ThermoGIS-HT-ATES: assessment of the potential for high temperature aquifer thermal energy storage in the Netherlands

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ABSTRACT

Successful development of HT-ATES requires specific geological conditions to mitigate buoyancy-driven flow and ensure a good recovery efficiency. This study presents the ThermoGIS-HT-ATES tool, developed to perform first-order assessments of HT-ATES potential. The tool integrates subsurface property maps and techno-economic models to estimate flow rates, power output, and storage efficiency on a 1 × 1 km grid scale. The tool was demonstrated in a regional case study of the Maassluis Formation near The Hague, a region with favourable heat demand and extensive subsurface data. Using a combination of well data, seismic interpretation, and regional hydrogeological modelling, the aquifer was characterised and used as input in the tool. Results showed significant spatial variability in aquifer thickness (10–90 m), leading to estimated storage powers ranging from 1 to 9 MW and efficiencies from 55% to 70%. This case highlights the necessity of detailed local subsurface data and modelling to accurately assess HT-ATES feasibility and supports the application of ThermoGIS-HT-ATES in early-stage planning for sustainable heat systems.

INTRODUCTION

Large-scale high-temperature aquifer thermal energy storage (HT-ATES) is a promising solution for the seasonal mismatch in sustainable heat supply and demand, especially in countries with a deltaic geological setting like the Netherlands, and will play a crucial role in the transition to sustainable energy (HEATSTORE, 2021). HT-ATES is a variant of open geothermal energy systems in which (excess) heat is temporarily stored in aquifers in the subsurface. The system typically consists of one or more (hot and lukewarm) wells in a water-bearing geological formation. During periods of surplus heat, in summer, energy is injected into the aquifer, then later extracted during winter when heating demand peaks, particularly in Northern European countries.

The Dutch subsurface is known to be well-suited for low temperature ATES (< 25 °C), as currently more than 3000 systems exist in the Netherlands (Bloemendal et al., 2023). This is due to the favourable fluvial and marine sediments deposited during the Cenozoic Era. However, HT-ATES introduces additional challenges related to buoyancy effects caused by the higher storage temperatures (60–90 °C). Consequently, the geological requirements for HT-ATES differ from those of low-temperature systems. To counteract buoyancy flow, for example, lower vertical hydraulic conductivities (higher anisotropy) and a confining clay layer above, and ideally also below, the storage aquifer are crucial for the success of a project (Dinkelman & Van Bergen, 2022; Beernink et al., 2022; Kleinlugtenbelt et al., 2023).

Identifying suitable aquifers for HT-ATES requires knowledge of these subsurface characteristics. In the Netherlands, exploration for thermal energy storage currently focuses on the Maassluis and Oosterhout Formations and the Breda Subgroup, which are all unconsolidated units of marine origin. These units are generally located deeper (> 200m) than those well-known for groundwater production or low temperature ATES, but shallower (< 800m) than the target reservoirs in the oil & gas world. Therefore, aquifers in this medium-deep interval are less well known, and large-scale regional or national geological models often lack sufficient well and property data, requiring more small-scale models with additional site-specific information.

Information on the occurrence of suitable stratigraphic intervals and methods to quickly calculate the potential are necessary to facilitate and ramp up the initial planning stages of new developments in thermal energy storage. Dinkelman & Van Bergen (2020) show a criteria-based mapping approach, including nine criteria for HT-ATES, which are used on eight aquifers in the Dutch subsurface to provide an initial overview of potentially suitable aquifers. However, more comprehensive techno-economic assessments require estimates of achievable flow rates and energy storage capacities. For geothermal energy in the Netherlands this is calculated by ThermoGIS, an in-house tool developed by TNO (Vrijlandt et al., 2019). Recently, Vrijlandt et al. (2023) adapted the ThermoGIS tool for geothermal energy to also be able to calculate the potential of HT-ATES, and the tool was tested on two aquifers.

This paper presents the ThermoGIS-HT-ATES tool designed to generate first-order estimates of HT-ATES potential, including the underlying calculations and assumptions. Furthermore, it shows the characterisation of a small-scale hydrogeological model of the Maassluis Formation in the region of The Hague, in the south-western part of the Netherlands, and demonstrates the tool on this aquifer.

METHOD

ThermoGIS-HT-ATES is developed to calculate the potential for thermal energy storage. The in-house tool is adapted from ThermoGIS for geothermal energy and calculates the potential for a typical thermal energy storage setup by passing subsurface property maps through a techno-economic evaluation. The main additions with respect to the geothermal application are the 3D modelling of the evolution of the warm water volume and flow rate limitations to avoid sand production. The sections below describe the technical and economic model.

Technical model

The production water temperature depends on the conductive and convective evolution of the warm water volume. To model this, a simple 3D model is automatically created using the input property maps, per grid cell, per aquifer. A charging and discharging flow simulation, allowing conductive and convective heat flow, is run with a constraint flow rate, and a distance between the two wells based on a thermal radius estimation. For efficiency, the first 15 years are modelled, assuming that the system is in a steady state afterwards. The technical model calculates the technical feasibility (power, energy, recovery efficiency) per 1 x 1 km grid cell.

