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HT-ATES systems in district heating networks, a Dutch benchmark study

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ABSTRACT

The Dutch research consortium WINDOW has developed and applied a converging selection process to identify preferred locations and integration concepts for HT-ATES in the Netherlands. A longlist of 22 locations was reduced to 7 feasible locations, based on criteria for geological conditions, legal constraints, preliminary business case, planning horizon and commitment of stakeholders. More elaborate exploratory studies and integration concepts were investigated for the remaining 7 locations. These exploratory studies were all carried out with a coherent set of assumptions and same approach, enabling a benchmark of the different studies. Key findings of this analysis: nearly 90% of the cost price variation is determined by the total water volume stored in the subsurface. The cost price of heat from a HT-ATES system can be lower than €15,-/GJ, if the stored water volume exceeds 300.000 m^3. The CO_2 emission reduction of HT-ATES heat supply ranges from 50% to 85% compared to gas boilers.

1. INTRODUCTION

Many urban areas rely on district heating networks for heating of buildings. Such systems allow for large scale and fast transition to sustainable heating and cooling. In moderate climates such systems exhibit a seasonal mismatch in demand and availability of sustainable heat, requiring large scale seasonal storage facilities. Aquifer thermal energy storage (ATES) is a technology that allows for storage of sensible heat in the subsurface with large volumes (>10 TJ) and for long periods (months) (Fleuchaus et al., 2018; Kallesøe & Vangkilde-Pedersen, 2019, Daniilidis et al., 2022). So far, most of ATES systems in operation worldwide store heat at temperature levels below 30°C. Although the use of high-temperature (HT-)ATES systems world-wide is still limited, it has been the topic of research for over 5 decades (Fleuchaus et al., 2018, Hamm et al., 2021, Buscheck and Allen, 1984). Frameworks have been developed for initial feasibility of HT-ATES, including theoretical, technical and economic potential (Wesselink et al, 2018). To boost development of HT-ATES in the Netherlands, compatible with the temperature levels of available sustainable sources of heat and required in district heating networks, a stepwise method has been developed towards the implementation of feasible demonstration projects.

The WINDOW research consortium has developed and applied this method in a converging selection process from 22 quick scans via 7 exploratory studies to 2 final designs of HT-ATES systems, ready for final investment decisions. The goal of this effort is: 1) to show-case the potential of HT-ATES in decarbonizing district heating networks, and 2) to identify key barriers and risks that emerge from site specific conditions. The ultimate goal is to demonstrate that HT-ATES can be successfully implemented for storage of (sustainable) heat in district heating projects and demonstrate their contribution to increased flexibility of heat delivery and the potential contribution to the energy transition. The novelty of this work is the overarching analysis of these exploratory studies that were all carried out with similar assumptions and approach.

2. OBJECTIVE

The main objective of the research consortium is to remove technical, legal and commercial barriers and to gain a better understanding of the effects for the responsible application of HT-ATES in the Netherlands. The results will contribute to cost reduction of collective systems at system level and optimal utilisation of renewable heat sources.

The objective of the first phase of the study was to conduct quick scans and exploratory studies in order to gain an early insight into the application conditions of HT-ATES and to select the most feasible locations to start with development of demonstration projects.

The comparison of the results of different locations provided insight into the key parameters of the feasibility of HT-ATES. The joint selection of the most feasible locations, together with all consortium partners, served another objective of the study: ‘learning by doing’.

3. MATERIALS AND METHODS

The joint approach for HT-ATES quick scans and exploratory studies was implemented by KWR, TNO, Deltares and IF Technology, with input from local stakeholder such as heat companies, provinces, municipalities and other stakeholders.

3.1 Locations in the Netherlands

A longlist of 22 locations was compiled, with locations all over the Netherlands. To select the most promising locations, a quick scan was performed, based 1) planning horizon 2) subsurface suitability, 3) legal constraints and 4) business case perspective. Subsequently, seven exploratory locations were selected, as listed in Table 1. In the selection process, the most feasible locations were chosen, but also aspects such as the variation of geographic locations, heating concepts and involved stakeholders were taken into account.

Table 1: Abbreviations for locations in the exploratory studies

Code	Locatie
HAL	Den Haag HAL
HHW	Heerhugowaard
HGN	Sittard/Het Groene Net
LWD	Leeuwarden
NES	Rotterdam Nesselande
TIL	Tilburg/N-Brabant
TUD	Delft University of Technology

For these seven locations exploratory studies were conducted in which a preliminary design of the HT-ATES system was drawn up. Again, a selection process took place, based on the outcomes of the exploratory studies. In the following paragraphs, the approach of the quick scans and the exploratory studies is described.

3.2 Base of design

In the quick scans, an (elaborated) base of design was not made. We made a rough estimate of the size of the heat storage, based on the general insight that HT-ATES storage volume amounts up to 15-25% of the total heat demand (Verhaegh, 2019). Also, we estimated the temperature difference between storage and heat supply and the need of a heat pump. In the quick scans these estimates were used to evaluate the business case (see section 3.6 Financial analysis).

In the exploratory studies, we made preliminary designs of the underground storage system and its integration in the district heating networks for all seven locations. Multiple configurations were developed if options were still open regarding the selection of storage formation, discharge rates, well design and temperatures, the integration of a heat pump and the type of heat exchangers.

