



# Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands

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## ABSTRACT

High temperature aquifer thermal energy storage (HT-ATES) can contribute to the integration of renewable energy sources in the energy system, the replacement of fossil fuel-based heat supply and the utilization of surplus heat from industrial sources. However, there is limited understanding on the drivers, barriers and conditions of HT-ATES implementation. The objective of this study is to partly fill this knowledge gap by developing a methodological framework for a quick scan on market potential of HT-ATES. Based on the application of this framework to a case study in the Netherlands, it is concluded that the proposed method is suitable for a pre-feasibility analysis on the HT-ATES market potential. The investigated case study has a planned district heating system with geothermal energy as the heat source. HT-ATES is found to be cost-effective compared to a reference technology, i.e. a natural gas boiler, in the scenarios under existing and more sustainable alternative policies. The lifetime of HT-ATES and the size of heat demand have a strong influence on the market potential.

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## 1. Introduction

Global warming, geopolitical concerns and other drivers initiated a global transition from a fossil fuel-based energy system towards a sustainable energy system [1]. The renewable energy sources (RES) required for this transition bring new challenges. Large-scale RES integration in the energy system potentially results in a mismatch between energy supply and demand. Increased flexibility of the energy system is required to manage such mismatches [2].

A technology capable of contributing to the flexibility of energy systems is seasonal thermal energy storage. Applications of seasonal thermal energy storage facilitate the replacement of fossil fuel-based heat supply capacity by renewable thermal energy sources (RTES) and enable utilization of excess heat from industries. This is particularly the case in district heating (DH) networks, where inefficient, expensive and carbon intensive peak capacity from heat-only boilers is often needed on cold winter days [3]. During the summer season, renewable thermal energy sources such as solar and geothermal installations may have surplus

capacity. Surplus heat can be stored and utilized in winter in a DH system with the application of seasonal thermal energy storage. Thermal storage in combination with DH networks can further provide competitive flexibility to the electricity system through system integration, e.g. through power to heat options.

An excellent place to store large amounts of thermal energy over seasonal timespans is the subsurface. In addition to having good isolating properties, the subsurface provides a large potential storage volume while keeping interference with other surface activities at a minimum. This makes underground thermal energy storage particularly suitable for urban environments [4], where most of the potential for thermal storage lies due to concentrated heat demand.

A promising technology that is suitable for the large storage capacities required for both DH networks and for balancing supply of RTES with the demand is *high temperature aquifer thermal energy storage* (HT-ATES). HT-ATES is based on the same principles as regular aquifer thermal energy storage (ATES), but differs on a few points. Firstly, the temperature of stored water is higher. While the hot well injection temperature of regular ATES typically reaches up to 30 °C [5], HT-ATES is characterized by a minimum hot well injection temperature of 50 °C (and maxima up to 150 °C in pilot projects) [6]. A second difference is that HT-ATES systems only store heat, while ATES systems generally store both heat and cold. As

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indicated in Fig. 1, a HT-ATES system consists of both a hot and a cold well, but the cold well does not contain water for cooling purposes. In summertime, formation water from the “cold” well is heated with surplus heat and stored in the hot well; in wintertime the formation water in the hot well moves through a heat exchanger back into the cold well. Depending on the DH network and well depth, the cold well temperature can be higher than the aquifer ambient temperature. Unlike a typical ATES, energy balance is unlikely to be achieved, resulting in a long-term increase in subsurface temperature. As a result of these differences, HT-ATES wells are typically (but not necessarily) located in deeper aquifers than ATES wells to reduce environmental impacts, the risk of interference with drinking water reserves or surface activities. The main advantage of HT-ATES compared with regular ATES (<30 °C) is that retrieved heat can be directly used for heating purposes without the need for upgrading (e. g. with heat pumps). The storage of water with higher temperatures can also increase both the energy storage capacity and overall energy efficiency [4,5]. In addition, HT-ATES enables the utilization of various higher temperature heat sources, e.g. geothermal heat and wasted heat from CHP plants.

Despite many advantages, a limited number of HT-ATES projects operate worldwide. The first development of HT-ATES technology dates from the 1970s. Pilot projects started in the 1980s and were mostly unsuccessful. To the authors' knowledge, only two operational HT-ATES systems exist, both in Germany: the Reichstag Building in Berlin, where water is stored at 70 °C [7], and the HT-ATES system in Neubrandenburg, where water is stored at 80 °C [8]. The main explanation of limited implementation of HT-ATES is that it is more complex as compared to regular ATES. The technical and operational challenges include minerals precipitation, corrosion of components in the groundwater systems and low recovery efficiency due to thermal advection under high buoyancy forces induced by density contrasts [5,6]. In the period 1985–1995, much research aiming to resolve these problems was done. To date, most of the technical challenges that hampered the early growth in implementation of HT-ATES systems have been solved and proven solutions are available, such as appropriate water treatment and materials selection to prevent minerals precipitation and corrosion [6,9,10]. The use of low permeability aquifers [8] and the use of salinity contrast for density difference compensation [11] are proposed to improve the thermal recovery efficiency.

Other points of concern which are important for the feasibility

of HT-ATES are the impact on the ground water and legal aspects. The potential impacts mainly induced by the change of temperature on the composition of groundwater include mobilization of organic carbon, increase of mineral solubility, algae growth and shifting of materials [12]. The impact on groundwater geochemistry and microbiology is still not fully known [5]. Application of HT-ATES in the shallow subsurface (<500 m) is now prohibited in most European countries and also countries outside Europe because of legislation [12,13]. Regulated threshold values for groundwater temperatures are county-specific. The most commonly applied maximum absolute groundwater temperature for heating is 25 °C (25–30 °C in the case of the Netherlands depending on province) [12,14]. The current HT-ATES in the Netherlands are pilot projects. The purpose of pilot projects is to gain practical experience and more insights on the technical performance and environmental impacts. Monitoring of groundwater quality, energy efficiency, hydrothermal effects, geo-chemical effects and effects on microbiological populations in the subsurface is therefore being executed. Knowledge from these pilot projects and monitoring programs can be used for the revision of the regulatory framework for HT-ATES [8].

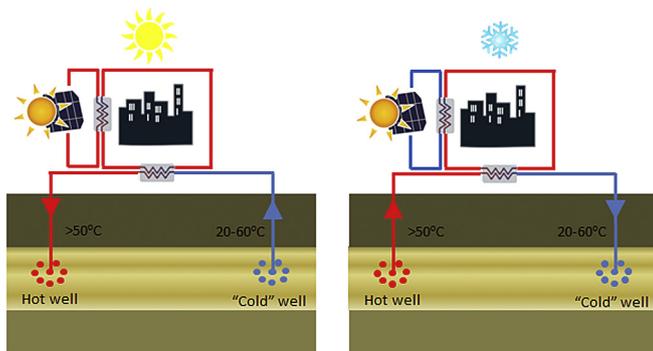
As discussed above, the focus of the scientific studies on HT-ATES is about technical design, operation and environmental impacts. Challenges need to be overcome in these areas but there is also a need to gain more insights on the market potential aiming to present the influence of policies on its application and the influence of technical, economic and social contexts on its business case. A review of studies assessing the market potential of energy technologies (see Table A1 in the appendix) shows that technical and economic potentials of energy technologies have been widely assessed while market potentials are assessed less. Particularly limited literature is available on the market potential of ATES and HT-ATES. In order to promote HT-ATES in the sustainable energy transition, it is crucial to understand the drivers, barriers and conditions for its implementation. The objective of this study is to partly fill this knowledge gap by developing a conceptual methodological framework for a screening assessment of the market potential of HT-ATES in a DH system and to showcase a part of this framework in the form of a techno-economic case study in the Netherlands. With this objective in mind, the conceptual methodological framework of the market potential assessment is discussed in section 2. The case study and its main characteristics, data and assumptions are also presented in section 2. The results of implementing the framework in the case study are interpreted and discussed in section 3 and 4. Finally the conclusions are drawn in section 5.