Flowrate constraints

Sand production is a major concern when producing from and injecting into the shallow depths that HT-ATES targets. The flow rates are constrained to minimise the risks of sand production.

The maximum flow rate is calculated using four different calculation methods. Three standards from the LT-ATES (in Dutch 'WKO') and drinking water sector are used. These are the NVOE extraction and injection standards (NVOE, 2006) and the Olsthoorn standard for injection pressure (Olsthoorn, 1982). These generally apply for (very) unconsolidated aquifers at a depth of <200m. The NVOE standards have to be corrected for higher temperatures when using for HT-ATES, this because the viscosity, and therefore the flow rate, of the water changes due to higher temperatures (IF Technology, 2012). The SodM protocol for maximum injection pressure is a standard that is used for the geothermal energy sector and generally applies for consolidated aquifers/rocks at depths of 1500-3000 km (SodM-AGE, 2019). All four standards are not specifically suitable for the depth interval and lithology at which HT-ATES systems will typically operate, i.e. at 200-500 m depth and in (semi)-unconsolidated aquifers, making especially the NVOE extraction norm too restrictive. Therefore, a depth factor has been added, which is estimated from existing HT-ATES wells. Due to a lack of definition within the current laws and regulations for the maximum flow rate in ThermoGIS-HT-ATES, all four existing flow rate standards are calculated for each grid cell, and the most conservative value is then used as the final maximum flow rate. The four flow rate formulas are as follows:

1. NVOE injection norm (NVOE, 2006; IF Technology, 2012):

$$Q_{max} = 1000\left(576\,\frac{\rho_f \cdot g}{\mu}k\right)^{0.6}\sqrt{\frac{v_v}{2\cdot \mathrm{MFI}\cdot U_{eq}}}\,2\pi r_{well}H$$

2. NVOE extraction norm (NVOE, 2006; IF Technology, 2012):

$$Q_{max} = 7200\,\frac{\rho_f g}{\mu}k\,2\pi r_{well}H * \text{depth factor}$$

3. Olsthoorn maximum injection pressure (Olsthoorn, 1982):

$$P_{max} = 0.2\,z$$

$$Q_{max} = \text{calculated with DC1D } (L = 150\text{m})$$

4. SodM maximum injection pressure (SodM & TNO-AGE, 2019):

$$P_{max} = (0.135 - i)\,z$$

$$Q_{max} = \text{calculated with DC1D } (L = 150\text{m})$$

With,

Q_{max}	max. flow rate (m^3/h)
ρ_f	density of fluid (kg/m^3)
g	gravitational force (9.81 m/s^2)
μ	viscosity of fluid (Pa·s)
k	permeability (m^2)
r_{well}	well radius (m)
H	filter length (m)
v_v	specific clogging velocity (m/y)

MFI	measured Membrane Filter Index[1] (s/l²)
U_{eq}	equivalent full load hours per year (h/y)
z	depth top of the filter (m)
L	well distance (m)
i	hydraulic gradient of injection water (bar/m)
DC1D	DoubletCalc1D (www.nlog.nl/tools)

Currently, the established standards for flow rate calculation represent the best available methodology in practice. When new insights and findings from ongoing research, such as in the ACCEL-UTES and Warming^UP *GOO* projects, become available, the calculation methods will be revised and updated accordingly to reflect the latest scientific developments.

Wells and well distance

The distance between the two wells at aquifer level is calculated for each aquifer and xy location. This is done using the thermal radius of the stored water volume. The stored water volume is calculated with the maximum flow rate and the theoretical loading scheme (number of days loading) as given by the user. The thermal radius is calculated in advance using formula 1 in Doughty et al. (1982). A fixed well spacing of 2 times the thermal radius (Beernink et al., 2020) was then used, but this value can be changed by the user. The assumed internal diameter of the casing between surface and aquifer is 800 mm (31”). The reservoir section is an open hole with the same diameter. A doublet with vertical wells is taken as the default well configuration.

3D simulation in ROSIM-DoubletCalc3D

For power and flow calculations in ThermoGIS-HT-ATES, the publicly available thermal flow simulator ROSIM-DoubletCalc3D is used. ROSIM-DoubletCalc3D[2] is a software developed by TNO that calculates the evolution of the subsurface pressure and temperature over time. It uses a simple (layered) subsurface model with an injector and producer well.

The technical input for the ROSIM-DoubletCalc3D calculation in ThermoGIS-HT-ATES consists partly of maps, partly of constant values and partly of calculated values (see Figure 1 and Table 1). The maps of the aquifers (depth, thickness) and aquifer properties (porosity, permeability and net-to-gross) are used as input. The temperature is taken from the 3D temperature model (Brett et al., 2025, this issue). Water salinity is calculated depth-dependently: water salinity [ppm] = 70000/1500 × depth [m]. The salinity determines, among other things, the density and viscosity of the pumped water, and thus the required pumping capacity.

