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A techno-economic evaluation of high temperature thermal aquifer storage (HT-ATES) for use with the geothermal well on the TU Delft campus

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ABSTRACT

Direct use geothermal projects are often considered to be able to supply base-load heating, which leaves a substantial portion of the heating demand to be covered by other (often fossil-based) sources during demand peaks. Additionally, during a substantial portion of the year there is less heat used from the geothermal well than is able to be produced. The consequence is that geothermal projects perform economically poorly or require substantial governmental subsidies. The use of heat storage provides a possibility to address both of these issues by providing seasonal storage of heat, thus increasing the peak supply and utilising more heat from the geothermal well. Given the required storage capacity needed for such projects, Aquifer Thermal Energy Storage (ATES) is the only realistic storage option. This paper presents a techno-economic analysis of using a High Temperature (HT)-ATES system in conjunction with a 2.2km deep direct use geothermal project for the TU Delft campus. The geothermal project has been designed as a 'living lab', a research and operational project, and adding an HT-ATES system would add to this dual purpose. The heat supply and demand, the available aquifers, initial project design, economics and greenhouse gas emissions are investigated. Two possible aquifers are identified for use, the first 50m thick at ~130m depth and the second about 50m thick at ~410m depth. The first is evaluated as more favourable economically, whereas the second reduces the potential for impact on other groundwater users. The amount of sustainable heat delivered for use on the TU Delft campus is calculated to increase from ~65% with only a geothermal well to ~95% when also a HT-ATES is used, with the same proportion of greenhouse emission savings. Several scenarios for heat delivery are considered, as the increased supply also allows a portion of the city around the university to be supplied with heat from the geothermal project and HT-ATES. The calculated net present value of the total project (i.e., the geothermal project and the HT-ATES project) improved by between €3m to €9m.

1. INTRODUCTION

Geothermal energy is being developed globally in order to provide a more sustainable source of heat. It is generally considered a baseload energy source and therefore peaks in the heat demand cannot be supplied by using geothermal wells. This has the consequence of requiring heat from other sources (often fossil derived) to supply heat at a sufficient rate to satisfy peaks, and therefore geothermal-based heating systems typically still have a substantial CO_2 emission, albeit substantially reduced from fossil-only derived heating systems. However, geothermal projects are also able to produce heat when there is a negligible demand (i.e., in the summer), and this offers a potential attractive solution, storing the heat from this period of time and utilising it to cover the peaks (e.g., Hartog et al., 2016). This concept is shown in Figure 1. Storing for annual demands requires a substantial capacity. The cheapest way (by far) to achieve such heat storage capacity is to use the subsurface, where the subsurface conditions allow this (IEA et al., 2013). For storage associated with deep geothermal systems, temperatures must be elevated beyond those normally associated with aquifer thermal energy storage (ATES), but these High Temperature (HT) ATES systems are gaining international attention (Kallesøe and Vangkilde-Pedersen, 2019; Drijver et al., 2019).

TU Delft is developing a research and operations geothermal project on its campus (Vardon et al., 2021), and as part of this project and a national research programme called WINDOW (KWR, 2020), an evaluation of whether HT-ATES would be feasible and beneficial has been carried out (Bloemendal et al., 2020). This paper presents the novel elements and key findings of this feasibility study. Various technical and economic aspects are addressed, and in addition, the advantage of having this project in a university to allow both research and education to take place gives additional value.

2. TECHNICAL FEASIBILITY

2.1 Heat demand and supply

About 27 000 people usually work on the TU Delft campus every day (although notably not for the majority of 2020). The heating of the majority of the buildings housing these people is currently delivered, via a district heating network (DHN), from the gas-fired central production plant via boilers and a combined heat and power plant (CHP). An example heat demand profile for a year is shown in Figure 2, alongside the load-duration curve. The total heat demand from the DHN is 200 TJ/y, which includes a ~10% heat loss from the DHN. The maximum demand (peak) is 27 MWt, whereas in the summer months the heat demand from the DHN is zero (domestic hot water supply is provided locally). There are several energy saving developments being implemented and planned, and an additional track of the DHN is planned to connect a number of buildings not yet connected to the DHN. For the purposes of feasibility, these two aspects are considered to have a neutral impact. At present, the DHN has a supply temperature between 90 and 130 °C and a return temperature of approximately 70 °C. The maximum supply temperature is needed during the lowest external temperatures (-10 °C). Various changes to the internal heating systems and heat exchangers between the DHN and the buildings are currently being implemented in order to reduce the temperatures in the DHN (supply: 75 – 90 °C; return: ~55 – 65 °C), to allow supply from the geothermal well or other low-emission sources. The maximum flow capacity of the DHN is 855 m^3/h.

