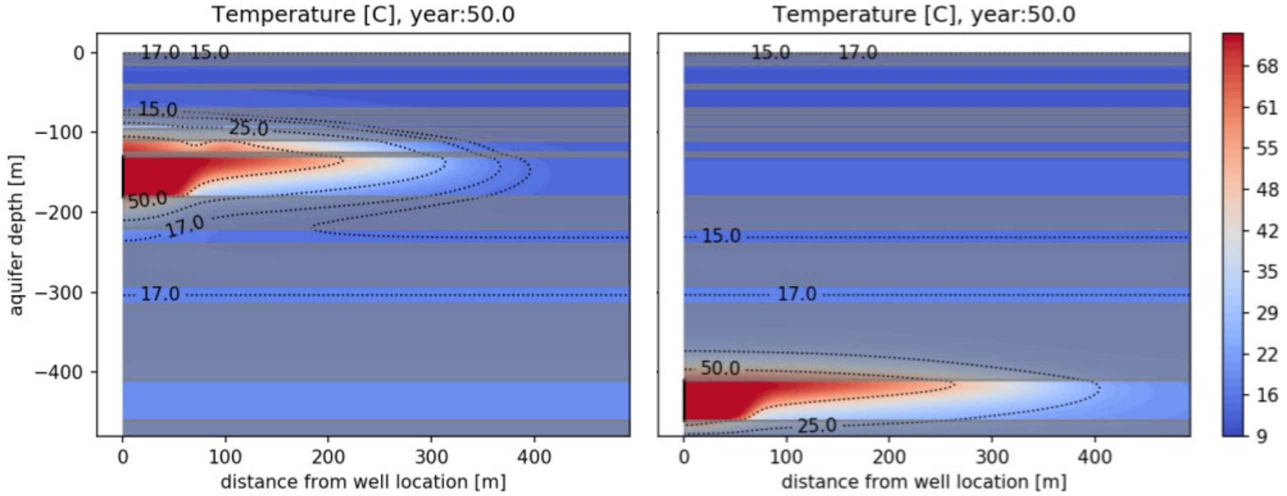


Figure 17. Temperature distribution in subsurface after 50 years of simulation for HT-ATES in Maassluis (Left) and Ommelanden (right) formations.

In Figure 18. HT-ATES well extraction temperatures. Top: AXI, only campus, Middle: AXI, campus and city of Delft, Bottom: 3D model Maassluis TU Delft campus and city of Delft. (bottom), the injection/extraction temperatures for a 3D simulation with all hot wells clustered centrally and 4 warm wells placed around the hot well demonstrate similar results as the axisymmetric analyses. In this specific simulation the distance between warm and hot wells was 2 times the thermal radius. The warm wells are shown to have a higher extraction than infiltration temperature at the end of the 10 year simulation indicates that care should be taken in optimising the well spacing.

4.4 Conclusion: Preliminary design

The preliminary design show that at the TU Delft campus, HT-ATES well configurations for the Maassluis and Ommelanden formations have roughly the same dimension in terms of the thermal radius and thus the distance between the wells. The major difference is the amount of warm wells, as well as the well depths. The Maassluis formation requires 4 hot wells and 8 warm wells, where the Ommelanden formation requires 4 hot wells and 6 warm wells.

Initial outline plans for the locations of the wells in the proximity of the DAPwell appears achievable, however further investigations need to be carried out in the next stage of the project.

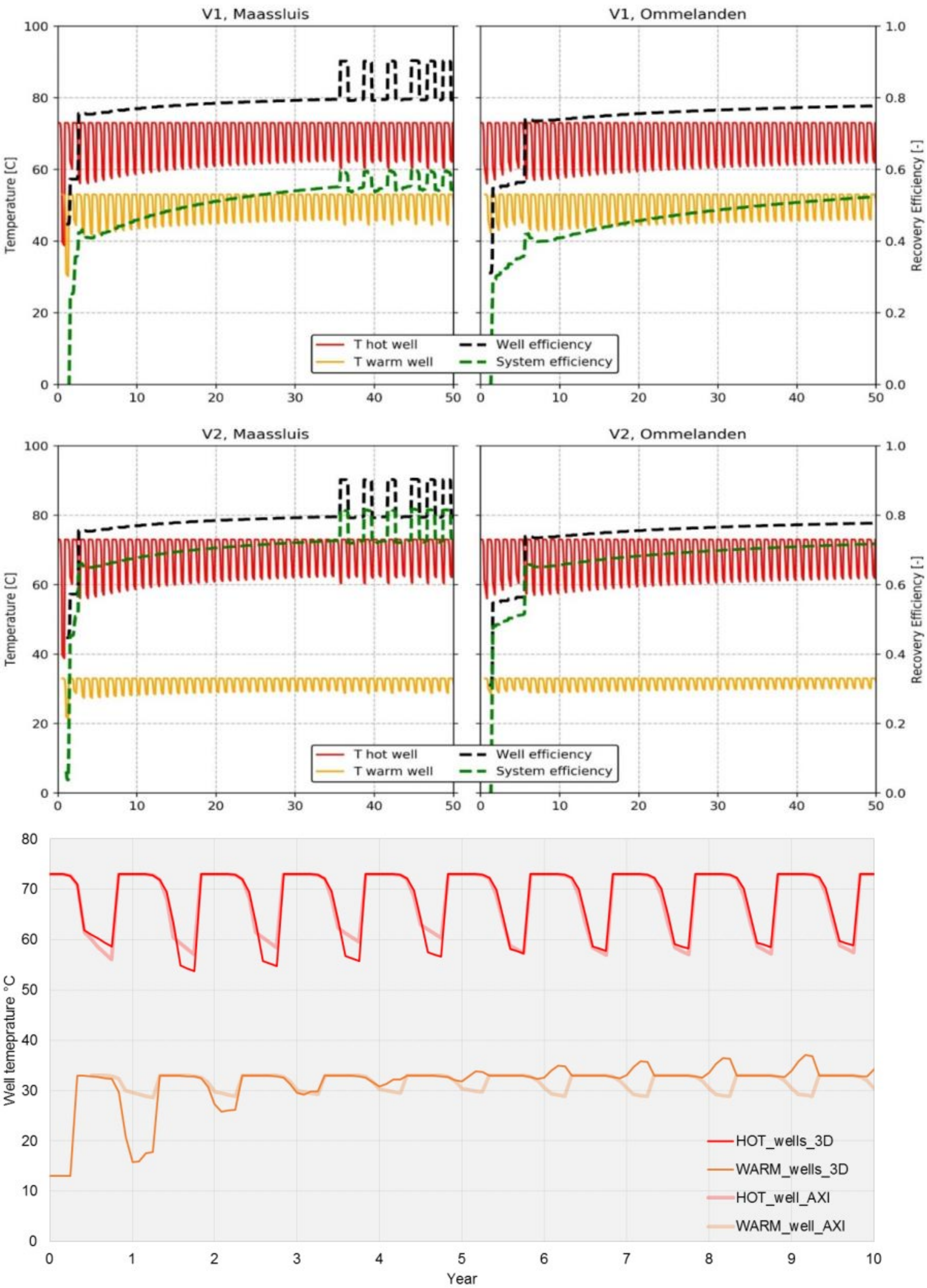


Figure 18. HT-ATES well extraction temperatures. Top: AXI, only campus, Middle: AXI, campus and city of Delft, Bottom: 3D model Maassluis TU Delft campus and city of Delft.

5 Technical feasibility IV: CO_2 savings

5.1 HT-ATES system environmental benefits

As one of the major drivers for the DAPwell project was to reduce the CO_2 emissions of the campus (due to the reduction of greenhouse gas emissions (GHGs) that are emitted during combustion of natural gas), the ability of the potential HT-ATES installation to further this goal has been quantified.

The HT-ATES system will allow a further reduction of natural gas use for heating purposes during high heat demand periods. TU Delft over the years 2013 to 2019 on average emitted ~16 000 tonnes of CO_2, with the year by year breakdown shown in Figure 19**Error! Reference source not found.**.

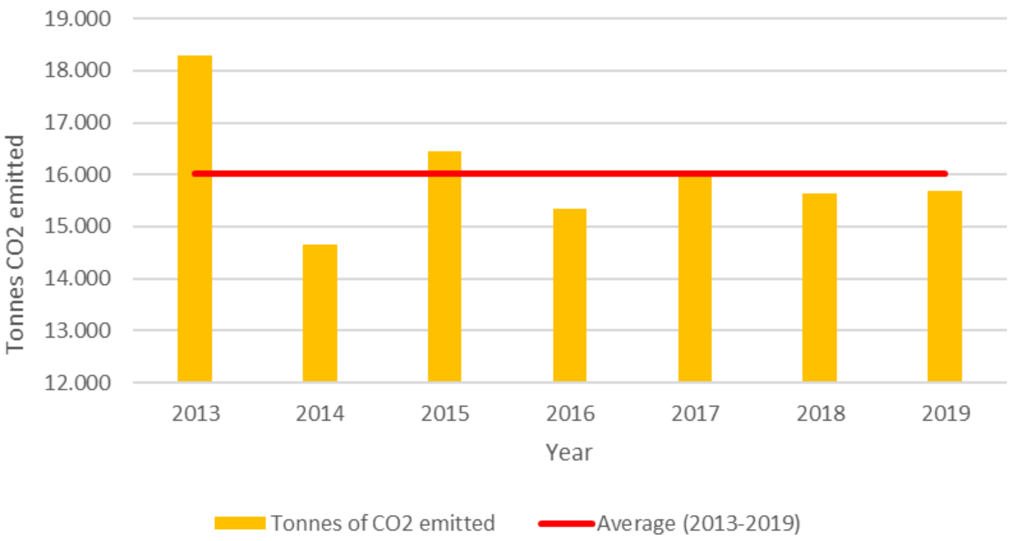


Figure 19. Yearly and average emissions of TU Delft (2013-2019) (Dutch Emissions Authority, 2020).

With the DAPwell, TU Delft has provisionally agreed to take 100 TJ or lower. This is lower than the 135 TJ directly supplied by the DAPwell calculated in Section 2.32.4. This is due to the DAPwell being able to directly supply heat during periods of time with a low demand – when without the HT-ATES system the flowrate of the DAPwell would be reduced.