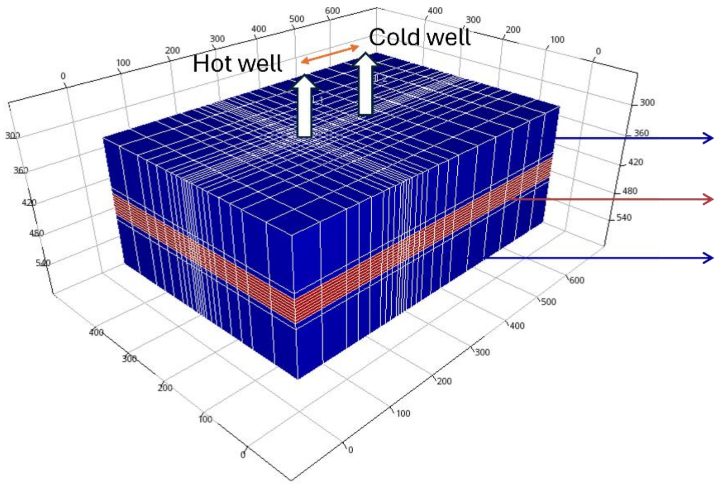

Figure 1 ROSIM-DoubletCalc3D subsurface model in ThermoGIS-HT-ATES. The properties of the clay layers are fixed. The properties of the storage aquifer come from the input maps.

Table 1 Property values as used in the default model.

	Depth (mNAP)	Thickness (m)	Perm xy (mD)	Perm z (mD)	Temperature (°C)	Porosity (%)	Net-to-gross (-)	Salinity (ppm)
Overburden clay	Top depth aquifer - 100	100	20	2	11 + depth * 0.34	0.1	1	70000
Storage aquifer	<grid>	<grid>	<grid>	Perm xy * anisotropy	<grid>	<grid>	<grid>	70000/1500 * depth
Underburden clay	Bottom depth aquifer + 100	100	20	2	11 + depth * 0.34	0.1	1	70000

[1] For more information on the MFI parameter, see Buik & Willemsen (2020)

[2] ROSIM-DoubletCalc3D application and manual are available via email: rosim@tno.nl and will soon be published on www.nlog.nl/tools (in prep.)

The over- and underburden clay layers consist of fixed input values and are assumed to be 'ideal' clay layers by default. The presence of such clay layers is needed to minimise heat losses from the aquifer to the surroundings. However, in reality, these clay layers can vary in thickness and properties, and therefore, a local study is always required. The well distance and flow rate are set to the calculated values discussed in the previous section.

Power, energy and thermal recovery efficiency

The main results of this technical analysis are maps of flow rate [m^3/hr], capacity [$MW_{thermal}$], energy injected [GJ], energy produced [GJ] and thermal recovery efficiency [%]. The thermal recovery efficiency is the energy produced / energy injected. Currently, only the P50 (median value) is calculated.

In the future, the option for a heat pump will be added; with this, the capacity of the HT-ATES and the quality of the produced heat (temperature level) can be improved.

Economic model

The cost of producing heat from the HT-ATES is calculated using a net present value model (discounted cash flow model), which is the same as used for ThermoGIS geothermal but with different input values. It assumes that the heat stored in the HT-ATES is free.

The CAPEX consists of well costs, base (installation) costs, and variable costs depending on the installed pumping capacity. The well costs are depth-dependent and are determined using the following formula (Vrijlandt et al., 2023):

$$\text{Well CAPEX} = 100{,}000 + 1000d + 0.3d^2$$

Where d is the depth of the well (in meters).

The OPEX depends on the electricity consumption of the pumps, maintenance, monitoring and water treatment costs.

The net present value model calculates the cost price (UTC) per unit of (heat) energy [€ct/kWh].

The economic potential is then calculated by comparing this cost price with reference prices. These reference prices are 5.6 €ct/kWh, in line with the SDE++ amount (Muller & Henriquez, 2023) for geothermal energy and the maximum heat price according to ACM (2024) of 13.3 €ct/kWh.

Figure 2 shows a full overview of the ThermoGIS-HT-ATES workflow, showing the input in the model, the flowrate and well distance calculations upfront and the technical and economic model, including the DoubletCalc3D subsurface model.

