PUSH-IT

Piloting Underground Seasonal Heat Storage In geothermal reservoirs

D1.6 Commissioning report of installations ATES-Delft: report of works, functioning of system, learnings from drilling, integration, push-pull test

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List of Abbreviations

ATES	Aquifer Thermal Energy Storage
CHP	Combined Heat and Power
DF	Drilling Fluid
DHN	District Heating Network
DTS	Distributed Temperature Sensing
DSS	Distributed Strain Sensing
EBN	Energiebeheer Nederland
EDGW	Expanded Diameter Gravel Well
ESP	Electronic Submersible Pump
EM	Electromagnetic
FEFLOW	Finite Element subsurface FLOW system
F-IEG	Fraunhofer Research Institution for Energy Infrastructures and Geotechnologies
GRE	Glass-fiber Reinforced Epoxy
GTD	Geothermie Delft
HGEO	Huisman Geo
HT-ATES	High Temperature Aquifer Thermal Energy Storage
HSE	Health, Safety and Environment
mBGS	Meter Below Ground Surface
MM	Multimode
OWD	Open Heatnetwork Delft
P&ID	Piping and Instrumentation Diagram
PVC	Polyvinyl chloride
SDE	Sustainable Energy Subsidy
SM	Single-mode
WKC	Heat plant boiler
WP	Work Package

1. Introduction

1.1. The PUSH-IT project

The PUSH-IT project, funded by the European Commission, will showcase the full-scale application of high temperature heat storage (up to 90°C) in geothermal reservoirs using three different technologies including, aquifer, borehole and mine thermal energy storage at six different sites. The three technologies addressed in PUSH-IT are relevant for different geological conditions, which are widely available in Europe. In PUSH-IT we will develop, deploy and test our technologies for a variety of configurations of heat sources, heat storage technologies, geological conditions, distribution systems, stakeholder populations and market and legal conditions. Hence, PUSH-IT provides a unique scope for demonstration, integration and advances for seasonal heat storage. These results will enhance the utilization of sustainable energy and create a balanced system for sharing benefits and burdens tied to sustainable heat generation, storage and distribution activities.

1.2. Goal of this report

Delft is one of the demonstration sites within the PUSH-IT project where a high-temperature aquifer storage system (HT-ATES) is planned to be developed and demonstrated. The goal of this report is to describe the work completed so far regarding the site exploration and construction of monitoring well. The aim is to share knowledge, experience and expertise with future projects to improve the operations and reduce the risks.

At the time of writing the report in December 2024, the production wells and fiber optic boreholes have not been installed. Hot-push-pull tests have not yet been conducted and additional monitoring wells for shallow groundwater monitoring have not yet been drilled. The report will be updated once these activities are completed.

2. Site description

2.1. Objective

The general objectives of the Delft demonstration site within the PUSH-IT project are:

- Characterization of the site to enable the realization of the HT-ATES system and facilitate research.
- The realization, operation and monitoring of an HT-ATES system in conjunction with a geothermal well, heat pump, and an expanding district heating network (DHN) in order to demonstrate the potentials of the technology (WP1).
- Facilitate research on public engagement, social benefits and risks with regards to HT-ATES (WP2).
- Facilitate research, testing and demonstration of enabling technologies including drilling and completion, control and integration, water quality and environmental effects, performance assessment and optimization (WP3).

2.2. Location (design)

Integration with DHN

The HT-ATES is to be installed at the TU Delft campus. It will be integrated in the TU Delft district heating network (DHN). This DHN is currently being fed with heat from gas fired boilers and a combined heat and power (CHP) unit. But this will soon be replaced by a geothermal well, producing heat at 77°C, together with a heat pump to boost temperature level to 90°C when needed to meet demand. The DHN will also be extended to the city of Delft, this is scheduled to start around 2025. Starting with a limited demand, but steadily increasing towards 2040.

Heat demand

The current version of the design (Q4 2024) foresees a target storage capacity growing towards 40 TJ (~600,000 m3 storage volume). With approximately 30-40 TJ heat delivery (500,000 m3 hot water) during the winter and 40-50 TJ loading of the HT-ATES system during summer (600,000 m3 water). The difference in volume and energy between loading and unloading is due to buildup of storage and loss of heat to the surrounding formation.

Scenario studies are underway on the future heat demand of the DHN. This will impact the heat demand and operational temperature limits of the HT-ATES, as these will remain uncertain.

Hydrogeology

The production zone is the Maassluis formation. According to information available before the start of the project from offset wells and a regional geological model (REGIS II), the sand layers in this formation extend between 120 and 180 mBGS (meters below ground surface). A more extensive description of the regional hydrogeology is included in the Deliverable 1.1 of the PUSH-IT project in the workplan on the Delft site (chapter 2).

Detailed information (cuttings analysis, borehole loggings, pumping tests) is collected during the drilling of the test and observation well which is used to further enhance the hydrogeological model of the production zone. This model forms the basis for design and operation of the HT-ATES system.

Design

The current version (Q4 2024) of the design foresees in the following infrastructure (see):

- Heat exchanger
- 2 hot wells
- 3 lukewarm wells
- Connecting pipes
- 1 observation well
- 8 fibre-optics boreholes

As outline in paragraph, this design may still require adjustment.

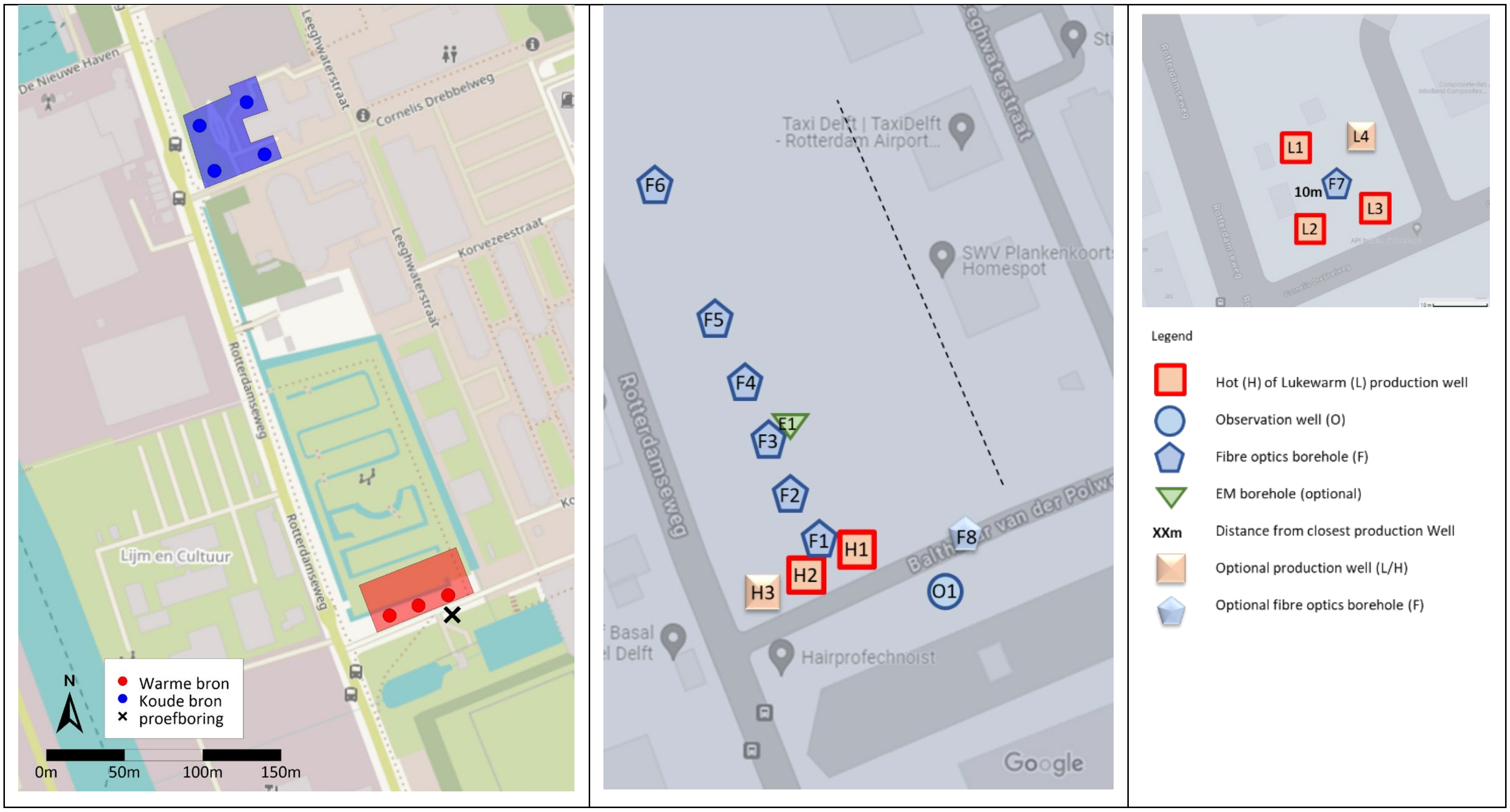


Figure 1: Anticipated location of the HT-ATES wells (left), monitoring system (middle), and Lukewarm wells (right). The latest version of the design foresees three lukewarm wells (L) and two hot wells (H)

2.3. Main stakeholders

There are several stakeholder groups which are of importance at the site in Delft:

- TU Delft – participant in the HT-ATES and shareholder of Geothermie Delf (GTD) and owner of the terrain. Also, stakeholder as neighbour of the system.
- Energiebeheer Nederland (EBN), Shell – participant in the HT-ATES and shareholder of GTD.
- Aardyn - shareholder of GTD and participant in PUSH-IT.
- Students and employees of TU Delft and other institutes on campus.
- Owners of neighbouring residential buildings and offices that operate an ATES system or are in the process of permitting it.

- Province of Zuid-Holland: competent authority ATES permitting.

Main changes to the stakeholder situation encountered during the PUSH-IT project were the takeover of Aardyn and Equans ownership.

The future operator of the ATES will be GTD, a joint venture between TUD, Shell, EBN and Aardyn. TUD, Shell and EBN were actively involved in the design, permitting and overseeing the construction of the monitoring well. They engage through bi-weekly meetings of a HT-ATES working group that oversees activities and reports to a HT-ATES steering committee encompassing the same organizations. Aardyn only very recently decided to join the HT-ATES initiative. This is an important step, as else it would have led to a lot of discussion and internal billing between with GTD for delivering heat for storage from their geothermal plant and using heat to feed the district heating network.

A more extensive description of the stakeholders is included in the Deliverable 1.1 of the PUSH-IT project on the Delft site workplan (chapter 2).

2.4. Status Q4 2024 (cause of delay)

The HT-ATES at the Delft site is integrated with a geothermal well and is part of a large heating system, with many (legal) entities and companies involved and investing. This involves considerable external investment (total >100 mEUR) and many external partners beyond the PUSH-IT partnership. Integrating the HT-ATES in such a complex setting has the opportunity to create the highest impact but involves challenging coordination and dependencies on decision making in other parts of the heat-chain. The main setbacks that result in a delay in the demonstration of heat storage and energy recovery within the PUSH-IT project planning at the Delft site are as follows:

- setback/Delayed in contracted heat, resulting in uncertainties in the guaranteed heat demand from the city of Delft [=external to PUSH-IT and TU Delft].
- Investment decisions on the new heat network which allows cost effective operation of the geothermal system, led to delays in the completion of the geothermal project – and the design of the heat pump centre [=external to PUSH-IT and TU Delft].
- Due to the general limited availability of materials and increase in price of materials and parts after start of Ukrainian war, the heat pump centre/plant room turned out too expensive for the heat grid owner/operator, so had to be redesigned [=external to PUSH-IT and TU Delft].
- Impossible pipework connections between all components and the heat pump centre required a change of location, meaning restarting permit procedures for the heat pump centre [=external to PUSH-IT].

These dynamics, where we are dependent on and cannot influence, are the biggest setback in the demonstration of the HT-ATES in Delft, as the heat pump centre is the place where the geothermal well and the heat grids are connected to the HT-ATES.

- **The new planning for the heat pump centre to be ready, operation and heat delivery to start, is by the end of 2026.** Note that this is a tight planning and requires that we do not encounter further delays.

Other smaller delays/setbacks:

- PUSH-IT partner Equans changed ownership and during this process there was uncertainty on their investments in the geothermal system (providing heat to the storage site), participation in the HT-ATES project and the PUSH-IT project.
- New insight on the negative impact of the HT-ATES hot wells on surrounding ATES systems. There are neighbouring shallow LT-ATES wells that were recently constructed or permitted, and thus not present during the feasibility study and conception of the PUSH-IT project. Also, a ground source heat pump was recently installed at a neighbouring company. These insights we only gained during the environmental impact assessment performed during application for a permit.
- New insights on the aquifer characteristics following from the monitoring well drilling and testing required a change in the design of the hot and warm wells.
- New practical limitations (limited site accessibility and land ownership) and extra costs for the connecting piping caused by a change of well location forced during the permitting process.
- New scientific insights gained during the PUSH-IT project on the influence of high temperature on the maximum permissible flow rate for well design.