The university campus is in close proximity of several new developments and existing buildings in the city of Delft. It is proposed that the city of Delft will utilise residual heat from the campus, i.e., from the return of the DHN. The heat demand from the city is asynchronous during each day, as it will be mostly residential. This may require inter-day storage, however, depending on the size of the DHN installed in the city, other sources may also be required, which could provide a more dynamic heat supply, therefore this has not been further considered here. It is considered that the demand from the city of Delft (population approximately 100 000), will be larger than can be supplied via residual heat, therefore it is considered to be able to consume all possible residual heat. The annual profile is considered to match that of the TU Delft campus, as this is mainly driven by the external temperature.

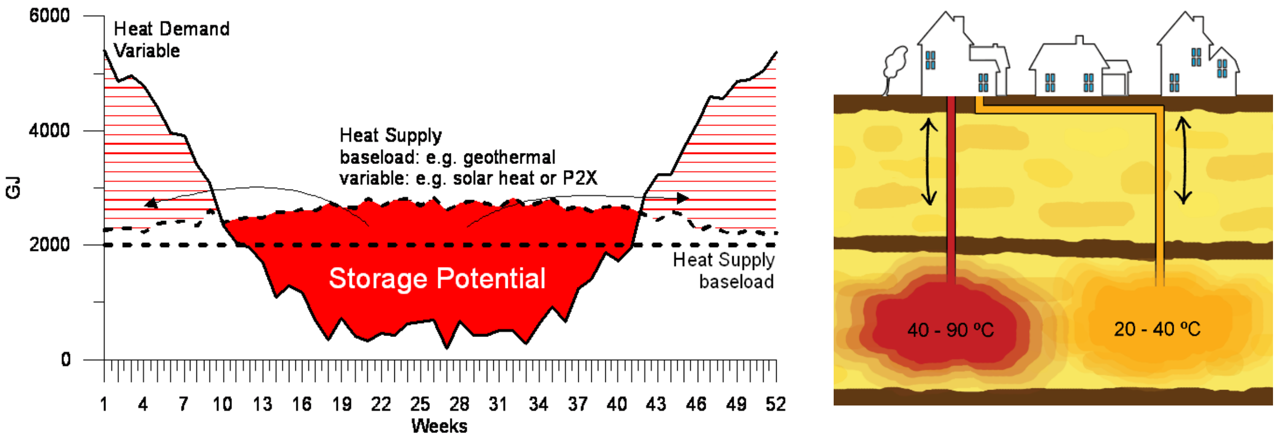

Figure 1: Left: Example of waste heat and variable heat utilisation with heat storage (Hartog et al., 2016). Right: basic working principle of HT-ATES.