The potential additional estimated maximum energy saving for TU Delft campus attributable to the HT-ATES system would be 78 TJ/year in Scenario I. Based on this value, an potential estimated 2 772 249 m^3 of natural gas use will be reduced, thus decreasing CO_2 emissions by an estimated 4 923 tonnes each year. This represents a decrease of 31%. Of course, this decrease in emissions is set to improve, with additional insulation work planned as well as decrease in overall heat demand of the campus from natural gas source. An overview of most important figures regarding environmental benefits can be seen in **Error! Reference source not found.Error! Reference source not found.**. Note, that these calculations are based on a zero CO_2 emissions electricity supply, as TU Delft purchases it electricity from a dedicated wind farm; additional costs due to this electricity supply are included in the finances in Chapter 9.

Table 12. Gas and emission reduction for HT-ATES system installation for Scenario 1 and 2-I.

	Scenario 1	Scenario 2-I*	*Unit*
Natural gas reduction	2 772 249	4 549 332	*m^3/year*
Emission reduction of CO_2	4 923	8 079	*tonnes/year*

Assuming all CO_2 cost and gas usage are equal to Scenario 1

5.2 Conclusion: CO_2 savings

A HT-ATES system will substantially increase the CO_2 saving both for TU Delft campus and the city of Delft. An HT-ATES system will increase the amount of the direct and indirect heat supplied from the DAPwell. This is both the direct heat supply, as it will be economic to have maximum flowrate for the majority of the year, and indirect heat supply as heat will be supplied from the HT-ATES system. For Scenario 1, approximately 5 000 tonnes of CO_2 emissions could be saved, and expanding the system to the city of Delft could allow another 3 000 tonnes to be saved.

6 Conclusion technical feasibility

6.1 Conclusions technical feasibility

Considering the heat demand and availability profile and quantity, it is concluded that there is potential for an HT-ATES system to significantly contribute to the sustainable heat delivery of the TU Delft campus and city of Delft. It is also concluded that several potential suitable layers for HT-ATES exist at the TU Delft campus, of which the most suitable is the Maassluis formation at 130 m depth. Table 13 provides an overview of the main benefits and characteristics of an HT-ATES system connected to the DAPwell in Scenarios 1 and 2. With a flow capacity of about 535 m^3/h (i.e. 5 MW in Scenario 1) around 89% of the TU Delft heating demand can be delivered from sustainable resources, increasing from under 70% with only the DAPwell. In Scenario 2-I, the same sized system, delivers (368 - 178 =) 190 TJ to the city of Delft (DAPwell delivers 140 TJ (275 – 135) directly to the city, the HT-ATES 50 TJ (93 – 43), in total 190 TJ).

Table 13 Overview HT-ATES characteristics

	Scenario 1	Scenario 2-I	*Unit*
Total heat DAPwell and HT-ATES	178	368	*TJ/y*
Directly by DAPwell	135	275	*TJ/y*
Heat supply attributed to HT-ATES*	78	128	*TJ/y*
Potential CO_2 saving	4 923	8 079	*tonnes/y*
HT-ATES			
Total available heat for injection**	100	210	*TJ/y*
Total heat extraction	43	93	*TJ/y*
Storage volume	1	1	*Mm^3/y*
Flow capacity	535	535	*m^3/h*
Thermal capacity	5	22	*MW*
Hot well temperature	73-63	73-63	*°C*
Warm well temperature	60-50	n.a.	*°C*
Cold well temperature	n.a.	33-23	*°C*
Number of hot wells	4	4	-
Number of warm wells	6-8	6-8	-
Simulated hot well efficiency***	~80%	~80%	*%*
Simulated system efficiency	~55% (Maassluis) ~50% (Ommelanden)	~70%	*%*

* Due to heat supplied by HT-ATES systems and increasing amount directly supplied by DAPwell

** Maximum potential heat to be stored. Simulations indicate that this number can be reduced, to be further elaborated in next steps. An R&D shutdown for up to 6 weeks is possible during the summer due to dual R&D and commercial nature of the DAPwell project, this would reduce the available heat.

*** The simulated recovery efficiency (Chapter 4) is higher than that assumed earlier (Table 3 and Table 4) and indicates that the total extracted heat from the HT-ATES is likely to be larger compared to the number presented in this table and used for further evaluation in the business case.

6.2 Next steps

6.2.1 Increasing level of detail of assumptions and current design

Further steps to improve design and expected performance comprise of:

- Detailed analysis of temporal variations in development of heat demand campus, e.g. will the summer stop stay when DUWO houses are connected?
- It was assumed that the geothermal well will produce at its full capacity throughout a year. However, it is not likely that the geothermal well is running throughout the whole year. Other geothermal projects have indicated that around 10% of the time the geothermal well will not produce any heat.
- Well design and flow capacity of the HT-ATES is to be further specified taking into account geohydrological conditions and more detailed analysis of heat availability and demand.
- Identification of size and location of current and future low temperature ATES systems in Maassluis formation, which should be carefully considered when determining the location of the high temperature ATES well such that they won't influence each other negatively.

6.2.2 Uncertainty reduction of Oosterhout and Ommelanden formations

To a depth of 240m detailed logs are available from drillings at the TU Delft campus and city centre. Less detailed but deeper drilling logs and the REGIS model provide some information on Oosterhout and Ommelanden. Therefore, the characteristics and properties of the Oosterhout and Ommelanden formations are uncertain. As a results of this uncertainty one of these layers may be more suitable than the Maassluis formation. To confirm Maassluis to be the best or show Oosterhout or Ommelanden can better be used, some more detailed information needs to be gathered. The drilling of the DAPwell and associated monitoring well will penetrate these formations, which offers a window of opportunity to collect additional data from these layers.

The drilling of the geothermal well presents a good opportunity to investigate the subsurface layout and the promising layers for the HT-ATES well. During the drilling and logging focus should be put on determining:

- Thickness of Oosterhout and Ommelanden formations (290m-310m) and (410m-460m)
  - Analysis of cuttings and logs.
- Material properties, chemical composition and hydraulic conductivity of Oosterhout and Ommelanden formation, samples from 300m, 430m and 450m.
  - Some samples/cuttings need to be taken and tested to give insight in material properties.
  - Undisturbed samples to determine the hydraulic conductivity and chemical composition.
- The composition of the confining layers in the Ommelanden formation (samples from 400m and 470m).
  - cuttings/logs.

6.3 Technical risks assessment

Item	Risk	Mitigation
Uncertainties characteristics target aquifer and confining layers, resulting in more expensive wells	High	More information will be gained by means of experiments and data acquisition during the drilling and completion phase of the DAPwell. Adapt well design accordingly
Heat availability and demand in practice make viable/sustainable operation impossible	High	Sensitivity of the business case should be established and staged construction can limit risk. Sensitivity analysis on heat demand and return temperatures.
Wells give too low yield	Medium	Test drilling, use DAPwell logging to obtain more info on target layers Design on the safe side, i.e. increase number of wells
Clogging of well or heat exchanger due to scaling	Medium	Test drilling, use DAPwell logging to obtain more info on target layers, and geo/water chemistry Adapt the installed water treatment Clean/regenerate the system
Too much heat loss in subsurface	Medium	Test drilling, use DAPwell logging to obtain more info on target layers Optimise design for optimal recovery: lower cut-of temperatures, well locations/design
Soil subsidence / swelling	Medium	Thermal expansion of soil is low and can be tested in the laboratory.
Material failing: pumps, well, completion, valves, heat exchanger, etc.	Medium	Spend enough time and effort on conceptual and detailed design studies. Use all available data from the surrounding systems and DAPwell in order to develop a system that fits the requirements.
Too high return temperatures in the DHN	Medium	Robust design of DHN and heat exchangers. Analysis and optimisation of building management systems.
Not possible to find well suitable locations	Medium	Minimise number of wells, timely discussion with CRE, municipality and possible other landowners about well locations.
Environmental effects are larger/other than expected	Low	Risk management System Monitoring program

7 Policy and permit

7.1 Legal framework

The legal framework that needs to be abided by for HT-ATES depends on the depth at which HT-ATES will be installed. Until 500 m-mv the water law regime is applicable, while at depths of over 500 m below ground surface (m-mv), the mining law will be applied. Pressure, temperatures and the risk of uncontrolled outflow of hydrocarbons increase with depth. For this reason the activities at depths of > 500 m-mv are subject to a stringent safety regime. The overview in Figure 20 shows the characteristics of the different regimes.

Figure 20. Characteristics of Water Law versus Mining Law.

This study focuses on aquifers up to 500 m-mv depth, which is within the scope of the Water Law regime. The planned HT-ATES depth of this project does not reach a deeper than 500 meters with (planned) targeting of the Maassluis or Ommelanden formations. Thus, the Water Law is the relevant law.

7.1.1 Rules for HT-ATES under the Water law

Both ATES and HT-ATES are covered by the term ‘open loop geothermal energy systems’: systems that store and extract cold or heat from the soil, by using the groundwater as a carrier for heat transport. Extraction and infiltration of groundwater for the benefit of ATES is subject to licenses under the Water Law. ‘Gedeputeerde Staten’ of the province is the competent authority (article 6.4 of the Water Law).

7.1.2 Amended Decree on ATES and BHE systems

The Wijzigingsbesluit Bodemenergiesystemen (Ministry of Infrastructure and the Environment, 2013) came into force on July 1, 2013. Article 6.11 of the Water Decree states that infiltration temperatures for ATES are not allowed to exceed 25 °C and may not have long-term heat surplus in the subsurface. However, exceptions can be made to the interest of effective usage of the ATES system. On this basis the HT-ATES system are eligible to be licensed. How the license consideration takes place is not described in the legal documents.

7.1.3 **Provincial policy for permitting HT-ATES**

Provinces have set a common approach for permit issuing of ATES (SIKB, 2015) and BHE systems, "Besluitvorming Uitvoerings Methode" (BUM). HT-ATES does not meet the standard requirements set out in the BUM, due to the infiltration temperature exceeding 25 °C and the long-term heat surplus in the soil. The BUM states that it is possible to deviate from the standard regulations in case systems are implemented as a research project, and the BUM concretely states that HT-ATES is also seen as such. It can be concluded that provinces may grant licenses for HT-ATES pilot projects and that no other interests are harmed.

The province of South Holland has shaped its policy regarding ATES in the work program 'Bodem en Ondergrond 2016-2020' (Provincie Zuid-Holland, 2015). The province of South Holland states in this document that the province is willing to allow HT-ATES pilot projects. The province of South Holland has granted a 5 year license for the HT-ATES pilot project Koppert-Cress as part of the Green Deal. Besides this project, there are several initiatives being discussed where HT-ATES systems are connected to existing geothermal sources and district heat networks.