Changes / Deviations & mitigation in Task 1.1. Delft

The following changes/mitigation actions were made compared to the grant agreement (bullet 1 and 2) and the Delft site workplan (bullet 3 and 4) based on the new insights and setbacks outlined above:

- The number of production wells is adjusted to three lukewarm wells and two hot wells based on the required energy storage as part of the wider energy system and subsurface composition and new permissible flowrate.
- Based on feasibility study and additional investigations, we also made adjustments to the technologies that will be tested, with the objective of testing the technologies that have the highest chance of making an impact on the HT-ATES market. We reduced the number of EDGW’s (Expanded Diameter Gravel Well) from two to one. GRE (Glass-fibre Reinforced Epoxy) casing is applied not from HGEO (Huisman Geo) but sourced from another company that can guarantee better performance under high temperatures. Instead of vacuum casing, we will test insulation using grout, since this is more cost effective.
- The position of the hot wells was moved to a different location to prevent thermal impact on existing other users.
- The position of the monitoring well and fibre optic boreholes is adjusted to allow monitoring of the hot wells at their adjusted location.

These new insights have caused considerable delays since they need to be resolved before we could proceed with the detailed design and start tendering and construction of the HT-ATES system. The delays were further enhanced by uncertainty of the role of Equans in the PUSH-IT project and the HT-ATES. They were responsible for large parts of the design that impacted the heat exchanger and thus the HT-ATES overall capacity.

Changes to the planning

The setbacks and new insights have caused a considerable delay since they need to be resolved before we could proceed with the detailed design and start tendering and construction of the HT-ATES system. The adjusted planning is outlined in chapter 7.

Current uncertainty

Note that the number of production wells may still be adjusted before construction, as further scenario studies on the heat demand are currently underway. It is also under consideration whether a heat pump is necessary to enhance the thermal recovery of the hot wells. These uncertainties need to be resolved before the production wells can be constructed.

Construction

So far, we have constructed and tested the observation well (see findings in remaining chapters of this report). Design and procurement for the production wells and fibre optic temperature monitoring boreholes has been initiated, despite uncertainty on the exact required number and their positioning.

3. Drilling and completion

This chapter concerns the drilling and completion of the observation well (HTO-M01).

3.1. Learning from drilling

During the drilling of the observation well, the team organised the planning such to have time to reflect on the drilling process and identify challenges and potential windows of improvement. For conventional water wells and LT-ATES, drilling in high-permeability layers using current methods provides a cost-effective and reliable approach. HT-ATES are targeting deeper aquifers, corresponding to lower permeability, over-consolidated soil and complex lithologies. In addition, for HT-ATES, due to the high temperatures, the technologies (including completion materials and drilling fluid chemistry) move towards geothermal applications and as a result significant cost increase. Thus, it is essential to improve and combine technologies from the shallow wells. To ensure safe, reliable and cost-effective drilling applications the following considerations and improvements are listed below:

<u>Drilling fluid, cuttings separation and mixing units:</u>

- The drilling process for such wells is commonly not 24/7, and is stopped at early evening; hence, the drilling fluid (DF) is static during the night for more than 12 hours. A reliable field method to evaluate the drill fluid's viscosity is the Marsh funnel and for a more detailed analysis the Fann 35 viscometer. The drilling fluid sampling in the morning (prior to the drilling) indicated that the Marsh funnel viscosity and gel strength (obtained from the API viscometer) were almost always higher.
- The drill cuttings are separated by settling in three different settling basins by gravity. The separation of the drill cuttings from the drilling fluid in the last setting basing, where the fine particles mainly, was generally poor. Even though the fluid properties are maintained, in the tank closer to the well there is a lot of cuttings accumulation. The poor solid control is an indication of non-solid-free drilling fluid and has negative implications in the drilling process, as drilling cuttings remain in suspension and result in alteration of desired DF-properties. For future drillings we will reconsider the mixing and recycling unit.
- The DF was poorly mixed, with lumps of additives floating in the fluid. A better mixing machine will be required in case more additives are added during future drillings for the production wells.

<u>Coring:</u>

- During the drilling phase, 12 core samples were obtained. Unfortunately, the initial core barrel was half-empty. Also, the Polyvinyl chloride (PVC) core holder got stuck because it was too long compared to the length of the coring machine. The cores therefore had to be hammered loose, which caused damage to the cores. After shortening the length of the core barrel by a few centimeters, we obtained ten full barrel cores with a length of 1 m and an average core recovery of 92%.

<u>Measurements and challenges:</u>

- The rate of penetration (speed of drilling) is controlled and steady at 10 m/h. The drilling rig is not instrumented, but from observations the teams were able to identify differences in the drilling behavior (vibrations of the drill string) due to differences in formation at the drill bit, even in a resolution of 30 cm. This also assist to identify formation tops.

- The reverse circulation technique allows cuttings to be pumped up to the surface through the drill pipe. At approximately 176 to 180 mBGS, the team observed severe vibrations. An unexpected event occurred when large rock segments plugged the inner part of the drill bit (since there is empty space for reverse circulation). To unplug the drill bit, a steel rod was lowered through the drill pipe and initiated hammering to break the rock. This occurred three times in an interval of 4 m, as a result it took almost all day to drill 4 m.

The observation well was drilled not only to characterize the subsurface but also to identify potential improvements for the construction process of upcoming wells such as treating of the mud and cuttings.

3.2. Completion

The final depth of the borehole was determined at 230 mBGS. As the main function of the well is to be a pilot drilling and observation well, the completion design had to serve multiple purposes including pumping tests, fibre optics installation and to incorporate piezometers on various intervals. The sealing clay layer above the target formation was approximately from 75 to 123 mBGS. In addition, the lower part of the borehole, from 184 mBGS to the final depth of the borehole, was mainly clay (Figure 2).

Characterization of the drill cuttings and analysis of borehole measurement in the open borehole were utilized to determine the optimum filter count, which corresponds to the number of filter sections. It was decided during the filter count to set as much well screen as possible in the sandy sections from 120 to 184 mBGS, so that information could be gathered about the geohydrological properties of the sand layers at different depths within the Maassluis formation through the planned tests. The drill cuttings analysis and borehole logs indicate strong but thin clay layers in the target aquifer, in which well screens are not placed. Despite the fact that, according to the drill samples, a clear layer of clay did not always emerge between these sections, the borehole measurement did show higher gamma ray (GR) values and therefore clay pellets were used as a backfill material at those depths: this clearly separated the three well screen sections within the borehole from each other and this made packer tests possible.

The main completion of the well for the pumping test was done with PVC, which is backfilled with clay pellets after to secure integrity once the hot HT-ATES wells are operational. In addition to the main completion, four blue PVC monitoring wells and five grey stainless steel monitoring wells have been placed. The screens of the stainless-steel observation wells are placed in the target aquifer to be used for pumping tests as well as during HT-ATES operation. The PVC monitoring screens are only used for the pumping test analysis and backfilled with clay after. demonstrates the well design with respect to depth and the corresponding placements of the piezometers (MF-F1 to 9).

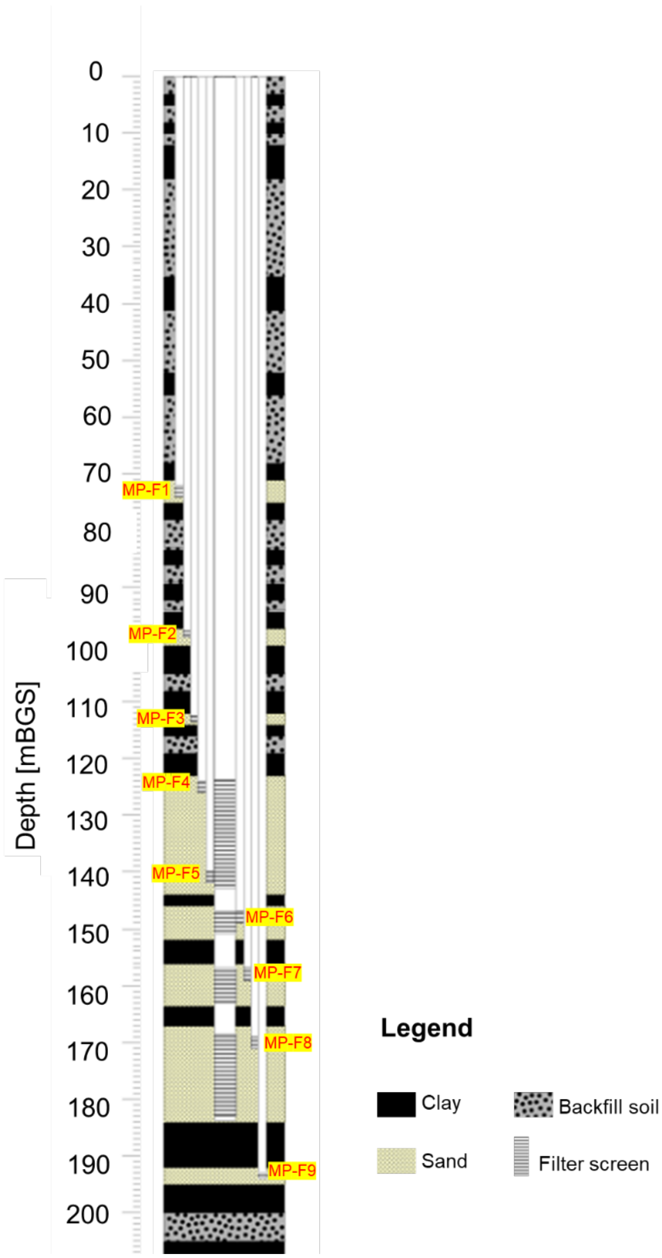
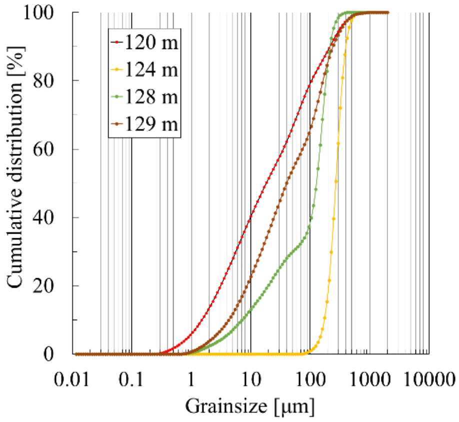


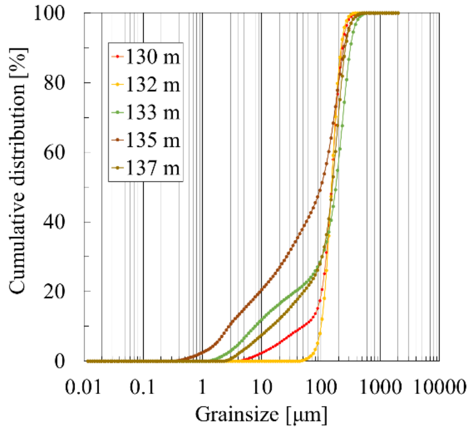
Figure 2: Well completion

3.3. Cuttings analysis

While drilling the observation well, drill cuttings were collected and labelled onsite for further analysis. Due to the small volume and uniformity of the cuttings, the main analysis is to evaluate the particle size distribution. The interval of interest is between 120 and 180 mBGS, with cores obtained from specific zones. Thus, the drill cutting analysis is conducted on depth intervals similar to the core samples. The particle size fraction is utilized to classify the intervals. Figure 3 shows that the particle size distribution can differ even within a distance of 1 m. Considering the formation's physical properties, it can be classified by following the classification procedure from Figure 4. We plan to do additional grain size analysis if and when we open the remaining cores.