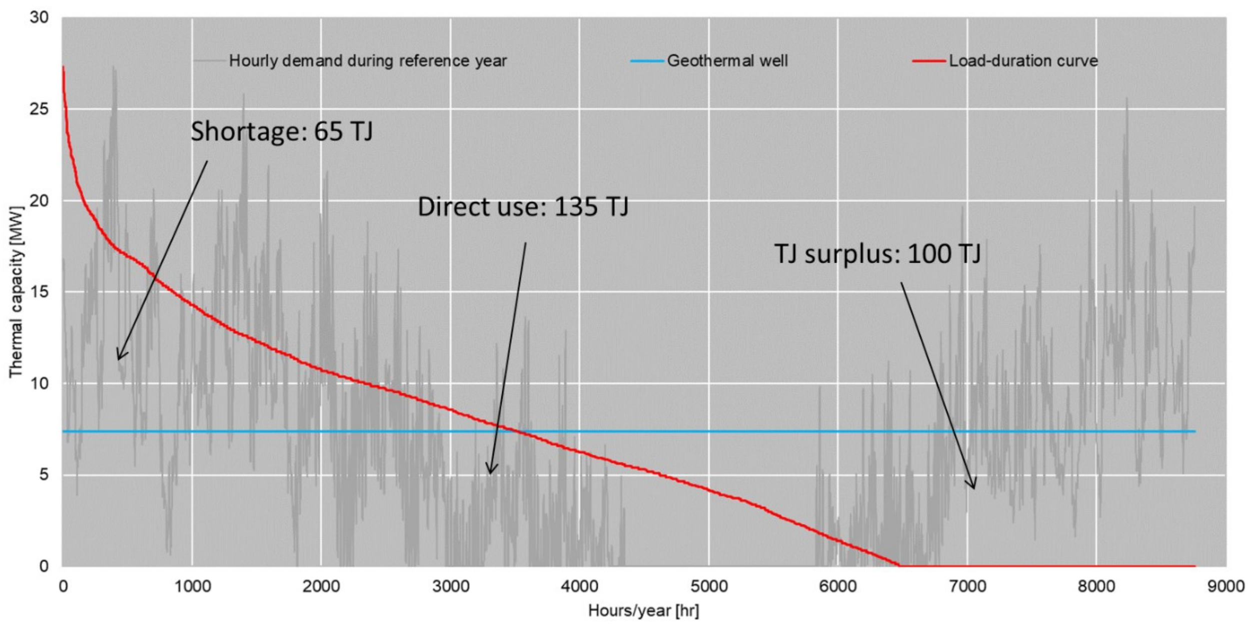

Figure 2: Heat demand and load-duration curve for the TU Delft campus and geothermal production.

The TU Delft campus deep geothermal project or "Delft Aardwarmte Project" wells (called DAPwell), which is under development, will replace the existing gas-fired system as the primary heat source for the campus DHN and thus the main source to load an HT-ATES system. The DAPwell is designed to be able to produce heat during the whole year, with a (P90) predicted maximum flow capacity of 320 m^3/h with a ~75 °C delivery temperature. This means the DAPwell can deliver 7.4 MWt with a 55 °C return temperature (as predicted from the campus DHN), or 14.8 MWt if the return temperature is 35 °C, which is proposed as the return temperature from the city of Delft. Any peaks that cannot be supplied by the geothermal or HT-ATES system are proposed to be supplied via the existing gas-fired system.

Figure 2 presents the maximum heat supply from the DAPwell for the campus DHN, i.e., 7.4 MWt, in comparison with the heat demand. It can be seen that there is a shortage of 65 TJ/y during the winter months and an over-supply of 100 TJ/y if production continues for the entire year. This implies that even with subsurface losses, the majority of the heat demand could be supplied from geothermal sources (the deep geothermal source and HT-ATES system). The DAPwell operating by itself is planned to be a baseload supply, i.e., cover the 'shoulder' of the load-duration curve shown in Figure 2; it is planned to be reduced in flow in autumn and spring and further reduced in the summer.

Two scenarios for the evaluation of the feasibility of including an HT-ATES have been defined: Scenario 1 – heat supply is limited to the current campus DHN; Scenario 2 – heat supply is extended to the city of Delft. These have been compared to the same situations without an HT-ATES system.

2.2 Subsurface

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 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 heated region 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 temperature differences.

The local geology has been evaluated via an analysis of nearby wells and using a national subsurface model called REGIS (TNO, 2017). 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.

A multi-criteria analysis was carried out, which resulted in the Maassluis and the Ommelanden Formations being deemed the most applicable. In general, the Maassluis Formation scored higher on costs and the Ommelanden scored better on reducing environmental impact. Both scored equally on reducing heat losses.

2.3 Preliminary design

An outline system design has been made for each scenario. For Scenario 1, the system design for peak heat delivery is shown in Figure 3. The maximum flow of the geothermal well is used, and a heat pump, which is placed between the supply and return of the geothermal pump and one branch of the return from the DHN. The rest of the DHN flow is first heated by the HT-ATES and then heated via a boiler/CHP to further increase the temperature. A heat pump could also be placed at the HT-ATES, but this would be a large heat pump and would only be required to be used at some times of the year, making it less cost effective. Indicative temperatures, including losses, and flows are also shown in Figure 3.

For Scenario 2, the system design, temperatures and flows for peak heating are shown in Figure 4. The campus heating and city heating system are most separated, which allows for different flows, and an easy addition of a buffer tank if needed. Both the DAPwell and the HT-ATES provide heat to both the campus and the city and the temperature difference between the wells of both systems is increased, which will increase the efficiency of both systems. Lower flow rates of both systems will be required to provide the same heat output.