7.1.4 **Required permits**

Development of HT-ATES at TU Delft will require a water license. For this purpose, the effects of the ATES system must be quantified by doing in an impact study. 'Gedeputeerde Staten' of the province of South Holland is the competent authority. Executive body "Omgevingsdienst Haaglanden: carries out the assessment of permit requests and issues permits for ATES systems on behalf Gedeputeerde Staten of the province of South Holland. The procedure time for applying for the Water law license is approximately 8 weeks. In the case of complex environmental interests, the province may deviate from this and declare the extensive procedure (lasting 6 months) is applicable. Since HT-ATES is not a standard/regular ATES system the 6 months procedure applies to this initiative. In practice, it is desirable to coordinate the licensing procedure with the competent authority before starting the official legal procedure for obtaining the Water law license.

Additionally, at the intended HT-ATES location, a zoning plan for regular ATES systems is in force (IF Technology, 2013). The competent authority for this zoning plan is the Municipality of Delft. It is expected that the development of HT-ATES fits within the zoning plan.

7.2 Interference with other interests

Due to the many systems in the area it is critical to have the overview of the locations of all existing ATES systems as well as the DAPwell. At the TU Delft campus there are various operational ATES systems, with additional systems planned for the near future (Figure 21).

The ATES plan was developed in order to avoid negative effects of mutual interaction between wells of differentiated temperature levels and optimise the usage of the subsurface. The Faculty of Applied Sciences (TNW) system is developed in the Maassluis formation, distance from CHP is 1.4km. Except for the TNW Zuid system all systems are developed in the Waalre formation with a maximum depth of 75m-mv.

The location of the HT-ATES wells will be selected to ensure minimal thermal disturbance of the existing ATES systems. The minimum vertical distance between top of the HT-ATES system and the bottom of LT- ATES systems is about 55m. The simulation results (Figure 17) show that LT-ATES systems in Waalre formation may experience some temperature effects when HT-ATES is applied in the Maassluis formation, as temperature changes to about 15°C. When the heat loss of the

HT-ATES affects the warm well of a LT-ATES this may have a positive effect on its performance. However, in these simulations, the LT-ATES systems are not included, therefore the exact effect on them cannot yet be quantified. There are no temperature effects observed in the case when HT-ATES is applied in the Ommelanden formation. More detailed simulations, including these well in operation should show how large this effect exactly is. The initial simulations indicate that HT-ATES is possible in the Maassluis formation, but care should be taken to ensure that the hot wells can be placed at a given minimum distance from the cold wells of LT-ATES systems.

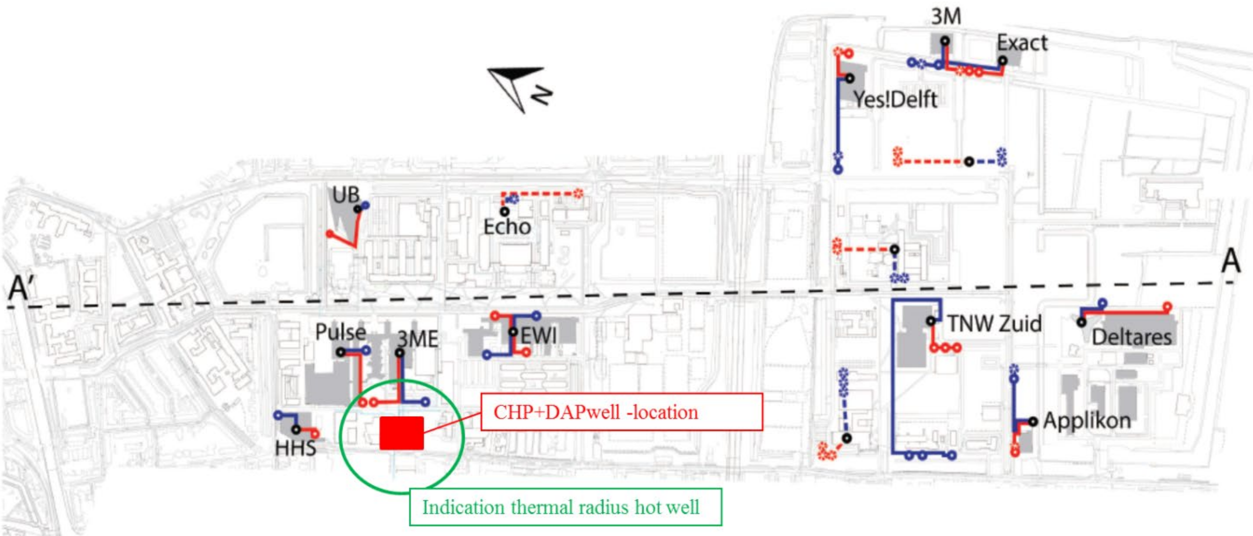


Figure 21. ATES systems currently in use at the TU Delft campus area and planned systems (dashed). Also the CHP and DAPwell drilling pad are indicated.

7.2.1 Stakeholder management

A crucial element in the successful development of both DAPwell and HT-ATES projects is stakeholders management. Such projects require cooperation with the relevant stakeholders like the province, municipality, water authority, interest groups, landowners, people living in the vicinity, etc. As the DAPwell project team is several years ahead of the HT-ATES project, and both projects aim for using the same locale, close cooperation and eventually integrating stakeholder management and communication activities of the HT-ATES system will be beneficial. In depth stakeholder analysis and developing a stakeholders management strategy will be an important subject in the next phase.

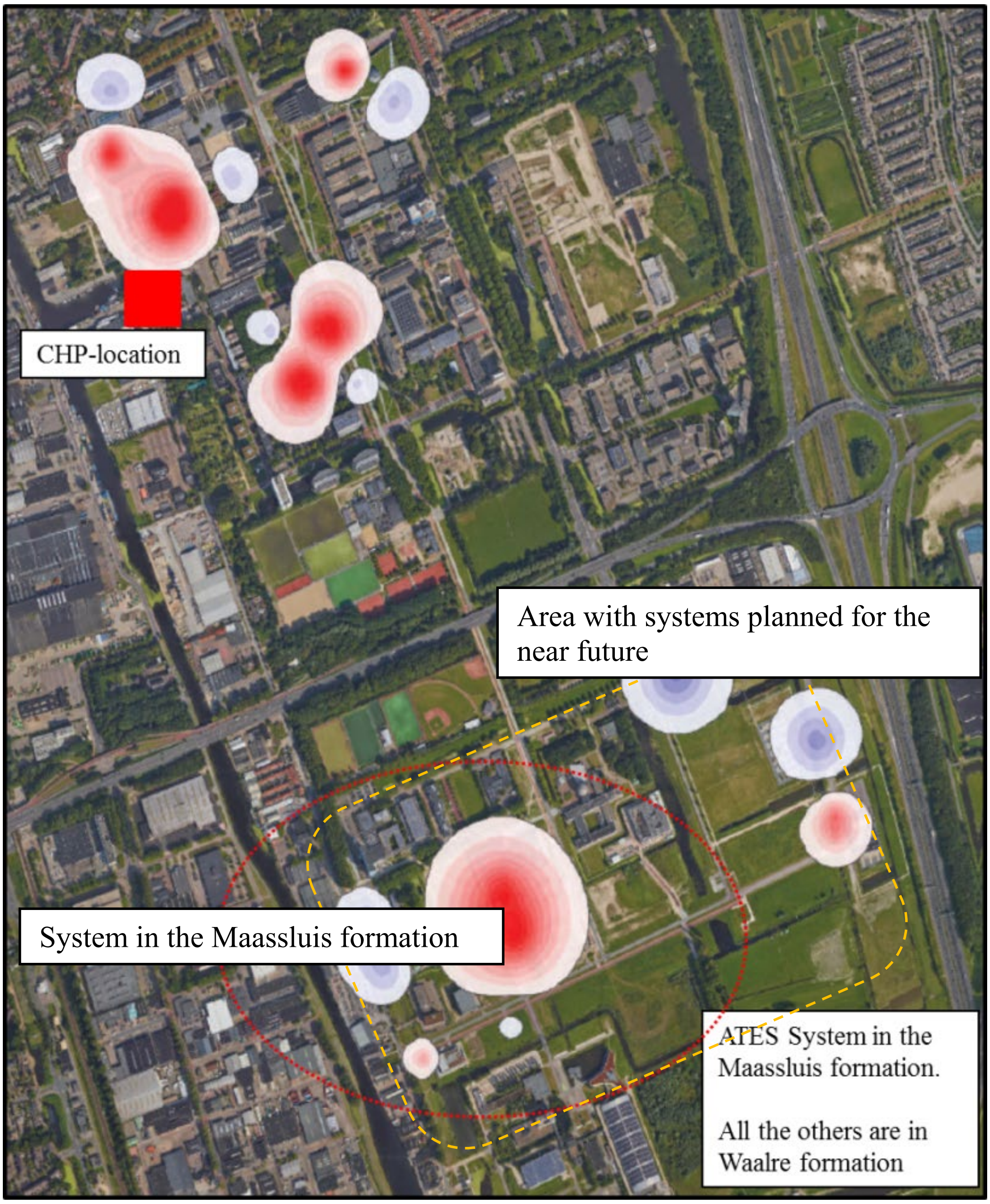


Figure 22. Thermal zones at the end of summer, based on average storage after 20 years operation. Red dashed circle indicates the system in the Maassluis formation. In the yellow dashed area new systems are planned.

7.3 Policy & permit risks assessment

Item	Risk	Mitigation
Permit not issued	High	Involve province, municipality and other stakeholders in early stage, agree on process and criteria for issuing of permits.
Public resistance, causing delays in the permit process or even prevent issuing of permit	High	Close cooperation with project team of the DAPwell. Streamline and integrate stakeholder management and communication activities of the HT-ATES with the stakeholder management and communication of the DAPwell.
HT-ATES impact cold wells of existing ATES systems or other interests. Permit is withdrawn during operation.	Medium	Careful impact assessment during design. Keep sufficient distance between the hot HT-ATES and cold ATES wells and other interests. Possibly the well configuration needs to be adjusted accordingly. As an alternative, the cold ATES well could be relocated. Monitoring plan
Only temporary permit (e.g. 5 years)	Medium	Involve province, municipality and other stakeholders in early stage, agree on process and criteria for issuing of permits.
Additional monitoring prescriptions given by the competent authority resulting in higher costs and deteriorating the business case towards a No-Go	Medium	Involve province, municipality and other stakeholders in early stage, agree on process, criteria and key effects to monitor for issuing of permits Investigate manners of public funding of additional costs due to the demonstration and additional monitoring efforts.
Disturbance of subsurface chemistry and integrity	Medium	Careful impact assessment during design. Use certified contractors
More expensive permit procedure	Low	Involve province, municipality and other stakeholders in early stage, agree on process and criteria for issuing of permits.

