

High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable

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1. Introduction

The concept of aquifer thermal energy storage (ATES) has evolved from theory to the point where system feasibility has been demonstrated technically and commercially, in particular for low-temperature applications. The most common application of a low-temperature storage system is space heating and cooling. The registered number of ATES systems in The Netherlands has grown from 5 in 1990 to 214 in 2000 and more than 1300 in 2010. Virtually all these ATES systems store low-temperature heat and cold in the range of 5 to 30 °C.

In contrast, high-temperature ATES (HT-ATES) applications have received less attention. HT-ATES applications can be of significant value, especially in connection with energy sources which are not controlled by immediate energy demand such as waste residual heat (e.g. from power plants or industrial processes) and renewables like geothermal and solar heat. By temporarily storing the energy excess, a better and more sustainable interplay between different energy sources can be obtained.

Table 1. Some characteristics for different types of ATES systems

temperature level	typical recovery efficiency*	heating	examples
< 30 °C (ATES)	70 - 90%	heat pump	> 1.300 systems in the Netherlands
30 - 60 °C (MT-ATES)	60 - 80%	direct / HT-heat pump	2 MW Haarlem, Heuvelgalerie Eindhoven, Dolfinarium Harderwijk
> 60 °C (HT-ATES)	40 - 70 %	direct	Utrecht University, De Bruggen Zwammerdam (near Gouda)

* ratio of the recovered amount of energy and the stored amount of energy, when equal amounts of water are injected and extracted. The amount of energy is calculated with respect to the ambient temperature.

The main advantage of HT-ATES compared to low-temperature ATES (< 30 °C) is that the heat that is retrieved can be used directly for heating purposes and is suitable for more applications. Low-temperature heat can only be used in combination with advanced low temperature heating systems or must be upgraded by means of heat pumps. The electricity consumption of heat pumps is much larger than for the rest of the low-temperature ATES system. HT-ATES systems do not need a heat pump (or to a lesser extent) and can therefore significantly improve the energy savings. Another important advantage is that large temperature differences between the extracted and infiltrated water can be achieved, so much more energy is supplied per cubic meter of water that is pumped. This means that the flow rate required for a specified heat demand is significantly lower than for low-temperature ATES. These advantages, combined with rising energy prices and an increasing focus on reduction of CO₂-emissions, have resulted in renewed interest in HT-ATES.

Yet, despite the significant advantages, HT-ATES is hardly used in practice. In The Netherlands more than 99% of the ATES systems store low temperature heat and cold. Only two projects with storage temperatures $> 80\text{ }^{\circ}\text{C}$ have been realized in The Netherlands and both have been closed. There are a few active ATES projects with storage temperatures in the range of $30\text{--}50\text{ }^{\circ}\text{C}$. To our knowledge only one HT-ATES system exists worldwide, that is still active: the Reichstag Building in Berlin, where heat of $70\text{ }^{\circ}\text{C}$ is stored (Sanner, 1999, Kabus and Seibt, 2000, Sanner et al., 2005, Kranz and Bartels, 2010). The main explanation for the limited number of projects is that HT-ATES projects is more complicated than low temperature ATES. In the 80s a lot of technical problems have occurred in experimental and pilot plants (Sanner, 1999). Issues that are important for the feasibility of HT-ATES are the risks of precipitation of minerals, corrosion of components in the groundwater system and low recovery efficiencies. The technical problems faced in cold storage and low temperature heat storage are much smaller than those met in high temperature heat storage (Snijders, 2000).

In the period 1985-1995 much research was done to solve the technical problems. This research was partly undertaken within national research programs and partly within the framework of the IEA-ECES research program. The research has demonstrated that the technical problems encountered can be solved and nowadays proven solutions are available: water treatment methods to prevent precipitation of minerals (Sanner, 1999; Drijver, 2011), proper material selection to prevent corrosion and the use of aquifers with a low permeability to reduce heat losses due to buoyancy flow. However, these solutions also have disadvantages.

Other points of interest for HT-ATES are the increased impact on the groundwater composition and legal aspects. The impact on the groundwater composition is relatively large due to the large changes in temperature. The most relevant issues are mobilization of organic carbon (Brons et al., 1991; Brons, 1992; Bonte et al., 2011), potential scaling (Griffioen and Appelo, 1993; Sanner, 1999) and upconing of deeper groundwater caused by buoyancy flow.