## 2. Method

Theoretical and technical potentials of a technology are generally assessed at a regional or country level to quantify the potential energy production of this technology within this area in a target year. Economic and market potentials are generally assessed at the local level or for a specific project. The application of the proposed framework facilitates a quick scan for identifying the feasibility of a HT-ATES case taking into account technical, economic and market conditions. In this study an exemplary case study is performed to show how a part of the market potential framework can be quantified.

### 2.1. Conceptual assessment framework of market potential

The developed preliminary market potential assessment framework is represented by Fig. 2. Each step contains a different set of prerequisites and key parameters affecting the assessment,



**Fig. 1.** Schematic diagram of a simple two-well HT-ATES operating in a district heating network with solar thermal as its main heat source. In summertime (left) more solar heat is produced than required and therefore part of the produced heat is injected into the HT-ATES hot well. In wintertime (right) less solar heat is produced than required and therefore additional heat from the HT-ATES hot well is produced. (Note that the cold well in this diagram is not used for cooling, but is used to store formation water from the hot well after it has passed through the heat exchanger. Optimal injection and production temperatures can strongly vary per project.)

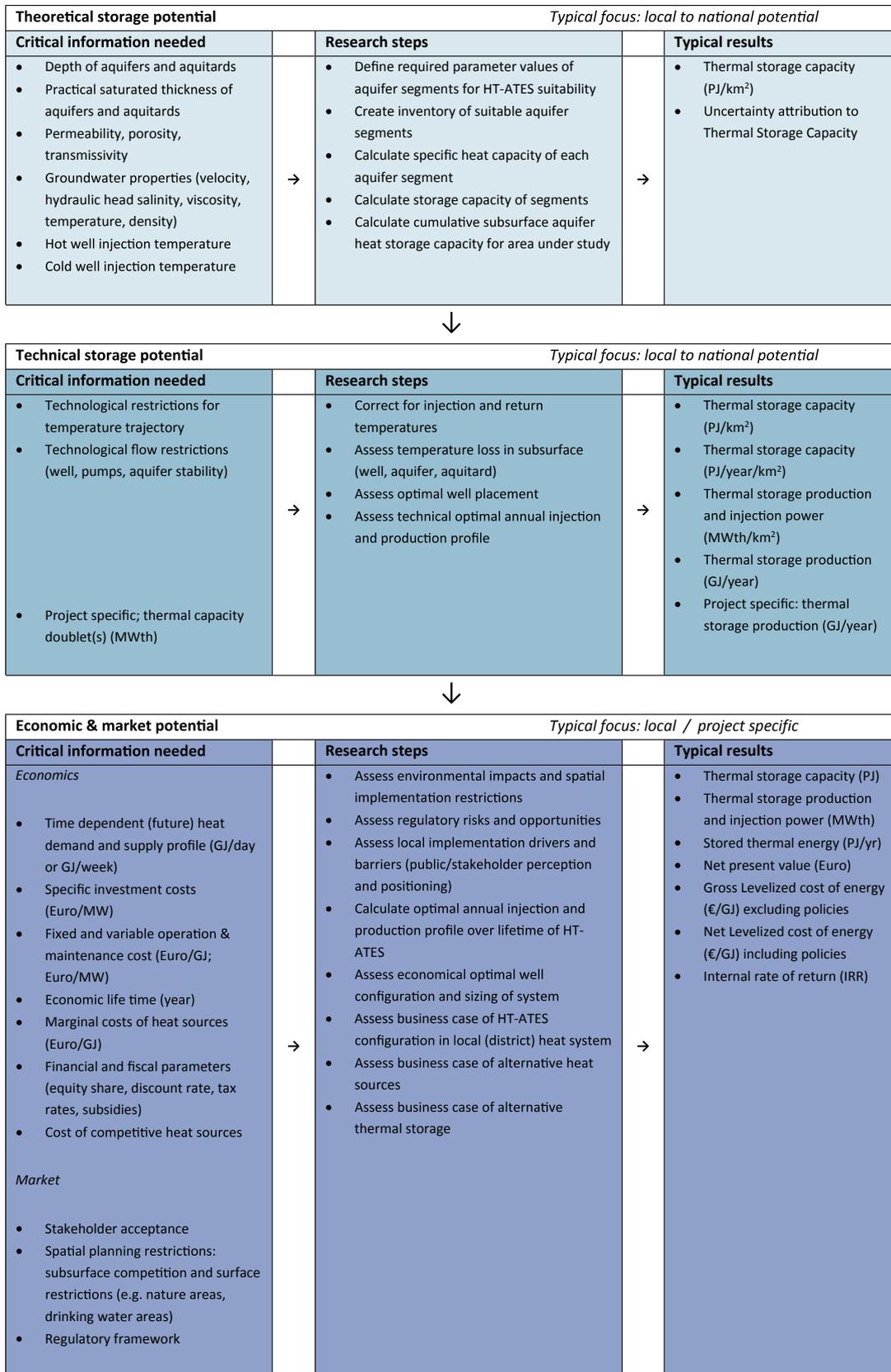


Fig. 2. Conceptual framework of assessing theoretical, technical and economic & market potential of HT-ATES.

which are explained in the following.

The **theoretical potential** of HT-ATES is ideally only limited by the available storage volume. The storage volume is delineated by the definition of HT-ATES in terms of its storage medium and the temperature of injection and return flows. The following main aspects therefore need to be studied and defined to estimate the theoretical potential: minimum permeability, aquifer thickness, depth range, impermeable layer requirements, background temperature and the injection and production temperatures of the hot and cold wells.

Technical barriers to fully exploit the storage volume determine the **technical potential**. The flow rate is the maximum amount of water (in  $\text{m}^3$ ) that can be produced and injected per hour. Together with  $\Delta T$ , it determines the thermal power of the system. The maximum flow rate depends on well performance properties and on a number of subsurface parameters that are different for each aquifer. The engineered components have their technical limitations: the applied pump pressure and flow is an important parameter, as is maximum temperature given material properties and operational challenges. The maximum flow rate must be determined for each case study individually as local subsurface conditions can vary considerably. Recovery efficiency is another constraint indicating the maximum of the recoverable share of injected heat.

The **economic potential** is determined by factors that influence the cost effectiveness of HT-ATES implementation. At a regional level, the heat demand and supply profiles including the quantity and pattern of supply and demand are two determining factors. HT-ATES installations inject or produce thermal energy when there is a mismatch between demand and supply of heat. The larger this mismatch, the higher the number of full load hours of the installation. Full load hours refer to the number of hours per year that a HT-ATES installation delivers heat at full capacity. It is calculated by dividing thermal energy produced from HT-ATES in a year (MWh) by production power of HT-ATES ( $\text{MW}_{\text{th}}$ ). An operational profile of HT-ATES is also required, i.e. the heat injection and production (in GJ/day or GJ/week) for each year during the economic lifetime. Such a profile also determines further operational data such as full load hours and the net heat balance per year.

In addition to these profiles, economic assumptions on heat sources, HT-ATES and competing (or reference) technologies are equally influential to determine the economic potential of HT-ATES. Typical assumption consists of investment and maintenance costs of HT-ATES, marginal costs of heat sources as well as investment and maintenance costs of competing technology options providing the similar service of heat supply. Economic indicators such as payback period (PP) and levelized costs of energy (LCOE) should be chosen and calculated to compare economic effectiveness of different options.

The economic potential is further narrowed down to the market potential by taking into account the impacts of policy and regulations as well as factors such as willingness to pay and local implementation. Stakeholder acceptance and the distance to protected areas are exemplary factors to be taken into account. Also existing policies like renewable energy subsidies, incentives on purchasing renewable heat and regulations of energy tax should be included. Moreover, the future policy changes should be considered if the medium and long term potential is assessed. The chosen economic indicators need to be re-calculated by taking into account these drivers and obstacles from the market point of view. A **sensitivity analysis** is helpful to identify the parameters with the strongest impact on the results and the degree to which the uncertainty range in single input values can potentially change the results.

## 2.2. The HT-ATES calculation tool

The explanation of the steps in section 2.1 is a simplification of the assessment conducted in this study, in which more (sub) parameters were taken into account. For the economic and market potential a modified and further developed version of the HT-ATES calculation tool [15] is used.