7.4 Conclusions policy and permit

The targeted reservoirs within this study do not reach deeper than 500 meters, which is within scope of the Water Law regime, with ‘Gedeputeerde Staten’ of the province as the competent authority. As the infiltration temperature exceeds 25 °C and the long-term heat surplus in the soil will occur HT-ATES does not fit standard ATES regulations. It is possible to deviate from these in case systems are implemented as a research project, which also account for HT-ATES projects. In order to make sure other interest are not harmed, the effects of the ATES system must be quantified by doing in an impact study. It can be concluded that provinces may grant licenses for HT-ATES pilot projects if no other interests are harmed.

At the TU Delft campus, various ATES systems are operational and several are planned in the near future. Except for one system which is located at sufficient distance, all other LT-ATES systems are developed in the Waalre formation having maximum depth of 75 meters. Initial simulations show that HT-ATES is possible in both target reservoirs, however more detailed simulations should be carried out in order to determine the exact effects.

8 Science case HT-ATES TU Delft

8.1 Research programme

An HT-ATES system on the TU Delft campus, alongside the DAPwell, would increase sustainable energy use and improve the efficiency and business case of the DAPwell. Additionally, an HT-ATES system would contribute significantly to the core tasks of the university, i.e. research and education, being part of a 'living laboratory'.

HT-ATES is a technology in development. There are many research questions concerning the widespread successful application of HT-ATES that need to be solved – although initial pilots and knowledge from non-HT-ATES systems have given confidence that systems can be designed and operated. These research questions not only relate to specific HT-ATES related issues, but also the integration and operation in heat networks and connected buildings. This makes the HT-ATES application at TU Delft campus a large opportunity, where such issues can be addressed. Together with the DAPwell, a well instrumented HT-ATES system (together with the existing ATES systems) will make TU Delft stand out as an international research institute on shallow and deep geothermal energy in the urban environment. In the light of the energy transition there also is a clear human resource challenge, boosting geothermal research will also attract students interested in working in the energy transition. The experience and data collected by running a HT-ATES on campus offers cases for courses, and data to be analysed in assignments and graduation theses.

Therefore, the HT-ATES system at TU Delft would have two primary goals: (i) to increase the supply of sustainable heat, and (ii) to create a unique education and research infrastructure of Worldwide relevance. The scientific programme that will be accommodated within the design of both DAPwell and the HT-ATES system will be developed with the following requirements in mind:

- To perform experiments and data acquisition during the drilling and completion phase of the wells;
- To perform experiments and data acquisition during multiple storage cycles and the full lifecycle of the HT-ATES.
- To research an integrated geothermal heating system in an urban environment, including challenges associated with demand management in buildings and transforming the conventional DHN to a future-proof DHN at various temperature levels.
- To allow access to other universities or institutions with active programmes in the field of Geothermal Science and Engineering to jointly carry out research and perform experiments.

The financing of the research programme will be modelled on the financing of the research programme in DAPwell, i.e. it will be separate from the operational financing. Close cooperation between both the research programme and operations programme is required to ensure that the joint primary goals can be achieved.

8.2 Research question HT-ATES

This section gives an overview of research opportunities arising from the presence of an HT-ATES on campus. The research activities will result in a wide range of innovations and enhanced knowledge in multiple scientific fields:

- Enhanced knowledge on the coupled thermo-hydro-mechanical behaviour of poorly-/ unconsolidated aquifers at elevated temperatures.
- Improved predictions on the operation of HT-ATES systems.
- Improved reliability of HT-ATES systems.
- Asses efficiency and effect of different storage cycle lengths (days, weeks, season)
- Improved efficiency and reduced CO_2 emissions from district heating networks in general and from geothermal heating systems specifically (>95% reduction compared to gas systems).
- Enhanced knowledge on transforming a conventional DHN to a future-proof medium-temperature DHN.
- Enhanced knowledge on optimal integration of (existing) buildings in medium-temperature DHN.
- Enhanced knowledge on transforming HVAC installations in buildings to cope with lower supply temperatures and deliver lower return temperatures.
- Enhanced knowledge on optimising a smart heat management system.

8.2.1 Underground heat transport

Key questions:

- How does buoyancy flow, driven by higher temperatures, occur in real conditions?
- How do heat losses, via conduction and free convection of heat from the storage system, develop?
- How do heterogeneous/anisotropic aquifers affect the heat transfer?
- What is the impact of thermal properties (heat capacity and thermal conduction) on thermal retardation?
- Does the heat transfer through confining layers follow predictions?
- What are the possible environmental effects on penetrated layers?

Methods:

- Network of distributed temperature sensing (DTS) fibre optic cables around the wells.
- Electro-magnetic geophysics.
- Cross-hole pulse testing.

8.2.2 Geochemistry

Key questions:

- How does geochemistry impact the aquifer properties and technical facilities?
- What water treatment techniques prevent precipitation/clogging?
- What is the impact of significantly elevated temperatures on water quality?

Methods:

- Fluid sampling at regular intervals
- Logging of wells to investigate reservoir changes
- By-pass facility to test impact of fluid chemistry during operations

8.2.3 Well design and completion

Key questions:

- What casing materials are possible given higher temperatures and in situ fluid chemistry?
- Can wells be designed to offer improved control on advective heat transport – to mitigate the adverse impact of buoyancy flow?

- Is clogging likely from mineral precipitation and transport of fines?
- Which well design concepts improve production rate in low permeable aquifers?

Methods:

- By-pass facility to test precipitation and fines transport during operations?
- Laboratory testing of casing materials and deployment of multiple options in operating wells?
- Network of distributed temperature sensing (DTS) fibre optic cables around the wells.
- Lab/field tests of new well design concepts

8.2.4 System integration

Key questions:

- How can available or new subsurface data be utilised to increase project performance?
- How can HT-ATES systems operate most efficiently in a geothermal heating system?
- How can systems be designed to maximise efficiency?

Methods:

- Simulate and test control approaches.
- Integrate available data from whole heating system.
- Detailed performance monitoring.

8.2.5 Surface and sub-surface thermo-hydro-mechanical effects

Key questions:

- How does increased temperatures affect stability and permeability of the reservoir and cap-rock?
- How does flow and thermal cycles impact fines transport, and how does this affect strength and deformation of the reservoir and cap-rock?
- Is thermal consolidation of the cap-rock and underburden significant?
- Is thermal collapse (plastic deformation due to elevating temperature in geomaterials) occur?
- Is subsidence observable and predictable?

Methods:

- Laboratory testing of material sampled during installation.
- Monitoring of surface settlements via satellites and fixed points.
- Develop simulation models including thermal consolidation.
- Monitoring changes in fluid composition and geochemistry.

8.2.6 Monitoring

Key questions:

- How can unexpected occurrences be identified early?
- How can operational decisions be informed by monitoring?
- How can operational data be integrated into short and long term predictions of system performance?

Methods:

- Analysis of geophysics, temperature/pressure and satellite data.
- Comparison of measured data with predictions.
- Data assimilation techniques.

8.3 Funding

A substantial investment in infrastructure and baseline monitoring is required prior to and during the system installation and during the early operating phase. There are two major funding options identified for this purpose shown in Table 14. For ongoing research activities, a variety of funding sources are anticipated, such as shown in Table 15.

Table 14. Available funding schemes for large scale research infrastructure.

Funding source	Call	Funds available	Comments
NWO Large-Scale Research Infrastructure	Likely 2022	Ms€	Funding applications in multiple stages. First stage in 2020 was to include HT-ATES in the roadmap as part of a phase 2 EPOS-NL..
RVO	DEI	95 M€ (2020)	Energy efficiency and renewable energy, gas free neighbourhoods are major topics.

Table 15. Available funding schemes appropriate for ongoing research in HT-ATES.

Funding source	Call	Funds available	Comments
Topsector Energy	TKI New Gas Programme line GeoEnergy	Depending on available industry match funding	Input to technical aspects of design and impacts on society. New call.
Topsector Energy	RVO-TKI Urban Energy tender	4.15 M€	Programme line “Flexibele Energie-infrastructuur”, incl. aardwarmte en ondergrondse opslag (max. 1M€ per project)
NWO-TKI Urban Energy	ERA-Net Regional Energy Systems	1.6 M€ for NL (max. 800k€ per project)	Integration of energy systems.
NWO-TTW	Open Technology Programme	~800k€ per application	Continuous applications
Dutch Science Agenda (NWA)		0.5-10M€	Route energy transition
Geothermica		4m€ for Netherlands	Regular calls
EU FP9	Renewable Energy Solutions	Several 10sM€	Heat storage is prominent within FP9 drafts.

8.4 Risk assessment scientific programme

Item	Risk	Mitigation
Scientific programme cannot achieve funding at the same time as operational project is financed	High	Infrastructure already included within the large-scale infrastructure roadmap. Project development can be uncoupled from DAPwell to enable more flexibility. Limited own-investment in research infrastructure can enable smaller research programme to continue without initial funding.
Scientific programme in conflict with operational programme	Medium	Close cooperation of project teams and learning lessons from DAPwell. Streamlining of objectives at the start. Partnership on operations and science.
Project is not successful	Medium	Pilot studies have suggested technology is ready for real-scale implementation. Staged development, e.g. testing single well before drilling multiple wells will enable staged research funding spend. A substantially reduced research programme on subsurface properties could be carried out even if the project is not successful, and many implementation lessons could be learnt.
Sustained funding not available	Low	A variety of sources are available.

8.5 Conclusions science case

An HT-ATES system, built in conjunction with the deep geothermal well (DAPwell), will enable key societal questions on future heating systems to be answered. Fundamental and applied scientific questions will enhance the state-of-the-art knowledge and engaged students will feed a developing industry with well-qualified personnel. There is a substantial amount of funding available and research topics can be covered in several faculties in the university.

9 Financial feasibility

9.1 HT-ATES system cost

The specific costs of the HT-ATES system are divided between two specific categories, CAPEX (capital expenditures) occurring during system build/installation phase and OPEX (operational expenditures) recurring throughout the operation timeline of the installation. Estimated costs that were taken into account for the business case model development are estimated costs involved in HT-ATES system installation, based on previously outlined technical information (Chapters 2 to 5) and practical industry experience. Both OPEX and CAPEX values were developed to be as representative as possible to real costs that would be incurred for HT-ATES installation with previously outlined technical requirements. However detailed design in the next phase will be the basis for more detailed cost estimation. Currently, most uncertainties can be found at the location of the wells (piping length), material use for the hot wells, exact drilling depths (based on DAPwell findings), and fitting the surface plant into the existing DAPwell plot.