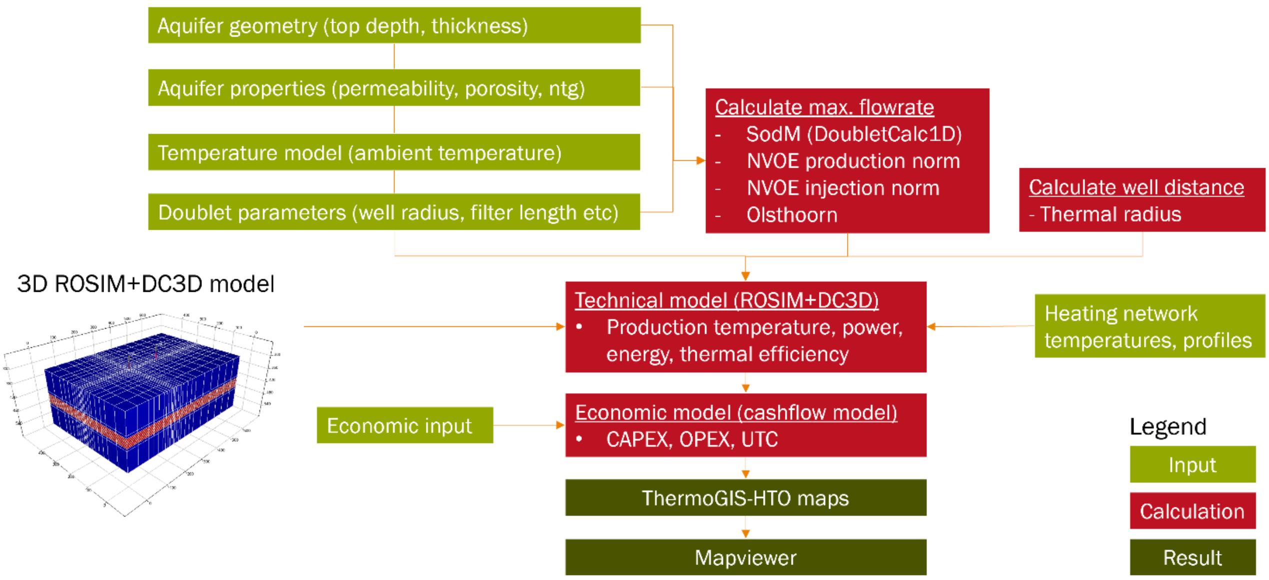

Figure 2 Workflow ThermoGIS-HT-ATES.

INPUT DATA

The ThermoGIS-HT-ATES app requires subsurface data and data regarding the aboveground system and heat network as input. Subsurface data are the (hydro)geological input maps of the potential storage aquifer, these are depth, thickness, porosity, permeability, net-to-gross and temperature.

The Maassluis Formation is a favourable formation for HT-ATES (Dinkelman et al., 2020). Maps of the Maassluis Formation exist on national scale in the regional hydrogeological model REGIS II v2.2, however the maps are created by interpolation between a limited number of wells in the Maassluis Fm., causing large uncertainties in areas with sparse data. Therefore, a regional study has been carried out in the city of The Hague in the Zuid-Holland province in the Netherlands. This area was chosen because of its urban heat demand, relatively good quality reprocessed seismic surveys and the availability of additional ATES wells that were not in the national well repository yet.

The area around the Hague has been a target for oil and gas exploration for 80 years resulting in a large database with 2D and 3D seismic and deep (> 500 m) well data. Further, the area was drilled for drinking water and/or geological exploration purposes down to shallow depths between 50 and 500 meters, especially in the dune area north of the city of The Hague. Lastly, data from numerous ATES wells are available, but the detail of the lithological descriptions is usually limited. Figure 3 shows the shallow and deep wells used in this study.

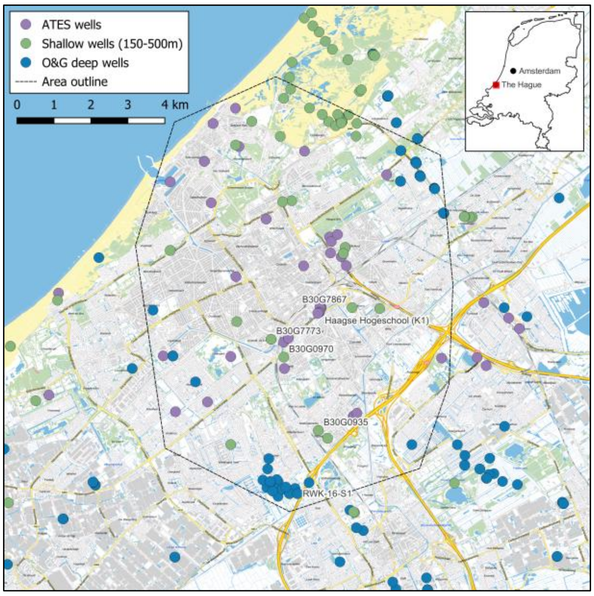

Figure 3 Study area showing well locations. Labeled wells are in shown in Figure 6 and Figure 7 (at the end of the paper).

The seismic data all target the deep oil and gas reservoirs. Although post stack processing was done on this data, the youngest layers that can be interpreted on seismic are those of the Oosterhout Formation underlying the Maassluis Formation. Figure 6 (at the end of the paper) shows that the transition of dominantly clayey sediment to sand was picked for the lithostratigraphic boundary between the Oosterhout and Maassluis Formations, but also that the clinoforms visible on seismic cut obliquely through the mostly horizontally assumed O-M boundary. Therefore, the interpretation of the depth and thickness of the Maassluis Fm was performed on well data (Figure 3). Most ATES wells target the lower part of the Maassluis, but seldomly drilled the aquifer completely, making the interpretation of the thickness challenging. Some of the shallow wells completely drilled the Maassluis Fm., and few O&G wells have gamma ray or other log data over the first 200 meters, making an interpretation of the depth and sometimes thickness of the aquifer possible. Figure 7 shows the sharp upper boundary of the aquifer between 160 and 180 meters, both in the gamma ray logs and the lithological descriptions, and the more gradual transition towards the clayey Oosterhout formation between 220 and 240 meters. All three wells show an intermediate clay and/or shell layer.