HT-ATES supplies until the cut-off temperature is reached. In cases without heat pump, the cut-off temperature depends on the heating grid supply temperature and the warm well temperature depends on the heating grid return temperature. In cases with heat pumps, a temperature lift can be applied. The warm and hot well temperatures and the cut off temperature are estimated on the local heat network conditions, heat source and presence of a heat pump. The HT-ATES is separated from the heating network by means of a heat exchanger in all configurations to avoid contact between the groundwater and the water from the district heating network.

The mismatch was analysed between the current supply and demand for heating and the supply and return temperatures of the network for a period of one year. The temperature of HT-ATES decreases during the discharge season due to heat losses in the subsurface. As heating networks require a certain supply temperature (usually between 75 and 90°C), a heat pump or peak boiler was included for some locations.

3.3 Geological suitability

<u>Suitable formations of HT-ATES in the Netherlands</u>

The subsurface of the Netherlands provide ample opportunity for the storage of heat due to the widespread presence, in particular in the western part of the country, of sand layers with excellent reservoir properties. The occurrence of these sand layers is the result of the geological history and conditions. The subsurface down to 500 mbgl is composed of coastal marine and fluviatile sequences deposited by large deltaic systems during the Tertiary and Quaternary (Wong et al., 2007). These sedimentary formations between 200 to 500 mbgl, with alternating sand and shale deposits provide the perfect medium for heat storage in the subsurface. In particular, the formations that were deposited under shallow marine conditions, such as the Maassluis, Oosterhout, and Breda Formation, are favourable for HT-ATES as they consist of medium- to fine-grained sediments with hydraulic conductivities ranging from 1-20 m/d. These relatively low hydraulic conductivities can prevent large effects of ‘buoyancy flow’ caused by the injection of hot water in the subsurface. Figure 1 shows a cross section of the Netherlands, showing these formations in blue and green. The Peize- and Waalre and Kiezeloöliet Formations (yellow and orange in Figure 1) are fluvial formations, consisting of more coarse-grained sediments, and therefore more prone to buoyancy flow, however, they can still provide suitable storage for HT-ATES and were therefore considered in the quickscan study. Also the deeper (> 500m) Lower-Detfurth Sandstone Member was taken into account, as it could, besides it relatively low hydraulic conductivity, provide storage solutions in the eastern part of the Netherlands.

The hot water is injected into the permeable sand layers, while the overlying shale layers ensure containment of the injected water and effectively insulates the reservoir, thereby limiting heat dissipation towards overlying aquifers. Critical drinking water aquifers occur at much shallower depth and remain unaffected by the injected heat.

Geohydrological suitability in the quick scans

The criteria used for the quick scans are lithology, depth, thickness, horizonal hydraulic conductivity, the presence of a confining cap (clay) layer, faults, groundwater flow velocity, chloride concentration and groundwater protection zones (Table 2). With the latter two being legal criteria with respect to the subsurface. The explanation of these criteria is described in a separate paper (Dinkelman & Van Bergen, this issue). The available data from the REGIS II v2.2 hydrogeological database (www.dinoloket.nl, Hummelman et al., 2019) were used to evaluate the hydrogeological suitability at the 22 locations. Moreover, these criteria were also used to evaluate the geohydrological suitability all over the Netherlands, resulting in a map of the HT-ATES potential in the Netherlands.

Use of geohydrological data in exploratory studies

In the seven exploratory studies, the geohydrological design of the wells was drawn up for suitable aquifers, using data from REGIS II v2.2 and data from neighbouring drillings available in the subsurface database of the Netherlands 'DINOLoket' (www.dinoloket.nl). If more than one suitable aquifer existed at a location, multiple well designs were drawn up and compared.

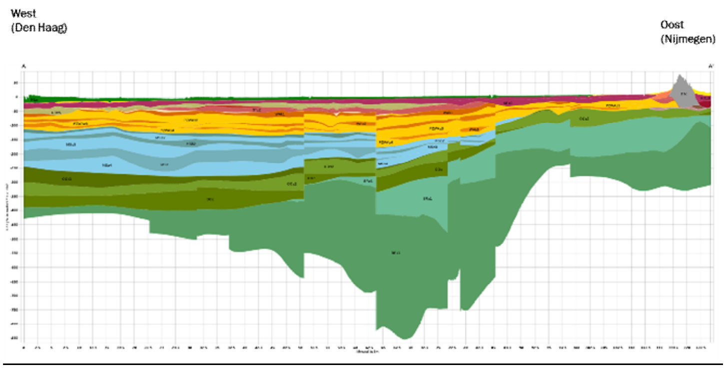

Figure 1: West-East cross section through the upper deposits of the Netherlands. The sand layers most prominently suited for HT-ATES are in the Maassluis (blue) and Oosterhout Formations (upper green) that are thickening towards the west. Source: www.dinoloket.nl.

Table 2: Subsurface criteria used for creating the national potential maps, including legal criteria.