With respect to the legal aspects in the Netherlands, the main issues are:

- storage of temperatures $> 25\text{ }^{\circ}\text{C}$ are not allowed;
- an energy balance is required and is not feasible for HT-ATES.

This means that HT-ATES can only be permitted if an exception is made. For that reason, most HT-ATES systems are pilot-projects.

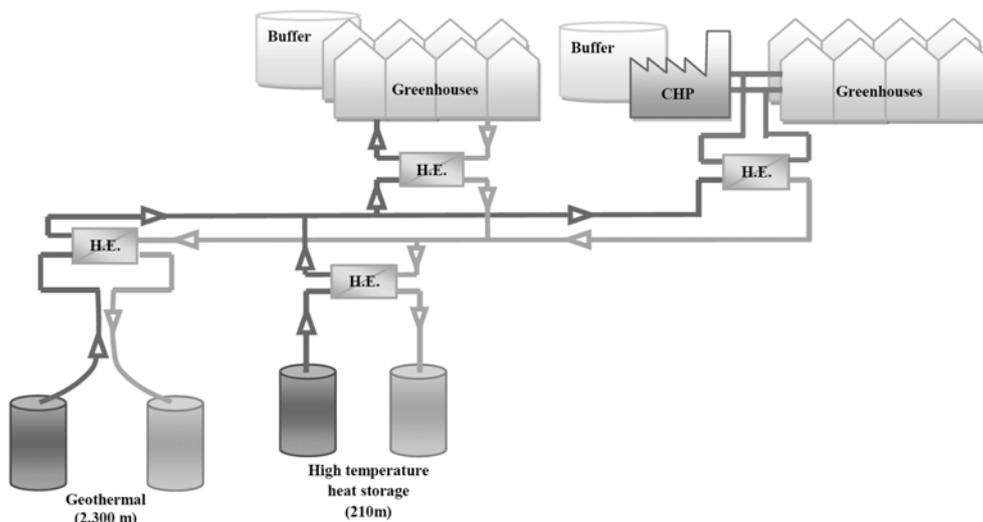


Figure 1. Global sketch of the multi-energy concept.

2. Materials and method

2.1 Integrated energy concepts

In this paper we focus on the recovery efficiency and a case study of a multi-energy concept project currently in development in the community of Vierpolders in the Netherlands (MEC-V, 2009). This study includes 50 hectares of greenhouses and 500 houses which will be heated by a combination of geothermal heat and HT-ATES. A deep geothermal doublet with a depth of 2,400 m will provide 22 MW at a temperature of approximately 85 °C. The HT-ATES is applied to balance the production from the geothermal plant and heat demands from the greenhouses and houses on a seasonal scale.

When the heat demand is lower than the geothermal production, the excess heat will be stored in the HT-ATES. When the heat demand is higher than the geothermal production, extra heat can be produced from the HT-ATES. The HT-ATES consists of three doublets, each 150 m³/h with a depth of 215 m. The maximum thermal storage capacity is 24 MW.

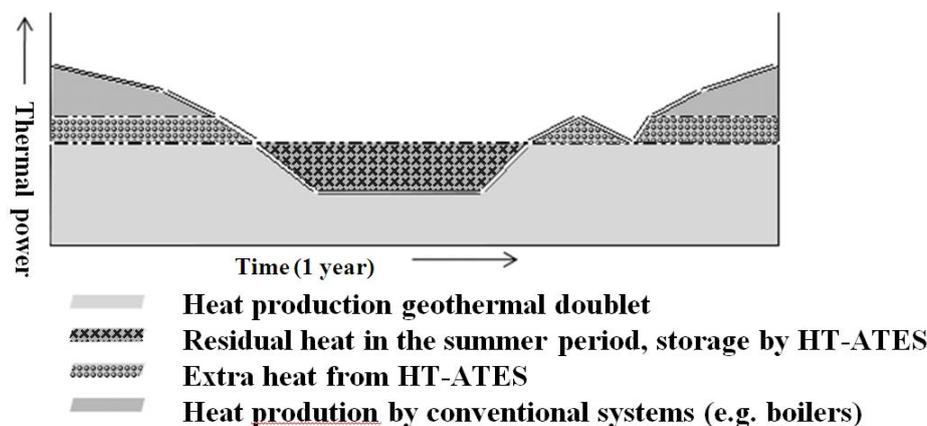


Figure 2. Relation between the available thermal power, required thermal power, heat storage and heat recovery.

