TRANSFORMING ATES TO HT-ATES, INSIGHTS FROM DUTCH PILOT PROJECT

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Keywords: ATES, High temperature ATES

ABSTRACT

Aquifer Thermal Energy Storage (ATES) systems combined with a heat pump save energy for space heating and cooling of buildings. In most countries the temperature of the stored heat is allowed up to 25-30°C. However, when heat is available at higher temperatures (e.g. waste heat, solar heat), it is more efficient to store higher temperatures because that improves heat pump performance or makes it unnecessary. Therefore, interest in HT-ATES development is growing. Next to developing new HT-ATES projects, there is also a large potential for additional energy savings by transforming 'regular' low-temperature LT-ATES systems to a HT-ATES. Such a transformation is tested for a greenhouse system in the Netherlands. This greenhouse has a LT-ATES system operational since 2012, and from 2015 onwards heat is stored in the warm well at temperatures up to 45°C. In this HT-ATES transformation pilot, water quality parameters are closely monitored as well as temperature distribution in the subsurface (using DTS). Together with the operators, the results from the ATES monitoring are used to continuously improve system performance. Numerical groundwater and heat flow simulations of actual and expected well pumping data are used to evaluate how well operation can be optimized. In this paper, the optimization using monitoring results and simulations is discussed as well as general and site specific lessons/conclusions for such transformations.

1. INTRODUCTION

1.1. Increase ATES efficiency

In the Netherlands many Aquifer Thermal Energy Storage (ATES) systems exist (Bloemendal and Hartog, 2018; Fleuchaus et al., 2018). ATES systems (Figure 1) provide sustainable heating and cooling to buildings, but still use a considerable amount of electricity to run the heat pump (Pape, 2017). Additionally, ATES systems' demand for subsurface space results in scarcity of space in many urban areas. For the energy transition it is, therefore, important to explore to what extent ATES systems efficiencies and subsurface space utilization can be improved. One possible solution to do so is to increase the temperature level of the warm well of the ATES system. This will increase the energy content of the groundwater, resulting less subsurface space use, and reduce the need for heat pump operation. To explore the effect of this possible solution an existing ATES system in The Netherlands is transformed to a HT ATES. This paper describes the state of affairs of the currently running pilot.

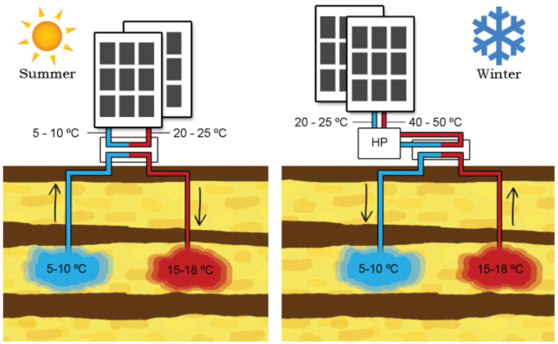

Figure 1. Basic working principle of ATES

1.2. Site description

Koppert-cress is a horticulture company in the town of Monster in the Netherlands. For the climate control in their greenhouses they rely on an ATES system since 2012. In 2015 the local authority (Province of Zuid-Holland) issued a permit (Hopman, 2015) to increase injection temperatures for the warm well up-to 45°C to save additional energy, by limiting the use of gas fired boilers. The Koppert-Cress ATES system thus received the status of a High Temperature ATES pilot. Since this project focuses on the transition from existing ATES to a HT-ATES, after the permit was issued in 2015, the necessary investments were made in the years 2016 and 2017 in order to be able to store extra heat in the warm well. Currently, there is capacity to annually store approximately 11TJ of additional sustainable heat from the solar collectors, condenser heat from heat pump and large cold room, surface water and the CHP of a neighboring greenhouse.

1.3. Goals of the research

The goals of the research associated with the pilot project is to develop knowledge needed for management, maintenance, monitoring and licensing of HT-ATES installations with the highest possible energy efficiency (in terms of CO_2 emission reduction).

- Well control for transition from ATES to HT-ATES and for HT-ATES operation.
- Risk assessment for well clogging, due to chemical precipitations as a result of water temperature increase.
- Identify and mitigate temperature effects to surrounding layers
- Environmental benefits; CO_2 reduction.

This paper discusses the intermediate results of the temperature and water quality monitoring and energy efficiency work packages.