Parameter	Barrier	Possible barrier	Favourable
Lithology	Silt, clay	Shells, glauconite	Sand
Depth		<50, >500 mbgl	50-500 mbgl
Thickness sand layer	< 10m	10-15 m	> 15 m
Horizontal hydraulic conductivity	< 5 m/d		≥ 5 m/d
Presence of confining cap layer (clay)		High risk of absence clay layer	Clay layer present
Faults		< 1 km	> 1 km
Groundwater flow velocity		> 20-30 m/y	< 20-30 m/y
Chloride concentration (legal)		< 1 g/l	> 1 g/l
Groundwater protection zones (legal)	Inside zone		Outside zone

3.4 Thermal recovery efficiency

During heat storage in the subsurface, energy losses occur from the thermal volume by conduction, dispersion and buoyancy flow. The magnitude of these losses is influenced by the size and temperature of the storage volume and the hydrogeological characteristics of the aquifer. Also, heat losses may occur due to ambient groundwater flow or interaction with neighbouring wells (Bloemendal & Hartog, 2018; Schout et al., 2014; Sheldon et al., 2021; Sommer et al., 2013).

The thermal recovery efficiency (η_{th}) is an important performance indicator for HT-ATES systems. It shows the amount of energy that is recovered after storage. For single wells, the well recovery efficiency is often calculated (Bloemendal & Hartog, 2018). For the entire HT-ATES system, having both a hot (e.g. 90°C) and a warm well (e.g. 40°C), the effect of energy losses from both wells has to be taken into account. The system recovery efficiency is used for this:

$$\eta_{system} = \frac{E_{recovered}}{E_{stored}} = \frac{V_{recovered} \cdot (T_{hot\_out} - T_{warm\_in}) \cdot c_w}{V_{stored} \cdot (T_{hot\_in} - T_{warm\_out}) \cdot c_w} \quad [1]$$

Where, V is the injection/extraction volume (m3), T the injected/extracted temperature of the hot/warm well (°C) and cw the volumetric heat capacity of water (J/m3/°C). When the same amount of volume is extracted as injected, and the energy losses from the hot and warm well are small (the difference between stored (T_in) and recovered (T_out) well temperature is small), the system recovery efficiency is close to 1, meaning a well performing system. The system recovery efficiency is thus influenced by the performance of the hot and warm wells, and the system specific cut-off temperature that determines how much of the stored volume is again recovered.

In the quick scans, no attention was given to the thermal recovery efficiency yet, except that the groundwater flow velocity was taken into account with the geohydrological suitability.

In the exploratory studies, the thermal recovery efficiency was calculated for each of the locations and for some locations for several design variations. To determine the performance of each unique HT-ATES system assessed in this study, numerical simulations were performed using the thermo-hydraulic SEAWAT model (Langevin, 2009). Equal model properties were used for each simulation. The simulations were adjusted for each system based on the determined local subsurface conditions (aquifer thickness, hydraulic conductivity, depth) and system specific operational conditions (storage volume, storage temperature, cut-off temperature), see Beernink et al. (2020) for a detailed description of these simulations.

3.5 Emission reduction

In the quick scans, no explicit attention to the emission reduction was taken into account, except that the source of the stored heat had to come from a sustainable source, e.g. biomass or geothermal heat..

In het exploratory studies, the CO_2-emission reduction of the heat supplied by the HT-ATES was estimated. We assumed base heat supplied by the primary heat source (e.g. biomass or geothermal heat). Secondly, additional heat is supplied by the HT-ATES. Currently, this additional heat is supplied by gas fired boilers. The CO_2-emission reduction is determined by comparing the CO_2-emission of the gas fired boilers with the CO_2-emission of the HT-ates, which consist of:

- CO_2-emissions of the stored heat (depending on heat source)
- CO_2-emissions of electricity used for:
  - transportation of heat stored
  - pump energy during charging and discharging of the HT-ATES
  - use of the heat pump (depending on case)

In this study, a CO_2- emission factor of 0,34 kg/kWh was used for electricity following NTA 8800 (NEN,2020).

3.6 Financial analysis

In the quick scans, the financial feasibility was estimated by a qualitative analysis. Input for the qualitative analyses were the temperature difference in stored heat temperature and heating grid supply temperature, whether a heat pump is required or not and the scale and the depth of the HT-ATES.

In the exploratory studies, we carried out financial analyses for the HT-ATES system in which the heat price was calculated to meet an internal rate of return (IRR) of 6% after 30 years of operation. For this, we estimated for the capital expenditures (CAPEX) and operational expenditures (OPEX) of the HT-ATES system, which are described below. This analysis is limited to the HT-ATES system and includes the cost of any new additional equipment required for the heat storage. Existing equipment/infrastructure is not taken into account. Moreover, we assume that reinvestment for heat pump, water treatment and nitrogen-installation is done after 15 years. Other reinvestments have been taken into account by the M&O costs. Furthermore, we assumed that the CO_2 savings represent a value of 24€ per ton of saved CO_2. We only calculated the CO_2 emissions for the configuration with the most optimal cost price at each location.

<u>CAPEX</u>

We estimated the capital expenditures of the HT-ATES system for each case. Data on actual costs have been used from the HEATSTORE project, for which a HT-ATES system is currently being realized. Costs are estimated for the following components:

- Exploratory drilling: a test drilling is required to get more detailed information on the subsurface needed for the detailed design but can also be used for monitoring purposes during exploration.
- Wells: this includes the drilling of wells and the costs of material and components required inside the well, like casings, screens, well housing and submersible pumps.
- Heat pump: The cost for high temperature heat pumps is estimated at 600 €/kW_{th}. Reinvestment for heat pump after 15 years.
- Surface installation & piping: this includes all required surface equipment for the HT-ATES system, like piping, valves, heat exchangers, water treatment and control system. The connecting pipework between the wells and the surface installation is also included.
- Design, consultancy and permit costs: estimated at 15% of the total capital expenditures.
- Unforeseen: estimated at 10% of the total investment costs.