2.2 Heat losses/recovery efficiency

One of the most important aspects controlling the feasibility of HT-ATES is the recovery efficiency. The recovery efficiency is often defined as the ratio between the recovered amount of energy and the stored amount of energy, with respect to the ambient temperature, when equal amounts of water are injected and produced. The recovery efficiency of an ATES system is governed by the energy losses that occur as a result of a number of processes.

Doughty et al. (1982) give an overview of the factors that control the recovery efficiency and the production temperatures for low-temperature ATES. The impact of density driven flow (usually insignificant for low-temperature ATES) and regional groundwater flow (usually insignificant in the aquifers where HT-ATES is applied) are neglected. Heat conduction results in heat losses in the vertical direction (to the confining layers) and in the horizontal direction (within the aquifer itself). Dispersion leads to heat losses because of mixing at the thermal front. Hydrogeological heterogeneity influences the distribution of heat in the aquifer, but the influence on the recovery efficiency is small in most cases (Buscheck et al., 1983; Ferguson, 2007; Caljé, 2010). However, if the heterogeneity is strong (Sauty et al., 1978, 1982) or the warm and cold wells are too close to each other (Sommer, in preparation), the impact of heterogeneity can be important.

Buoyancy flow

The most important process causing heat losses in HT-ATES projects is density driven flow (also called buoyancy flow of free convection). Buoyancy flow is caused by the difference in density between the injected water and the ambient groundwater. The hot water that is stored

has a lower density and flows upward in the aquifer. Buoyancy flow causes the initially vertical thermal front (transition zone between the hot water and the surrounding cooler groundwater) to tilt. In the top part of the aquifer hot water flows away from the well and in the lower part of the aquifer colder water flows towards the well screen. The rate of tilting of the thermal front is given by the characteristic tilting time (Hellström and Tsang, 1988a), which can be calculated as follows:

$$t_0 = \frac{H}{\sqrt{k_a^h \cdot k_a^v}} \cdot \frac{C_a}{C_w} \cdot \frac{\pi^2(\mu_0 + \mu_1)}{32G(\rho_0 - \rho_1)g}$$

Where H is the aquifer thickness, k_a^h and k_a^v are the horizontal and vertical permeability [m^2], C_a and C_w are the volumetric heat capacities of the (water saturated) aquifer and of water [$J/(m^3 \cdot ^\circ C)$], μ_0 and μ_1 are the dynamic viscosities of the ambient and the injected water [$kg/(m \cdot s)$], ρ_0 and ρ_1 are the densities [kg/m^3] and G is Catalan's constant (0.916). The time constant t_0 was derived by Hellström et al. (1979) for the plane case, but the magnitude does not change appreciably for the radial case. If the thermal front is diffuse rather than sharp, the tilting rate is slightly lowered. Furthermore, as the thermal front tilts, the flow resistance in the hot part of the aquifer is reduced because of the lower viscosity of hot water. Forced convection, then, gives an increase of the tilting rate during injection periods and a decrease during production periods for hot water storage (Doughty et al., 1982). Because the angle of tilt is larger during production than during injection, this tends to decrease the impact on the recovery efficiency.

According to Doughty et al. (1982) the buoyancy tilting of an initially vertical front during a time t_0 is about 60° . If the time of the cycle is smaller than t_0 , then the tilting is expected to be moderate. The most important factors are the temperature levels, which determine μ and ρ , and the permeability. This means that thermal losses due to tilting can be minimized by a reduction of the temperature difference (by choosing a lower the storage temperature or a deeper aquifer with a higher ambient temperature) and/or by selecting a low permeability aquifer.