If there is only the DAPwell providing geothermal heat, a reduced flow will be set for spring and autumn, and a minimum flow set for the summer. This implies that for occasional cold periods in those seasons, reduced peaks will be supplied via the gas-fired system. For both HT-ATES scenarios, the addition of an HT-ATES system allows more heat to be provided directly from the DAPwell as the flow will not be reduced, in addition to the heat provided directly by the HT-ATES system. Moreover, for Scenario 2, more heat is provided for the same flow rate, as the return temperature is greatly reduced. Table 1 shows a summary of the calculated heat supplied and characteristics of the designed HT-ATES system.

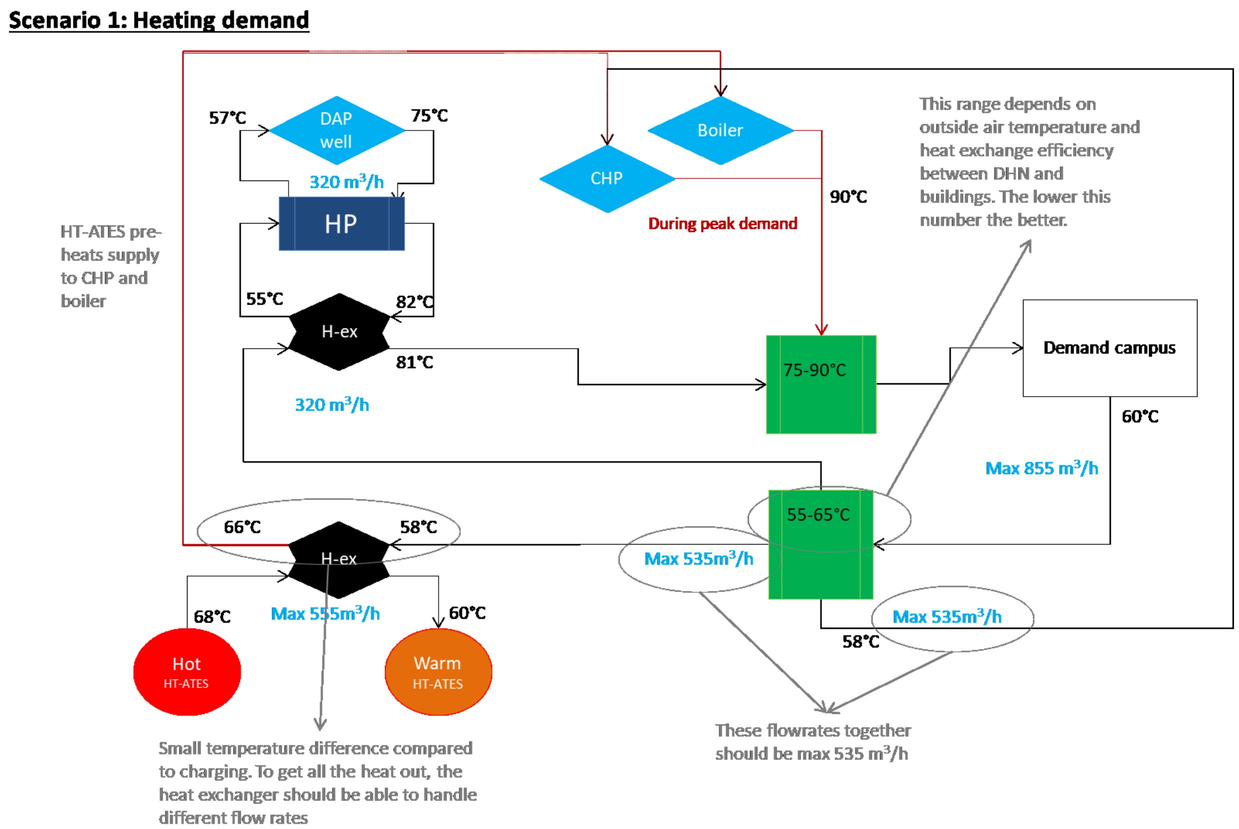

Figure 3: Scenario 1 - Dominant heat flows and temperatures of the TU Delft campus heating system including the DAPwell with HT-ATES for peak heat demand.