<u>OPEX</u>

The yearly operational costs have been estimated for each case for the following parameters:

- Storing heat: heat is stored in the ATES in summer. The value used differs from case to case. The cost of the heat to store is often difficult to determine, because the heat price can be positive, but also negative due to subsidies renewable heat. In most cases, a base value of 0 €/GJ have been used. Both positive and negative prices have been used in a sensitivity analysis.
- Electricity consumption of all components: The price for electricity per kWh is given by the district heating company and differs from case to case.

- Maintenance and operation costs (M&O): the cleaning of the wells (every 5 years) costs approximately 10 k€ per year per well. The submersible pumps need to be replaced once every 5 year. The M&O cost are estimated at 2% of the investment cost for the heat and at 4% for all other components.
- Water treatment: water treatment is requited for HT-ATES to prevent precipitation. Based on HCl-treatment, the costs are estimated at 1 €/MWh of heat stored. Reinvestment for water treatment and nitrogen-installation after 15 years. Monitoring and inspections: estimated at 30 k€ per year.

3.7 Legal considerations

Legal considerations of HT-ATES in the Netherlands

In the Netherlands ATES systems up to 500 m depth are subjected to the Wateract for which the Provinces are the governing authorities (Schultz van Haegen, 2014)., Since 2013, the legal, regulatory and quality certification frameworks for the permission, design, realization and exploitation of low temperature (<25C) ATES systems up to 500 mbgs are well-developed) has been updated to facilitate easy and high quality adoption of such systems (Schultz van Haegen, 2014).

Within this streamlined and standardized regulations for ATES, there are 2 criteria that cannot be met by HT-ATES systems: 1) injection temperatures should remain below 25°C and 2) no net heat was can be added to the subsurface. In spite of Although legally HT-ATES systems up to 500 mbgs are covered by the same definition as ATES, tthe fact that these two standard criteria cannot be met for HT-ATES hinders its large-scale implementation. HT-ATES, law still allows application of HT-ATES is legally possible on the condition that a) the interest of the protection of the subsurface is not violated and b) the subsurface is effectively used for ATES.

Hence, HT-ATES is possible, but there is no streamlined permitting procedure. The practical experiences reported in WINDOW show that this rather broad criteriathis situation has led to uncertainties for both the applicant and as well as the permitting authority. This has resulted in long and complex permitting procedures with unknown outcomes, which has deterred other initiatives and formed a major barrier for HT-ATES development.

Criteria for legal aspects in the quick scans

As provinces are the governing authorities, their policy on issuing permits for HT-ATES varies. The first check is to see if a province allows/considers permit applications for HT-ATES. If it does, it also makes sense to directly identify possible other groundwater users in the area where the HT-ATES is projected. In their permitting procedure, provinces will evaluate how the HT-ATES affects existing interests. Hence, these interests are an indication on possible problems in the permitting procedure and could also be input for the design/location of the HT-ATES to limit interaction and smooth permitting procedure.

Development of an assessment framework for HT-ATES permitting

In the exploratory studies, the permitting authorities were involved, as an early start for the permitting process. The WINDOW consortium has brought together market parties and permitting authorities in order to streamline the permitting process of HT-ATES. This has resulted in a general assessment framework for the safe and streamlined permitting of HT-ATES systems. This framework builds on the existing ATES rules and guidelines. During the development and permitting procedures of the WINDOW pilots, this assessment framework will be tested in practice and after evaluation and improvement with the various stakeholders the pathways towards implementation will also be discussed.

4. RESULTS

4.1 Key results of the quick scans

Results of geological suitability in the quick scans

In the quick scans 22 locations were evaluated. The locations and their score are indicated in Figure 2. The evaluation of the geological suitability was a major part of the work. In addition of the 22 locations, the geological assessment was also performed for the Netherlands in total, resulting in qualitative potential maps for HT-ATES in the Netherlands (Figure 2). The suitability was mapped for eight geological formations, as reported by Dinkelman & Van Bergen (2022, this issue). A traffic light system was used to show potential barriers: no barriers (green), potential barriers (yellow) and one or more barriers (orange). For each formation, the eight subsurface criteria listed Table 2 were checked and ranked. If a location has one or more formations with no barriers, the final ranking is green.

The results show that the locations in the western part of the Netherlands are in general more favourable for HT-ATES, which is beneficial as this area also offers great potential for geothermal energy and it is as well the most densely populated area with high heat demand density and existing heat networks. This is largely, but not exclusively, due to the more favourable geological conditions in this part of the country. The subsurface risks that were identified as possible barriers (yellow) were mainly due to the thicknesses of aquifers, and the absence of a confining layers. Also lithology formed a barrier, for example in the Noord-Brabant province where the presence of shell fragments in a certain aquifer was identified as possible scaling risk. In the eastern part of the Netherlands, less suitable aquifers are present and the aquifers that were considered show relatively low hydraulic conductivity. When hydraulic conductivity is low, the possible flow rate in the aquifer is limited and therefore complicates the feasibility.