9.1.1 Investment costs (CAPEX)

The major part of capital expenditure of HT-ATES system installation are attributed to following aspects:

- HT-ATES wells
- Surface plant
- Distribution network (connections & piping)
- Permits, engineering and construction

Table 16 shows the estimated costs (excluding VAT) of the complete HT-ATES system. The costs outlined are representative on industry standard estimations, based on experience in ATES and geothermal system development.

Table 16. CAPEX breakdown of expected HT-ATES installation for Maassluis & Ommelanden.

	Maassluis	**Ommelanden**	*Unit*
HT-ATES wells	1 880	3 288	*k€*
Surface plant	960	900	*k€*
Permits, Engineering & construction	284	419	*k€*
Contingency	284	419	*k€*
Total	**3 408**	**5 026**	***k€***

HT-ATES wells

The HT-ATES wells post consist of hot and warm wells, completions, filter, electric submersible pump (ESP), piping and cabling. Cost for realisation of the system, such as drilling, cleaning and installation of the various instruments, are included as well. The breakdown of well costs can be seen in Table 17. Cost estimates of the hot wells show the highest degree of uncertainty as high operating temperatures require non-standard ATES materials, like glass-fibre reinforced epoxy (GRE) piping and stainless steel filters. The major differences between the systems arise due to the differences in depth.

Table 17. CAPEX breakdown of HT-ATES wells for Maassluis & Ommelanden.

	Maassluis	Ommelanden	*Unit*
Hot well	**232**	**465**	***k€***
- *Drilling*	*102*	*290*	*k€*
- *ESP*	*100*	*140*	*k€*
- *Appendages*	*20*	*25*	*k€*
- *Cellar*	*10*	*10*	*k€*
Warm well	**119**	**238**	***k€***
- *Drilling*	*79*	*188*	*k€*
- *ESP*	*15*	*25*	*k€*
- *Appendages*	*15*	*15*	*k€*
- *Cellar*	*10*	*10*	*k€*
# hot wells	**4**	**4**	#
# warm wells	**8**	**6**	#
Total	**1880**	**3288**	***k€***

Surface plant
The HT-ATES surface plant is a surface installation that will be integrated within the existing heat plant buildings and consist of the piping between the wells, heat exchangers, buffer system (20m^3), distribution pump and water treatment installation. Table 18 shows expected costs of HT-ATES system installation in either Maassluis or Ommelanden formations, based on industry standard and target formation specifics. The (minor) differences arise due to the different number of wells required.

Table 18. CAPEX breakdown of Surface plant for Maassluis & Ommelanden.

	Maassluis	Ommelanden	*Unit*
Piping	460	400	*k€*
Heat exchangers	280	280	*k€*
Distribution pump	20	20	*k€*
Buffer system	30	30	*k€*
Water treatment installation	20	20	*k€*
Building construction	50	50	*k€*
Connection to the district heat network	100	100	*k€*
Total	**960**	**900**	***k€***

9.1.2 Operational costs (OPEX)

The HT-ATES system operational expenses are anticipated from (Table 19 and Table 20):

- Maintenance and replacement of parts
- Water treatment
- Monitoring and water quality assessment
- Electricity use (Table 20)

Table 19. Yearly maintenance OPEX breakdown of HT-ATES system.

	Maasslluis	Ommelanden	*Unit*
Maintenance of the wells	**200**	**238**	*k€*
- *Long run maintenance*	*2 (x12)*	*3 (x10)*	*k€*
- *Small maintenance*	*3 (x12)*	*3 (x10)*	*k€*
- *Electrical submersible pump (ESP), hot*	*20*	*28*	*k€*
- *Regeneration*	*64*	*108*	
Maintenance of the surface plant	**40**	**40**	*k€*
- *Long-term maintenance*	*16*	*14*	*k€*
- *Small maintenance*	*24*	*22*	*k€*
Water treatment	**31**	**31**	*k€*
Monitoring and reporting	**30**	**30**	*k€*
Total	**245**	**293**	***k€***

Maintenance
Regarding the yearly maintenance costs (Table 19), the largest costs come from the 5 yearly regeneration of the wells and replacement of the ESP. In long run maintenance other replacement cost are taken into account. Small maintenance represent various maintenance activities, mostly man-hours, that will be required to ensure optimal performance during years of operation.

Water treatment
It is assumed that hydrochloric acid solution dosing will be utilised in both target layers to treat stored water. It is estimated that 5 litres of HCl (30% concentration) will be required for 1 MWh of energy stored. Based on this assumption, and a cost of 200 €/tonne of HCl (including transportation), it is calculated that for water treatment an investment of 1.15 €/MWh (0.32 €/GJ) of stored heat is required. For expected amount of energy stored yearly, the average OPEX cost for water treatment comes to €31k per year.

Monitoring
OPEX costs for monitoring are composed of compensation for monitoring, interpretation and the yearly inspection. The required certification costs are also covered under this operational cost estimation.

Electricity Consumption
The electricity costs for the facility operation (Table 20) is based on the energy needs of the pumps, with other electricity demanding machinery costs assumed to be sufficiently represented under the pump energy use estimations (explained below). To estimate electricity use in the system, expected pressure of the system (and hydraulic power needed), flowrate-based estimations of system loading/ discharging hours per year, as well as an inefficiency factor were taken into account. All of the assumptions taken for calculations of electricity consumption for HT-ATES operation can be seen in Table 21 below.

Table 20. Yearly electricity cost (OPEX) breakdown of HT-ATES system.

		Unit
Electricity needed for facility	1389	*MWh/year*
Electricity cost (+ tax)	0.094	*€/kWh*
Total electricity costs	**131**	***k€/year***

Table 21. Assumption breakdown for HT-ATES electricity use calculations.

		Unit
Pressure difference (system)	10	*BAR*
Pump efficiency	60	*%*
Hydraulic power needed (est.)		
- *Charging (320 m^3/h)*	*148*	*kW*
- *Discharging (535 m^3/h)*	*248*	*kW*
Hours of pumping (est.)		
- *Charging*	*3 125*	*h/year*
- *Discharging*	*1 870*	*h/year*
Inefficiency factor	50	*%*
Electricity needed for pumps		
- *Charging (3125 h @ 320 m^3/h)*	694	*MWh/year*
- *Discharging (1870 h @ 535 m^3/h)*	695	*MWh/year*
Total electricity use*	**1 389**	***MWh/year***

*The total electricity is thought to be conservative due to the inefficiency factor

These values were utilised in calculations to ensure sufficient energy use is estimated, as pumps not only pump water to and from target formation, but also have to overcome heat exchanger pressure difference. Over the period of a calendar year, the HT-ATES loads and discharges the system in various flowrates (with only the peaks peak charging and discharging in 535 m^3/h and 320 m^3/h flowrates, respectively), thus an estimated inefficiency factor allows to simplify calculations of electricity use, while ensuring whole facility electricity needs are sufficiently represented. The electrical pumps would require 148 and 248 kW of power for charging and discharging hot water at peak flowrates, respectively. Based on 1 Mm^3 of storage volume, charging and discharging values were found for estimate hours of pumping. With the inefficiency factor taken into account, the electricity demand of the system was calculated and found to be ~1 389 MWh/year. Costs are similar for each system due to approximately hydrostatic in situ water pressure.

Table 22 gives final values of yearly expenses expected for the HT-ATES operation and calculated heat storage cost per GJ delivered. The largest contribution to operational expenses of HT-ATES plant operation comes from electricity use of the facility operation, as well as man hours and supervision/maintenance of the facility. Without taking into account extra costs of research oriented expenses in operational sense, operational costs per year can be estimated quite accurately from industry ATES project development and operation experience, and industry standards.

Table 22. Total OPEX cost per year for HT-ATES system.

	Maassluis		Ommelanden		*Unit*
	Scenario 1	Scenario 2-I	Scenario 1	Scenario 2-I	
Total OPEX costs* *(based on total maintenance + electricity)*	**376**	**376**	**424**	**424**	*k€/year*
Yearly depreciation *(CAPEX is written of over 15 years)*	**227**	**227**	**335**	**335**	*k€/year*
Delivered heat cost *(based on total yearly costs)*	**14.16**	**4.83**	**17.65**	**6.07**	*€/GJ*

*please note: Scenario 1 and 2-I OPEX cost do not change because same amount of water is pumped. GJ price changes due to more heat delivered to city and lower return temperature.

Considering the overall operational costs estimation of the HT-ATES installation (representative after the CAPEX is depreciated after 15 years), 1 GJ of heat delivered in from Maassluis formation would cost €8.75 in Scenario 1 and €3.01 in Scenario 2-I, while from Ommelanden €9.86 and €3.39 respectively. Overall, it can be seen that operational expenses will be larger if project targets Ommelanden rather than Maassluis formation, due to additional maintenance costs of the system.

9.1.3 HT-ATES system CO_2 saving cost benefits

The CO_2 savings, quantified in Chapter 5, also have a financial benefit, which is quantified in Table 23. The maximum amounts relate to both the additional heat supplied directly from the DAPwell (due to running at maximum flowrate for the entire year) and the minimum those supplied directly from the HT-ATES system.

The financial benefits arise from both the reduction of both natural gas purchases as well as reduction in CO_2 emission rights purchases. Combined, both reduction of rights purchases and natural gas purchase reduction is set to save TU Delft ~€623k per year. Such savings soften the overall operational and investment cost to HT-ATES system development.

Table 23. Benefits (financial + emission reduction) of HT-ATES system installation for Scenario 1 and 2-I.

	Scenario 1	Scenario 2-I*	*Unit*
Natural gas reduction	2 772 249	4 549 332	*m^3/year*
Emission reduction of CO_2	4 923	8 079	*tonnes/yea*
Cost per tonne CO_2 emitted with tax (emission rights)	24	24	*€/tonne*
Cost per m^3 of natural gas with tax	0.18	0.18*	*€/m^3*
Total emission reduction savings	120	258	*k€/year*
Total natural gas purchase reduction savings	503	1 089	*k€/year*
Total savings due to HT-ATES installation	**623**	**1 347**	***k€/year***

**Assuming all CO_2 costs and gas usage are equal to Scenario 1*

9.1.4 DAPwell and HT-ATES cost relation

The geothermal business case is also impacted by the HT-ATES installation use. As the geothermal source is used to charge HT-ATES system storage, increased operational costs, heat price fluctuations, performance of the well – all have substantial impact to both HT-ATES system and DAPwell business cases. For this reason, multiple scenarios of business cases for both scenarios (TU

Delft only, TU Delft + Delft city) were developed, taking into account sensitivities that impact the business case of the DAPwell and how it changes with HT-ATES system present.