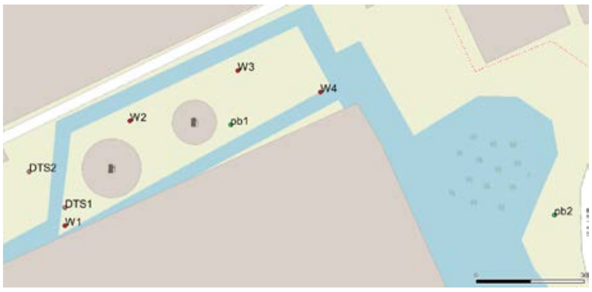

Figure 2. Warm well, DTS and monitoring well (pb) locations.

2. MONITORING

2.1. Temperature

The subsurface temperature is measured with distributed temperature sensing technology at 4 and 18m distance from one of the warm wells, Figure 2 and Figure 3. Also the measured injection temperatures in the plant room confirm the transition to HT-ATES, Table 1. Table 1 shows that the infiltration temperature regularly exceeds 30 ° C and the year average temperature difference between the warm and cold well is about 6°C higher than the national average of 4 ° C (Willemsen, 2016). The temperature measurements in the subsurface, show that the extend, or thermal radius, around the warm well is limited, because no change in temperature is measured at 18m from the well. This is caused by a combination of A) the short cyclic storage and recovery and B) the application of the storage in 2 different aquifers of which the deeper part was expected not to contribute much to the well flow.

Ad A) As a result of the required climatic conditions in the greenhouse, the HT-ATES is often used for daily storage and recovery. During the day heat is stored and extracted again the next night, or within a week. These short storage cycles contribute to the total storage volume and energy saving of the HT-ATES system. But keep the thermal radius limited.

Table 1. Maximum monitored infiltration temperatures in to the warm well and temperature difference between warm and cold well.

	T_warm [°C]	ΔT [°C]
Max. yearly average	18	11
Max. daily average	36	29
Max. 5min average	43	37

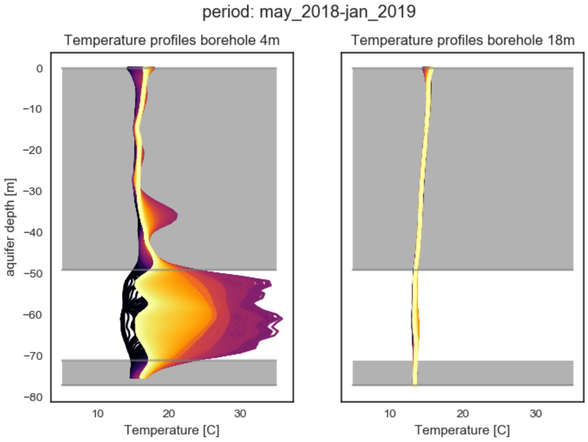

Figure 3. DTS temperature measurements at warm well, at respectively 4 and 18 m distance. each line is the temperature profile at different time, dark: May ’18, light: Jan ’19.

Ad B) At first it was not known whether the well was screened in 2 aquifers. When the temperature monitoring results showed limited thermal extent around the well it became clear the well was deeper than anticipated. In such conditions the deeper aquifer screens do not contribute much to flow, in Dutch groundwater wells. Therefore a well flow test was carried out (Figure 4). This indicated that about 60% of the well capacity is coming from/going into the deeper aquifer. As a result of this analysis an additional DTS monitoring points will be installed early 2019, at 4 and 10m distance up to 170m depth.

The additional monitoring then also allows to evaluate the spreading of heat in between the two different screens. The temperature measurements from the existing DTS (Figure 3) already gives some insights:

- Seasonal effect of changing temperature at surface level affects temperature profile up-to 10m depth. There is however a difference between the 2 monitoring points; the one at 4m from the well is in the grass and also very close to a ditch, while the one at 18m is under a concrete plate. These conditions clearly affect the effect of the seasonal temperature change in shallow subsurface.
- Where the well is not screened the temperature vary more close to the well as a result of heat loss from thermal conduction through the well casing, like was also discussed by Lopik et al. (Lopik et al., 2015).

- The large temperature change around 35m depth coincides with the presence of a very course sand layer. So ambient groundwater flow may enhance heat transport from the well casing, or the casing is leaking (to be further investigated.

Next steps: additional DTS measurements to obtain more insight in heat distribution to confining layers, reproduce measurements with simulations (MODFLOW/ SEAWAT) to obtain insight in (magnitude of) processes affecting heat transport.