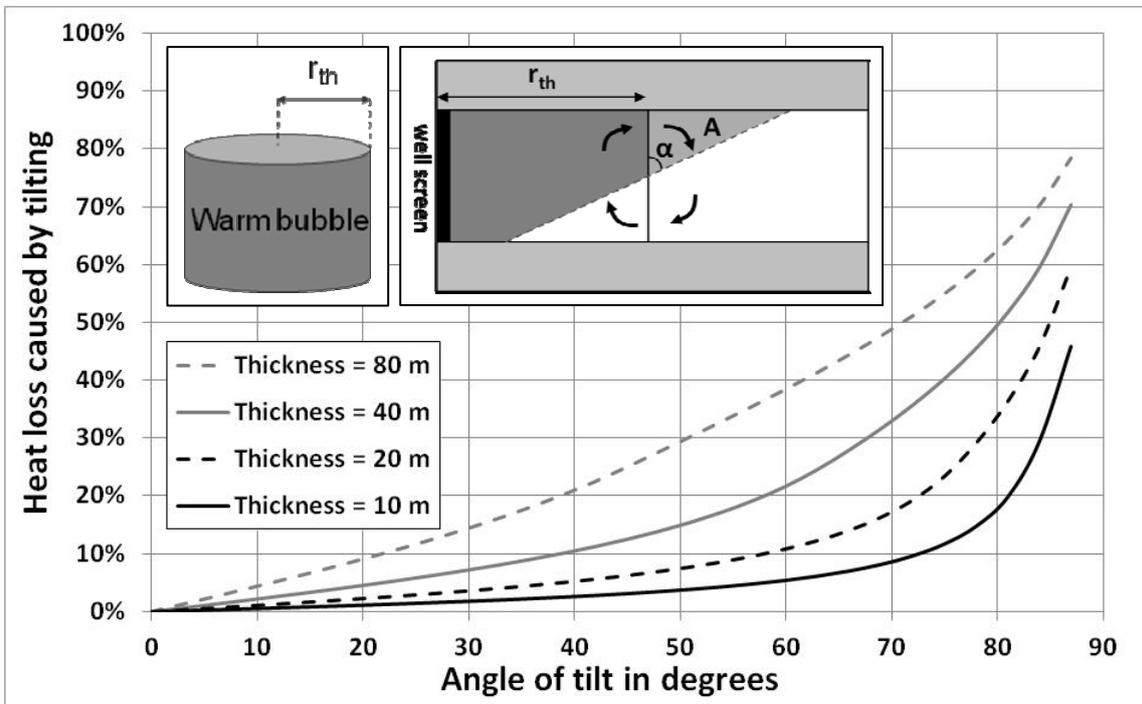


Figure 3. Heat losses caused by tilting for different values of the aquifer thickness based on geometry. The assumed thermal radius (r_{th}) of the warm bubble is 40 m.

The characteristic tilting time is also linearly dependent on the aquifer thickness, which suggests the selection of thick aquifers. However, the impact of the same tilting angle increases as the thickness increases. This is the case because the thermal radius of an ATEs system is more or

less fixed: on the one hand by the design standards for wells that limit the flow rate of the well and on the other hand by the wish to maximize the energy savings by using the HT-ATES. A realistic range for the thermal radius is 20-60 m. When a thermal radius of 40 m is assumed, a tilting angle of 60 degrees represents a certain percentage heat loss that depends on the aquifer thickness. Assuming a straight sharp thermal front and an equal flow distribution over the length of the (fully penetrating) well screen, these heat losses can be easily calculated based on geometry. Figure 3 shows the calculated percentages of heat loss caused by buoyancy flow for different values of the aquifer thickness. It has to be kept in mind that the calculations are based on a number of simplifying assumptions, which result in an overestimation of the heat losses by buoyancy flow. It concerns the assumptions of the first cycle (an initially cold aquifer), a sharp thermal front (higher tilting rate) and disregarding the partial reversal of the rotation during production. Therefore figure 3 should be considered a worst-case estimate. On the other hand, the heat losses caused by other processes are not included and have to be added to get the total heat losses.

The calculations show that the percentage heat loss is smallest for small values of the aquifer thickness. On the other hand, the characteristic tilting time is also smaller for thin aquifers. If a fixed volume has to be stored, choosing a relatively thin aquifer is advantageous from the recovery efficiency point of view. However, the disadvantage of a thin aquifer is that the flow rate per well will be relatively small which can increase investment costs.

System parameters

In addition to the hydrogeological parameters a number of system parameters are relevant for the recovery efficiency. It concerns the storage volume, the shape of the thermal volume (height versus thermal radius of the hot bubble), the cycle number (heat that is left behind increases the ambient groundwater temperature), duration of a cycle (time for heat losses to occur) and (if applicable) the cut-off temperature. Another relevant aspect is the presence of other wells and the distance between the wells.