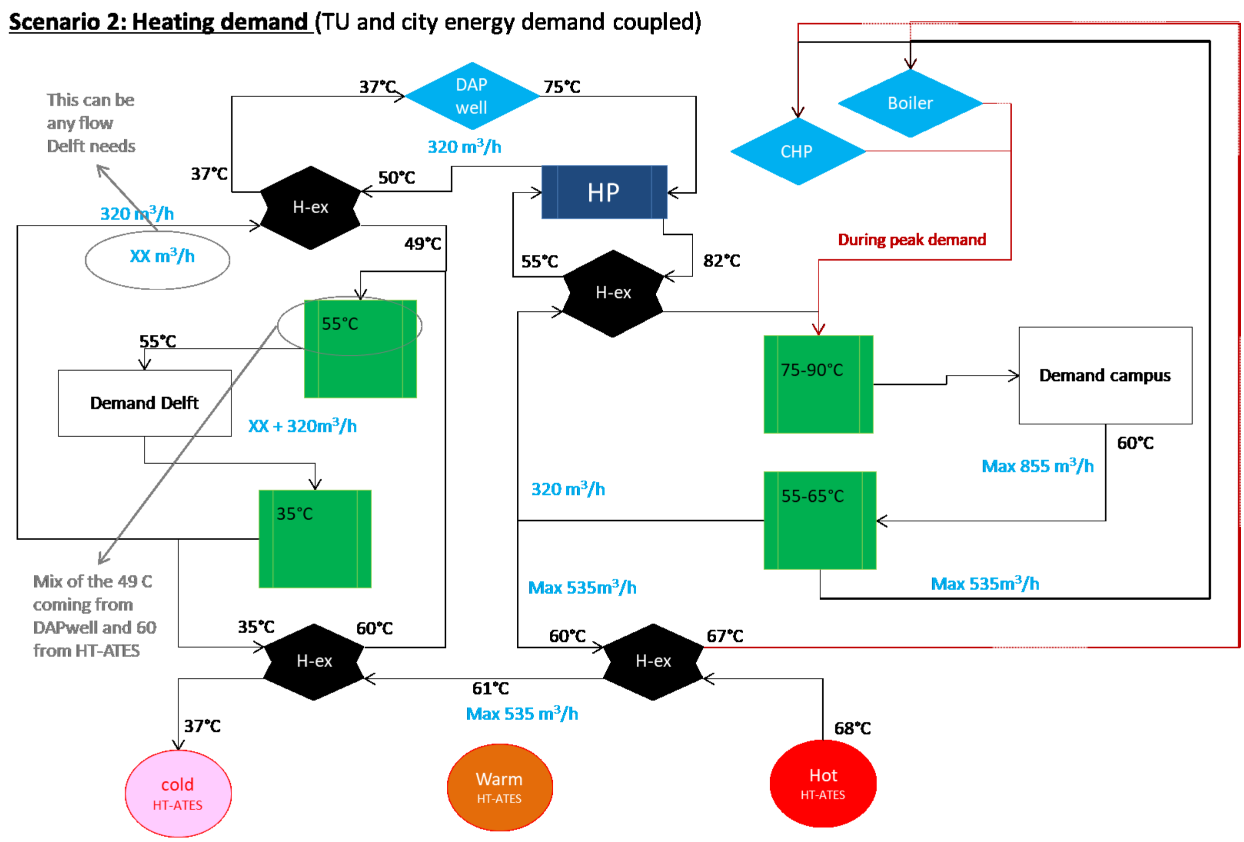

Figure 4: Scenario 2 - Dominant heat flows and temperatures for decoupled energy delivery to TU Delft and city including the DAPwell with HT-ATES for peak heat demand.

Table 1: Overview of the designed HT-ATES characteristics.

	Scenario 1	Scenario 2	*Unit*
Total heat DAPwell and HT-ATES	178	368	*TJ/y*
Directly by DAPwell	135	275	*TJ/y*
HT-ATES			
Total heat 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*

The number of wells is controlled by the infiltration rate required. The maximum expected DAPwell heat output is 320 m^3/h, therefore this is the required hot wells' infiltration capacity.