The basic version of this tool allows to perform a cash flow analysis and to calculate levelized cost of recovered heat from the HT-ATES based on some key parameters. The most important parameters are the recovery efficiency, variable operational costs based on pump energy and cost of non-recovered heat, pump energy which is calculated based on pressure loss in the well and reservoir and investment costs which scale with depth and thermal capacity. Subsurface parameters are crucial inputs for the model calculations, i.e. transmissivity of the target aquifer is one of the most important parameters as it influences the maximum well flowrate and with it the thermal capacity of the HT-ATES [15].

For this study the tool and related workflow were upgraded and now includes:

- Dynamic annual load and unloading profiles;
- The Dutch subsidy scheme to automatically calculate the level of subsidy and impact on levelized cost of heat;
- Sensitivity analysis module; a spread sheet model to calculate the reference LCOE for the natural gas fired alternative. This entails a module to calculate natural gas costs including taxes for alternative policy scenarios (including sensitivity analysis).

## 2.3. Method and data of case study

The selected case is a DH network in Groningen in the Netherlands. It is currently being developed and is expected to eventually supply heat to 11,700 household equivalents [16]. A 3500 m deep geothermal well located at the Zernike Campus is planned as the main heat source with a formation water temperature of  $116^\circ\text{C}$ , which will be reinjected at  $60^\circ\text{C}$  after passing through a heat exchanger. Each cubic meter of formation water contains a predicted  $1 \text{ m}^3$  of natural gas, which will be separated and directly combusted in a small combined heat and power (CHP) plant located next to the geothermal well. Peak heat supply will be provided by four natural gas boilers situated within the DH network. In this quick scan HT-ATES is investigated as a potential alternative for these natural gas boilers.

The key subsurface requirements for determining theoretical storage potential of HT-ATES have been listed in Table 1. An impermeable layer above an aquifer reduces density-driven vertical movements of the stored hot water and reduces warming of more shallow aquifers above it. Adequate local geological data in the HT-ATES depth range is unavailable for the case study area, therefore interpolated data from literature on shallow direct geothermal heat is used [17]. An overview of key parameter values for four formations in the Zernike area is given in Table 2. The depth of base of all three formations in the Zernike area is the same due to the high uncertainty range, which is caused by the interpolation from unevenly distributed well logs and the strong salt tectonics in the area [17]. The Formation of Oosterhout is chosen as the preferred formation, due to its higher flow rate and thickness. With the main subsurface parameter values known, some key HT-ATES parameters are calculated (see Table 3).

All techno-economic data for the geothermal well, DH network, HT-ATES and peak boilers are listed in Table 4. As the DH network is still under construction, the target year of the market potential assessment is set at 2020. The number of household equivalents

**Table 1**  
Key subsurface parameter values for HT-ATES suitability in the Netherlands.

Parameter	Preferred/required value	Remarks and reference
Transmissivity	>50 Dm	M.P.D. Pluymaekers, pers. comm., April 15, 2016
Depth	- Minimum: fresh/salt water interface (150 mg Cl <sup>-</sup> /L) 200 m depth. - Maximum: 968 m depth	- Minimum depth to prevent overlap with drinking water reserves [18] - Maximum depth to prevent overlap with direct geothermal heat potential; max. 40 °C ambient temperature assumed [19]. Assuming geothermal gradient is 31 °C per km depth [20] and ground level temperature is 10 °C [21]
Impermeable layer thickness	≥30 m	An impermeable layer above the storage aquifer prevents unacceptable heat losses due to upwards density-driven flow and reduces heating of more shallow layers [22]

**Table 2**  
An overview of a course regional assessments of three formations in the Zernike area with their main characteristics [17].

Parameter	Unit	Brussels Sand	Formation of Breda	Formation of Oosterhout
Depth of base	Meters	301–450	301–450	<b>301–450</b>
Practical saturated thickness <sup>a</sup>	Meters	30–60	0–50	<b>100–150</b>
Well flow rate <sup>a</sup>	m <sup>3</sup> /hour	1–15	25–50	<b>55–100</b>

<sup>a</sup> The expected maximum pumping rate that can be achieved according to the assumptions of [17].

**Table 3**  
An overview of key HT-ATES parameters calculated based on the data of the case and subsurface data of Oosterhout formation in Table 2.

Maximum flow rate	77.5 m <sup>3</sup> water/hour <sup>a</sup>
Well depth	312.5 m <sup>b</sup>
Thermal capacity	3.15 MW <sub>th</sub>

<sup>a</sup> The average value of the range in Table 2.

<sup>b</sup> Assuming<sup>b</sup> that the wells reach to the center of the formation. Centre of formation calculated assuming the average regional depth and thickness of the formation from Table 2.

connected to the network will gradually increase after 2020 (Fig. 3). The assumed economic lifetime of the HT-ATES installation is 15 years, making the period over which the assessment is conducted 2020–2034. Detailed model projections for heat demand per hour for each year were provided by the DH network owner. For reasons of confidentiality the temporal resolution was lowered to a weekly scale.

The technical potential for a case study is expressed as the thermal capacity the system delivers and the amount of heat that

**Table 4**  
Overview of the main parameters of the geothermal well, DH network, HT-ATES and backup boilers.

Item	Value	Unit
<b>Geothermal heat supply</b>		
Geothermal capacity	11.37	MW <sub>th</sub> <sup>a</sup>
CHP capacity	1.04	MW <sub>th</sub> <sup>a</sup>
Temperature formation water	116	°C <sup>a</sup>
Temperature formation water at reinjection	60	°C <sup>a</sup>
<b>DH network</b>		
Initial temperature of DH water	95	°C <sup>a</sup>
Return temperature of DH water	60	°C <sup>a</sup>
<b>HT-ATES</b>		
Recovery efficiency	70	% <sup>b</sup>
Economic lifetime	15	year
Investment cost of HT-ATES	1,480,883	€
Fixed O&M	1	% of total HT-ATES capex per year
Investment cost on well drilling	310 and 1000	k €/well and €/m depth
Investment cost of pump	0.1	M EUR/pump every 5 years
Electricity costs for pump(s)	50	€/MWh <sub>e</sub>
Marginal costs of geothermal heat	2	€/GJ <sup>a</sup>
Inflation	2.0065	%
Loan rate	8	%
Required return on equity	6	%
Percentage of investment (loan: equity)	80:20	–
Term loan	15	year
<b>Heat-only peak boiler (data of one boiler)</b>		
Manufacturer and type	FH Crone CLW 275 6 bar (no condenser)	–
Thermal capacity	10.8	MW <sub>th</sub>
Investment cost	51,305	€
Fixed O&M	1	% of investment cost [23]
Economic lifetime	15	Year
Thermal efficiency	88.2 (LHV)	% [24]
Price natural gas in 2020–2034	11.51	€/GJ <sup>c</sup>

<sup>a</sup> Information provided by Warmtestad.

<sup>b</sup> Median value of the combined efficiency range 50–90% stated in literature [22,25].

<sup>c</sup> Projected 2020 natural gas price without taxes and levies [26]. Corrected for inflation until 2020 and assuming 1 boe = 1700 kWh, 1 m<sup>3</sup> = 9.769 kWh and 1 EUR = 1.36 USD. Natural gas price is kept constant in the 2020–2034 period due to the high degree of uncertainty in the projection for 2020.

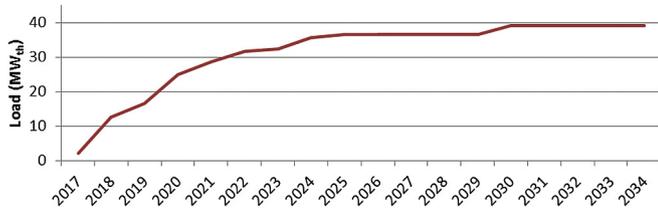


Fig. 3. Projected growth in peak demand connected to the DH network between 2020 and 2034.

could be ideally injected. To assess the maximum technical potential of HT-ATES in the case study, the following formula is used:

$$P_{max} = \frac{Cap * 8760 * 3.6}{\left(1 + \frac{1}{eff}\right) * 1000} \quad (1)$$

$P_{max}$  The maximum amount of heat that an HT-ATES can produce per year (GJ/yr)  
 Cap Thermal capacity of doublet (MW<sub>th</sub>)  
 eff The recovery efficiency, i.e. ratio between heat produced and heat injected.