(a)



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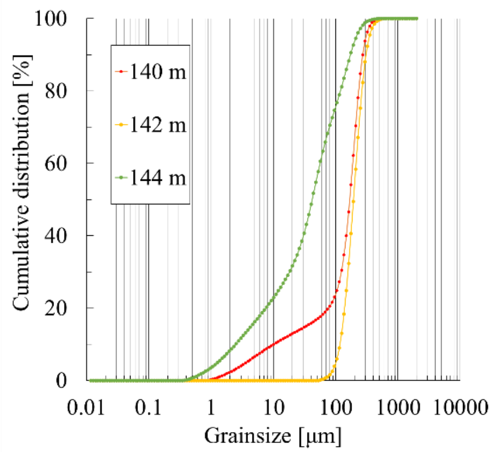

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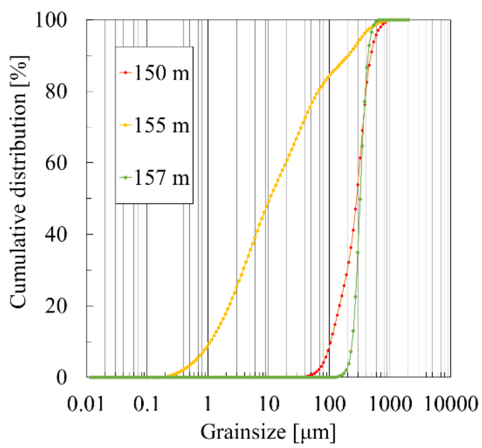

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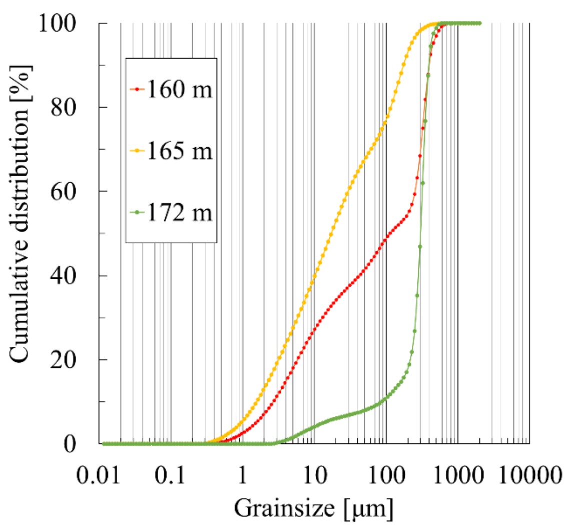


(e)

Figure 3: Particle size distribution analysis from several depths

Figure 4: Soil classification according to ISO 14688-1

The identification procedure allows the unconsolidated sample to be categorized based on the percentage of silt, clay, and sand. According to the International Standard (ISO 14688-1), sand is from 0.05 to 2 mm, silt is from 0.002 to 0.05 mm, and clay is below 0.002 mm. Thus, Table 1 classifies the formations drilled based on soil grain size.

Table 1: Soil classification, median size and coefficient of uniformity

Depth [mBGS]	Percent Clay [%]	Percent Silt [%]	Percent Sand [%]	Classification	d50 [µm]	Coef. Uniformity
120	13.07	52.31	34.62	Silt loam	18.50	23.65
124	0.00	0.00	100.00	Sand	271.40	1.68
128	2.18	27.27	70.55	Sandy loam	130.10	19.02
129	3.56	49.52	46.92	Loam	40.35	17.45
130	0.00	9.79	90.21	Sand	148.00	3.32
132	0.00	0.15	99.85	Sand	148.00	1.60
133	1.08	20.46	78.46	Loamy sand	176.00	26.90
135	6.25	31.53	62.22	Sandy loam	100.30	49.34
137	0.00	19.41	80.59	Loamy sand	154.70	11.31
140	2.21	14.53	83.26	Loamy sand	168.70	18.23
142	0.00	0.00	100	Sand	191.90	1.84
144	8.05	46.69	45.26	Loam	45.99	22.62
150	0.00	0.55	99.45	Sand	283.70	3.08
155	17.73	57.82	24.45	Silt loam	10.54	18.20
157	0.00	0.00	100.00	Sand	322.80	1.47
160	6.89	34.18	58.93	Sandy loam	114.10	90.50
165	12.79	54.22	32.99	Silt loam	16.69	19.85
172	0.00	7.84	92.16	Sand	296.00	3.36

3.4. Core analysis

Drill cores of 1 m length were retrieved from several intervals for further characterization of the subsurface. The core is retrieved with a core barrel bade of a thin PVC pipe. Initially, the core is scanned with a medical CT scan, obtaining snapshots of a specific resolution. As the next step, the raw files are utilized to reslice the snapshots in different orientations. The following figures shows the steps to obtain a 3D reconstruction of the core using FIJI ImageJ. Figure 5 and Figure 6 illustrate the reconstructed core sample for different depths. Some images show that there is layering, which may cause anisotropy (=lower vertical than horizontal hydraulic conductivity).

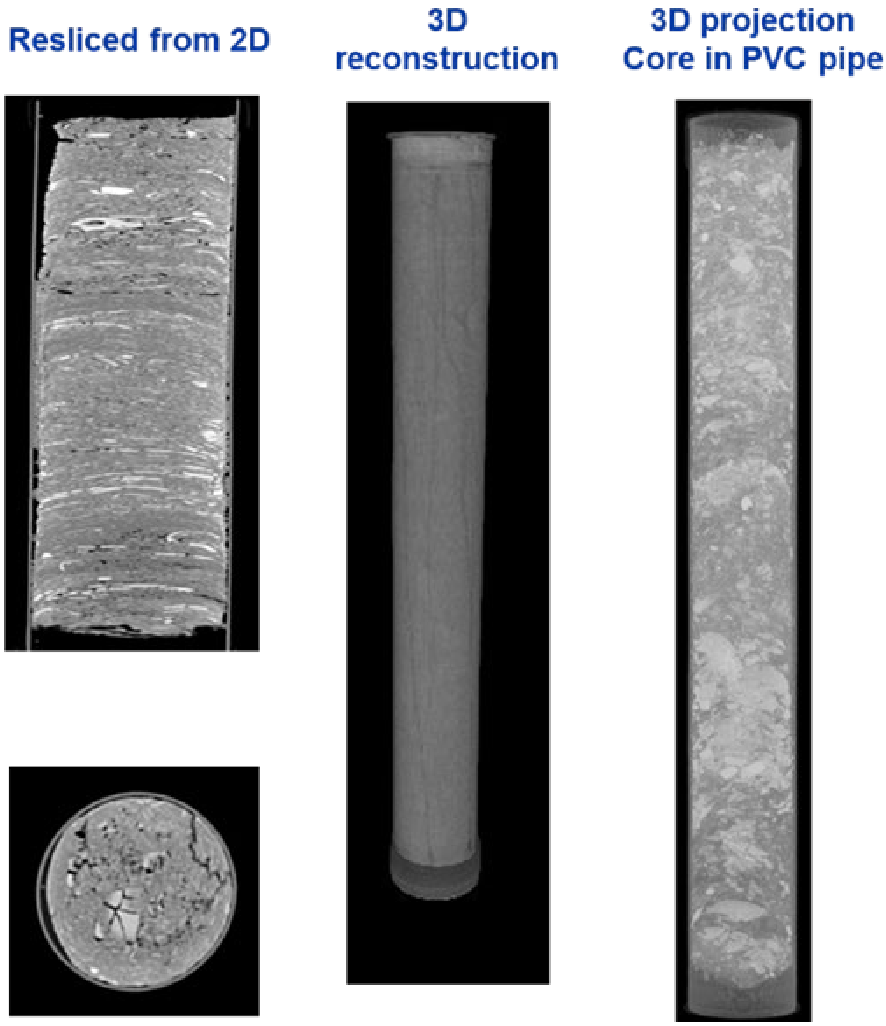


Figure 5: The 2D images (slices) obtained from the medical CT are processed to reconstruct the sample in 3D

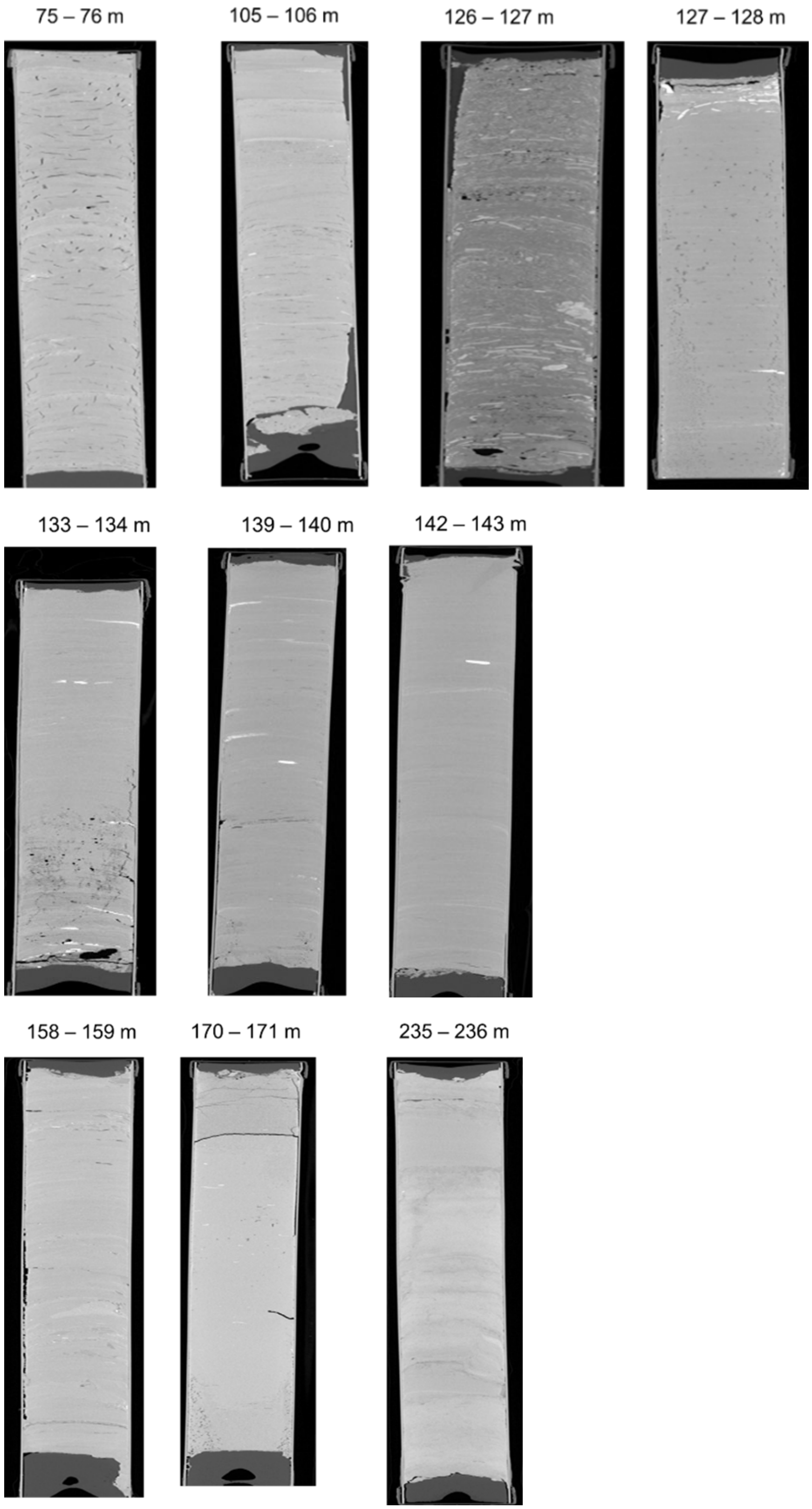


Figure 6: Retrieved core samples after reconstruction using a medical CT

3.5. Well logging

Well logs provide information about the geological units and properties by applying geophysical logging devices down a borehole. Well logs are carried out at a speed of about 7.5 m/minute and reported with a resolution of 0.05 m.

In principle, clean sand intervals with fresh water are characterized by low gamma ray rates (<8 count/sec) and high resistivity values ranging from 20 to 200 Ohm-m. For sand in saline formations a similar threshold (<8 count/sec) was used for gamma ray rates while resistivity values are <10 Ohm-m. On the other hand, for clays in both fresh and saline water high gamma ray rates (>17 count/sec) and low resistivity values (<10 Ohm-m) are utilized. For interlays containing sand and clay gamma ray rates are ranging between 8 – 17 counts/s and resistivity values between 10 and 20 Ohm-m (Milzow et al., 2009). In general, resistivity values can be influenced from various formation properties including porosity, salinity, clay content and permeability (Matsui et al., 2000). In addition to the threshold that were mentioned above, clean saturated sand resistivity values can also be ranging between 5 to 15 Ohm-m (Hudson, 1996). This indicating the variation in resistivity depending on formation properties,

For the current analysis clean sand intervals with fresh water are characterized by low gamma ray rates (<10 count/sec) and resistivity values ranging from 20 to 200 Ohm-m. For sand in saline formations a similar threshold (<10 count/sec) was used for gamma ray while resistivity is <20 Ohm-m. On the other hand, for clays in both fresh and saline water, high gamma ray rates (>17 count/sec) and low resistivity values (<20 Ohm-m) are utilized.

The corresponding ranges of gamma-ray rates and resistivity values partially capture the entire spectrum. For example, saline aquifers have similar gamma ray rates but significantly lower resistivity values. In our case gamma ray rates below 10 count/sec is the initial indication of sandy layer, and then the distinction between fresh or salty water is obtained from the resistivity measurements (<20 Ohm-m is salty). In addition, interlayers of sand and clay have moderate gamma ray rates and resistivity values. Figure 7 provides an overview of the subsurface based on gamma ray rates and resistivity values.