Well test results from 19 ATES wells were interpreted (Veldkamp et al., in prep). No spatial correlation could be found in the hydraulic conductivity data, nor clear correlations with depth, thickness, etc. Therefore, it was decided to use an average hydraulic conductivity of 6.2 m/d for the entire area based on four tests in the relevant depth range, which equals 8 Darcy (at 15°C, 25 bar and 13.5 g/kg salinity). Shallower layers have higher hydraulic conductivities, but in the study area, the modelled aquifer is located at relatively large depth, probably leading to a lower hydraulic conductivity.

Although some clay layers can be observed in the deeper part of the Maassluis Fm., a net-to-gross of 1 was adopted because the aquifer permeability was calculated for the gross reservoir thickness.

The fluid salinity was derived from a study by Deltares (2021), which shows 7.5 g/l chloride content or 13.5 g/l salinity. Nearby wells show that the temperature gradient is close to 20 °C/km with a surface temperature of 10 °C. At mid aquifer depth of 190 + 50/2, this results in a temperature of 14.3 °C.

Input regarding the aboveground system is, among others, the storage temperatures in the hot and cold well, the cut-off temperature, the flow profile and economic input. A scenario was run with an injection temperature in the hot well of 80 °C, and 40 °C in the lukewarm well, with a cut-off temperature of 45 °C. The loading and unloading periods are 150 days each.

RESULTS

The created input maps are shown in Figure 6 (top row) and were used in the ThermoGIS-HT-ATES tool to calculate HT-ATES potential for the area of The Hague (Figure 6, bottom row). The depth of the top of the aquifer is shallowest in the eastern and southern part of the area (165m), and deepest in the west (205m). Although wells are available outside the mapped area, the inter-well distance and the limited quality of the seismic data prevent a correlation of the top sealing clay layer outside the study area. The base of the aquifer, and therefore also the thickness, was determined on a limited number of wells, because most ATES wells only penetrate the Maassluis Fm., and have their final depth in the sand – it is uncertain if the aquifer extends further downward. The mapped thickness decreases from 90m in the east and west to less than 10m in the north and southwest, but this decrease may well be a mapping artefact caused by the limited number of wells in the west of the area that fully penetrate the Maassluis Fm.

The resulting power largely follows the thickness of the aquifer: up to 9 MW in the east and west down to 1 MW in the north and southwest. The efficiency ranges from about 58% in the north and southwest to over 66% in the eastern and western part.

The ThermoGIS model that was used for the maps in Figure 4 assumes an ideal clay layer of 100m thick on top of the Maassluis Fm. (Table 1). However, in the well logs (Figure 7), it can be seen that the clay layer on top of the Maassluis Fm. in The Hague area is more likely to have a thickness in the order of 4-5m. Therefore, the model was adapted to see the effect of the clay layer on the power and efficiency maps. A 5m thick clay layer with an overlying sand layer of 95m was added and the resulting maps are shown in Figure 5. The thin clay layer causes more heat losses to the overburden and therefore the power and efficiency are slightly lower, in the order of 1 MW or 2% efficiency.