The HT-ATES will increase the overall production hours of the DAPwell. However, due to the addition of HT-ATES the ESP and other installations will be able to run at a more constant speed, which allows it to run more efficiently and in term potentially also reducing maintenance costs. It is important to note however that the opinions on this vary between engineers from no expected reduction in maintenance to "*significant*" reductions in maintenance costs. For the business case calculations it is assumed that improved efficiency equals increase in production hours and therefore electricity consumption is kept constant. Potential reductions in the DAPwell maintenance costs is seen a potential benefit and will not be included in the business case.

9.2 SDE+ subsidy

9.2.1 SDE+ subsidy grant for DAPwell

On June 7th, 2016 the SDE+ subsidy was granted for the geothermal project to be developed in TU Delft campus by RVO. The start of the subsidy was indicated for 1st of September, 2018 with the end-date 31st of August 2033 (a standard 15 years of operation subsidy + 1 year banking). Subsidy based on 5 500 load hours per year with maximum tariff of 42 €/MWh (11.67 €/GJ) was granted, with a corrective amount no lower than basic energy price in the subsidy period. The basis of facility production was identified as 14.5 MW of thermal energy (heat), with a P50 probability and 5 500 productive hours per year.

On the basis of yearly productions, in the SDE+ application it was identified that in calendar years following start-up years (meaning year 3 of operation onwards) an estimated 79 585 MWh to be produced, with year 16 acting as "buffer" year to deliver heat that was under-produced in start-up years 1 to 3. Overall, expected ~1 092 938 MWh of thermal energy (heat) is to be delivered under SDE+ subsidy, part of which will be stored in HT-ATES system as discussed earlier in this feasibility study.

Delays in the DAPwell developmental timeline has reduced the financial benefit for the already granted SDE+. Therefore, it has been considered to apply for a new SDE++ subsidy with only 3500 productive hours per year. This would have a significant (negative) impact in the business case. Currently the two options are further investigated in alignment with RVO. However, the most likely scenario is that the project will continue to work based on the current SDE+ subsidy. The HT-ATES system could allow the project to 'catch-up' i.e. by providing more heat in future years, if not losing more than 1 year, the unused subsidy could be received (see the following section for details).

9.2.2 SDE+ specifics

According to decision "Besluit stimulering duurzame energieproductie", SDE+ does not subsidise or take into account any specifics regarding heat storage technologies under the subsidy programme. This means any installation used to store energy (e.g. HT-ATES system) that is linked together with SDE+ subsidised project (in this case the DAPwell), falls under the financial feasibility of the geothermal project and subsidies gained by it.

In this case, the HT-ATES system and DAPwell heat production is seen as singular unit. Under article 55 of "Besluit stimulering duurzame energieproductie", any energy stored from the DAPwell geothermal well into the HT-ATES system will be subsidised by government even before it is consumed by the end user (e.g. introduced into active heat network). The "overhead" of the stored heat in the HT-ATES system that has not been effectively used yet will not be subsidised for a second time when it is used.

The SDE+ subsidy has specific conditions to the maximum amount of kWh that can be transferred to the following year that would still fall under SDE+ subsidy- called under-production banking (or forward banking). In case of less heat use than planned in calendar year, the production deficit can be carried over to following calendar year to make up for missed subsidy amounts. This principle works in favour of energy storage.

In case of overproduction of heat (DAPwell and HT-ATES heat utilisation above kWh amounts outlined in granted SDE+ application), backwards (over-production) banking is used. A maximum of 25% of total energy production that is eligible under SDE+ application can be carried over to a year where there was a shortage of production, thus reducing the impact of shortage years. This softens the impact of extended maintenance, breakdowns or any other issues regarding production deficits of years following full production periods and allows to recuperate possible subsidy losses.

9.3 HT-ATES Business cases

In this paragraph the effects of the HT-ATES system will have on the DAPwell business case is presented. Assuming that the required heat can be extracted from the DAPwell and injected and extracted from the HT-ATES at the given system efficiency levels stated in Table 13. In addition, these cases assume that no SDE+ subsidy is lost due to delays in the DAPwell project.

9.3.1 Assumptions

In addition to the assumptions for capital and operational expenditures, the following business case assumptions have been used:

- Operating time of the system is 30 years
- All energy and maintenance prices have an indexation rate of 1.5%
- SDE+ subsidy is granted for 15 years (+1 year banking) and can be fully consumed without subsidy losses due to the postponed starting date
- Heat sales revenues is taken over the whole operating time of 30 years
- Discount rate on future cash flows is 5.5%
- Electrical submersible pump is replaced every 5 years
- Large maintenance on the DAPwell is scheduled in the year 2037

9.3.1 Revenues

Each unit of heat produced by the DAPwell and HT-ATES will be compensated by the heat sales prices and SDE+ subsidy. Characteristics of the SDE+ is described in paragraph 9.2. The two heat off takers, TU Delft and city DHN have significantly different heat sales prices. While the city heat sales price is still under negotiation, the city heat sales price is assumed to be little over 25% of the TU Delft heat sales price (7.4€/GJ). It can be concluded that the majority of revenues will come from the SDE+ subsidy, followed by the TU Delft heat sales and just a small fraction is generated by the city heat sales.

9.3.2 **Business cases**

In order to show the financial impact of HT-ATES various business cases have been developed (see Table 24. Different business cases financial feasibility of HT-ATES system). Starting with the DAPwell (owned by GTD) and heat offtake by TU Delft campus only, in the second case the HT-ATES is added (Scenario 1). Cases 3 and 4 connect the city DHN and 100% utilisation of the DAPwell, without and with HT-ATES (Scenario 2). The business cases are calculated for both Maassluis and Ommelanden.

Table 24. Different business cases financial feasibility of HT-ATES system.

Business cases	Maassluis		Ommelanden	
	NPV k€	**IRR (Post Tax)**	**NPV k€**	**IRR (Post Tax)**
1 TUD	(11 801)	0.00%	(11 801)	0.00%
2 TUD + HT-ATES*	(2 963)	3.94%	(4 364)	3.31%
3 TUD + City	1 992	6.48%	1 992	6.48%
4 TUD + City + HT-ATES**	6 933	8.62%	5 121	7.73%

* Scenario 1 - heat for TU Delft campus, see Section 2.4.1

** Scenario 2 - heat for TU Delft and city of Delft, see Section 2.4.2

Business case 1 shows a negative NPV and low IRR, which makes this case unfeasible if finances are the only driver. This may be conservative due to the assumption of TU Delft campus using 100 TJ/year, however, even if this amount is increased to the maximum amount of heat at full flow a negative NPV occurs. Adding the HT-ATES system (case 2), still shows a negative NPV, but will improve the business case significantly over case 1, mainly due to the improved utilisation of the DAPwell heat.

Connecting the city DHN to the DAPwell will improve the business case results for all cases, however between the various cases the results differentiate. The added value of the HT-ATES depends on the DAPwell productive hours, until the subsidised productive full load hours (5 500) are met there is a clear benefit for the HT-ATES. Higher productive hours will slowly reduce the financial added value of the HT-ATES.

Between the two formations investigated, the Maassluis formation is most favourable. Differences are mainly due to the larger depth resulting in larger CAPEX for the Ommelanden formation. Resulting in nearly €1.8M difference in NPV. Appendix IV illustrates cashflow overviews for the business cases 2 and 4 in the Maassluis formation.

A short summary of factors that influence the business case is given in Table 25. Factors that influence the business case.

9.3.3 **TU Delft internal business case (including CO_2 certificates)**

It is important to note that savings because of reduced natural gas purchases and CO_2 certificates are not included in business cases in Section 0 as they are not attributed to the combined DAPwell and HT-ATES system. These savings account for the whole TU Delft energy expenditures. Due to fact that TU Delft purchases sustainable electricity generated by wind mills, no CO_2 emissions will occur. Therefore, it is assumed that there is no CO_2 emission from electricity consumption at the DAPwell and HT-ATES installations.

Table 25. Factors that influence the business case.

Factor	Effect	Impact	Reasoning
Heat Price	Positive	High	Effect on full volume
Under-utilisation of SDE+	Negative	Very High	SDE+ generates largest share of revenues
Additional offtake sales after annual maximum subsidised MWh is reached	Positive	Low	Minor share of revenues from offtake sales, especially after 5 500 hrs
Reduction in Capex	Positive	Medium	HT-ATES CAPEX is small comparing to the overall CAPEX of the DAPwell + HT-ATES
Reduction in OPEX	Positive	High	HT-ATES OPEX is relatively large due to 5 yearly regeneration of wells
Increases in efficiency of HT-ATES system	Positive	Low	SDE+ revenues based on loading of HT-ATES, not extracting heat

A short separate business case can be made for TU Delft in this case of estimated emission reductions related to DAPwell and HT-ATES use (Table 26. TU Delft emission reduction NPV calculation.). Note, no contractual agreements are in place for the TU Delft heat offtake and this estimate includes heat offtake within the TU Delft campus by other companies.

Table 26. TU Delft emission reduction NPV calculation.

Business case scenarios	**1.TUD 100 TJ/y**	**2.TUD+ HT 178 TJ/y**	**3.TUD+ City 240 TJ/y**	**4.TUD+ City+HT 368 TJ/y**	*Unit*
Total emission reduction savings	153	272	367	562	*k€/year*
Total natural gas purchase reduction savings	645	1 148	1 548	2 374	*k€/year*
Heat purchases per year from DAPwell and HT-ATES	(737)	(1 312)	(1 769)	(2 712)	*k€/year*
Total savings per year due to DAPwell and HT-ATES installation	**61**	**108**	**146**	**224**	*k€/year*
Discount rate	5%	5%	5%	5%	
Time period of operation (expected)	30	30	30	30	*Years*
Net Present Value (total after 30 years)	**938**	**1 660**	**2 244**	**3 443**	***k€***

Using the heat from the DAPwell only would decrease yearly expenses for TU Delft by €61k regarding emission certificate and natural gas purchases. Adding a discount rate of 5% for 30 years, that would equate to savings of €938k. Addition of the HT-ATES system next to DAPwell instead of the boilers will further decrease the yearly expenses for TU Delft with a total of €108k at current prices (7.4 €/GJ), with NPV of 30 years of €1 660k. Introducing the city into the system would increase the NPV to €2 244k (€146/year) without HT-ATES, and to €3 443k (€224k/year) with HT-ATES use. Note that in cases involving the city, CO_2 emission certificates may not be eligible for reduction, making any additional financial benefit internally to TU Delft (in addition to co-ownership of the HT-ATES system) lower as more heat is produced.