To assess the economic and market potential of HT-ATES in the case study, the LCOE in EUR/GJ<sub>th</sub> is compared with the LCOE of the reference technology, in this case natural gas boilers. The **gross LCOE** is the LCOE without taking into account the effects of policies and regulations targeted at (renewable) energy technologies, while in the **net LCOE** these policies and regulations are incorporated.

The LCOE is calculated by applying the formula below:

$$LCOE = \frac{EQ - \sum_{y=1}^n \left( \frac{I_y - C_y - L_y - T_y}{(1+r)^y} \right)}{\sum_{y=1}^n \left( \frac{1}{(1+r)^y} * (P_y) \right)} \quad (2)$$

Where:

LCOE Levelized cost of energy (Euro/GJ)  
 EQ Equity investment (in Euro)  
 I<sub>y</sub> total income (inflation corrected) in year y (in Euro)  
 C<sub>y</sub> total costs (inflation corrected) in year y (in Euro)  
 L<sub>y</sub> Loan charges in year y (in Euro)  
 T<sub>y</sub> Tax in year y (in Euro). Note Tax is excluded in the gross LCOE calculation.  
 P<sub>y</sub> Heat produced from ATES in year y (in GJ)  
 r discount rate or required return on equity  
 y year (starting year of ATES)  
 n economic life time

In the eq. (2), equity investment (EQ) is calculated based on temperatures, flow rate, depth and standard costs for drilling, pumps, heat exchanger. Well depth, the parameter has the strongest influence on EQ and therefore, is analyzed in the sensitivity analysis. The total costs in year y are expenditures that are made during HT-ATES operation. It consists of fixed and variable expenditures. The main variable expenditures are heat purchase and electricity costs for the submersible pumps, while the main fixed expenditures are related to maintenance (e.g. pump replacement; operation). Two most important parameters in the calculation of C<sub>y</sub>, e.g. the price of electricity and geothermal heat, are discussed in the sensitivity analysis.

Heat produced by HT-ATES (P<sub>y</sub>) over its lifetime follows from its

activity throughout each year. HT-ATES activity (MW<sub>th</sub>) at a given moment is determined by geothermal capacity (MW<sub>th</sub>), heat demand (MW<sub>th</sub>), and amount of stored heat (GJ). The moment heat demand exceeds the geothermal capacity there is a heat demand for HT-ATES. It complements the geothermal heat source up to HT-ATES thermal capacity as long as the amount of stored heat is not limiting (see eqs (3) and(4).

$$P_y = \sum_{h=1}^t \left( D_h - Cap_{geothermal} \right) * 3.6 \quad (3)$$

$$0 \leq \left( D_h - Cap_{geothermal} \right) \leq P_{HT-ATES} \quad (4)$$

Where:

D<sub>h</sub> heat demand in hour h (in MW<sub>th</sub>)  
 Cap<sub>geothermal</sub> thermal capacity of geothermal (in MW<sub>th</sub>)  
 P<sub>HT-ATES</sub> Power of HT-ATES production (in MW<sub>th</sub>)

### 3. Results

#### 3.1. Theoretical and technical potential

In this study the theoretical and technical potential is governed by the locally determined case study parameters and no regional study is performed on the theoretical or technical potential. The thermal capacity of the system is calculated at 3.15 MW<sub>th</sub> (see Table 3) which allows a maximum of 1.9 TJ of heat to be produced or injected per week using one doublet and a recovery efficiency of 70% is assumed. With eq. (1), the simple technical optimum for this case study is calculated at 58 TJ for injection and 41 TJ for heat recovery per year from the HT-ATES doublet. It should be stressed that this is a simple technical optimum. Detailed 3D subsurface heat and groundwater flow modelling is needed to better estimate the thermal capacity and status of loading of the system over time. This also would allow estimating the development of recovery efficiency over time as the subsurface system gradually heats and efficiency improves.

#### 3.2. Economic potential

##### 3.2.1. Heat demand and supply profiles assessment

Due to the gradually increasing number of household equivalents connected to the DH network and the resulting load increase, each year of the assessment has its own heat supply and demand profile. The profiles for 2020 and 2034 are shown in Fig. 4. The green areas show weeks with lower heat supply than demand. Part of the green areas is below the supply capacity line, which is the result of lowering the temporal resolution of the data. Projected heat demand in these cases is higher than the supply capacity at one or several moments in a week (e.g. peak demand during early morning), but the overall demand over the week does not necessarily exceed supply capacity. These mismatches can be balanced with small-scale thermal storage solutions such as hot water tanks. The green areas above the supply capacity line represent heat shortages of a seasonal character, for which HT-ATES is a potentially suitable solution.

In 2020, there is only a (seasonal) heat shortage in week 2, while in 2034 there is a (seasonal) heat shortage in more weeks and the shortages per week are higher. Nevertheless, the area below the supply capacity line and above the demand line is several times bigger than the (seasonal) heat shortage area, meaning that several times more heat than required can potentially be injected. A numeric overview of supply and demand profile is given in Table 5.

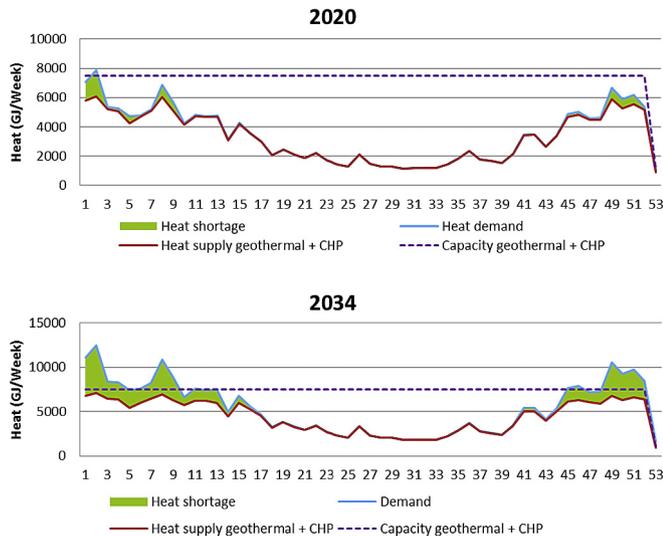


Fig. 4. Projected heat demand, heat supply and maximum heat supply capacity for each week in 2020 (upper graph) and 2034 (lower graph).

### 3.2.2. Modelling HT-ATES operation

Based on the heat demand and supply profiles, the HT-ATES injection/charging and production are calculated by the HT-ATES tool. Both injection and production are limited by HT-ATES thermal capacity, while production is also limited by the remaining heat available from the hot well.

The predicted HT-ATES charging in 2020 and 2034 is shown in Fig. 5. The injection potential is the supply capacity minus demand, corrected for HT-ATES thermal capacity. It is the maximum amount of heat that can potentially be injected into the HT-ATES installation. This potential is several times larger than the produced heat in all analyzed years. Whether heat is injected depends on operator behavior, which is directed by expected heat demand. In the financial calculations the injected heat over an entire charging season equals the expected produced heat in the same year divided by the recovery efficiency.

### 3.2.3. HT-ATES gross LCOE calculation

The calculated HT-ATES gross LCOE is 20.50 €/GJ. The LCOE is calculated over the output for all years in the 2020 to 2034 period and based on the subsurface and surface conditions within the scope of this study, as well as the data and assumptions stated in section 3.

## 3.3. Market potential

### 3.3.1. Policy analysis and the alternative policy scenario

Two policy scenarios were developed to identify changes of or additions to the existing policy package which are beneficial for the deployment of HT-ATES. The *business-as-usual* (BAU) scenario

Table 5  
Key outcomes of the heat supply and demand profiles in 2020 and 2034.