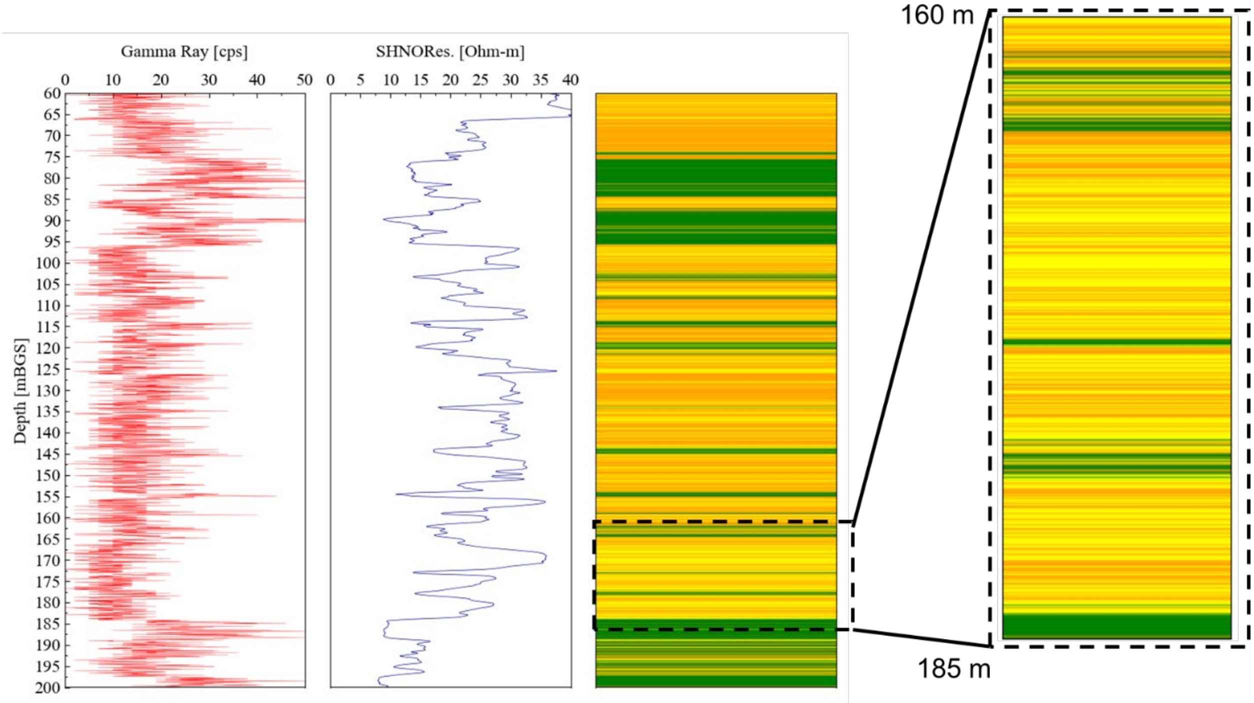


Figure 7: Borehole logs interpretation. Green is clay, yellow is sand, and orange is interlayer mixture of sand/clay/silt

The intervals of interest (which includes both the production zone and the clay layer below and above) lies between 80 to 200 mBGS. Within this interval, cumulative thickness of sand is 35.09 m, 31.59 m of clay and 53.15 m of sand/silt. The remaining 0.17 m meters are unclassified.

As mentioned, the cuttings are obtained 1 m in front of the coring interval; thus, it can be assumed that they are similar in lithology. For the initial stage, the cutting analysis is not integrated into the solution with the loggings. Based on the results obtained from the logging and cuttings. Figure 8 shows the correlation of the borehole loggings, drill cuttings and pumping tests.

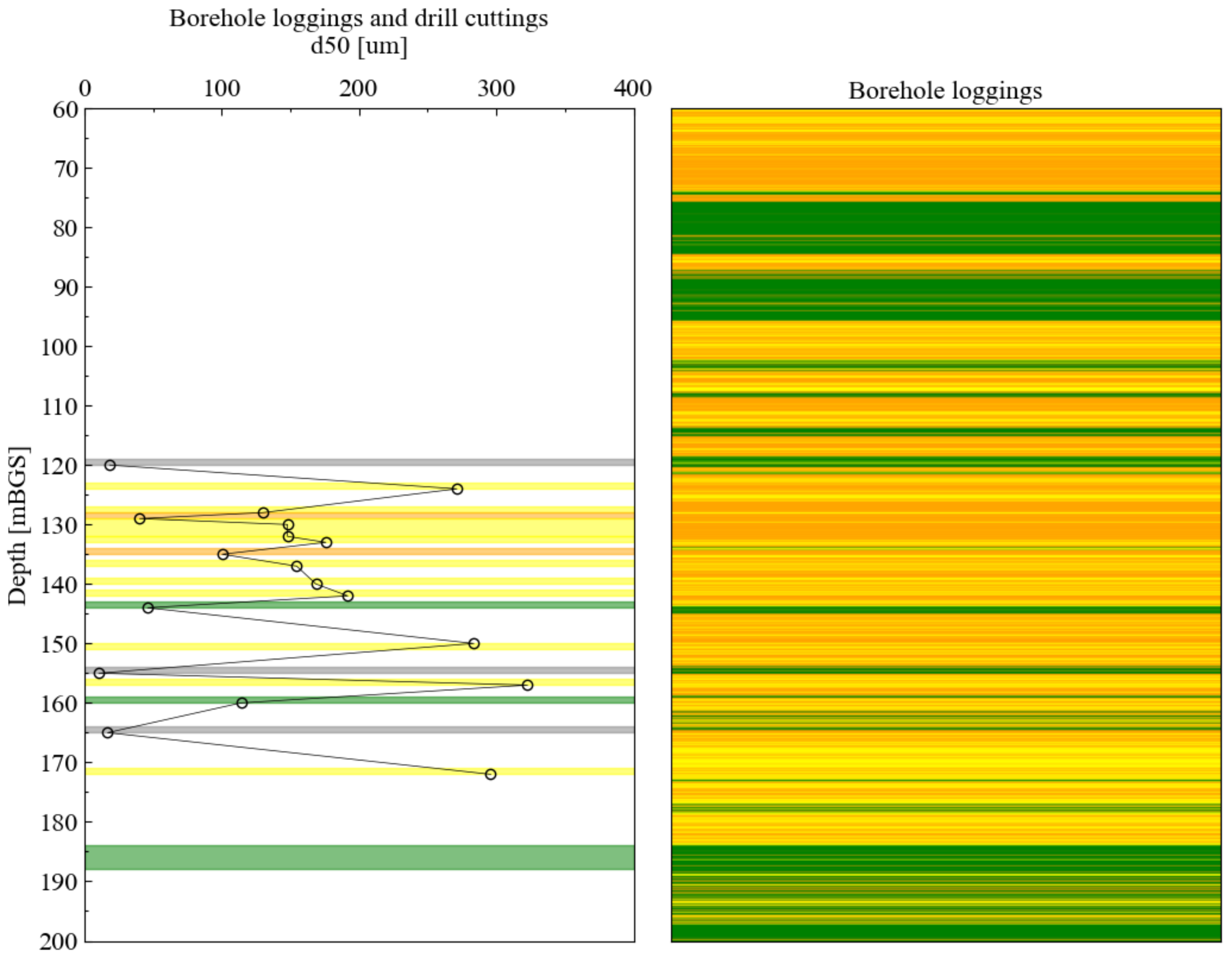


Figure 8: Correlation of drilling cuttings analysis and borehole logs interpretation. Green is clay, yellow is sand, orange is interlayer mixture of sand/clay/silt and grey is silt

Generally, the correlation between borehole loggings and cuttings is good. A key advantage of the drill cuttings analysis compared to the borehole loggings is the ability to provide more detailed differentiation between clay and silt formation. For example, at 155 mBGS the soil is classified as silt loam (grey color) from the drill cuttings compared to clay from the borehole loggings.

The drilling crew reported grain size according to observations with the naked eye and a "sand ruler" (which contains calibrated grains of a certain size for visual reference). We found that the grain size found through particle size distribution using the laser scanner (PSD laser diffraction meter) resulted in slightly different (both larger and smaller) grain size than those reported by the drilling company.

4. Performance assessment and optimization

This chapter concerns the drilling and completion of the monitoring well.

4.1. Hot Push-Pull Test and Pumping Test

The Hot Push-Pull Test in Delft is not yet carried-out, since we can only do this after the construction of a production well.

However, the observation well was completed with a temporary production screen in the aquifer that we will target for HT-ATES. The production screen is temporary as it was made from PVC, and must be backfilled before taking the HT-ATES into production because the heat will cause a loss of structural strength of the PVC. The temporary PVC screen allowed to perform a pumping test and a screen flow measurement in the observation well. In between different pumping tests we installed packer between the four screens and backfilled the bottom two screens with grout in order to also test a subset of the screens, and thus gain insight in the hydraulic properties of different depth ranges. The results in Table 2 indicates that the aquifer has ample hydraulic conductivity to allow injection and extraction of hot water. Also, it was found that the clay layer immediately above and below the target aquifer both have good hydraulic resistance to limit heat losses to the confining layers.

Table 2: Hydraulic properties of the target aquifer found during pumping tests in the observation well (IF-technology, 2024)

Section	Top	Bottom	D	k	kD	c
	[mBGS]	[mBGS]	[m]	[m/d]	[m^2/d]	[d]
Screen 1	123	144	21	10.500	22	
clay				0.050		40
Screen 2	146	154	8	11.600	93	
clay				0.044		45
Screen 3	156	164	8	17.700	141	
clay				0.057		35
Screen 4	166	185	18	12.300	221	

mBGS = meter below ground surface; D = Thickness; k = horizontal / vertical conductivity; kD = horizontal hydraulic transmissivity, c= vertical hydraulic resistance.

A screen flow measurement was carried out to evaluate the contribution of different aquifers to the total flow rate of the well. We found that these were in line with the findings of the pumping test, meaning that screens with a highest estimated transmissivity contributed most to the total flow rate of the well (Figure 9).

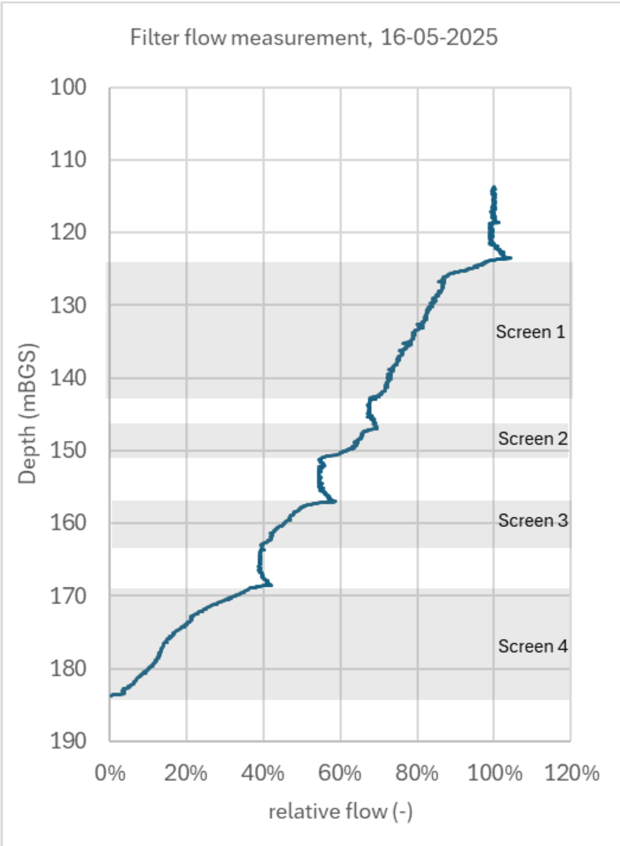


Figure 9: Distribution of the cumulative flow rate in the production screen (x-axis) as a function of depth (y-axis). The increase of flow at the top of each screen is a measurement artefact cause by a change of the flow pattern within the vertical pipe due to a change of the wall of the pipe material (from a perforated screen with horizontal inflow to a smooth watertight pipe)

4.2. Co-simulation results

The key input information and data needed for the co-simulation models are the system layout, temperature thresholds, modes of operation, the subsurface conditions including thermohydraulic properties of the reservoir rocks, and the thermal energy demands. Information has been compiled (Bloemendal and Vardon, 2023) with both the subsurface data and system layout updated as information has become available, i.e. those derived from Figure 10. As described in chapter 2, due to ongoing design work for the central plantroom/heat pump centre, commissioned outside PUSH-IT, required data/information was not available until recently.

A comparison of different integration options of the HT-ATES and the wider energy system has been investigated in an MSc thesis project using the Tespy model code (Grzesiek, 2024), which has fed into the system design. Two main options were proposed as shown in Figure 10, which significantly impact the behaviour of the energy supply from the HT-ATES (and therefore performance). Informed by these results, the system design is currently being revised, with an updated design due in December 2024. Some first results of the simulation are mentioned in Figure 11.