For the Vierpolders project an inventory of the hydrogeology was made and the two most suitable aquifers were selected. For both aquifers model calculations were performed for two scenarios. For the calculations the computer programme HstWin-2D was used, a code specially developed for heat and solute transport in porous media. The code takes into account the dependency of the fluid properties such as viscosity and density on temperature and concentration changes (Kipp, 1987). A 2-D radial configuration was used to model the expected symmetrical effects around the storage/recovery well.

3. Results and discussion

3.1 Hydrogeology

Table 2 shows the results for the hydrogeology. In the shallow part (0-500 mbgl) the Maassluis Formation, mainly consisting of relatively fine sands, is considered the most suitable formation and in the deep part (> 500 m bgl) this is the Brussel Sand. The estimated permeability values are 8 Darcy for the Maassluis formation and 0.5-1.0 Darcy for the Brussel Sand. The ambient groundwater temperature in both formations is 14 and 33 °C respectively. In both formations the regional groundwater flow is negligible. In the Maassluis Formation the expected well capacity is 150 m³/hour. For the Brussel Sand this is 100 m³/hour.

Table 2. Expected geology at the Vierpolders site

depth [mbgl]	Formation	Lithology
0 - 70	Quaternary deposits	fine to coarse sand with clay lenses
70 - 215	Maassluis Formation	fine to coarse sand with some clay lenses
215 - 335	Oosterhout Formation	sand and sandy clay with shells
335 - 350	Breda Formation	alternation of sand and clay
350 - 460	Rupel Clay	tight clay
460 - 615	Vessem	fine to coarse sand with some clay layers
615 - 650	Asse	clay
650 - 760	Brussel Sand	fine sand with bands of sandstone and limestone
760 - 1.085	Ieper	silty clay with sandy lenses
1.085 - 1.095	Basal Sand of Dongen	fine humic sand
1.095 - 1.160	Landen Clay	clay

3.2 Model calculations

Model calculations were performed for both the deep and the shallow aquifer for two system sizes:

- Large system
 - 4 doublets of 16.4 MW in the Brussel Sand (storage of 75 °C).
 - 3 doublets of 18.3 MW in the Maassluis Formation (75 °C).
- Small system:
 - 1 doublet of 4.1 MW in the Brussel Sand (75 °C).
 - 1 doublet of 6.1 MW in the Maassluis Formation (75 °C).

For the large system an extra scenario was investigated with a geothermal doublet at increased depth (3,000 m) and the storage temperature increases to 93 °C. Figure 4 shows the well configurations for the large (a) and the small (b) system. While the cold wells have a higher injection temperature (40 °C) than the original groundwater temperature, they can be used to separate the warm wells from the cold original groundwater and thereby reduce the heat losses. For the doublet system (configuration b) this effect is expected to be minimal. The model input is shown in table 3.

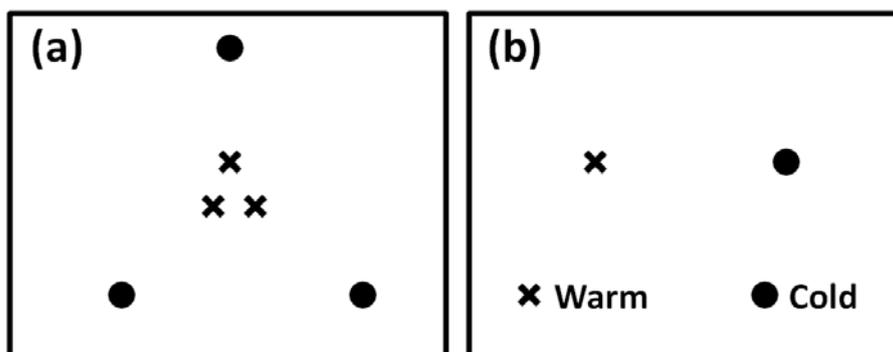


Figure 4. Example well configurations for the large (a) and the small (b) system.