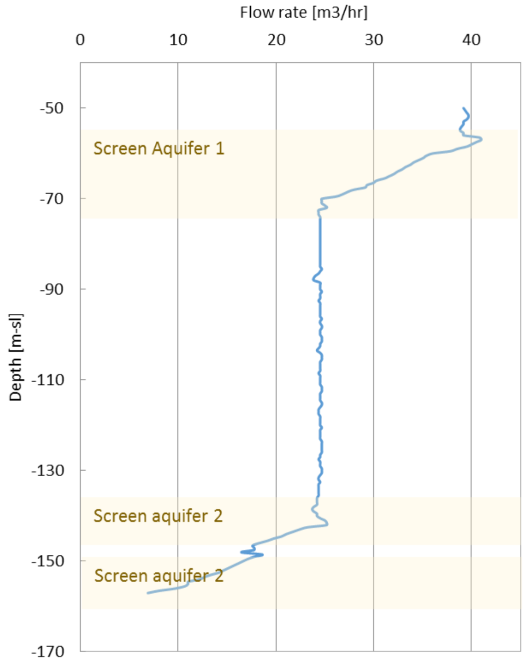

Figure 4. Result of well flow test.

2.2. Groundwater quality

Water samples are taken from 2 monitoring wells, one at 20 and 100m from a warm well (Figure 2) to respectively assess affected water and have a reference measurement. Also water is taken from groundwater circuit inside the plant room. So each monitoring round we have 2 water samples that have been heated and 1 reference. The parameters, the water samples are analyzed for are indicated in Table 2.

Table 2. Water quality analysis parameters

Chemical pH, ER, Oxigen, Chloride, Nitrate, DOC, Methane, Sulphate, hydrogenecarbonate, ortho-fosphate, Ammonium(N)
Microbiologic Escherichia coli, SSRC, Vibrio spp, Legionella pneumophila, Acanthamoeba spp., Stenotrophomonas maltophilia, Nontuberculeuse Mycobacteriën, ATP

As a result of the limited extent of the thermal radius, at sampling monitoring point at about 20 meters from the warm only a limited temperature change is observed at the end of the summer. So also to obtain more valuable information an additional monitoring well will be drilled closer to the well to obtain insight in the water quality changes in the aquifer.

Due to the limited temperature change in this monitoring well, there is currently no insight into the effects of temperatures above 25 ° C on chemistry and microbiology in the vicinity of the well. Water samples coming directly from the well inside plant room, which do heat up, do not show significant changes in water quality up to now. Also there are no indications of well clogging.

Next steps: install monitoring well closer to warm well, continue groundwater quality analysis when warm groundwater samples can be taken from the aquifer.

3. ENERGY EFFICIENY

The abovementioned changes in the installation to store extra heat in the warm wells, together with an increase in the greenhouse area affect the energy flows in the Koppert-Cress climate systems and thus also the required storage capacity of the ATES system, Table 3. The table shows a strong increase in energy flows, which are accommodated by the ATES system as a result of the higher warm well infiltration temperature. The net heat demand from the greenhouses to the wells will remain higher than the cooling demand. The facilities to capture extra heat bridge the gap between heating and cooling demand as they can together collect about 11 TJ each year.

Table 3. Energy demand from wells for various scenario's

	Cooling demand wells	**Heating demand wells**
Scenario	[TJ]	[TJ]
ATES situation 2012	6	8
HT-ATES End 2017	10	18
After expected expansions up-to 2020	16	23*

*based on a heat pump COP of 6, monitoring data showed heat pump performance of 6 - 6.5 over 206-2018.

The intermediate results of the analysis of the energy flows of the Koppert-Cress ATES system and the pumped flows and temperatures show that the ATES is used differently than intended. This is caused by the expansion of the greenhouses and the changes in the system, i.e. the facilities to obtain extra heat. The functioning of the (HT-)ATES system is reflected in Table 4, and shows that despite larger energy demand pumping rate have gone down, as a result of the higher warm well temperature. Where regular ATES systems have a temperature difference between warm and cold well

Table 4. monitoring data well flows and temperatures

	Cooling	**Heating**	**avg T_Warm**	**avg dT**
year	[m^3]	[m^3]	[C]	[C]
2012	149,754	714,312	14.6	5.0
2013	163,894	586,306	15.0	5.5
2014	335,405	516,749	15.3	6.0
2015	345,772	497,880	16.9	8.1
2016	226,985	480,448	17.4	7.9
2017	206,670	458,014	17.7	10.6
2018	243,894	450,854	17.6	11

MODFLOW/SEAWAT simulations (Appendix I) show how the short-cycle storage of heat is an efficient way to save energy, Table 5. The first few times at the beginning of spring excluded, the recovery efficiency of the short storage cycles is higher than average, because relatively little loss occurs during the short storage time and because there is already heat in the aquifer, reducing conduction losses further.