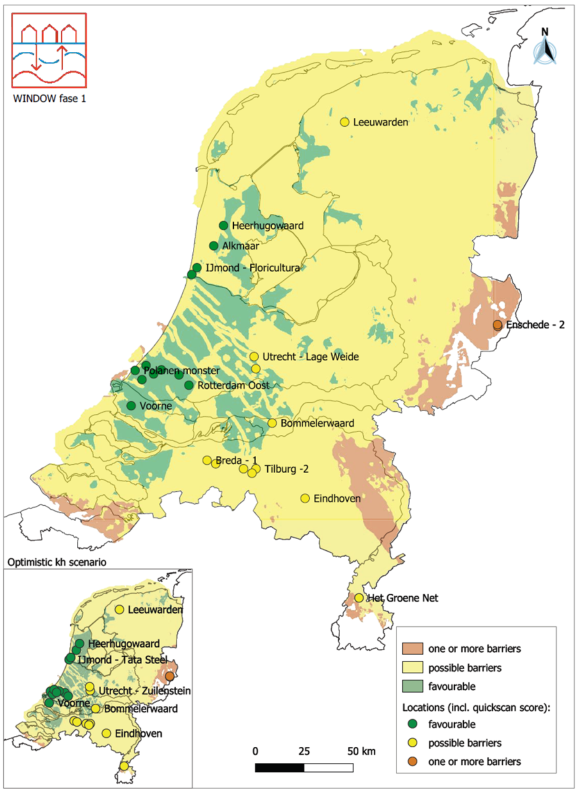

Figure 2: HT-ATES potential map of The Netherlands, including quick scan locations and their score based on the subsurface criteria analysis. From: Dinkelman et al. (2020)

Results of other aspects in de quick scans

Other location specific aspects of HT-ATES development, apart from the subsurface, were also assessed in the quick scans for the 22 locations, according to a similar traffic light system: stage of realisation, legal situation and the business case. These aspects were not extended to maps, covering all of the Netherlands.

Table 3 shows the outcomes of 7 of the 22 locations of the quick scan. These 7 locations were selected for the exploratory study and are presented as example results.

Table 3: Outcomes of the first phase of the quick scans for 7 of the 22 locations. Tested on the 4 main criteria: stage of realization, subsurface suitability, legal constraints and business case perspective. From: Zwamborn & Kleinlugtenbelt (2020).

		Realisation	Subsurface	Legal	Business case
HAL	Den Haag HAL	average	good	good	good
HHW	Heerhugowaard	good	good	good	good
HGN	Sittard/Het Groene Net	good	average	average	average
LWD	Leeuwarden	average	average	average	average
NES	Rotterdam Nesselande	good	good	good	good
TIL	Tilburg/N-Brabant	good	average	mediocre	good
TUD	Delft TU	good	good	good	good

= good
=average
= mediocre

One of the main barriers identified regarded legal constraints. For example, the suitable aquifers in the southern province Noord-Brabant are protected by law for drinking water extraction (location Tilburg). In the quick scans this was rated as a mediocre barrier, later on in the process, this appeared to be a showstopper. Other barriers regarding subsurface risks were related to the possible absence of confining clay layers (Leeuwarden), and the effect of high temperature injection on peat layers in the subsurface and the fact that the location was located near a faulted area (Sittard). The location in Heerhugowaard was rated as 'green' in the quick scans, however later on in the study a showstopper appeared for stakeholder commitment, after weighing the pros and cons resulting from the exploratory study.

The locations that scored low on business case, mainly needed a heat pump to overcome the temperature difference between high supply temperature and relatively low storage temperature. For more detailed information on the quick scans, see Zwamborn & Kleinlugtenbelt (2020) or the individual exploratory studies of the WINDOW project team (2020).

4.2 Key results of the exploratory studies

Conceptual design

Figure 3 shows the conceptual design for the exploratory study of Rotterdam Nesselande. In the summer, 74 TJ of heat of the biomass energy plant (BEP) is stored in the HT-ATES at a peak capacity of 5.6 MWth. In the winter, HT-ATES supplies approximately 37 TJ, which equals approximately 20% of the total heat demand of Nesselande. During heat supply, the hot well temperature drops from 86°C to 58°C. Instead of using a heat pump, heat from the high-temperature transmission grid is used to boost the temperature as soon as the temperature of the HT-ATES is below the required supply temperature (75°C).

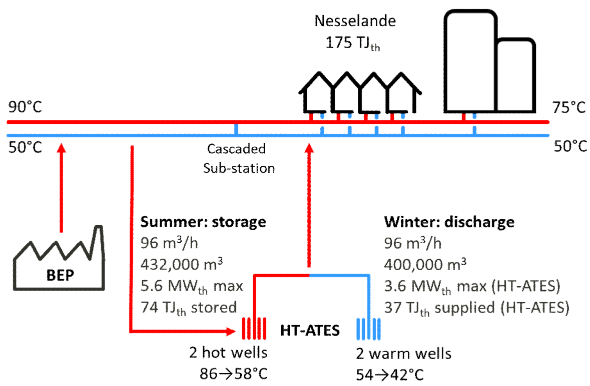

Figure 3: The conceptual design in the exploratory study of Rotterdam Nesselande, case without heat pump.