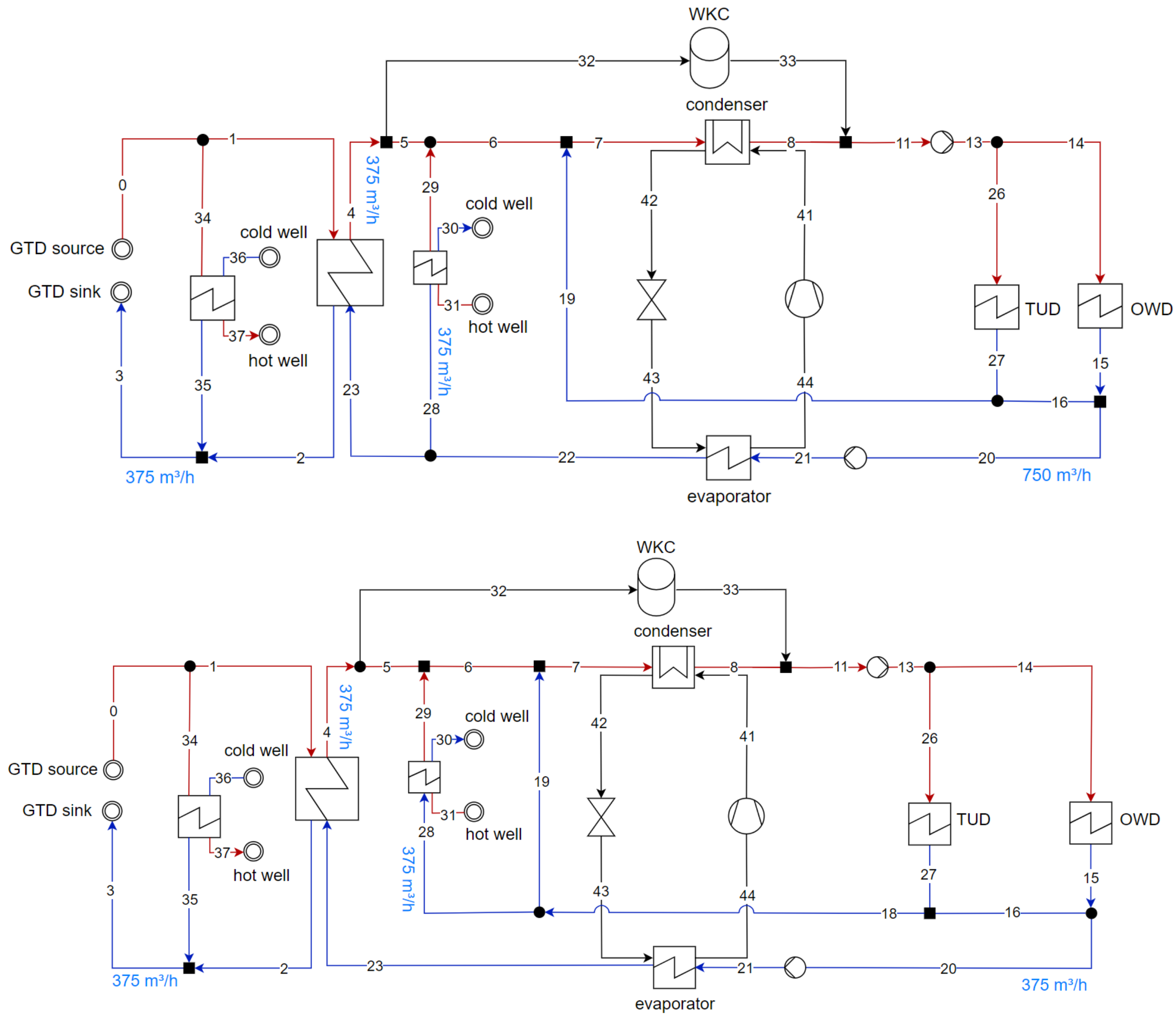


Figure 10: Piping and Instrumentation Diagram (P&ID) schematics for two different options for system integration (Grzesiek, 2024). Top-subplot: HT-ATES behind the evaporator. Bottom-subplot: HT-ATES preheats return. The goal of this diagram is to show the basic schematics. It does not to actually represent the valve settings. WKC = Heat plant boiler. OWD = Open Heatnetwork Delft. GTD source and GTD sink are the Geothermal producer and injector

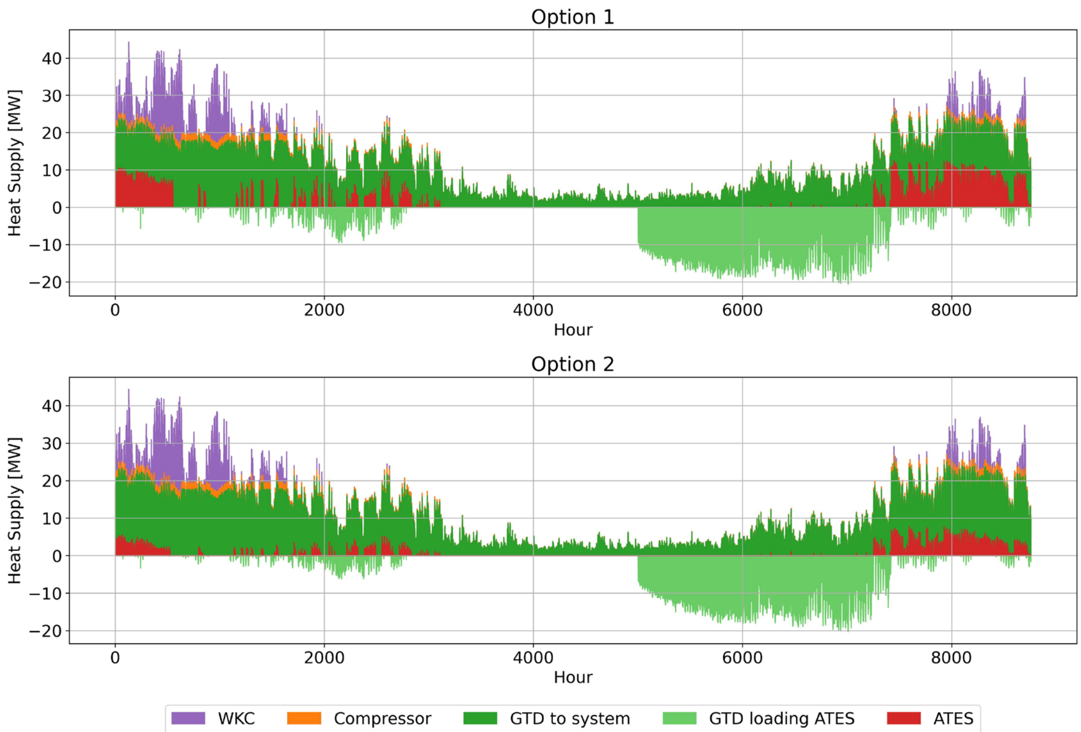


Figure 11: First results for the co-simulation (Grzesiek, 2024). Option 1: HT-ATES behind the evaporator. Option 2: HT-ATES preheats return

Further investigations are being performing by the project partner TUDA. Based on data from the borehole, the underground finite element model was updated (Figure 12). This model was also transferred to F-IEG (Fraunhofer Research Institution for Energy Infrastructures and Geotechnologies) to benchmark simplified models. Additionally, the co-simulation model was also developed in Dymola software based on models from the master's thesis project. The heat transport in the subsurface was simulated using a FEFLOW model.

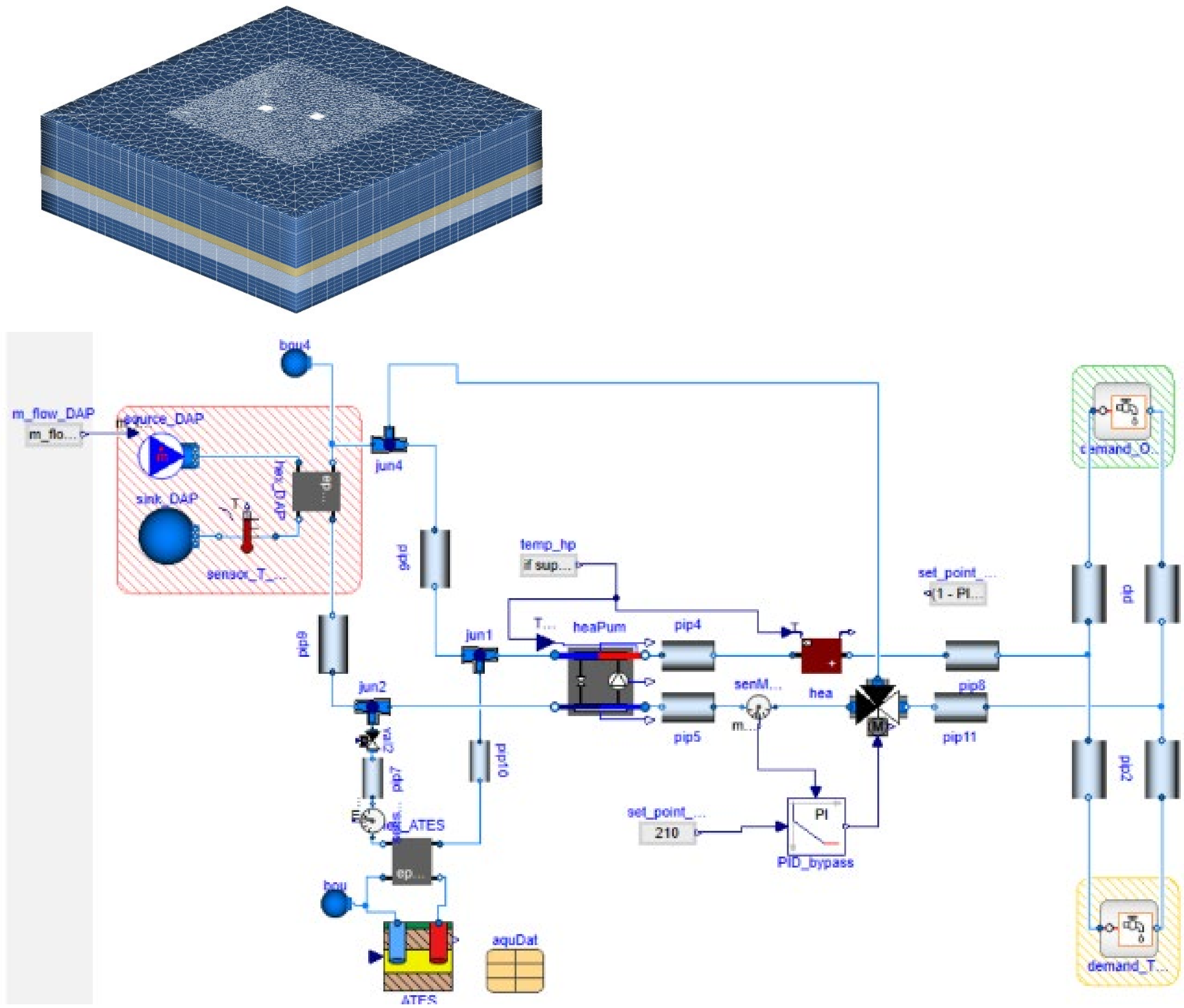


Figure 12: FEFLOW model (top) and co-simulation model (bottom)

4.3. Connection plan

The HT-ATES system will be connected to the heat exchange in the plant room / heat pump centre by means of horizontal thermally isolated pipes that will be placed in the subsurface. From the heat exchange centre, the system will be able to deliver and receive heat from the district heating network and geothermal plant.

Construction of the pipes is foreseen shortly before or after drilling the wells. We are currently optimizing the trajectory of the connections. Pipe diameter and material has been designed. Also at the geothermal well plot currently preparation work to the plant room/heat pump centre foundation and connection to boiler house is ongoing, while doing so also the last part of the HT-ATES pipes are already installed into the ground.

4.4. Control

Control mechanisms are currently in the process of being designed. The control system requires both the system design (and behaviour), and the control objectives to be established. After the underground installations are ready and connected to the plant room / heat pump centre, the control system can be installed and tested. Currently, TUD, TU Darmstadt, Fraunhofer IEG and VITO are investigating different concepts for controllers that take into account energy demand of individual buildings.

A design document has been produced compiling all the available information on the system layout, the interaction between different subsystems, the energy demand and future scenarios, and the scope, objective and plans for the network controller (Vanhoudt, 2024). The design of the interaction between the controller and the co-simulation model is schematically shown in Figure 13.

Since some choices on the hydraulic configuration still have to be detailed, the controller algorithm scope still needs refinement afterwards. Besides the definition of the scope, also the data communication interfaces are being discussed, as a step towards real-life implementation of the controller.