Table 3. Model input

parameter	units	small	large	scenario 93°C
Injection temperature hot well	[°C]	75	75	93
Injection temperature "cold" well	[°C]	40	40	40
Cutoff temperature	[°C]	60	60	60
Ambient temperature Maassluis Formation	[°C]	14	14	14
Ambient temperature Brussel Sand	[°C]	33	33	33
Injection volume = extraction vol.	[m ³]	303.500/ 405.000*	1.214.000	804.000
Energy stored	[MWh _t]	12.500/ 16.650	50.000	50.000
Flow rate	[m ³ /h]	100/150	400/450	300
Distance between hot and cold wells	[m]	80	160	160
Distance between mutual hot wells	[m]	-	30	30

* deep/shallow

The stored heat will spread into the aquifer due to conduction, dispersion and free convection. This affects the storage efficiency (for this case defined as the ratio between (a) the amount of energy that can be produced before the cutoff temperature is reached and (b) the amount of energy that was stored). The efficiency increase of the HTES during the first five operational years is illustrated in figure 5 and table 4. Over the years the efficiency will increase from 33% in the first year of operation to 60% in the fifth. The increase in recovery efficiency and extraction temperature in successive cycles is a common phenomenon in (HT-) ATEs systems and can be attributed to the heat losses from previous cycles that result in a higher ambient groundwater temperature at the start of the next cycle. This results in a reduction of the thermal gradient, which decreases the heat losses by heat conduction and dispersive mixing. The heat losses are in fact not lost, but have a beneficial effect in later cycles.

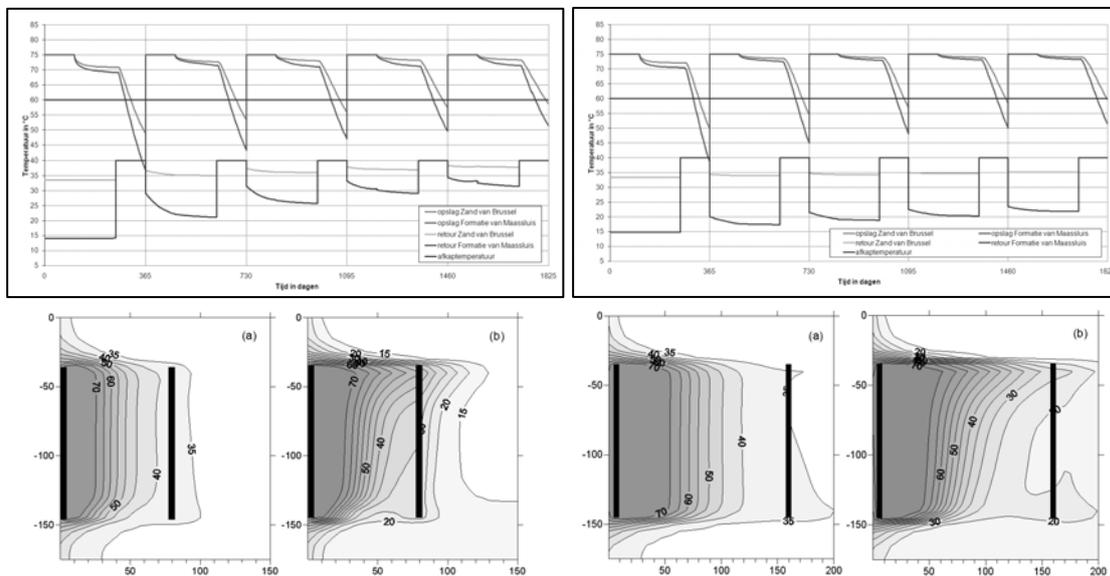


Figure 5. Calculated temperatures in the wells (top) and vertical cross sections with the calculated groundwater temperatures after 5 years of heat storage in the Brussel Sands (a) and the Maassluis Formation (b). To the left the results for the small system and on the right side the results for the large system.

Table 4. Calculated recovery efficiency for different scenarios

Formation	small system	large system	scenario 93°C
Maassluis	22 - 40%*	32 - 48%	41 - 59%
Brussel Sand	38 - 68%	49 - 75%	61 - 80%

* recovery efficiency in the first and the fifth year

Table 4 shows the calculated recovery efficiencies. The Brussel Sand has a low permeability, a relatively high ambient temperature and therefore a high storage efficiency. The disadvantage of the Brussel Sand is the lack of accurate data on the permeability and the groundwater composition. Because of the higher permeability, buoyancy flow occurs when storage is applied in the Maassluis Formation. This can be seen in the cross sections in figure 5. The recovery efficiency is therefore lower than in the Brussel Sand. Although the recovery efficiency will be lower, the Maassluis Formation has the advantage of the shallow depth (much lower price per well). Furthermore, there is less uncertainty in the permeability. The Maassluis Formation was therefore selected as most suitable aquifer.