Figure 4 shows the conceptual design for the exploratory study of HAL. In the summer, 34 TJ of geothermal heat is stored in the HT-ATES at a peak capacity of 2.3 MWth. In the winter, HT-ATES and the heat pump (HP) supplies approximately 26 TJ, which equals 19% of the total heat demand of HAL. During heat supply, the hot well temperature drops from 76°C to 50°C. A heat pump is used to lift the HT-ATES supply temperature to 73°C, while cooling down the return temperature to 40°C.

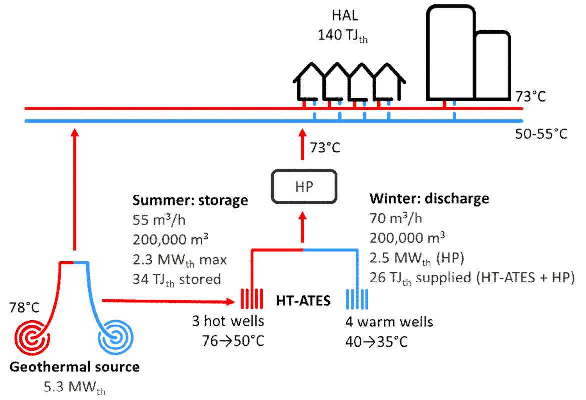

Figure 4: The conceptual design in the exploratory study of HAL, case with heat pump

<u>Summary of results of the exploratory studies</u>

In Table 4, the results of the exploratory studies are summarized. The main design parameters and the resulting calculated system efficiency, cost price and CO2 emission are listed. The CO2 emissions are calculated only for one configuration per location. In the following paragraph, a meta analyses based on these data is described. For more detailed information see the individual exploratory studies of the WINDOW project team (2020) and (Zwamborn & Kleinlugtenbelt, 2020).

4.3 Meta analysis of HT-ATES performance and cost price

The system recovery efficiency, which is the combined result of the energy losses in the hot and warm wells of each HT-ATES system, varies between 0.37 and 0.79 (Figure 5). In general, with larger ΔT between the hot and warm well temperature, high system recovery efficiency is observed. This is the case because for systems with small ΔT, a small drop in extraction temperature (from both the hot and warm well) has a relatively large effect, when compared to a system with a large ΔT. The range of system recovery efficiency that is observed for equal ΔT is a result of the hydrogeological and operational differences between each HT-ATES system (Beernink et al., 2020; Bloemendal & Hartog, 2018).

Table 4: Results of exploratory studies and calculated CO_2 emissions for the preferred conceptual design per location.

Code	Water volume [1000 m^3]	ΔT HT-ATES [°C]	HT-ATES Power [MW]	Heat pump Power [MW]	System efficiency year 10 [-]	Cost price [€/GJ]	CO2 emission heat [kg/GJ]	CO2 emission electricity [kg/GJ]	CO2 emission total [kg/GJ]
HAL	200	36	2.9	2.5	0.64	27.9	13.7	16.3	30.0
HAL	181	36	2.5	2.3	0.36	32.9			
HAL	154	44	3.9	6.8	0.72	37.0			
HAL	151	44	3.0	6.3	0.48	41.5			
HHW	380	58	10.2	6.0	0.74	14.7	0.9	17.7	18.6
HGN	243	43	5.1	4.4	0.43	24.7	2.7	18.4	21.1
HGN	243	43	5.1	4.4	0.30	30.3			
LWD	400	36	5.0	-	0.60	12.4	13.3	5.0	18.3
LWD	400	48	6.7	3.0	0.72	16.8			
LWD	400	58	8.1	8.4	0.78	17.9			
NES	432	32	3.6	-	0.50	8.8	3.3	5.0	8.3
NES	504	32	4.2	-	0.57	11.1			
NES	369	46	4.4	5.3	0.64	15.0			
NES	441	46	5.3	6.9	0.70	16.0			
TIL	554	58	11.4	5.7	0.70	-			
TUD	750	40	25	-	0.68	4.8			
TUD	750	40	25	-	0.67	6.7			
TUD	750	13	8.1	-	0.45	14.2			
TUD	750	13	8.1	-	0.40	17.7			

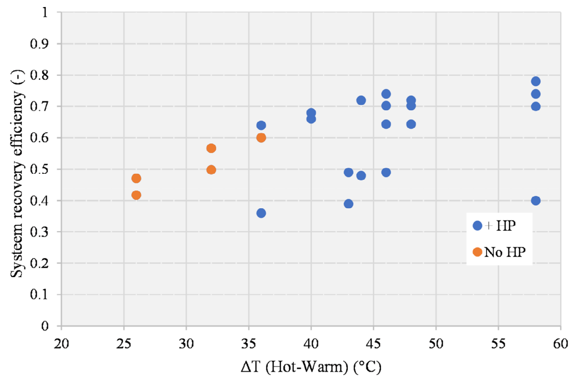

Figure 5: System recovery efficiency (year 10) for different ΔT of the varying HT-ATES systems. In blue configurations with heat pump, in orange configurations without heat pump.