Item	Unit	2020	2034
Annual heat demand	GJ/year	181,019	284,894
Annual supply of geothermal heat	GJ/year	172,025	232,813
Annual supply potential of geothermal heat	GJ/year	391,375	391,375
Full load hours geothermal well	Hours/year	3850	5211
Power HT-ATES (injection)	MW <sub>th</sub>	5.04	5.04
Power HT-ATES (production)	MW <sub>th</sub>	3.65	3.65
Full load hours HT-ATES (production)	Hours/year	29	1634
Heat demand for HT-ATES	GJ/year	383	21,498

includes the existing policies which may directly and indirectly influence the HT-ATES market potentials of the case study. In the *alternative* (ALT) scenario the policies in the BAU scenario are adapted to increase the HT-ATES market potential compared to the BAU policy package, or more generally to stimulate investments in CO<sub>2</sub>-emission reduction measures. The scenarios only differ in the policies over the whole period and not in the technological or societal status. An overview of the policies in the two scenarios is shown in Table 6.

The energy investment rebate (EIA) allows an investor in an energy efficiency technology to deduct 58% of the investment from the earnings before tax. HT-ATES is one of the approved technologies [27]. In the ALT scenario, the EIA percentage is increased to 78%.

SDE<sup>+</sup> is a Dutch subsidy scheme encouraging the production of renewable energy by compensating for its higher generation costs compared to non-renewable energy. It applies to biomass, solar PV, hydro, wind and geothermal installations. The amount of subsidy is determined by the difference between the generation costs per unit of heat by a specific renewable energy project and the current price of non-renewable energy. SDE<sup>+</sup> applies to the heat source (in this case a geothermal installation) and not to the HT-ATES installation itself. However, if HT-ATES facilitates an increased heat production by the geothermal installation, the extra SDE<sup>+</sup> received is here allocated to the HT-ATES business case. A maximum number of full load hours (FLH) of 7000 per year applies to this subsidy, however. In the ALT scenario this limitation is removed by allowing 8760 FLH.

The energy tax on natural gas influences the reference LCOE, and therefore the HT-ATES market potential. When comparing the energy tax of natural gas and electricity in the first tax bracket of Table 7. (<170,000 m<sup>3</sup> and <10,000 kWh respectively), it stands out that energy tax per unit of energy is almost four times higher for electricity than for natural gas. This has implications for the transition to a sustainable heat supply, e.g. by discouraging investments in household scale heat pumps and district heating networks (as the price cap for heat is determined by the natural gas price in the Netherlands). Considering that electricity is produced from natural gas with an efficiency of roughly 50%, the energy tax on natural gas is ideally half that of electricity instead of one fourth [28]. In the ALT scenario this philosophy is applied to the first tax bracket, while keeping energy tax on electricity at the current level. The sustainable energy levy is included in the calculations, but not changed in the ALT scenario as its effect is similar to the energy tax.

### 3.3.2. Net HT-ATES LCOE calculation

The gross LCOE is equal in both policy scenarios and does not include any effects of market drivers. The calculated HT-ATES net LCOE is 3.54 €/GJ and 2.76 €/GJ in BAU and ALT scenarios respectively (see Figs. 6 and 7). SDE<sup>+</sup> has the largest impact on the HT-ATES LCOE and is equal in both policy scenarios. This is due to the fact that in none of the years the BAU maximum number of FLH (7000) is exceeded. Extra FLH of the geothermal well facilitated by HT-ATES are calculated based on extra geothermal heat produced by HT-ATES rather than heat injected into HT-ATES. Although the latter is the actual additional geothermal heat produced, only the heat produced by HT-ATES is used for heating and therefore is in accordance with the purpose of the SDE<sup>+</sup> program. Adding the contribution of the EIA leads to the net LCOE values, i.e. the gross LCOE plus the contributions of SDE<sup>+</sup> and EIA. The energy tax on natural gas does not affect the HT-ATES LCOE and is included in the next step.

### 3.3.3. Reference LCOE calculation and comparison with HT-ATES LCOE

Fig. 6 shows the LCOE calculation results of both HT-ATES and

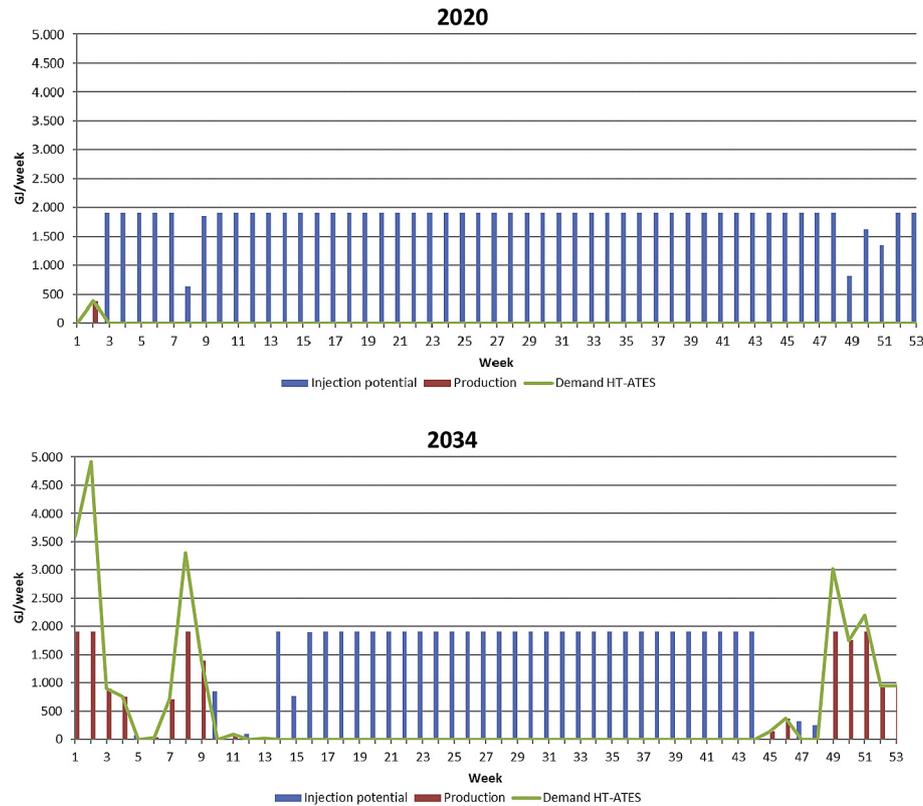


Fig. 5. HT-ATES injection and production profile in 2020 (upper graph) and 2034 (lower graph).

**Table 6**

An overview of existing (BAU) and alternative (ALT) policies that may influence the HT-ATES market potential.

Policy	BAU	ALT
Energy investment rebate (EIA). Percentage of investment.	58%	78%
Full load hours cap under SDE <sup>+</sup> scheme for geothermal systems (3500 m or deeper)	Max. 7000 full load hours	Max. 8760 full load hours
Energy tax	4 times lower on natural gas than on electricity based on final energy content	2 times lower on natural gas than on electricity based on final energy content

**Table 7**

An overview of the 2016 energy tax rates in the Netherlands for natural gas and electricity in the BAU [29] and ALT scenario, and 2016 sustainable energy levy rates for natural gas.