Based on an analysis of installed maximum flow rate and annual heat delivered, a thermal capacity of 5 and 22 MWt (Scenario 1 and Scenario 2) has been selected. Further increasing the capacity does not result in a substantial addition to the energy supply. To supply these capacities, the system must be able to reach a 535 m^3/h extraction flow rate 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. Assuming a ~1 m diameter well (commonly used in ATES systems), the system in the Maassluis Formation requires 8 warm/cold wells and 4 hot wells. In the Ommelanden, 6 warm/cold wells and 4 hot wells would be required. Care must be taken in the layout design to ensure that the wells do not hydraulically affect each other and that the thermal plume from the hot wells and warm/cold wells do not unduly interact. Table 2 gives an overview of the characteristics of the designed HT-ATES systems in the two analysed formations.

Table 2: HT-ATES design and characteristics of the Maassluis and Ommelanden aquifers.

	Maassluis	Ommelanden	*Unit*
Thickness / screen length	50	50	*m*
Horizontal hydraulic conductivity	10	15	*m/d*
Vertical hydraulic conductivity	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*
Average thermal radius	95	94	*m*
Number of hot wells	8	6	*#*
Number of warm/cold wells	4	4	*#*

The behaviour of the HT-ATES system has been explored via simulations using the numerical model SEAWAT (USGS, 2012). Axisymmetric analyses have been carried out for individual wells, and fewer 3D simulations for the full system. Figure 5 shows the temperature distribution around a hot well and in confining layers (axisymmetric analyses) after 50 years of operation of the HT-ATES for each of the formations. The results show that at a 400m radius the groundwater has been heated up by around 4 °C (compared to the natural groundwater temperatures of 11 and 21 ° C, respectively, for the two formations) as a result of operating the 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. For the simulation for the Maasluis Formation (Figure 5, left), a minor impact is observed for the Waalre aquifer, where the in-situ temperature is raised from 12 to 15 °C. This implies a minor impact on cold ATES wells immediately above HT-ATES hot wells, which needs to be considered in detailed design.

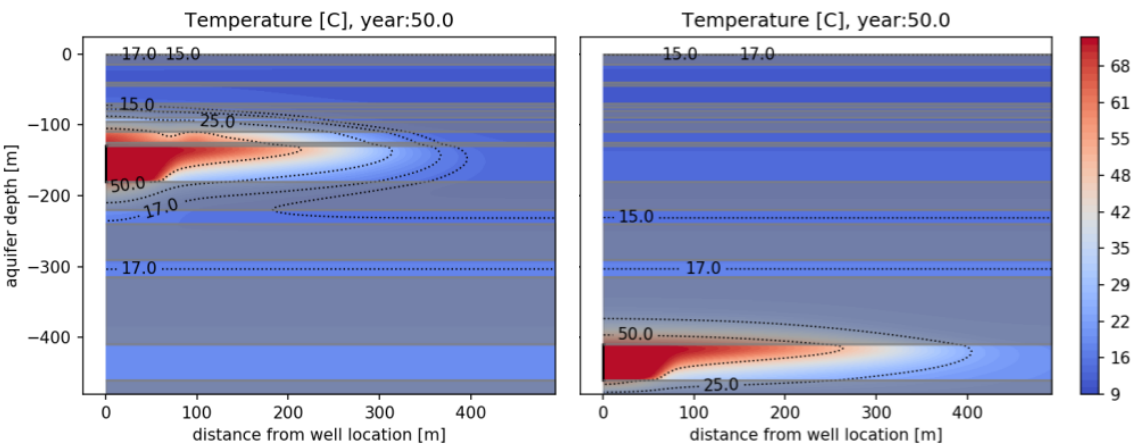

Figure 5:1 Temperature distribution in subsurface after 50 years of simulation for HT-ATES in Maassluis (left) and Ommelanden (right) Formations.

2.4 Greenhouse gas emissions

TU Delft over the years 2013 to 2019 on average emitted ~16 000 tonnes of CO_2, with ~12 600 tonnes occurring from the central heating system. The DAPwell, operating alone, is predicted to be able to supply ~100 TJ/y, which corresponds to a CO_2 emission reduction of 6 312 tonnes/y (approximately 0.0018 tonnes CO_2/m^3 of gas used). The HT-ATES system will allow a further reduction of natural gas use for heating purposes during high heat demand periods. This is calculated to increase the CO_2 emission reduction to 11 235 tonnes/y and by also including the city, this increases to 23 228 tonnes/y. It is noted that this does not include any emissions for electricity use as TU Delft purchases its electricity from a wind farm. These cases are summarised in Table 3.