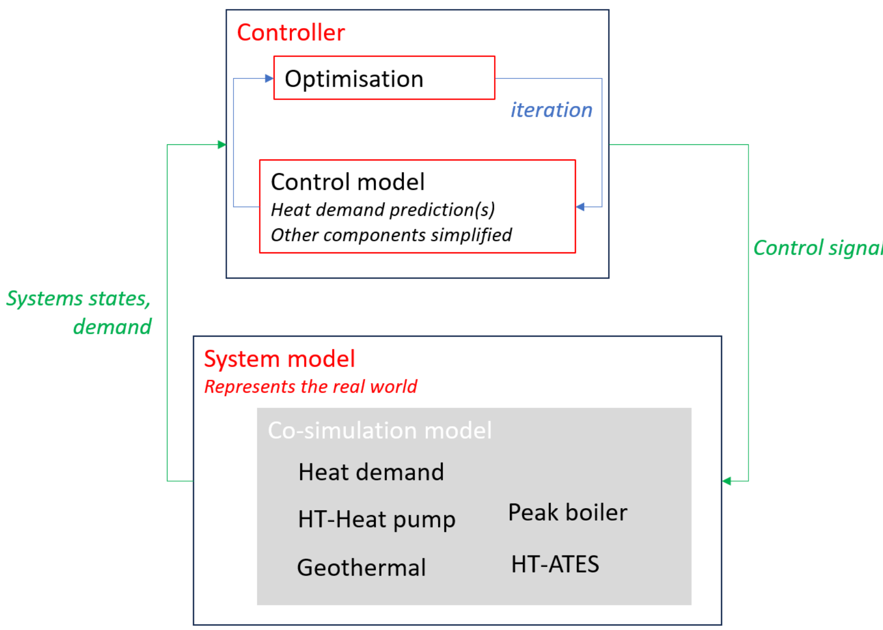


Figure 13: Interaction between the controller and the co-simulation environment

5. Monitoring system

5.1. Long term thermal impacts

The monitoring plan foresees in equipping the production wells, observation well, and fiber optic boreholes with fiber optic cables to enable continuous temperature monitoring. The Distributed Temperature Sensing (DTS) cables will facilitate the tracking of temperature changes in the storage formation and shallow groundwater formations.

To decide on the position of the DTS-cables, the thermal radius was computed using an analytical approach by simplifying the warm and hot plume to a cylindrical shape centered around the warm and hot well. Since it is currently uncertain how the heat demand will evolve over time, and how the HT-ATES system will be designed and operated, a total of four (2x2) scenarios were computed:

- In the initial five years (until 2030), there is a net oversupply of heat. For the years from 2030 onward, two scenarios were considered. One in which the net loading of the hot plum continues and a second one whereby there is no net loading of the hot plume after five years.
- Installation of production screens in the top half of the aquifer versus the entire aquifer.

The simulated thermal radius of the hot plume will increase over time but has a large range of uncertainty. After five years, the thermal radius is between 40 and 55 m. In the period thereafter, it may either stabilize or continue to expand until 110 m. Please note that the actual radius influenced by heat injection is much larger since there will also be losses due to convection and dispersion.

The positions of the fiber optics wells presented in Figure 14 are selected to accommodate a robust monitoring within the range of uncertainty predicted by the analytical model and taking into account some additional convention and dispersion losses. DTS-cables are also foreseen in the production and observation wells.

Apart from temperature measurements, the project will also investigate the integrity of annular material (such as grout) during heating and cooling cycles. This will be achieved by installing Distributed Strain Sensing (DSS) cables. In practice this means that, apart from the multi-mode fibers required for DTS-monitoring, there also need to be tight buffered single mode fibers in the cable. The DSS cables will only be installed in the production wells since these are most vulnerable to loss of well integrity. The fiber optic boreholes are less effected by the heating and cooling cycles.

To prevent interference with electromagnetic (EM) borehole measurements (outside scope of PUSH-IT), cables with non-metallic armoring or no metallic parts will be prioritized. For the fiber optic boreholes, this is essential as the production well casings are metallic.

All fibers will be looped with a downhole assembly. This way, all the fiber optic boreholes can be connected to a single interrogator and thus be monitored continuously and automated.

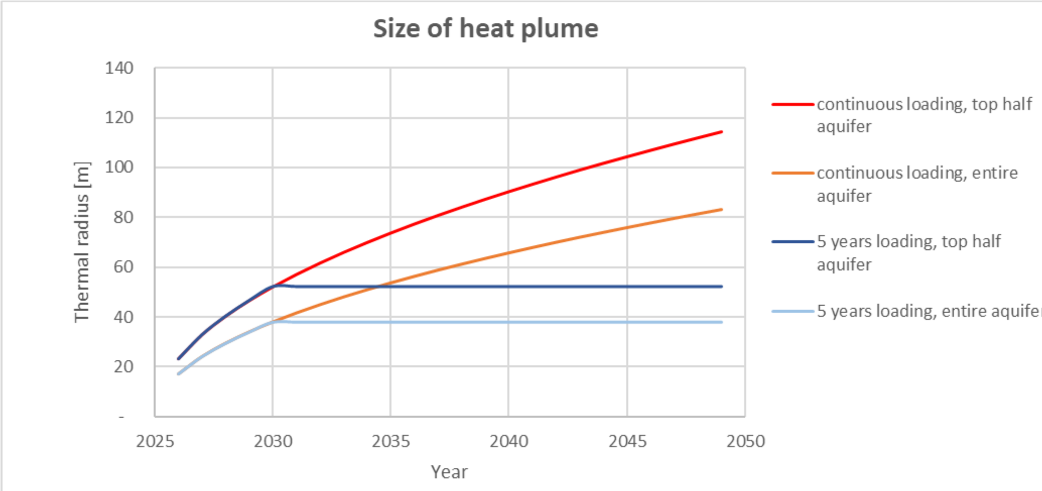


Figure 14: Thermal radius of the hot plume different loading scenario and well configurations

5.2. Hydrogeological monitoring, water quality

TUD and BRGM have taken water quality samples from an observation well which is installed at approximately 20 m of the planned location for the hot wells. The purpose of the measurement was to get a reference (benchmark) of the native groundwater quality.

The piezometers F4 to F8 are in the thermal storage zone of the hot wells and were sampled while the production screen was being pumped. This prevents mixing of water from different layers due to short circuit flow through the production screen (which was not backfilled during the sampling). The more shallow and deeper piezometers (F1 – F3 and F9) are in the over and under burden respectively.

The samples have been analysed for the parameters listed in Table 3. Results indicate that the water is partly saline and that there is a gradient from methanogenic to sulphate reducing groundwater in the target aquifer.

Table 3: Overview of water quality samples taken from the observation well (O1) in July – September 2024 (IF-Technology 2024)

Putcode	unit		MP-F1	MP-F2	MP-F3	MP-F4	MP-F5	MP-F6	MP-F7	MP-F8	MP-F9	Bron
Diepte peilfilter	m-mv		72-74	97.5-98.5	12.5-114.	124-126	140-142	147-149	157-159	169-171	193-194	124-183
Diepte peilfilter top	m-mv		72	97.5	112.5	124	140	147	157	169	193	124
Diepte peilfilter basis	m-mv		74	98.5	114.5	126	142	149	159	171	194	183
Datum bemonstering	-		07-08-24	07-08-24	28-08-24	22-05-24	23-05-24	23-05-24	23-05-24	22-05-24	28-08-24	22-05-24
Opmerkingen	-		Bron uit	Bron uit	Bron uit	Bron aan	Bron aan	Bron aan	Bron aan	Bron aan	Bron uit	Bron aan
Veldmeting	eenheid	lab	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
Datum meting		IF	07-08-24	07-08-24	28-08-24	22-05-24	23-05-24	23-05-24	23-05-24	22-05-24	28-08-24	22-05-24
EC	µS/cm	IF	6870	8220	8008	9550	10510	10810	11610	12490	11040	11320
pH	-	IF	6.5	8.9	6.7	7.14	6.6	6.7	7.6	7	12	6.7
zuurstof	mg/l	IF	0.95	0.45	0.89	0.2	0.25	0.11	0.2	0.51	0.2	-
watertemperatuur	°C	IF	14.5	16.5	13.9	14.6	14	14.1	14.3	13.8	14.7	13.9
Observatie gasbellen	-	IF	ja	ja	ja	kleine bell	kleine bell	geen	geen	geen	nee	-
Observaties overig	-	IF	GFP 33m	GFP 33m	GFP 28m	troebel	:peild 143,5m			troebel	GFP 28m	
NTU	-	IF	8.26	4.78	8.77						28.2	
Laboratorium chemie	eenheid	lab	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
Datum analyse		SGS										
DOC	mg/l	SGS	8.9	9.8	9.4	6.1	8.4	7.5	16	3.9	8.6	
pH	-	SGS	6.7	6.8	6.9	6.9	7	7	7	7.1	7.6	
temperatuur tbv pH	°C	SGS	21.6	21.5	22.1	20.3	20	20.4	19.5	20.2	22	
arseen	µg/l	SGS	20	13	4	<1	<1	<1	<1	<1	2	
barium	µg/l	SGS	230	250	230	250	290	300	390	250	120	
Borium	µg/l	SGS	59	110	140	320	260	250	370	690	1700	
cadmium	µg/l	SGS	<0.2	<0.2	<0.2	<0,2	<0,3	<0,4	<0,5	<0,6	<0.2	
calcium	µg/l	SGS	600000	560000	540000	470000	450000	440000	460000	340000	120000	
chroom	µg/l	SGS	<1	<1	1.5	<1	<1	<1	<1	<1	<1	
kobalt	µg/l	SGS	3	2.8	<2	<2	<2	<2	<2	<2	<2	
kalium	µg/l	SGS	9100	15000	18000	28000	33000	30000	42000	47000	43000	
koper	µg/l	SGS	<2	<2	<2	<2	<2	<2	<2	<2	<2	
lithium	µg/l	SGS	<50	<50	55	77	60	65	67	57	<50	
lood	µg/l	SGS	<2	<2	<2	<2	<2	<2	<2	<2	<2	
magnesium	µg/l	SGS	55000	75000	95000	170000	140000	130000	220000	260000	170000	
mangaan	µg/l	SGS	830	560	360	220	140	120	150	110	60	
molybdeen	µg/l	SGS	<2	<2	<2	<2	<2	62	<2	<2	2.3	
natrium	mg/l	SGS	690	1000	1000	1200	2100	1600	1900	1700	1900	
nikkel	µg/l	SGS	10	5.7	<3	<3	<3	<3	<3	<3	<3	
Silicium	µg/l	SGS	13000	15000	17000	23000	18000	18000	14000	10000	4200	
vanadium	µg/l	SGS	<2	<2	<2	<2	<2	<2	<2	2.2	<2	
ijzer	µg/l	SGS	19000	16000	12000	8200	6700	6200	5700	4700	1500	
zink	µg/l	SGS	28	10	19	<10	<10	14	21	<10	<10	
ammonium	mg/l	SGS	4.7	5.3	6.1	10	8.6	8.4	11	14	11	
fluoride	mg/l	SGS	<0.2	<0.20	<0.20	<0,2	<0,2	<0,2	<0,2	<0,2	<0.20	
bromide	mg/l	SGS	6.7	9.7	7.9	12	11	11	12	17	12	
fosfor (totaal)	mgP/l	SGS	0.29	0.44	0.42	0.73	0.47	0.38	0.25	0.25	0.36	
bicarbonaat	mg/l	SGS	730	860	930	830	740	600	490	350	370	560
chloride	mg/l	SGS	2250	2780	2190	3650	3260	3310	3670	5200	3350	
nitraat	mgN/l	SGS	<0.05	<0.05	<0.05	<0,05	<0,05	<0,05	<0,05	<0,05	<0.05	
nitraat	mg/l	SGS	<0.2	<0.20	<0.20	<0,2	<0,2	<0,2	<0,2	<0,2	<0.20	
sulfaat	mg/l	SGS	22	9.9	26	<1,0	25	15	60	240	160	
(ortho)fosfaat	mgP/l	SGS	<0.1	<0.1	<0.1	<0,1	<0,1	<0,1	<0,1	<0,1	<0.1	
Alkaliteit	mgCaCO3/l	SGS	580	690	730	690	620	530	400	280	300	
Alkaliteit	mmol/l	SGS	12	14	15	14	12	11	8	5.5	6.1	
Gasanalyses TNO	eenheid	lab	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
argon	mg/l	TNO				0.44	0.59	0.55	0.61	0.74		
zuurstof	mg/l	TNO				<0.10	<0.10	<0.10	0.35	<0.10		
stikstof	mg/l	TNO				12.01	14.65	14.13	18.07	19.62		
methaan	mg/l	TNO				19.27	9.09	4.47	<0.10	<0.10		
kooldioxide	mg/l	TNO				117.94	104.58	87.35	48.2	24.93		
Gasanalyses Isolab	eenheid	lab	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
argon	mg/l	Isolab	0.64	0.56	0.53	0.57	0.67	0.7	0.76	0.81	1.4	0.75
argon	mg/l	Isolab + corr.				0.57	0.67	0.71	0.77	0.85		0.73
zuurstof	mg/l	Isolab	0.30	0.22	0.20	0.32	0.32	4.61	0.74	0.37	1.5	0.33
zuurstof	mg/l	Isolab + corr.				0.31	0.32	4.65	0.75	0.38		0.33
stikstof	mg/l	Isolab	17.06	14.19	13.05	14.72	16.73	20.29	17.41	21.11	96.3	18.1
stikstof	mg/l	Isolab + corr.				14.62	17	20.64	18.26	21.88		18.54
methaan	mg/l	Isolab	29.02	27.96	30.33	20.43	8.85	2.96	0.07	0.01	0.22	6.07
methaan	mg/l	Isolab + corr.				20.33	9.93	2.96	0.07	0.01		6.15
kooldioxide	mg/l	Isolab	226.08	234.29	211.88	179.92	149.62	100.65	105.83	39.42	0.61	100.48
kooldioxide	mg/l	Isolab + corr.				187.05	155.76	104.78	110.27	41.06		104.63
Microbiologie	eenheid	lab	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
Datum analyse	-	KWR	08-08-24	08-08-24	29-08-24	23-05-24	24-05-24	24-05-24	24-05-24	23-05-24	29-08-24	
ATP	pg/ml	KWR	25	14	18	5	<3.4	<3.5	<3.3	5.8	16	
Berekeningen	eenheid	partij	**MP-F1**	**MP-F2**	**MP-F3**	**MP-F4**	**MP-F5**	**MP-F6**	**MP-F7**	**MP-F8**	**MP-F9**	**Bron**
SO4/Cl-	-	IF	0.0098	0.0036	0.0119	0.0003	0.0077	0.0045	0.0163	0.0462	0.0478	
Redoxklasse	-	IF	SO4-Red	SO4-Red	SO4-Red	Meth.	SO4-Red	SO4-Red	SO4-Red	SO4-Red	SO4-Red	

6. Public Engagement, Social Benefits and Risks

6.1. Societal Engagement

Engagement with the site owner and future operator

The site owner is TUD. Within TUD, Campus Real Estate (CRE) is responsible for the energy supply and facilities in the buildings. They were actively involved in the selection of the site, because they wanted to ensure that no negative thermal influence on the existing ATES system elsewhere on the campus will occur. The change of location was partly made at their demand. Interactions mainly consisted of joint meetings and sharing reports.