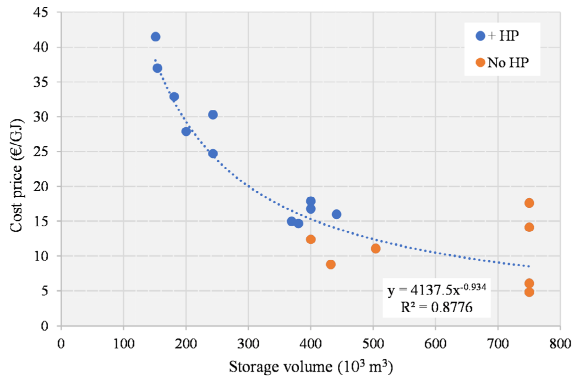

Figure 7: Cost price of heat for different storage volumes of the HTO. In blue configurations with heat pump, in orange configurations without heat pump.

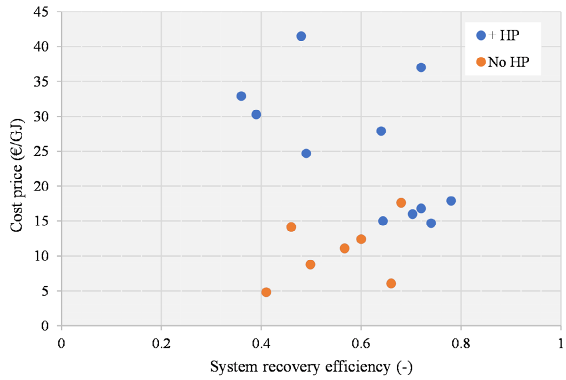

Figure 6: Cost price for different system recovery efficiency of the modelled HT-ATES systems. In blue configurations with heat pump, in orange configurations without heat pump.

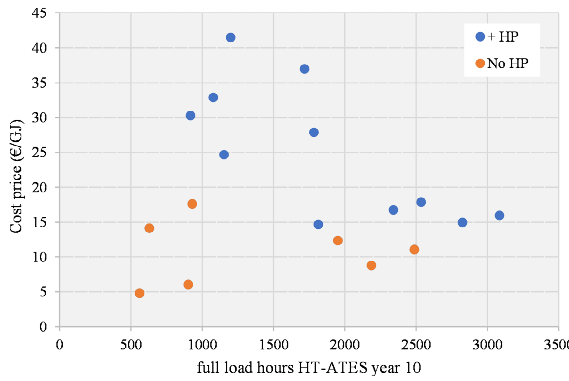

Figure 8: Cost price of heat for different full load hours of the HTO in year 10. In blue configurations without heat pump, in orange configurations with heat pump.

The cost price of heat from the HT-ATES is shown as a function of the system recovery efficiency in Figure 6. Systems with a low system recovery efficiency may have a relatively low cost price, compared to other systems that have a better performing storage system. A clear difference is observed here between the system without a heat pump and with a heat pump. Systems without a heat pump are cheaper, and, no correlation is observed with the system recovery efficiency. For systems with a heat pump, cost price decreases with increasing system recovery efficiency.

Figure 7 shows the cost price for different storage volumes of the HTO. A clear trend appears in this figure: the larger the volume the lower the cost price, and nearly 90% of the cost price variation of heat delivered is determined by the stored water volume. The cost price of heat from a HT-ATES system can be competitive and lower than 15 €/GJ, if the stored water volume exceeds 300,000 m3; big is beautiful in this respect.

The six locations with a heat price more than 20 €/GJ are at HAL and HGN with water volumes of 200,000 m3 or less. The presence of a heat pump in the integrated design has a large share in the cost price.

Figure 8 shows the heat price as a function of the full load hours in year 10. The cases with heat pump clearly show a decreasing trend in the number of full load hours. The data indicates that with a heat pump, at least 2,000 full load hours are needed to achieve reasonable heat prices. The configurations without a heat pump show no specific trend. It is noted that the four orange dots with less than 1,000 full load hours have high peak capacity and the largest water volumes.

The CO_2 emission associated to the heat delivered from the HT-ATES is 50-85% lower than the emission of a conventional gas boiler (Figure 9). The theoretical minimum CO_2 emission equals the emission of the stored heat, indicated with the yellow line. The CO_2 emission due to electricity consumption for heat transportation, pump energy during charging and discharging adds up. For the configurations with a heat pump, the electricity use of the heat pump adds up as well, resulting in higher CO_2 emissions. In this study, the CO_2 emission of the electricity mix is based on a conservative emission factor of 0.34 kg CO_2/kWh(e) following Dutch guideline NTA 8800 (NEN, 2020). The CO_2 emission values will further improve as the Dutch electricity mix becomes more sustainable.

The target value for 2030 is 18.9 kg CO_2/GJ of delivered heat. Heat stored and delivered with a HT-ATES system is able to meet this target, especially when no heat pump is used. Configurations with a heat pump meet this target with a more sustainable electricity mix in future.

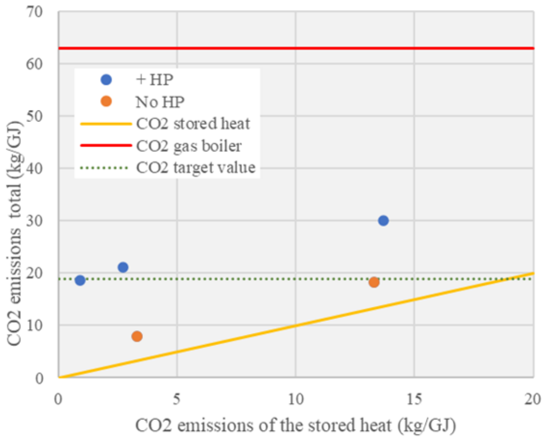

Figure 9: CO2 emissions in kg/GJ delivered heat in reference year 30, plotted against the CO2 emission of the stored heat in kg/GJ. In blue configurations with heat pump, in orange configurations without heat pump.