Table 3: 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)	6 933	5 121	23 228

3. ECONOMIC FEASIBILTY

3.1 Costs

The specific costs of the HT-ATES system are divided between two specific categories, capital expenditure (CAPEX) occurring during system build/installation phase and operational expenditure (OPEX) recurring throughout the operation timeline of the installation. The major CAPEX and OPEX components are presented in Table 4. The wells and surface plant are the major CAPEX costs, with well maintenance and electricity the major OPEX costs.

There is no differentiation in either the CAPEX or OPEX depending on whether Scenario 1 or 2 is considered despite the large differences in energy yield (see Table 1). This is due to the flow rates being the same and the energy differences are due to a larger temperature difference.

Table 4: Estimated cost breakdown of HT-ATES systems installed in Maassluis and Ommelanden.

	Maassluis	**Ommelanden**
CAPEX (*k€*)		
HT-ATES wells	1 880	3 288
Surface plant	960	900
Permits, Engineering & construction	284	419
Contingency	284	419
Total	**3 408**	**5 026**
OPEX (*k€/y*)		
Maintenance of the wells	200	238
Maintenance of the surface plant	40	40
Water treatment	31	31
Monitoring	30	30
Electricity costs	131	131
Total	**376**	**424**

3.2 Revenues

Revenues associated with the HT-ATES system have two sources, the heat price and the national subsidy scheme for renewable energy generation, called the SDE+ (Netherlands Enterprise Agency, 2020). The heat price for heat delivered to the TU Delft campus is based on the current price (26.50 €/MWh or 7.4 €/GJ), while the city heat sales price is assumed to be ~25% of the TU Delft heat sales price due to required DHN infrastructure needed to be put in place.

The 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 an 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. A subsidy for the DAPwell has been granted with a maximum tariff of 42 €/MWh (or 11.7 €/GJ). The basis of facility production was identified as 14.5 MWt of thermal energy (heat), with 5 500 productive hours per year.

The SDE+ subsidy has specific conditions to the maximum amount of kWht 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 a calendar year, the production deficit can be carried over to the following calendar year to make up for missed subsidy amounts. This principle works in favour of energy storage. 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 increases the robustness of the business case of geothermal-based heating systems.

TU Delft must also pay for CO_2 emissions via the purchase of certificates. Avoiding emitting CO_2 therefore provides an additional revenue, which is not included in these calculations. The estimated benefit has been estimated to be ~€120k per year for both scenarios, as the heat that is being replaced in the city is not subject to this charge.

3.3 Business case

Four business cases have been worked out, which correspond to Scenarios 1 and 2, with and without the HT-ATES system, the results give the overall financial performance of the geothermal heating system, i.e., not isolated to the HT-ATES system. These are shown in Table 3 in terms of Net Present Value (NPV) with a discount rate of 5.5%.

Business case 1 (TU Delft heating demand supplied by the DAPwell) shows a substantially negative NPV (~€-12 M), which makes this case unfeasible if finances are the only driver. This case may be conservative due to the assumption of TU Delft campus using only 100 TJ/year from the DAPwell. In this case, additional heat required is considered to be provided by gas-fired equipment. Adding the HT-ATES system (business case 2), will improve the business case significantly; additional heat sales/subsidy result in ~€1.5 M per year, resulting in a financial business case of around €-3 M NPV over 30 years for the HT-ATES system installed in the Maassluis Formation. Business case 3 (TU Delft and the city heating demand supplied by the DAPwell), has a positive result (€2 M), whereas adding the HT-ATES system adds another €5 M. Supplying additional heat to the city has a reduced financial benefit due to the lower heat price and the maximum amount of heat covered by the subsidy scheme.

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. The result for the business cases including an HT-ATES system in the Ommelanden Formation is a ~€1.8 M lower NPV (although still positive).