Engagement with the public and local community

Several engagement activities have taken place, focusing both on the local community and general public. For the most part, these have focused on providing information about drilling activities and the wider project. TUD takes part in bimonthly meetings with WP2 to help inform and support the design of engagement plans and activities. WP2 local surveys and focus groups (planned for 2025) will gauge public understanding of UTES and contribute to future public engagement approaches.

There was some discussion with a student living close to the drilling site who experienced noise. The noise was caused by the drilling rig (in the daytime) and by a generator (at nighttime) required for electricity used to secure the place against theft and vandalism with camera and lights. Upon his request, we replaced the generator with electricity from another local electric connection to limit noise during the night.

Engagement with local stakeholders

We organized several site visits during the drilling period for (1) the employees of Shell and EBN, (2) employees of TUD, (3) students of a European Geothermal PhD meeting and (4) participants from various companies participating in a research project with TUD on drilling groundwater wells. These are all within the b) and c) category: a) general public and local community, b) local stakeholders (site owner, regulators etc), c) scientific and wider business community.

Table 4: Overview of engagement activities with stakeholders and the wider public (source: PUSH-IT engagement tracker)

When	Who	Target audience	Description
2023 Q4	TUD, KWR, EQS	municipality, consultants, operator	coordination for permit request
2023 Q4	TUD	company close to HT-ATES site	discuss long term impact of HT-ATES-system on ground source heat pumps used in neighbouring offices
2024 Q1	TUD, GBBH, AARD	TUD staff, operator	site visit during drilling of pilot borehole
2024 Q1	TUD	general audience	webpost for story of science on the pilot borehole
2024 Q1	TUD	residents near HT-ATES system	poster banner at the drill site

When	Who	Target audience	Description
2024 Q2	TUD	residents near HT-ATES system	Letters/mailing to residents around drill site to inform them about drilling
2024 Q2	TUD	residents near HT-ATES site	adjust working hours and generator power supply after contact with a student complaining about noise
2024 Q3	TUD	province and municipality representatives	closed meeting
2024 Q3	TUD, KWR	province civil servants	site visit to the HT-ATES site
2024 Q3	TUD, KWR	province civil servants	coordination for permit request

Engagement with the scientific and business community

The past years, there has been communication to the wider public via the PUSH-IT and TUD websites, including regular blogs and news updates. PUSH-IT also maintains a presence on LinkedIn, where news and blogs are also regularly posted. The team has presented at various conferences and events, as shown in Table 5. The scientific and business community were targeted via several.

Table 5: Overview of communication and dissemination activities (source: PUSH-IT engagement tracker)

When	Who	Target audience	Description
2023 Q2	TUD	Industry, business partners; Research communities	Interview for local professional journal (VV+) om PUSH-IT activities in Delft
2024 Q2	TUD	Industry, business partners	Website article on PUSH-IT activities in Delft
2023 Q1	TUD	Scientists; Industry, business partners	Symposium in Energy Geotechnics 2023, presentation by Tessel Grubben TU Delft
2023 Q4	TUD	Industry, business partners; Policy-makers and authorities, national; Scientists; Education/training org anization/learners	Invited Talk Geothermal workshop, University of Bern. Focussed on the work we do on HT-ATES in Delft specifically
2023 Q2	TUD	Industry, business partners; Policy-makers and authorities, national; Civil society, national, regional or	Invited talk DAP symposium Delft. Focussed on the work we do in PUSH-IT in general and on HT-ATES in Delft specifically

When	Who	Target audience	Description
		local; Public; Scientists; Innovators; Specific end-user communities; Education/training organization/learners; Policy-makers and authorities, regional or local	
2023 Q4	TUD	Scientists	Symposium on Energy Geotechnics, Delft October 2023, short presentation for fellow researchers on the creation of Expanded Diameter Gravel Wells (enabling technology).
2024 Q2	TUD	Research communities	High-Temperature Aquifer Thermal Energy Storage (HT-ATES) system for research development and demonstration on the TU Delft campus, EGU General Assembly 2024
2023 Q4	TUD	Research communities	Invited talk at the EERA geothermal workshop Utrecht, focussed on the work we do in PUSH-IT in general and on HT-ATES in Delft specifically
2023 Q4	TUD	Research communities	Swiss Geosciences meeting, Mendrisio. Focussed on the work we do in PUSH-IT in general and on HT-ATES in Delft specifically
2024	TUD	Industry, business partners	Turkey Geothermal Congress 2024
2023 Q3	TUD	EU institutions; Public;Scientists; Innovators; Education/training organization/learners;	Dublin Workshop 2023: Low-Medium Tempeature Geothermal heating and Cooling Solutions
2024 Q2	TUD	Research communities	Presentation to MIT sustainability team on geothermal (deep geothermal and HT-ATES) projects. Focus on joint innovation and commercial objectives. 16-05-2024
2024 Q2	TUD	EU institutions	Presentation to European Commissioner for Climate Action (Wopke Hoekstra) on geothermal developments (focus on innovation) on the TU Delft campus. 02-05-2024
2024 Q3	TUD	Industry, business partners	Celle Drilling Conference: Presentation focused on a work we do in PUSH-IT for grouting and pellet materials
2024 Q4	TUD	National authorities	19^{th} NRW Geothermal Conference: Presentation focussed on the TU Delft activities

6.2. Regulation and Governance

Notifications on the pilot borehole

Notifications for drilling and testing the pilot borehole were submitted with the regional environmental agency. A notification for discharging abstracted groundwater in the sewage system was also made with the local water board. Finally, we performed a “Klic-melding” to check for cables and pipelines in the subsurface at the drilling site.

Engagement with public authorities and regulators

The HT-ATES initiative was discussed several times with the province (which is the competent authority for ATES permitting) and the regional environmental agency (who carries out permitting on behalf of the province). Discussions started very early before the start of the PUSH-IT project. The draft environmental impact assessment and draft version of the permit request was discussed several times with both the agency and policymakers of the province. Also, a memo with procedural agreements was set up to gain a mutual understanding of how the permit request would be discussed between the government agencies and the Delft HT-ATES partners.

Permits for the HT-ATES system

A waterlaw permit (Waterwet) is required for ATES-systems. The permits are issued by the regional environmental agency (Omgevingsdienst Haaglanden) on behalf of the province Zuid-Holland. Within ATES general permitting, it is only possible to inject water with a maximum temperature of 25 °C. It also requires thermal equilibrium meaning that the heat injected in the warm well must be balanced by the cold well. In the case of the HT-ATES, the maximum temperatures of 90 °C are far higher and there is a net storage of energy in the subsurface. Regional water authorities therefore use a decision making framework “afwegingskader HTO” [Bloemendal et al. 2022] to assess permit requests and monitoring requirements.

An environmental impact assessment was performed in 2023. It formed the basis for the permit application that was entered in December 2023. Both the environmental impact assessment and the permit application were later updated in spring 2024. However, it was essential to submit a first version before January 1st 2024 because then a new law (Omgevingswet) came into force which would lead to a lot of uncertainty and possibly delay in the application process. The permit application included a request for permission to inject and abstract tracers (dissolved compounds) during the Hot Push Pull Test.

The waterlaw permit was granted in December 3rd 2024. It includes limitations on the temperatures and net energy injected into the subsurface. Monitoring requirements are also included including measurements of injected volumes and temperatures and water quality in the monitoring well next to the hot well (O1).

6.3. Economics

Prognosis of future energy demands by the district heating network of TUD and the city of Delft, have been used as input for scenario studies on the utilization of the geothermal well and the HT-ATES. This forms the basis for an update of the business case that is being performed in Q4 2024. We find that the Sustainable Energy Subsidy (SDE) has a large influence on the financial viability of the project.

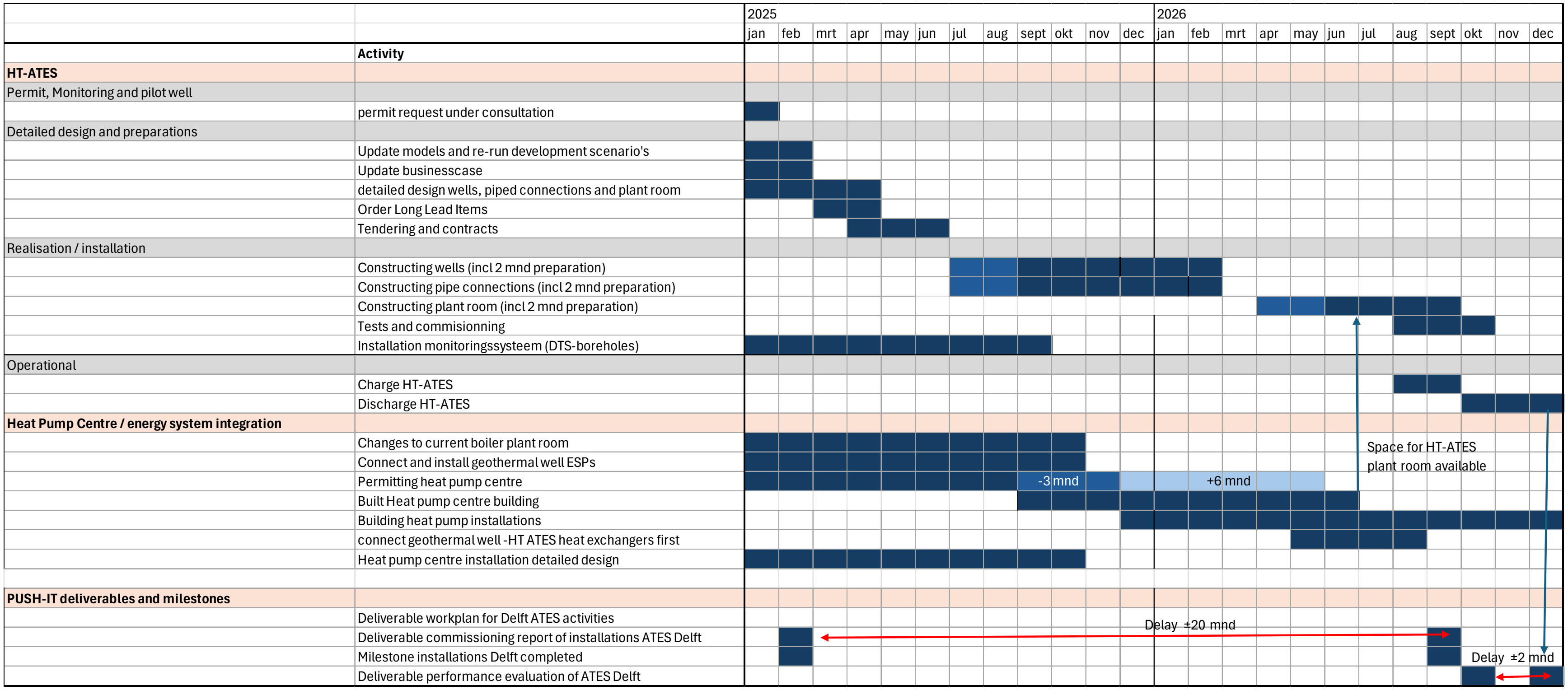
7. Tasks and Plan of Action

As explained in section 2.4, the Delft site has experienced numerous setbacks. This has the following consequences for the planning of the Delft activities in work package 1 (with the adjusted planning in **blue** and the adjusted planning marked **red**):

- Well drilling and heat plant installation [**M1-24** → **M1-44**]
- Monitoring/water quality/environmental impacts/performance [**M1-48**]
- System integration control [**M1-48**]
- Public engagement/legal/ economical [**M1-48**]

A more detailed adjustment of the planning is below in Table 6.