Consumption range and type		BAU energy tax rate		ALT energy tax rate		Sustainable energy levy
Natural gas (m <sup>3</sup> /year)	Electricity (MWh/year)	Natural gas (€/GJ <sup>a</sup> )	Electricity (€/GJ)	Natural gas (€/GJ <sup>a</sup> )	Electricity (€/GJ)	Natural gas (€/GJ)
0–170,000	0–10	7.16	27.97	13.99	27.97	0.0520
170–1,000,000	10–50	1.98	13.88	1.98	13.88	0.0606
1,000,000–10,000,000	50–10,000	0.72	3.70	0.72	3.70	0.0375
>10,000,000 (private)	>10,000 (private)	0.34	0.30	0.34	0.30	0.0260
>10,000,000 (business)	>10,000 (business)	0.34	0.15	0.34	0.15	0.0260

<sup>a</sup> : for the conversion to EUR/GJ, a caloric value of 9769 kWh/m<sup>3</sup> is assumed.

reference boilers in the BAU scenario. It indicates the contributions of different policy components on LCOE values. Similarly, Fig. 7 presents the LCOE results of HT-ATES and reference boilers in the ALT scenarios. With respect to the economic potential, the HT-ATES gross LCOE is slightly higher than the gross LCOE of the reference boiler. Regarding the market potential, the net LCOE of HT-ATES taking into account taxes and subsidies is much higher than that of the reference boilers, which is largely the result of the effect of SDE<sup>+</sup> subsidies. In this specific case study setting, the ALT policy package improves the business case of HT-ATES implementation,

but does not seem to be strictly necessary. This is to a large extent the result of SDE<sup>+</sup>.

### 3.3.4. Sensitivity analysis

The parameters that are chosen for sensitivity analysis are listed in Table 8. A sensitivity range of  $\pm 10\%$  is applied to these parameters. Additionally, a parameter specific range based on literature or estimates is applied. For some parameters no specific uncertainty range is applied due to lack of insight in their uncertainty range, or because the uncertainty range agrees with the standard  $\pm 10\%$

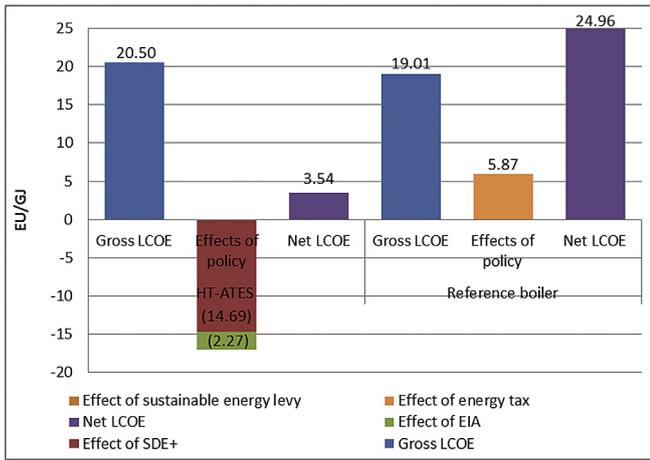


Fig. 6. The LCOE results of HT-ATES and reference boilers in the BAU scenario.

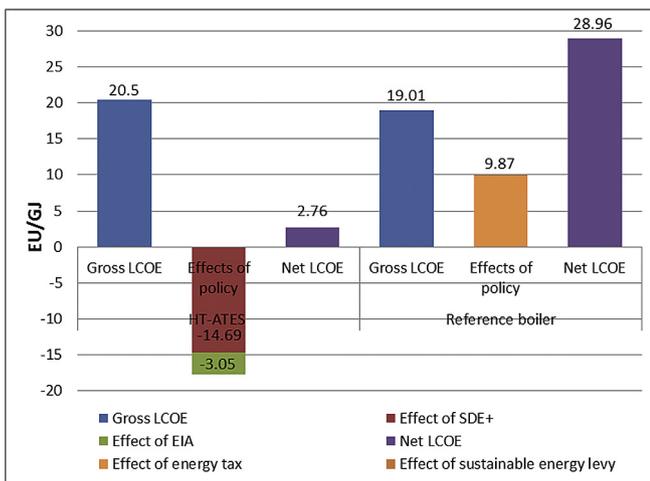


Fig. 7. The LCOE results of HT-ATES and reference boilers in the ALT scenario.

range. We chose to use a local sensitivity analysis as we wanted to provide insight in the relative influence of each parameter on the business case/market potential. Other type of sensitivity analysis, e.g. a global sensitivity analysis would result in a larger range.

Figs. 8 and 9 show that the HT-ATES LCOE is most strongly influenced by the lifetime and demand. The strong influence of these parameters can be explained by the fact that HT-ATES has high investment costs and relatively low fixed and variable operation and maintenance costs. Lifetime and demand results in more produced units of heat (GJ) to spread the investment cost over. Due to the high coefficient of performance (COP = 80), changes in electricity price have a negligible influence on the model output. The relatively low influence of changes in equity share are due to the small difference between the assumed loan rate (8%) and discount rate (6%). Comparing with the lifetime and heat demand, the recovery efficiency, which is the current research focus of the technical aspect [8] [11], has less influence on the economic performance of the system. There is a need to place HT-ATES in a local/regional heat supply system and design/optimize system configuration in order to improve the overall techno-economic performance.

Figs. 10 and 11 indicate that, contrary to the HT-ATES net LCOE, the reference boiler net LCOE is dominated by operational rather than capital expenditure. For instance, a 10% decrease of the natural

Table 8

Input for sensitivity analysis on the HT-ATES net LCOE calculation. Low and high values represent the lower and upper extremes of the uncertainty range of each parameter.

Variable	Unit	Low	Default	High	Remarks
<b>HT-ATES</b>					
Well depth	M	226	312.5	399	<sup>a</sup> [17],
Price geothermal heat	€/GJ	–	2	–	
Recovery Efficiency	%	50	70	90	[22,25]
Lifetime	Years	10	15	20	[30]
Equity share	%	0	20	100	
Electricity price	€/MWh	40	50	60	
Discount rate	%	3	6	15	
Demand size	MW	–	n.a.	–	<sup>b</sup>
<b>Peak boiler</b>					
Lifetime	Years	10	15	30	<sup>c</sup> [31],
Gas price (excl. tax)	€/GJ	6.51	11.51	16.51	
Equity share	%	0	20	100	
Energy tax	€/m <sup>3</sup>	–	n.a.	–	<sup>d</sup>
Discount rate	%	3	6	15	
Demand	GJ/week	–	n.a.	–	
Boiler efficiency	%	–	82	–	

<sup>a</sup> Well depth is the parameter that has the strongest influence on the capital expenditure and also has the highest uncertainty. Therefore, it is used as a proxy for the investment cost in the sensitivity analysis.

<sup>b</sup> Demand depends on the chosen year in the HT-ATES lifetime. Therefore, the default value is not listed here. No uncertainty range is available.

<sup>c</sup> 10 years warranty provided by manufacturer FH Crone (R. van Leeuwen, personal communication, June 20, 2016).

<sup>d</sup> Energy tax in first bracket. The default value depends on the chosen policy scenario. No uncertainty range applied, as this parameter is part of the policy scenarios.

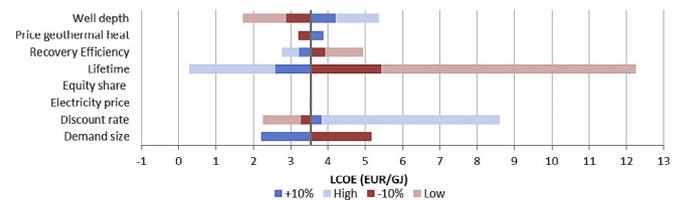


Fig. 8. Sensitivity analysis of HT-ATES net LCOE to selected input factors in the BAU policy scenario. The baseline is at 3.54 €/GJ.