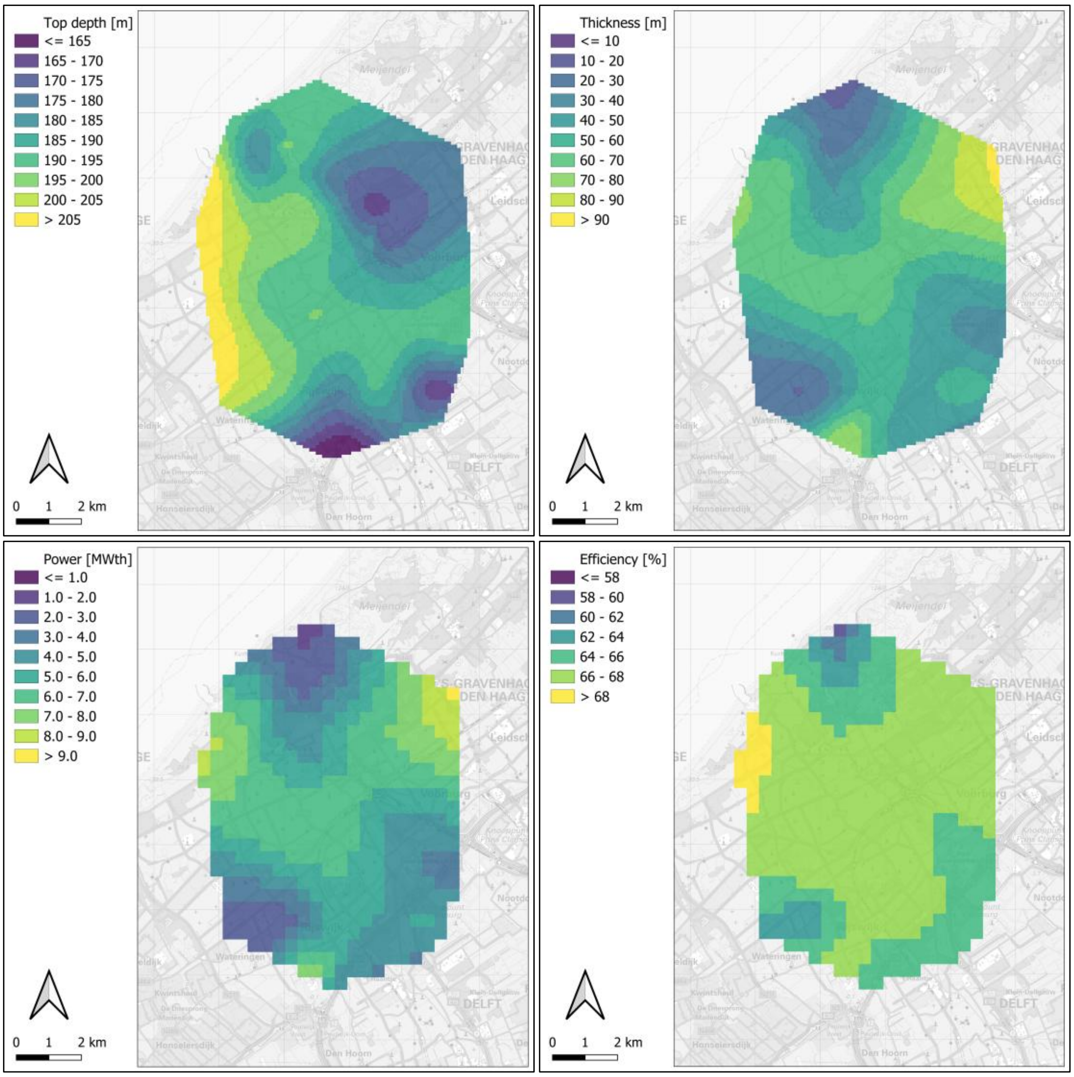

Figure 4 Above: top depth and thickness of the aquifer. Below: power and efficiency maps.

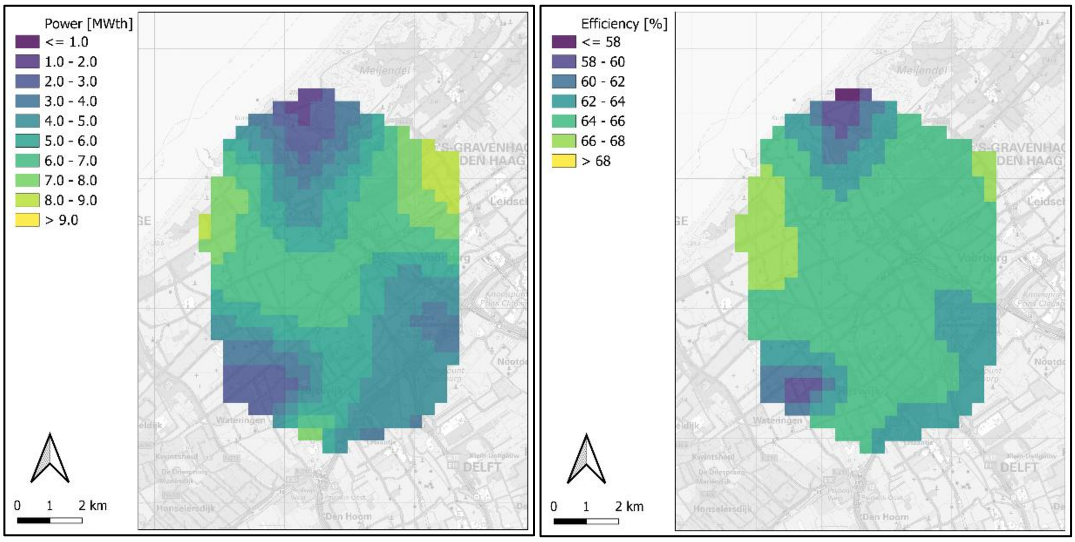

Figure 5 Power and efficiency maps for a scenario with a more realistic clay layer. The clay layer was chosen to be 5 m thick with a horizontal permeability of 40 mD and a vertical permeability of 4 mD. Above the clay layer is a 95 m thick sand layer with a horizontal permeability of 8 D a vertical permeability of 1 D.

DISCUSSION

Inherent uncertainties are an unavoidable aspect of subsurface modelling. Standard deviations for the input maps are derived from the available data, for thickness the standard deviation is 10m and for permeability ~4000 mD (3 m/d). As this study is currently only deterministic, no uncertainty maps have been produced yet.