Table 5. Recovery efficiencies at short storage cycles. At weekly storage cycle the storage volume is also larger, therefore, also the recovery efficiency.

	T=25°C		**T=45°C**	
Cycle duration:	**day**	**week**	**day**	**Week**
Start of spring	0.64	0.66	0.54	0.56
Start of summer	0.88	0.93	0.79	0.86
End of summer	0.98	0.99	0.97	0.98

An important observation is that the short storage cycles result in more use of heat storage and recovery, while at the same time the thermal area of influence is smaller than foreseen for permit issuing in 2015. The total amounts of heat that are stored and recovered show that Koppert-cress has saved a lot of energy. As a result of this HT-ATES operation Koppert-Cress currently saves around 15 TJ natural gas equivalents and 3.5 TJ of electricity annually

Next steps: determine recovery efficiency of ATES wells, optimize use of ATES wells by simulation future scenario's, asses performance of other components to improve energy performance of system as a whole.

4. DISCUSSION

This is ongoing research, so definite conclusions cannot yet be drawn. Important observation, however, is that despite various things going differently than expected / wrong, still this energy system saves a lot of energy. The short cyclic behaviour was not anticipated but appears to work well for diurnal energy demand variations. Further improvements on the monitoring infrastructure and simulation tools should provide more detailed insight in key processes and components for optimal and efficient utilisation of HT-ATES.

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ACKNOWLEDGEMENTS

This research was funded by Topconsortia voor Kennis en Innovatie from the Dutch Ministry of economic affairs. The authors thank Koppert-Cress for the opportunity and cooperation in this research.

APPENDIX I: SIMULATION FRAMEWORK

As losses due to conduction, dispersion and displacement occur simultaneously, MODFLOW (Harbaugh et al., 2000) simulations is used to evaluate their combined effect on recovery efficiency. For the simulation of ambient groundwater flow and heat transport under various ATES conditions, a geohydrological MODFLOW model (Harbaugh et al., 2000) coupled to the transport code MT3DMS (Hecht-Mendez et al., 2010; Zheng and Wang, 1999). These model codes use finite differences methods to solve the groundwater and (heat) transport equations . This allows for simulation of infiltration and extraction of groundwater in and from groundwater wells and groundwater temperature distribution, as was done in previous ATES studies e.g. (Bonte, 2013; Caljé, 2010; Sommer, 2015; Visser et al., 2015). In the different modeling scenarios the storage volume is varied according to the monitoring data with flow rates proportionally ranging from 5 to 40 m^3/hour and no ambient groundwater flow. Density differences are taken into account via a linear density dependency. The parameter values of the model are given in Table 1, the following discretization was used:

- Model layers; 2 m thickness
- The spatial discretization used in horizontal direction is 5 x 5 m at well location, gradually increasing to 250 x 250 m at the borders of the model. A sufficiently large model domain size of 6x6km was used to prevent boundary conditions affecting (<1%) simulation results.
- A temporal discretization of one week is used, which is sufficiently small to take account for the seasonal operation pattern and resulting in a courant number smaller than 0.5 within the area around the wells where the process we care about occur. The simulation has a horizon of 10 years, sufficiently long to achieve stabilized yearly recovery efficiencies.

The PCG2 package is used for solving the groundwater flow, and the MOC for the advection package simulating the heat with a courant number of 1.

Table 6, MODFLOW simulation parameter values (Caljé, 2010; Hecht-Mendez et al., 2010)

Parameter	**value**
Horizontal conductivity aquifers	25 m/d
Horizontal conductivity aquitards	0.05 m/d
Longitudinal dispersion	0.5 m
Transversal dispersion	0,05 m
Bulk density	1890 kg/m^3
Bulk thermal diffusivity	0.16 m^2/day
Solid heat capacity	880 J/kg °C
Thermal conductivity of aquifer	2.55 W/m °C
Effective molecular diffusion	$1 \cdot 10^{-10}$ m^2/day
Thermal distribution coefficient	$2 \cdot 10^{-4}$ m^3/kg
Drho/dT	-0.35 -