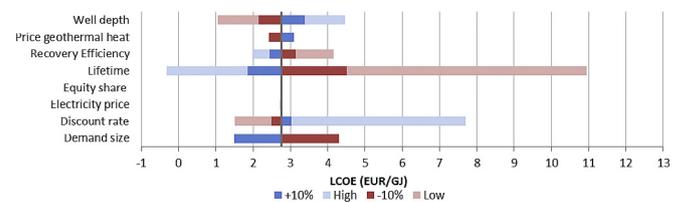
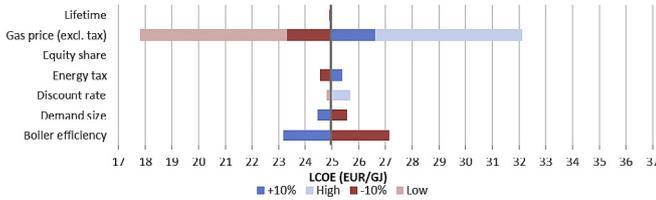
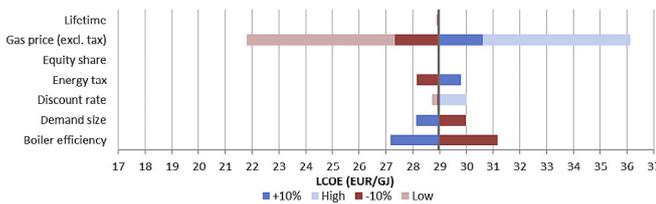


Fig. 9. Sensitivity analysis of HT-ATES net LCOE to selected input factors in the ALT policy scenario. The baseline is at 2.76 EUR/GJ.

gas price before tax results in a 7.1% (BAU) and 6.0% (ALT) decrease in LCOE. In the ALT scenario, the energy tax shows a significant influence on the LCOE as well, while its influence in the BAU scenario is smaller. Boiler efficiency is the most influential factor, as it directly affects the amount of natural gas required to produce a GJ of final heat. If more gas is required, the costs for natural gas, energy tax and sustainable energy levy increase simultaneously. Another parameter that illustrates the capital expenditure dominance of HT-ATES and operational expenditure dominance of natural gas boilers, is the discount rate. Varying the discount rate has little influence on the gas boilers as their investment costs are relatively low. The HT-ATES net LCOE significantly changes when the discount rate is varied, due to the high investment costs which are partially



**Fig. 10.** Sensitivity analysis of the reference boiler net LCOE to selected input factors in the BAU policy scenario. The baseline is at 24.96 €/GJ.



**Fig. 11.** Sensitivity analysis of the reference boiler net LCOE to selected input factors in the ALT policy scenario. The baseline is at 28.97 €/GJ.

financed with equity.

Certain parameters, such as lifetime (HT-ATES) and natural gas price (reference boilers), have a significant uncertainty range. However, the impact of the uncertainty range of single parameters on the net LCOE, is not sufficient to create overlap between the LCOE values of the HT-ATES and reference boilers in either policy scenario. This is largely the result of the effect of SDE + subsidy on the HT-ATES LCOE.

#### 4. Discussion

The methodological framework was deliberately developed as a conceptual framework for pre-feasibility studies and quick scans of market potential of HT-ATES. In this study a part of this framework is applied and quantified in the form of a techno-economic quick scan of a case study in the Netherlands. This case study includes some critical parameters that need to be taken into account when addressing the techno-economic part of the market potential. Other important aspects have not been assessed, but are considered needed to understand the local or regional market potential. Examples are the 'Market parameters' in Fig. 2: stakeholder acceptance, spatial planning restrictions, regulatory framework and environmental impacts. Until further research into societal factors is conducted, any calculated HT-ATES market potential is preliminary.

A few simplifications of the method are pointed out in particular. Firstly, the subsurface data used was not local, due to the unavailability of measurements in the appropriate depth range. Consequently, the uncertainty range in this data was rather large and the median values were used. The second point is the limited insight in the heat demand. The DH network has yet to be constructed and is planned to connect primarily to existing buildings. Contracting with the owners and users of these buildings is an ongoing process and the number of connected household equivalents in each analyzed year is thus uncertain. The effects of climate change and insulation of buildings are an additional uncertainty. Thirdly, recovery efficiency was assumed to be the median of the ranges stated in literature. As the wide range of efficiencies suggests, there is a large variability in recovery efficiency in different HT-ATES projects. The profound 3D modelling of the local subsurface that is required to make a case-specific estimation is not yet performed. A fourth highly uncertain parameter is the price of

natural gas, which plays a major role in the reference LCOE. Finally, the continuation of policies is uncertain and information on planned changes is largely unavailable. Therefore, the 2016 policies were assumed to remain in place in the assessed period (2020–2034), despite past trends such as increasing energy tax [29].

To assess the implications of the uncertainty in the described parameters as well as their relative influence on the HT-ATES market potential, a local sensitivity analysis is conducted. No individual changes in single parameter values within their uncertainty ranges changed the cost-effectiveness of HT-ATES compared to the reference boiler. However, to validate that also the combined uncertainty ranges of all parameters simultaneously cannot change the outcome, a Monte-Carlo analysis is required [32]. This would require detailed insights into the interrelation of parameters and how they influence each other's uncertainty range, which is out of scope for this study.

A few operational concerns have not been considered in this study. Firstly, the so-called *charging phase* of the HT-ATES installation was neglected. HT-ATES installations have relatively low recovery efficiencies during the first years of operation. After the first few cycles, the injected heat in previous years increases the aquifer ambient temperature, which results in a higher recovery efficiency [8]. In this study it is assumed that the charging phase is completed before 2020, but the costs of this phase is not included in the LCOE calculation as estimations of the required amount of heat require profound modelling. The second limitation involves the operational strategy of HT-ATES installations. An operator must decide how much heat is injected each charging season to cover heat demand in the production season afterwards. Among other factors, this decision depends on the expected weather in the production season. Operators can therefore never inject the optimal amount of heat, as was assumed in this case study.

Recommendations for further research are proposed. Firstly, more thorough research is required on the levelling of the energy tax proposed in the ALT scenario. The tax brackets for electricity and natural gas are unequally distributed, which hinders full levelling. Moreover, the side effects of levelling have not yet been addressed sufficiently. Secondly, the integration of modelling the HT-ATES performance using 3D subsurface modelling, and modelling its role as part of the heat network in more detail, provides a better understanding of the strengths and limitations of the technical performance and business case for HT-ATES. The final recommendation concerns the prospects of HT-ATES in smart energy system (SES) and how this role can be translated into its business case. Although this role - for example the application of large scale power-to-heat offering flexibility in an integrated power and heat infrastructure - is potentially an important driver for HT-ATES implementation, it was not taken into account in the market potential assessment in this study. In-depth studies are required to reach a level of understanding that enables quantification and inclusion of this application in HT-ATES market potential assessments.

#### 5. Conclusion

In order to fill the knowledge gap on understanding the drivers, barriers and conditions for HT-ATES implementation, a conceptual methodological framework has been developed for a preliminary feasibility assessment of the market potential of HT-ATES. By applying the proposed framework, a case study of coupling HT-ATES and geothermal heat in a planned DH system in the Netherlands has been carried out.

The results of applying the proposed framework are site specific. The case study in Groningen indicates that there is a market

potential for HT-ATES under existing policies and more sustainable alternative policies. The net levelized cost of energy (LCOE) of HT-ATES is significantly lower than the reference boiler LCOE due to the SDE<sup>+</sup> subsidy for geothermal heat. This outcome reveals good prospects for HT-ATES combined with geothermal heat as well as other sustainable heat sources with low costs in the Netherlands. Furthermore, it was found that the LCOE of HT-ATES is most strongly influenced by the lifetime of HT-ATES and the heat demand due to the fact that HT-ATES has high investment cost and relatively low variable costs. The gas price and boiler efficiency have larger impacts on the LCOE of reference boilers than other parameters.

The case study illustrates that the proposed methodological framework is suitable and applicable for a quick scan for HT-ATES market potential as well as for a pre-feasibility study. For more detailed results on which an investment decision can be made,

more data and analysis of both subsurface and surface conditions is required. This study provides first insights in promising applications of HT-ATES. Considering the large-scale integration of renewable energy and alternative heat sources in future smart energy systems, more synergies of applying HT-ATES with different heat sources are recommended to be further evaluated.

## Acknowledgement

The authors sincerely thank Warmtestad Groningen for sharing their data and cooperating in this study.