Oerlemans et al. (2023) conducted a similar study on HT-ATES in the Maassluis Formation in an (larger) area in Zuid-Holland (Den Haag, Rotterdam and Leiden). To improve the subsurface knowledge, they applied a comparable approach by integrating an additional 74 ATES wells from their own database with the 88 wells from the Dutch DINO database. The key distinction between this study and the study by Oerlemans et al. (2023) lies in the selection of the top aquifer and aquifer thickness. They use the top of the Maassluis Formation (first sandy interval, MSz1) around ~80-130 mbgs, as top of the storage aquifer and include all lower sand intervals (albeit interbedded with clayey intervals) as potential storage aquifer. They indicate the thickness of clay layer on top with a clay layer overlay map. On the other hand, this study only included the lower part of the Maassluis Formation as storage aquifer, by choosing a deeper, more heterogeneous, aquifer top around 165-200 mbgs, with a ~5m clay layer above. Both approaches could be justified from a HT-ATES and subsurface point of view, and have their strengths and limitations. The fact that two studies in the same area and formation use a different approach and therefore result in different maps, also clearly indicates the complexity of characterisation of the subsurface for HT-ATES.

Although ThermoGIS-HT-ATES is a useful tool to provide a regional overview of the potential in terms of flow rate, power and economic potential of HT-ATES in the Netherlands, it is important to keep in mind that the maps created with the tool provide a first estimation and are based on many (uncertain) input parameters. The resulting maps are suited for screening purposes, but no exact values for a specific location can be deduced from the maps. For a pilot study, it is always required to do a more detailed local study.

The main uncertain assumptions in the tool are the flow rate calculations, while this study also shows that the flow rate calculation is a very determining factor for the potential. For the calculation of the flow rate maps in this study, the state-of-the-art knowledge has been used. The flow rate guidelines are continuously under development and will have to be updated when more knowledge on the maximum flow rate for HT-ATES is gathered in future (experimental) research and HT-ATES pilots.

Furthermore, the stored volumes and temperatures, and therefore the storage geometry, are strongly impacting the HT-ATES performance (Beernink et al., 2024). As these parameters are highly project-specific, an interactive tool is being developed to enable users to input site-specific values. Other future developments of the tool or its input data include:

- mapping of moderately deep regional hydrogeological models;
- the addition of aquifers in ThermoGIS-HT-ATES;
- an interactive app where users can use their own input values (such as heat network specific temperature levels) and calculate potential maps;
- improving computational methods for HT-ATES;

- including uncertainty (P-values) in the potential maps;
- integrating a heat pump model to ThermoGIS-HT-ATES workflow;

CONCLUSION

This paper presents the ThermoGIS-HT-ATES tool, which was successfully developed to generate first-order estimates of HT-ATES potential. The tool calculates the HT-ATES potential (flow rate, power, energy produced, efficiency) for each aquifer grid cell, based on hydrogeological input data and assuming certain injection temperatures, a cut-off temperature and a (un)loading schedule.

Furthermore, this study showcases the characterization of a small-scale hydrogeological model of the Maassluis Formation in the The Hague region, demonstrating the application of the tool to this aquifer. The resulting maps show significant variations in aquifer thickness and efficiency across the study area, with higher efficiency and power potential observed in the east, middle and west. However, uncertainties remain due to limited subsurface data, particularly in the western section. The comparison with Oerlemans et al. (2023) highlights the complexity of aquifer characterisation and the impact of different methodological approaches on HT-ATES potential assessments.

Future improvements in HT-ATES assessments will depend on ongoing research efforts to improve and benchmark the flow rate calculations, incorporate uncertainty maps, and include a heat pump model. The continued development of the ThermoGIS-HT-ATES app—including interactive user input capabilities and integration with heat pump modelling—will further support the first-order evaluation of HT-ATES potential on a regional and national scale.

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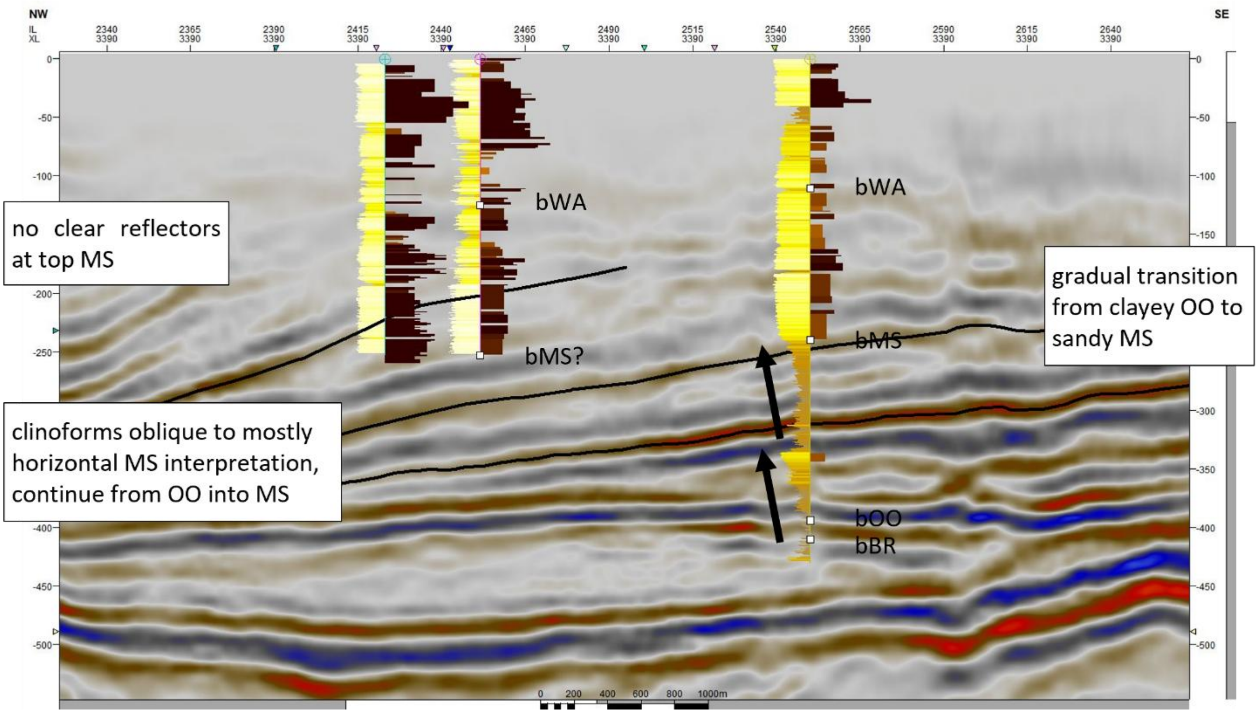