5. DISCUSSION

<u>Overall discussion</u>

When drawing up the project plan for this study, the perspective was that many locations would be discarded and that we would be happy if there was sufficient commitment for further development at two locations. However, the researchers were pleased with a strong commitment from the stakeholders of three locations: Rotterdam Nesselande, Leeuwarden and TU Delft.

The criteria used and the considerations made in comparing and selecting the locations provide insight into how the potential of underground heat storage is assessed within the WINDOW project. This will serve as an example for the assessment of the possibilities for HT-ATES at other locations.

Note that this analysis only deals with exploratory studies and not with realized projects.

<u>Risks associated with HT-ATES</u>

Key risks related to HT-ATES projects have been listed and evaluated on the basis of legacy projects (e.g. TNO, 2016; TNO & IF Technology, 2016, 2019) and expert surveys (Fleuchaus et al. 2020). The classification and description of the risks are based on TNO & IF Technology (2019). A distinction is made between generic risks, that are associated with each HT-ATES project, and location specific risks for individual projects. Elementary risks have been taken into account in the evaluation implicitly because such risks would affect feasibility directly.

However, it is not possible to assess all risks on a detailed level at an early stage of feasibility assessment. As detailed conditions could make a HT-ATES not feasible, it is key to be aware of all possible risks and address them in early stage. Which could mean that for one project e.g. legal feasibility could be a key show stopper, while it is not at another location. Such risks have been evaluated per location and the individual outcomes were qualitatively assessed. Mitigation measures have been identified to tackle key risks.

The following main risks categories are used in literature (Fleuchaus et al. 2020), and some example considerations from the benchmark study are given

- Financial risks.
  These include volume and price risks, high contingency costs, efficiency and quality of the produced heat, connection and fit to the heat network. This risk category is strongly related to market and financing conditions, which may be difficult to change. Also expected costs and revenues influence this risk , which a strongly linked to the design and integration of the system.
- Legal/political risks.
  These include the environmental (conflicts of) interests in the subsurface in the proximity of the HT-ATES, the (uncertainty about) effects that occur in the subsurface due to the application of HT-ATES, the inclusion of strict regulations in the permit by the governing authority (which can entail uncertainty and/or high (monitoring) costs for the user of the system), the expected and realized energy efficiency and support in the direct surroundings and of the users. Hence, at an early stage we not only assessed if HT-ATES would allowed by local Authority, we also checked if there would be other groundwater users, that would complicate the permit procedure.
  Taxation and subsidies could also play a role in this risk category.
- Technical and geohydrological risks.
  These include the risk of encountering unfavorable properties of the reservoir and overlying formations due to the geological uncertainty, the operational performance and component integrity of pumps and well materials in particular, and the well integrity
- Environmental and safety risks.
  These include physical/chemical properties of the groundwater, microbiology, ground movement/mechanics, effect of water treatment on the water quality, heat loss to shallower formations, leakage of drilling fluids or radioactive

fluids associated with logging, leakage of injected water to shallower formations.

- Organizational risks.
  These include the lack of stakeholder commitment and the incorporation of the HT-ATEs into the energy system/heat network, as well as social perception and grid connection.

In the exploratory studies, the risks have been evaluated per location. Those risks that were standing out for particular locations were described and evaluated in more detail. Mitigation measures have been identified to reduce these particular risks. Such risks evaluations should form the basis for the dialogue with designers, customers, authorities and stakeholders, to set the goals for resolving the risks hampering HT-ATES feasibility, and to set-up a robust strategy for the operational incorporation of the HT-ATES.

Fleuchaus et al. (2020) point out that technical risks are expected to be less critical than legal, social and organizational risks. The selection process in WINDOW proved indeed that several locations appeared to be unfeasible or less feasible due to these non-technical aspects.

Many risks are influenced by local boundary conditions, therefore the development of project-specific risk management strategies is highly recommended. To decrease uncertainty about these types of risks, sharing data and experience is important and will be crucial for the upscaling of HT-ATES in the Netherlands.

6. CONCLUSIONS

In this study we successfully developed a method to assess and compare different HT-ATES project on their feasibility. Key assessment criteria are: business case, legal, risks, commitment and planning.

The benchmark of the potential HT-ATES sites showed that nearly 90% of the cost price variation of heat delivered is determined by the stored water volume. This is caused by the fact that A) many running hours of the system create cost-effective use of installed infrastructure and B) large storage volumes suffer from fewer relative losses. Other parameters that affect the business case include the temperature difference between the hot and warm well, the related winter return temperature of the district heating grid, and the presence of a heat pump in the integrated design.

We show that the cost price of heat from a HT-ATES system is competitive and lower than €15-/GJ, when the seasonal stored water volume exceeds 300,000 m^3; big is beautiful in this respect. The CO_2 emission reduction of HT-ATES heat supply ranges from 50% to 85% compared to gas boilers at the current electricity mix in the Netherlands.

The approach of ‘learning by doing’ proved to be helpful in this study. The involvement of the local/commercial participants was high and the joint input of boundary conditions, knowledge and experience has contributed to the development of underground heat storage in the Netherlands.

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