## Appendix

**Table A1**

A review of market potential studies on energy technologies and measures

Ref.	Potential	Key assumptions	Examples of key parameters	Outputs
<b>Wind and solar energy</b>				
[33,34]	TheP	<ul style="list-style-type: none"> <li>- Physical constraints</li> <li>- Theoretical Physical constrain</li> <li>- Energy content of resource</li> </ul>	<ul style="list-style-type: none"> <li>- Direct radiation value (kwh/m<sup>2</sup>/day) (CSP);</li> <li>- Wind speed (m/s)(wind energy)</li> <li>- Annual gross capacity factor &gt;30% (km<sup>2</sup>)(wind energy)</li> </ul>	GW; GWh
	TechP	<ul style="list-style-type: none"> <li>- System/topographic constraints</li> <li>- Land-use constraints</li> <li>- System performance</li> </ul>	<ul style="list-style-type: none"> <li>- Minimal spaces with slope&lt;Roman&gt; = &lt;/Roman&gt;3% (km<sup>2</sup>) (solar PV and CSP)</li> <li>- Installation density (MW/m<sup>2</sup>) (solar PV, CSP, wind energy)</li> <li>- Distance to all protected lands (km)(wind energy)</li> </ul>	
	EP	<ul style="list-style-type: none"> <li>- Projected technology costs</li> <li>- Projected fuel costs</li> </ul>	<ul style="list-style-type: none"> <li>- LCOE</li> <li>- ALCOE (LCOE + transmission costs + declining value of RE-existing tax intensive)</li> <li>- LACE (marginal generation price + capacity value + value of avoided emissions)</li> </ul>	ALCOE -LACE; GWh
	MP	<ul style="list-style-type: none"> <li>- Policy impacts;</li> <li>- Regulatory limits</li> <li>- Investor response</li> <li>- Regional competition with other energy sources</li> </ul>	–	–
<b>Centralized solar power</b>				
[35]	TheP	<ul style="list-style-type: none"> <li>- Resources availability</li> </ul>	<ul style="list-style-type: none"> <li>- Direct radiation value (kwh/m<sup>2</sup>/day)</li> </ul>	GW
	TechP	<ul style="list-style-type: none"> <li>- Access to existing transmission line</li> <li>- Load constraints</li> <li>- Operating reserve constraint</li> </ul>	<ul style="list-style-type: none"> <li>- Minimal spaces with slope&lt;Roman&gt; = &lt;/Roman&gt;1% (km<sup>2</sup>)</li> <li>- Distance to major urban, wetland or protected land (km)</li> </ul>	
	EP	<ul style="list-style-type: none"> <li>- Reserve margin constraint</li> </ul>	<ul style="list-style-type: none"> <li>- Installation, operating and maintenance costs of both generation and transmission capacity (\$/MW)</li> <li>- The costs of reserve capacity (\$/MW)</li> </ul>	LCOE; GW
	MP	<ul style="list-style-type: none"> <li>- Impacts of extension of the investment tax credit</li> <li>- Impact of a production tax credit</li> </ul>	–	–
<b>Wind energy</b>				
[36]	TheP&AP	<ul style="list-style-type: none"> <li>- Energy content of resource</li> <li>- Legal and environmental constraints</li> </ul>	<ul style="list-style-type: none"> <li>- Wind speed (m/s)</li> <li>- Maximum altitude, maximum land slope</li> <li>- Distance to protected area (km)</li> </ul>	GWh
	TechP	<ul style="list-style-type: none"> <li>- General technical rules</li> </ul>	<ul style="list-style-type: none"> <li>- Utilization Factor of the Wind parks (%)</li> <li>- Energy density (MWh/km<sup>2</sup>)</li> </ul>	
	EP	<ul style="list-style-type: none"> <li>- Average costs of electricity production</li> </ul>	<ul style="list-style-type: none"> <li>- Total installation cost (€/MWh)</li> <li>- The yearly O&amp;M cost (€/MWh)</li> <li>- Subsidy on investment (€/MWh)</li> </ul>	LCOE; GWh
	MP	<ul style="list-style-type: none"> <li>- Demand of energy</li> <li>- Competing technologies</li> <li>- Financial incentives</li> </ul>	<ul style="list-style-type: none"> <li>- Taxes</li> </ul>	
<b>Electric demand side management</b>				
[37]	TechP	<ul style="list-style-type: none"> <li>- Applicable and technically feasible measures</li> </ul>		CS (GWh);
	EP	<ul style="list-style-type: none"> <li>- Cost-effective measures</li> </ul>	<ul style="list-style-type: none"> <li>- Total resources costs (Million \$)</li> <li>- Value of avoided energy production (Million \$)</li> </ul>	PSP (MW);
	MP	<ul style="list-style-type: none"> <li>- Market barriers</li> <li>- Policy impacts</li> </ul>	<ul style="list-style-type: none"> <li>- Penetration of customer incentives (%)</li> <li>- Customer incentives (Million \$)</li> <li>- Net benefits (Million \$)</li> </ul>	
<b>Biomass + CCS</b>				
[38]	TechP	<ul style="list-style-type: none"> <li>- Resources available for conversion and use</li> </ul>	<ul style="list-style-type: none"> <li>- Crop productivity (10<sup>3</sup>ton/yr)</li> <li>- Land use constraints (km<sup>2</sup>)</li> </ul>	EJ/yr

(continued on next page)

Table A1 (continued)

Ref.	Potential	Key assumptions	Examples of key parameters	Outputs
	ReP	- Deployment rate	- Installed capacity (MW)	
	EP	- Expected energy demand - Cost of resource use - Cost of competing technologies	- Energy demand (GJ/yr) - Price of biomass at factory gate (€/GJ) - CO <sub>2</sub> price and storage price (€/ton) - Alternative fossil fuel price (€/GJ)	LCOE; EJ/yr
	MP	- Market obstacles and drivers - Policy obstacles and drivers	- Subsidies/taxes - Feed in tariff - Green certificate	–
<b>CO<sub>2</sub> geological storage</b>				
[39]	TheP	- Maximum amount of CO <sub>2</sub> could be stored in a geological formation	- Porosity and permeability - Average thickness reservoir (m) - Net to gross reservoir (%) - Typical thickness seal (m) - Average depth to the top of the reservoir depth (m)	Mt
	EffP	- Geological or engineering cut-offs	- Distance to protected area (e.g. groundwater)	
	PraP	- Legal, economic and regulatory constraints	- Storage site costs and CO <sub>2</sub> transmission costs - Decommissioning costs	Mt; CONE(€/MWh); SCC (€/tonne)
	MP	- Source and sink matching	–	–
<b>Energy efficiency improvement</b>				
[40]	TechP	- Technical feasibility - Applicability of measures	- Equipment energy use intensity (kwh/unit) - Saturation share and remaining factor (%) - Saving factor (%)	CS (MWh)
	EP	- Cost effectiveness of measures	- Measure costs (\$/kWh) - Avoided costs (\$/kWh) - Total resource costs	
	AchP	- Market barriers - Customer awareness - Willingness to pay	- Initial year/long term market adoption rate (%) - Incentive (\$/kWh)	
[41] [2]	TechP	- Applicability and feasibility of technologies/measures	- Estimated energy savings (kwh/unit) - Applicability factor - Feasibility factor	CS (GWh)
	EP	- Cost effectiveness of measures	- Measure costs (\$/kWh) - Avoided costs (\$/kWh) - Total resource costs	
	MP	- Market barriers - Willingness to pay	- Payback period (year) - Split incentives (\$/kWh)	
[42]	TechP	- Technical feasibility	- Estimated energy savings (kwh/unit)	CS (TWh)
	EP	- Cost effectiveness of efficiency and conventional measures	- Measure costs (\$/kWh) - Program administrative costs (\$/kWh) - Avoided costs (\$/kWh) - Total resource costs	
	AchP	- Market adoption - Market barrier	- Market adoption rate (%)	

(TheP: theoretic potential; AP: available potential; TechP: technical potential; EP: economic potential; MP: market potential; ReP: realizable potential; EffP: effective potential; PraP: practical potential; AchP: achievable potential; PV: photovoltaic; LCOE: Levelized cost of energy generation (€/GJ); ALCOE: Adjusted levelized cost of energy generation (€/GJ); LACE: levelized avoided cost of energy (€/GJ); CS: cumulative saving; PSP: peak saving potential; CCS: carbon capture and storage; SCC: specific CCS costs; CONE: cost of net electricity with and without CCS).

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