9.4 Scientific programme

The scientific programme will require a relatively high initial installation of infrastructure (coring/monitoring equipment) and then require ongoing funding for researchers. Following the model of the DAPwell, this will be funded separately than the operational project and will be funded via government subsidies, e.g. via NWO or RVO. See Section 7.3 for more details.

9.5 Assessment financial risks

Item	Risk	Mitigation
Loss of SDE subsidy	High	Close cooperation with the DAPwell project team in order to cooperate with RVO and keep them up to date on the latest developments as the ultimate decision on the SDE+ subsidy lays with them. Apply for SDE++.
Reduction of SDE+ subsidy due to project delays	High	Close cooperation with the DAPwell project team in order to cooperate with RVO and keep them up to date on the latest developments as the ultimate decision to extent the SDE+ period lays with them.
Budget overrun due to market pressure on contractors	High	Tendering during crisis. Allow for flexible planning.
Budget overrun during design and building related to new technology	High	Set up proper governance and use and experienced and skilled project team. Invest sufficient time in the development and design phase → Thorough design and implementation plan. Connect to research projects, so additional funding helps to address new developments.
Delay in DHN construction and connection to the city (initiation Scenario 2)	High	Ensuring that business case of project can withstand delays in DHN connection (Scenario 2 launch) without making project unfeasible. Make robust operational strategy.
Change of SDE+ (5500 hrs) towards SDE++ (3500 hrs)	Medium	Close cooperation with DAPwell project team. Look at the integral energy system with the DAPwell, HT-ATES and the DHN of the city instead of the focussing on individual systems like the DAPwell only.
Lower heat price	Medium	SDE+ subsidy is most important income element, make sure it is guaranteed. TU Delft has multiple roles as heat user and initiator of DAPwell and the HT-ATES system. Support integral decision making. Stimulate options for other heat users connected to the DHN.
Operational mismatch heat availability and demand	Medium	Robust operational strategy for various seasons and modes of operation Reduce temperature levels in the grid (improve building performance/efficiency). Guarantee demand from HT-ATES in contracts.
Not sufficient trust/commitment of stakeholders	Low	Robust Business case, regular update. Clear agreements with all parties involved.

9.6 Conclusion financial feasibility

It is concluded that the HT-ATES system will improve the business cases for all scenarios. In both cases with only the TU Delft connected the NPV is negative making these cases unfeasible from solely a financial point of view. However, the case is significantly improved by adding an HT-ATES.

In order to generate a positive NPV the city needs to be connected. Adding an HT-ATES further improves the business case. The added value of the HT-ATES system depends on the DAPwell productive hours, until the subsidised productive hours (5 500) are met there is a clear benefit for the HT-ATES.

In all cases the Maassluis formation shows better financial feasibility, which originates from lower CAPEX comparing to the Ommelanden formation.

10 Conclusions

10.1 Main Conclusions

An HT-ATES system, working in conjunction with the DAPwell, at the TU Delft campus has been assessed to be technically and financially feasible, and will result in substantial CO_2 emission savings for TU Delft and potentially also the city of Delft. Table 27 gives an overview of the financial and CO_2 reduction characteristics.

It was shown that while four aquifers were feasible to be used, two were preferable and were further assessed. The Maasluis formation, at ~130-190m depth, is the most cost effective, whereas the Ommelanden formation, at around 410-460m depth, costs more to install, but has a lower chance of affecting other ATES systems in shallower aquifers.

Table 27. Financial and emission reduction characteristics of a potential HT-ATES system.

Cases	NPV k€		CO_2 reduction	
	Maassluis	Ommelanden	tonnes/y	% of total campus emissions
1 TUD	(11 801)	(11 801)	6 312	39%
2 TUD + HT-ATES (Scenario 1)	(2 963)	(4 364)	11 235	70%
3 TUD + City	1 992	1 992	15 149	106%
4 TUD + City + HT-ATES (Scenario 2-I)	6 933	5 121	23 228	145%

While not currently regularly able to be permitted, HT-ATES systems have a route to obtain permits, as pilot projects. This process would take around 6 months.

A research program can be established, answering important question on how such systems can be designed and operated successfully, from the subsurface to the operation of heat networks to interfaces with heat consumers. The program can be cross-faculty, where TU Delft covers the full chain from subsurface to energy consumer. The location on the TU Delft campus, ensures easy access for researchers to the system to monitor in detail the operation, and will generate knowledge able to be used in the Netherlands and beyond.

10.2 Mitigation measures for high risks

Technical

Uncertainties characteristics target aquifer and confining layers, resulting in more expensive wells	High	More information will be gained by means of experiments and data acquisition during the drilling and completion phase of the DAPwell. Adapt well design accordingly
Heat availability and demand in practice make viable/sustainable operation impossible	High	Sensitivity of the business case should be established and staged construction can limit risk. Sensitivity analysis on heat demand and return temperatures.

Policy

Permit not issued	High	Involve province, municipality and other stakeholders in early stage, agree on process and criteria for issuing of permits.
Public resistance, causing delays in the permit process or even prevent issuing of permit	High	Close cooperation with project team of the DAPwell. Streamline and integrate stakeholder management and communication activities of the HT-ATES with the stakeholder management and communication of the DAPwell.

Science case

Scientific programme cannot achieve funding at the same time as operational project is financed	High	Infrastructure already included within the large-scale infrastructure roadmap. Project development can be uncoupled from DAPwell to enable more flexibility. Limited own-investment in research infrastructure can enable smaller research programme to continue without initial funding.

Financial

Loss of SDE subsidy	High	Close cooperation with the DAPwell project team in order to cooperate with RVO and keep them up to date on the latest developments as the ultimate decision on the SDE+ subsidy lays with them. Apply for SDE++.
Reduction of SDE+ subsidy due to project delays	High	Close cooperation with the DAPwell project team in order to cooperate with RVO and keep them up to date on the latest developments as the ultimate decision to extent the SDE+ period lays with them.
Budget overrun due to market pressure on contractors	High	Tendering during crisis. Allow for flexible planning.
Budget overrun during design and building related to new technology	High	Set up proper governance and use and experienced and skilled project team. Invest sufficient time in the development and design phase → Thorough design and implementation plan. Connect to research projects, so additional funding helps to address new developments.
Delay in DHN construction and connection to the city (initiation Scenario 2)	High	Ensuring that business case of project can withstand delays in DHN connection (Scenario 2 launch) without making project unfeasible. Make robust operational strategy.

10.3 Proposed next steps

The following next steps can be taken if there is sufficient agreement to proceed from TU Delft and partners:

1. Organise project organisation, responsible for the proposed next steps. This includes engagement with GTD (DAPwell owner and operator).
2. Start trajectory / process with province for permit procedure and criteria.
3. Carry out stakeholder analysis and make a plan for stakeholder management.
4. Test drilling or ensure information collection from wells drilled for DAPwell, to, for example, undertake a well test in the target formation aquifer, assess the thickness of the aquifer and confining layers, and test water quality.
5. Assess results of the test drilling and adapt preliminary well design and water treatment accordingly.
6. Improve model of energy demand TU Delft and City. Identify various scenarios for heat availability and demand. Make a design and an operational plan for these scenarios.
7. Explore subsidy possibilities to reduce financial risk.
8. Explore and apply for research funding possibilities. Explore for additional research funds at local governments / companies.
9. Draft monitoring plan.
10. Make preliminary permit request.
11. Tender installation of wells and connections to DAPwell and CHP.
12. Building/installation of the HT-ATES system.
13. Commissioning of the HT-ATES system.
14. Run and monitor HT-ATES.
15. Regular evaluation.

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Appendix I: Gas produced by the DAPwell

When the geothermal well is operating, gas is produced as by-product. This is an inevitable process. The total gas that is produced depends on the flow rate of the geothermal well. For each m^3 of geothermal production, approximately 1 Nm^3 of formation gas is predicted to be produced. There are many different options for what can be done with this formation gas, with the three most feasible being:

1. Burn the gas in the boilers that are present on the campus.
2. Upgrade the gas and inject into the gas network.
3. Re-inject the gas in the subsurface.

The first one is not preferred by TU Delft as this will require on campus storage and could increase CO_2 emissions. As TU Delft strives for zero CO_2 emission on the campus, the first option is considered as the least fitting option in terms of their goal for the future of the campus. The last option is regarded as technically challenging and is therefore not likely that this will be the solution. If either of the latter two are used, then the gas is not considered as an available source of heat to the heating system or to load the HT-ATES well. For the scenarios of this study the energy of the gas is not included.

If the formation gas would be used for heat production this could add another 57 TJ to the total availability of heat (see Table 28).

Table 28. Thermal energy from gas.

Property	**Heat from formation gas**	***Unit***
Energy per cube	32	*MJ/m^3*
Efficiency of boilers	80	*%*
Delivery temperature	100-90	*℃*
Capacity	2.25	*MW*
Potential total heat delivery	57	*TJ/y*

Appendix II: Detailed subsurface information

Name	zTop	zBot	kh	kv	Temperature
	[m-mv]	*[m-mv]*	*[m/d]*	*[m/d]*	*[C]*
Hlc	0	16	0.000	0.000	10
KRz2,3	16	33	40.000	8.000	11
URz1,2,3,4,5	33	38	45.000	9.000	11
WAk1	38	46	0.097	0.032	11
PZWAz2	46	70	15.000	3.000	11
WAk2	70	75	0.066	0.022	12
PAWAz3	75	80	10.000	2.000	12
WAk3	80	87	0.014	0.005	12
PZWAz4	87	96	12.000	2.400	12
MSk1	96	109	0.011	0.004	12
MSz2	109	125	9.000	1.800	13
MSk2	125	130	0.012	0.004	13
MSz3	130	145	10.000	2.000	13
Clay layer	145	146	0.009	0.003	13
MSz3	146	182	10.000	2.000	14
MSc	182	222	3.500	0.012	15
MSz4	222	240	5.000	1.000	15
OOk1	240	287	0.015	0.005	16
OOz2	287	313	6.000	1.200	17
Ooc	313	380	0.600	0.005	18
	380	410	0.600	0.005	18
Omm	410	460	15.000	3.000	19
	460	500	0.600	0.005	19

Targeted aquifer for HT-ATES
Aquifer
Aquitard

The parameter values in this table are established in close interaction between TU Delft (M.Bloemendal), TNO (D.Dinkelman) and IF Technology (B.Drijver). The basis is the information obtained from REGIS II, of which some values are adapted accordingly to the retrieved local information obtained from the drilling at Technolpolis and the train station of Delft.