4. OTHER ASPECTS

4.1 Policies and permits

In the Netherlands, the Water Law (Ministry of Transport, Public Works and Water Management, 2009) applies to subsurface developments shallower than 500m below surface, therefore it applies for the formations considered here. An amending decree (Ministry of Infrastructure and the Environment, 2013), 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 in the interest of effective usage of an ATES system. On this basis, HT-ATES systems are eligible to be licensed and have been for pilot cases. The provinces in the Netherlands are the authorities that grants licences, and for complex cases this requires an extended application procedure which lasts 6 months. In South-Holland, where the TU Delft campus is located, a pilot project has been granted a 5-year licence, therefore it is likely this project will also be granted a permit. At the location of the TU Delft, there is no drinking water resource, which reduces the potential impact.

At the campus location, a zoning plan for a regular ATES systems is in place, regulated by the Municipality of Delft (IF Technology, 2013). An initial scoping suggests that the proposed HT-ATES system and target formations would fit within this plan. On campus, there are ten existing and four planned ATES systems, mostly serving the newer buildings. All of the existing systems, except one, are in the Waalre Formation. The other system is in the Maassluis Formation, and is located 1.4 km away from the proposed HT-ATES location, which is immediately adjacent to the DAPwell to reduce transport and associated infrastructure costs. No thermal or hydraulic influence is therefore expected. The closest systems are within 200 m, and have a minimum vertical distance to the Maassluis Formation of ~55m. Initial simulations show that for a 50-year operation, a minor thermal interaction could occur for the system in the Maassluis Formation and zero for the system in the Ommelanden. Care in detailed design could remove or reduce possible thermal interaction for the Maassluis system.

4.2 Science

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’. 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. The intention would be to install a high level of instrumentation and take measurements during installation. The research activities will result in:

- Enhanced knowledge on the coupled thermo-hydro-chemical-mechanical behaviour of poorly-/ unconsolidated aquifers at elevated temperatures.
- Improved predictions on the operation of HT-ATES systems.
- Improved reliability of HT-ATES systems.
- Assess efficiency and effect of different storage cycle lengths (days, weeks, season, lifetime).
- 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 optimising a smart heat management system.

4.3 Risks and uncertainties

A wide number of potential risks have been identified, including potential mitigating measures (Bloemendal et al., 2020). A summary of the risks that have been assessed to be the highest are presented in Table 5, alongside mitigating measures. The major unknowns that are not found in the majority of new technologies are the uncertainties of the aquifers, which can be partially addressed during exploration undertaken when drilling the DAPwell, and due to delays of implementation, which affects subsidies. A high level of attention should be given to stakeholder engagement, alongside the stakeholder engagement of the DAPwell.

Table 5: Overview of major risks for the implementation of the HT-ATES system.

Risk	Mitigation
Technical	
Uncertainties with the characteristics of target aquifer and confining layers, resulting in more expensive wells.	More information will be gained by means of experiments and data acquisition during the drilling and completion phase of the DAPwell. Update modelling studies and adapt well design accordingly.
Heat availability and demand in practice make viable/sustainable operation impossible.	Sensitivity of the business case should be established and staged construction can limit risk.
Policy	
Permit not issued.	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.	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	
Scientific programme cannot achieve funding at the same time as operational project is financed.	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 or reduction of current subsidy.	Close cooperation with the DAPwell project team in order to cooperate with subsidiser and keep them up to date on the latest developments, as the ultimate decision on the SDE+ subsidy lays with them. Apply for new subsidy (SDE++).
Budget overrun due to market pressure on contractors.	Allow for flexible planning. The HT-ATES system can be installed after the DAPwell.
Budget overrun during design and building related to new technology.	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).	Ensuring that business case of project can withstand delays in DHN connection (Scenario 2 launch) without making project unfeasible. Make robust operational strategy.

5. CONCLUSIONS

An HT-ATES system at the TU Delft campus, working in conjunction with the campus geothermal project (DAPwell), is assessed to be technically and financially feasible, and results in 11 kt CO_2 emission potential reduction for TU Delft and potentially another 12 kt for the city of Delft. It is shown that while four aquifers are feasible to be used, two are preferable and are 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. In the Netherlands, HT-ATES systems have a route to obtain permits, as pilot projects, which is projected to take around 6 months. The local authority currently welcomes new HT-ATES pilot projects. Installation of an on-campus HT-ATES offers the opportunity to establish a research programme answering important questions on how such systems need to be designed, and to tackle major outstanding questions, from the behavior of (heat in) the subsurface to the operation of heat networks to interfaces with heat consumers.

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