Optimization options

Further optimization of the recovery efficiency can be investigated by modeling different well distances. If the wells are too far apart, the reduction of the temperature gradient will be negligible. If the wells are too close to each other, part of the injected hot water will be produced in the cold well. The optimum well distance will be dependent on the cut-off temperature (Kowalczyk and Havinga, 1991). Another option is to apply partial injection and or extraction, for instance extraction from the top part of the well screen (Buscheck et al., 1983) or by lowering the injection temperature in the cold well.

Energy Savings

By applying this multiple-energy concept, savings on fossil fuels are 83% compared to heat delivery based on a gas fired boiler. The yearly reduction of CO₂ emission adds up to 31.000 tons.

Economical analysis

An economical analysis was made for the different scenarios. Table 5 shows the results in terms of the cost price per GJ of extracted thermal energy from the large systems. The energy prices were based on a depreciation period of 20 year and 6% interest on the investments.

Table 5. Cost price per GJ of thermal energy for the large system combined with deep geothermal energy.

	combination with geothermal doublet at 2,400 m depth	combination with geothermal doublet at 3,000 m depth
Maassluis Formation	€ 3.50	€ 1.90
Brussel Sand	€ 5.70	€ 4.10

In recent years the commodity of natural gas ranged between € 6.30 and € 12.60 per GJ. This means that all scenarios are interesting from an economical point of view. The Maassluis Formation has a lower price per GJ than the Brussel Sand and is therefore preferred. Furthermore the combination the price per GJ for the HT-ATES can be significantly reduced when it can be combined with a geothermal doublet at 3,000 m instead of 2,400 m.

4. Conclusions

4.1 Conclusions

HT-ATES has large potential for the storage of (waste) residual heat and use with a high energetic efficiency. However, the technique has hardly been used so far, partly because of some specific problems that have to be tackled and partly because of too low energy prices in the past. The main issues that require attention for HT-ATES projects are the recovery efficiency, impact on groundwater composition and scaling (water treatment). Here we focused on the recovery efficiency and a case study in the community of Vierpolders, where an excess heat from a geothermal doublet should be stored using HT-ATES.

The recovery efficiency for HT-ATES is mainly controlled by buoyancy flow. While buoyancy flow can be reduced by choosing aquifers with a low permeability, fine grained aquifers are

preferred. Deep aquifers have the advantage of higher ambient temperatures due to the geothermal gradient, but the investment costs for the wells will be higher. At the location two promising aquifers were selected: a shallow aquifer (Maassluis Formation) and a deep aquifer (Brussel Sand). The recovery efficiency was best for the Brussel Sand due to the lower permeability and the higher ambient temperature.

The calculated cost price per GJ of heat produced for the large systems are significantly lower than the commodity of natural gas, which makes the project interesting from an economical point of view. The Maassluis Formation has the lowest price per GJ of heat produced. A combination with a geothermal doublet at increased depth (3,000 m instead of 2,400 m; producing heat with a higher temperature) reduces the price per GJ of heat produced from the HT-ATES. The feasibility of a deeper geothermal doublet is therefore worth investigating.

The multi-energy concept includes a HT-ATES which stores the excess heat produced by a geothermal heat plant and delivers extra heat on demand for 50 hectares of greenhouses and 500 houses. This will reduce the use of fossil fuels with 83%. This is equivalent to an annual reduction of CO₂ emissions of 31,000 tonnes. The concept is not only suitable for a combination with deep geothermal energy, but also with other heat sources like waste residual heat (e.g. from power plants or industrial processes) and other renewables like solar. In this way the concept of HT-ATES is sustainable and multi-usable.

4.2 Recommendations

An important aspect is that the current legislation does not allow HT-ATES. Both the maximum allowable storage temperature of 25 °C and the required energy balance cannot be met. HT-ATES can only be permitted in the framework of a pilot-project. For the project concerned, consultation of the authorities is therefore required.

For future developments some aspects require further research. It mainly concerns the impact on groundwater geochemistry and microbiology which is not fully known. Furthermore alternative water treatment methods are desired (mainly for fresh water) as well as optimization options to improve the recovery efficiency. A simple method to estimate the recovery efficiency for HT-ATES projects based on the controlling parameters is currently being developed in the framework of a research project funded by SKB.

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