Appendix III: Groundwater model

The flopy model, initially created by Bakker et al. (2016) is used to run SEAWATv4 (Langevin et al., 2007). SEAWATv4 combines MODFLOW (computer program to model 3D groundwater flow by using a finite-difference method (McDonald and Harbaugh, 1988)) and MT3DS (Multi-Species modular 3D transport model (Zheng and Wang, 1999)). Because of the similarity between the equations for solute and heat transport, MT3DMS can be used to model transport of heat, by treating heat as a solute species (Hecht-Mendez et al., 2010; Langevin et al., 2008). The MODFLOW/SEAWAT model is used to simulate subsurface flow with heat transport, from which well efficiencies are determined. This simulation environment can handle heat exchange to adjacent confining layers and the surrounding aquifer, which can be at the ambient temperature or temperatures corresponding to injection by neighboring wells.

Spatial discretisation:
To accurately simulate the temperature in the subsurface of Delft due to the ATES wells operation the subsurface was modelled with a 2x2m grid in the area of the building locations. A zone of 100 meter with the same cell sizes is constructed around the well-area to minimise numerical dispersion errors. Around this area the model extents for at least 1000m with a logarithmically increasing cell size up to a maximum cell size of 200. The resolution thus stays well within the minimum cell-size required by Sommer et al. (2014) to adequately model the temperature field around ATES wells.

To minimise computational time while being able to optimise the grid discretization around the well, an axisymmetric model is used (Langevin, 2008). At distance r from the well the following cell properties are therefore corrected: hydraulic conductivity (K), porosity (n), bulk density (ρ_{bulk}) and specific storage (s_s).

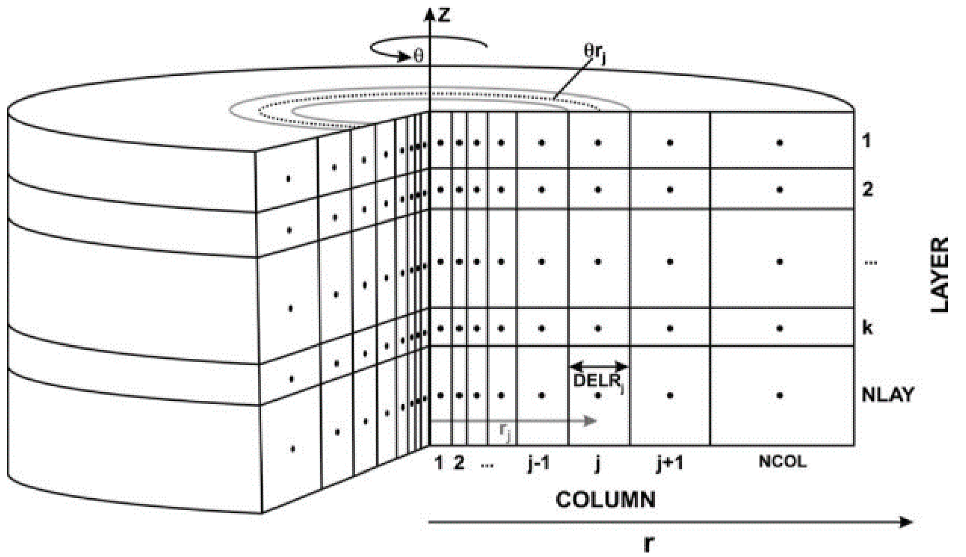

Figure 23. Schematic representation of an axisymmetric model in SEAWATv4 (Langevin, 2008).

For this study only one well is modelled. The following assumptions are made:

- Well screens are fully penetrating the injection aquifer
- Injected volume is equally distributed over the entire well screen length
- Homogeneous aquifer conditions
- Fixed longitudinal dispersion for all simulations

Temporal discretisation and simulation horizon

Test runs with time steps of 5 days, weeks and months are carried out. These showed that monthly time steps are sufficiently small to distinguish between performance under varying well placement policies and capture seasonal storage cycle dynamics. MT3DMS automatically takes smaller (internal) time steps if necessary to meet courant condition. Note that building-climate installation model operation is at hourly basis, which results are aggregated to monthly input for the MODFLOW model.

The simulation horizon of each simulation is set to 50 years.

Initial and Boundary conditions

Model boundaries are set to have fixed heads and temperatures at the boundaries. Ambient temperatures are set at 12 °C, which is the assumed average ambient groundwater temperature of the shallow subsurface. Initial and starting heads are set to surface level of the model.

Parameter settings

Aquifer properties are taken as homogeneous; the effect of heterogeneity on ATES well efficiency has been studied by Caljé (2010), Sommer et al. (2013), Possemiers et al. (2015) and Xynogalou (2015), who concluded that only in specific conditions heterogeneity may have a considerable effect, conditions which are not present in Delft. Temperature-density and Temperature-viscosity dependency is taken into account following the relation given in Figure 24.

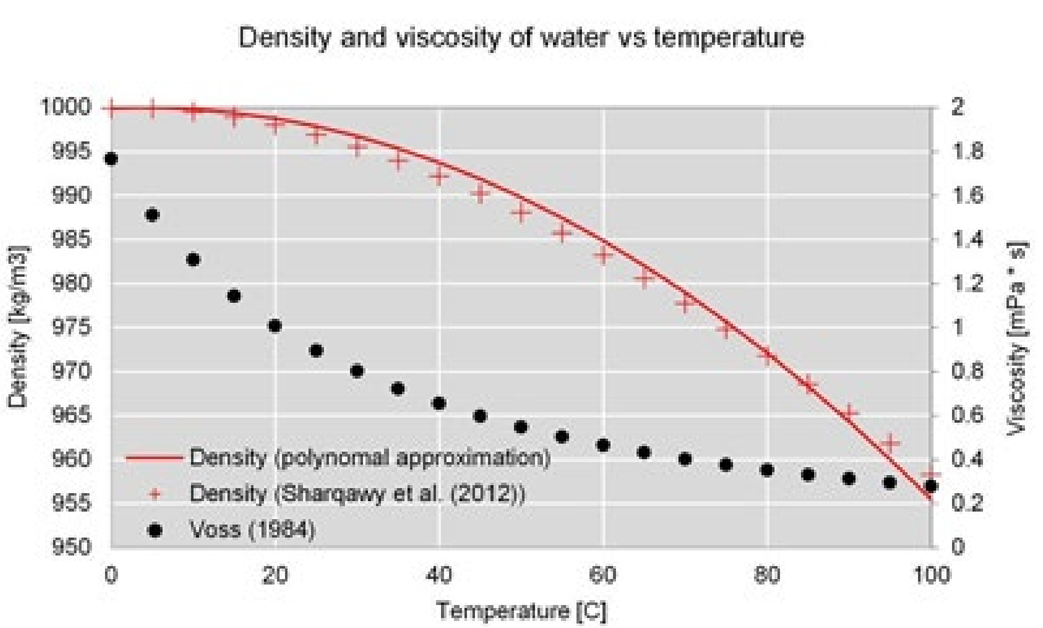

Figure 24. Water density and viscosity dependency under changing temperature conditions. The polynomial approximation is applied in the model.

The horizontal and vertical hydraulic conductivity follow the values presented in Appendix II, resulting in the layer model set up shown in Figure 25. The other thermal and numerical parameters follow literature values and are given in Table 29.

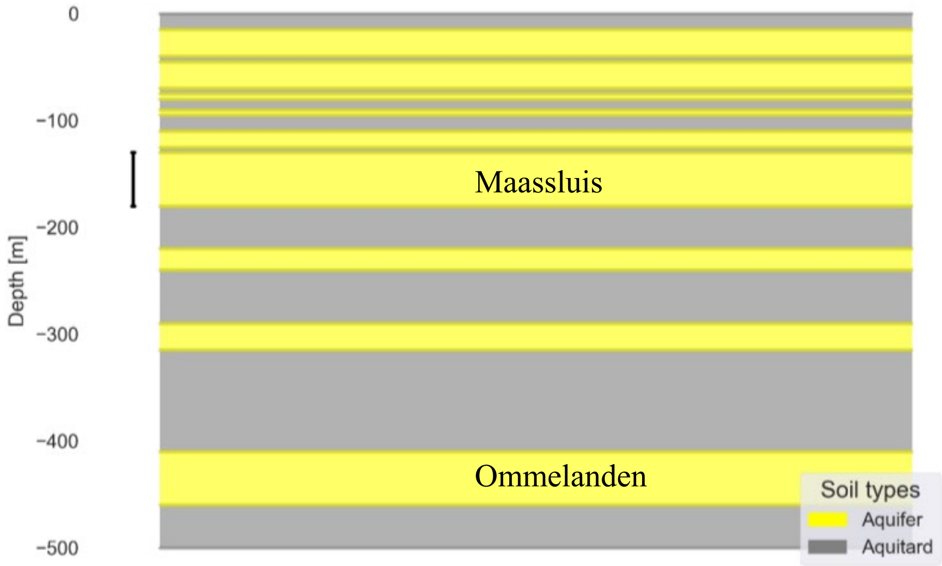

Figure 25. Model set-up of layers.

Table 29. SEAWAT simulation parameters (Caljé, 2010; Hecht-Mendez et al., 2010; Langevin et al., 2008).

Parameter	Value	Package
Solid heat capacity*	710 kJ/kg °C	RCT
Water reference density	1,000 kg/m^3	RCT
Solid density*	2,640 kg/m^3	RCT
Water thermal conductivity	0.58 W/m/°C	RCT
Solid thermal conductivity	2.55 W/m/°C	RCT
Thermal distribution coefficient#	$1.7 \cdot 10^{-4}$ m^3/kg	RCT
Thermal retardation+	2.21	RCT
Porosity	0.3	BTN
Specific storage aquifer	$6 \cdot 10^{-4}$ /m	LPF
Longitudinal dispersion	0.5 m	DSP
Transversal dispersion	0.05 m	DSP
Vertical dispersion	0.005 m	DSP
Effective molecular diffusion heat#	0.15 m^2/day	DSP
Effective molecular diffusion salt	$8.64 \cdot 10^{-6}$ m^2/day	DSP

Assessment, recovery efficiency equation:

$$\eta = \frac{E_{out}}{E_{in}} = \frac{\int_{t=0}^{t=t_{end}} Q_{out}\rho c(T_{hot} - T_{warm})}{\int_{t=0}^{t=t_{end}} Q_{in}\rho c(T_{hot} - T_{warm})} \qquad [1] \qquad [1]$$

NB. The used simulation tools are developed by KWR and TU Delft. The same models and approach are used for the “verkenningen” of the WINDOW program.

Appendix IV: Cash flow overview