Table 6: Delft site planning (version Q4 2024) assuming the project is completed in 2026



8. Risks and mitigation

8.1. Foreseen project risks

Before the start of the project, potential risks and their mitigation measures were identified. The occurrence of these risk at the Delft site is summarized Table 7.

Table 7: Project risks for HT-ATES in Delft

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
1	Site and drillings not ready for TES tests and implementation (i: low / ii: high)	Use of follower sites already within project for demonstration or implement at alternative sites within project network. Each example technology has a follower site, which can be upgraded to an implemented demo site.	Yes	Yes	Due to earlier described delay in heat pump centre / ATES plant room we can only start charging heat in ~M46. Temporary facilities cannot be put in place while they are also constructing the final installation
2	Permissions not obtained for drilling, testing, and/or operation. (i: low / ii: high)	Sites have been selected due to their relative maturity and existing work on integrating with legal authorities. All sites have received initial positive reaction to the demonstration activities. If permits are unsuccessful mitigation is execution at follower sites.	No	No	Permit is granted in December 2024 by Provincial authorities; in theory third parties can submit objections until February 2025. The permit will then become final
3	Financial: associated projects for demonstration and follower sites are postponed or not realised. (i: medium / ii: medium)	Associate projects are not necessary to demonstrate heat storage, but for some demo/follower sites are necessary to store renewable heat, thus main objectives are	No	No	

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
		not at risk (Delft, Litoměřice). For the sites with associated projects project funding is already in place. Mitigation is via the use of demonstration and follower sites, such that activities can be moved from one site to another within the project to still achieve the aims.			
4	Administrative/financial: tendering procedure failure (i: medium / ii: medium)	Detailed planning in collaboration with an experience international expert team prior to the tender execution allowing optional well design reflecting ground water flow rates, careful risk assessment, consultations with drilling companies, quotations providing real costs and delivery times	No	No	
5	Local communities uninterested in engagement activities about the demonstrator site. (i: low / ii: medium)	Engagement plans will follow co-creation design principles to establish needs and wants of local communities. Due to existing plans for the pilots, social stakeholders are already aware and partners have access to them. Preparatory work, while developing this proposal by leaders of WP2, resulted in an initial engagement with stakeholders. Mitigation via	No	No	

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
		identification of groups who have already engaged in energy system development at each demonstration.			
7	Limited material / equipment availability due to strained international market situation (i: medium / ii: medium)	Time buffer considered in project time planning, timely ordering of equipment.	No	Yes	This partially occurred in Delft as the delay in decision making of the heat pump centre was partly caused by international market situation
8	Price increases make budget unrealistic at time of implementation, e.g. for manufacturing full novel well casings or other equipment. (i: medium / ii: medium)	Go / no-go moment for novel (more expensive) components, so that budget can be transferred to standard (cheaper) components and overall objectives and results can be achieved.	Yes	Yes	We changed the design based on technical specifications and subsurface conditions to reduce costs but still of optimal integration of HT-ATES in the whole heating system.
9	Feasibility of novel aspects, including casing-while-drilling, is seen to be not technically or financially feasible. (i: low / ii: medium)	Experience of project partners has been used to develop work plan and budget. Where the feasibility is not clear at the current time, a task is defined to carry out a detailed study in advance of designing and carrying out activities. Mitigation is that budget for those on-site activities is transferred to other project sub-goal, and these do not damage the overall project goals.	No	No	

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
10	Co-simulation computational time too long. (i: low / ii medium)	Simplify the subsurface model to enhance integration in the DHN.	No	No	
11	DH network controller testing: unwillingness of building owners to participate. (i: medium / ii: low)	Since we aim for a proof-of-concept test only, only a limited number of buildings is needed to test the controller. As the demonstration sites are universities with the buildings on campus there are a limited number of stakeholders who are already engaged in the project.	Yes	Yes	The controller design is underway, data is available on the broad network operation and temperatures, and co-simulation will soon provide simulated data. The detailed design of the pipe system is underway with several partners and we are involved in this discussion.
12	DH network controller testing: technical issues with respect to measurement data acquisition or control of the heat demand of the building. (i: medium / ii: medium)	This can be overcome by installing additional hardware in the buildings. Enough budget is foreseen for the installation if this is the case. The project partners involved are experienced in solving these issues.	No	No	
13	ATES reservoir property uncertainties. (i: medium / ii: high)	ATES hydraulic conductivity is critical for project success. Mitigation has been carried out via a pilot borehole in the demo site in same formation carried out in 2022.	No	No	
14	Drilling / workover failures. (i: medium / ii: low)	All sites have multiple boreholes/wells. If proposed activities fail, remedial or alternative methods can be	No	No	

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
		used. Drillers have required certifications as a precaution for failures			
16	Undetected heat losses occur. (i: medium / ii: medium)	All sites have extensive monitoring and simulation activities. In the event of poor recovery efficiency due to heat losses that are not detected additional analysis and simulations will be carried out to identify the source of these losses.	No	No	
17	Aquifer contamination / Aquifer temperature threshold. (i: low / ii: medium)	Prediction of flow/temperature before full implementation, through injection/ production tests, to calibrate proper flow and temperature levels.	No	No	
18	No permit for use of tracer during HPPT. (i: medium / ii: medium)	Start permitting >1 year before start experiments, so that there is enough time to develop an alternative plan.	No	No	

8.2. Unforeseen risks

In November 2024, an overview was made as part of the mitigation strategy of unforeseen risks that occurred during the course of the PUSH-IT at the Delft site and other demonstration and follower sites. Table 8 summarizes how these risks pertain to the Delft site.

Table 8: Occurrence of risks that were unforeseen at the start of the project at HT-ATES in Delft

	Risk description **level of (i) likelihood, and (ii) severity**	**Risk mitigation measures foreseen before start of project**	**Were risk mitigation measured applied**	**Did the risk materialize**	**Comments, for example why risk measures could not be applied**
U1	Heat pump centre/plant room needs to be redesigned	Installing a temporary connection and heat exchanger between geothermal well and HT-ATES.	yes	yes	Due to the relocation of the ATES wells at the Delft site, the heat pump centre/plant room needs to be redesigned, which will result in delays in ability to connect geothermal well to HT-ATES. Temporary connection cannot be made at a building site.
U2	Delay of monitoring well installation resulting	Prepare final design of well before outcomes of pilot/monitoring well.	yes	yes	Delay in installation of monitoring wells due to repositioning of wells at Delft site due to new BTES system and greater than expected impact on shallow ATES in vicinity of HT-ATES hot wells. This has resulted in a delay in the final design of the HT-ATES wells.
U3	Drilling issues and delays due to unforeseen geological conditions	Developing an alternative solution (e.g. new well design) to achieve the overall	no	no	

	Risk description level of (i) likelihood, and (ii) severity	Risk mitigation measures foreseen before start of project	Were risk mitigation measured applied	Did the risk materialize	Comments, for example why risk measures could not be applied
		objectives and results and stay within the budget.			
U4	Workover activities (cement removal / site track) at research well are not successful	Drilling the sidetrack to reach the production horizon.	no	no	
U5	Low availability of subcontractors	New tendering / adapting the project schedule to subcontractor availability. Possible delays should not affect achievement of overall objectives.	no	no	
U6	Lack of local stakeholder engagement /conflicts in aligning strategy with local design of other buildings	Organising meetings with stakeholders to discuss the joint strategy. Make it a priority to ensure that the PUSH-IT objectives are met.	no	no	
U7	Delay in connection design	Leverage the experience of project members and external experts to select the best connection design.	no	no	
U8	Unexpected loss of technical support and community engagement staff	Adjust the programme for the coming months to take account of the loss of total working hours. New recruitment.	no	no	
U10	Site not ready for MTES tests and implementation	Adapt the programme for the coming months to achieve the overall goals and objectives. If not possible, use the follower site or back-up site (in Bochum).	no	no	

8.3. Unforeseen future risks, newly identified in January 2025 for mitigation measures

At this moment, a number of new future risks are foreseen, that were not foreseen at the start of the project but that may materialize in the remainder of the project.

Table 9: Occurrence of risks that were unforeseen half-way of the project at HT-ATES in Delft

Risk No	Description	WP No(s)	Risk Mitigation Measures		State of the Play		
				Period	Did you apply risk mitigation measures? *	Did your risk materialise? *	Please add here your comments. If the risk mitigation measures couldn't be applied, please explain why. *
UFR1	The timeline for the construction of the HPC building as well as internal installation is very tight to meet HT-ATES demonstration within 48M contract period. Any delays in construction of HPC and internal installation is major risk for delay of commissioning for HT-ATES. Such delays can be cause by many issues related to factors outside the influence of the project team. Factors are listed in section 1.1	1	Closely monitor progress and directly act upon encountered issues. A detailed planning and workplan is in place to ensure smooth transitioning for building phases/installation elements.	2025 - 2026	Not yet applicable	Not yet applicable	This risk is relevant to Delft ATES site

Risk No	Description	WP No(s)	Risk Mitigation Measures		State of the Play		
				Period	Did you apply risk mitigation measures? *	Did your risk materialise? *	Please add here your comments. If the risk mitigation measures couldn't be applied, please explain why. *
UFR2	It is uncertain if the HPC (in Delft) will be completed in time to start charging in the summer of 2026. A delay means that we do not meet the 2026 heat delivery deadline.	1	Installation and connecting the HT-ATES well first in HPC before completing the remaining part of the installation. It is not yet clear if this is possible and safe and efficient to do extensive construction work in an installation that is already partly heated. This will be part of the detailed work planning of the heat pump center after tendering	Aug 2026	Not yet applicable	Not yet applicable	This risk is relevant to Delft ATES site
UFR3	It is uncertain if the HPC can deliver heat in the fall/ winter of 2026. This means that the deadline to demonstrate HT-ATES and heat delivery might not be met in Delft in time. Any further delay in the construction of HPC and we do not meet the 2026 heat delivery deadline.	1	Directly after commissioning of HPC, directly start delivering heat from HT-ATES, that was charged just before. This may result in lower economic returns since it is generally not efficient to deliver heat from HT-ATES that was only charged for a short while with heat as we currently plan to do. Also, we depend on the weather. If it is too warm, then there is no heat demand and thus no reason to use the HT-ATES.	Oct. 2026	Not yet applicable	Not yet applicable	This risk is relevant to Delft ATES site

Risk No	Description	WP No(s)	Risk Mitigation Measures		State of the Play		
				Period	Did you apply risk mitigation measures? *	Did your risk materialise? *	Please add here your comments. If the risk mitigation measures couldn't be applied, please explain why. *
UFR4	Limited time for monitoring of long-term effects and / or system performance evaluation	1	Without the project extension: the monitoring period will start as soon as possible in order to obtain maximum data and to make the resulting recommendations as robust as possible. With the project extension: an additional 12 months will allow for a more thorough and detailed monitoring and proof of concept phase, which would provide the basis for solid conclusions.	2026	Not yet applicable	Not yet applicable	This risk is relevant to all three demonstration sites

8.4. Health, Safety and environment

A Health, Safety and Environment (HSE) expert was hired by the commissioning organization to regularly oversee the drilling of the monitoring well. No HSE incidents have occurred during construction at the Delft site.

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PUSH IT

The EU aims to have a net-zero greenhouse gas (GHG) economy by 2050, with 55% reduction on 1990 levels by 2030. At present, heating and cooling represent around 50% of the final energy demand in Europe and are mainly supplied by fossil fuel derived energy. It is therefore essential for heating and cooling to decarbonise to achieve EU ambitions.

A challenge for decarbonizing heat systems is the size of the seasonal mismatch between demand for heat and heat generation from sustainable sources – this mismatch is much larger than the equivalent intermittency in electricity supply and demand. The two main solutions to address this mismatch are: (i) to install a large capacity, so that peak demands can be met even at low production levels; or (ii) to store energy for later use if it is not needed at time of conversion. Many sustainable heat supply systems are characterised by high capital expenditure and low operational costs. Therefore, an installed capacity tailored at peak demand is not cost effective, while extending the annual operation period is advantageous for meeting energy needs, reducing levelised cost of energy (LCOE) and decarbonisation. Optimal utilisation of sustainable heat requires storing large amounts of heat to account for seasonal supply and demand fluctuations. Various technologies have been proposed for large-scale heat storage in geothermal reservoirs and low temperature storage is routinely applied. PUSH-IT focuses on extending storage temperature ranges to high temperatures. We will tackle remaining barriers, demonstrate applicability, increase public engagement, and optimise and de-risk operations. We will showcase three technology options that are fit for a wide variety of geological conditions covering most locations in Europe.

PUSH IT

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