Figure 6 NW-SE Seismic section with shallow wells B30G7773, B30G0970 and B30G0935 (from left to right) showing that the Maassluis interval cannot be mapped accurately from seismic data. BR = base Breda Fm., OO = Oosterhout Fm., MS = Maassluis Fm., WA = Waalre Fm. Left log: GR, right log: sand median grain size. The target aquifer is the lower half of the Maassluis Fm. Well locations are shown in Figure 3.

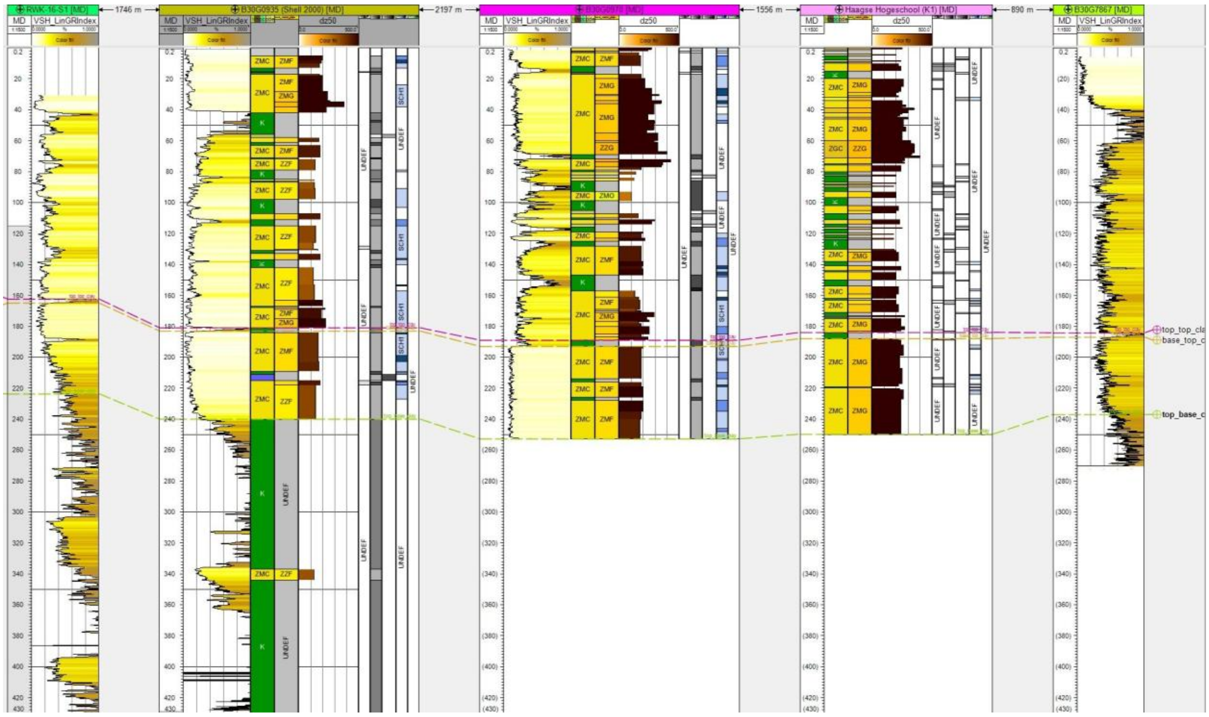

Figure 7 Well panel from south to north showing from left to right the RWK-16 O&G well (GR only), two shallow wells with lithology descriptions and GR log, the ATES well 'Haagse Hogeschool' having a lithology description only and a shallow well with GR-log only. The tracks show GR, scaled GR, lithology, sand grain class and size, clay, silt and sand fractions, and shell content. Interpreted horizons are the top and bottom of the top sealing clay, and the base of the aquifer where applicable. Well locations on Figure 3.