HEATSTORE

State of the art HT-ATES in the Netherlands

Evaluation of thermal performance and design considerations for future projects

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HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

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About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority - 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage, which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
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Table of Content

1 Summary

In the Netherlands over 3,000 (licensed) ATES systems have been installed since 1985. For more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in six projects. The first relevant HT-UTES project in the Netherlands was installed in the Beijum district in Groningen (1985: storage of 60 ºC solar heat using BTES). The first HT-ATES projects were made at Utrecht University (1991: storage of 90 ºC heat from a CHP installation using ATES) and a health care institution in Zwammerdam in the late nineties (storage of 90 ºC heat from a CHP installation using ATES). Furthermore, four medium (< 50 °C) temperature storage systems were build the last 15 years.

The measured recovery efficiency for all the HT-ATES is lower than designed. The main reasons are:

- The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in the building was not adapted to the extraction temperatures from the heat store.
- The storage volumes of the projects are lower than designed. This makes them extra vulnerable for high thermal losses;
- Some low temperature projects (Harderwijk and Eindhoven) are made in formations with very course sand. Buoyancy flow will decrease efficiency;

All the projects were evaluated with the HSTWIN-3D-software. The modelled recovery efficiency and temperature fields show good similarity with the measured values.

In general more than 50 % of the stored energy in the HT-ATES projects was not used for heating. Besides the negative influence on the profitability of the HT-ATES project, also the authorities and other subsurface stakeholders will have their concerns about thermal and environmental impact of HT-ATES. For future projects the recovery efficient will have to be increased to at least 70 %.

For future HT-ATES the next design rules for high thermal efficiency (> 70 %) must be considered:

<u>Underground:</u>

- <u>Design HT-ATES with a sufficient size</u>
  For the Dutch target formations (Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis) the following design considerations could be defined based on the following assumption: Screen length 50 m (to get economical feasible projects), K horizontal < 10 m/d, minimal recovery rate: 70 %, Anistropie 2-5:
  - A HT-ATES with a temperature of 90 °C needs a <u>minimum</u> storage volume between 250.000 and 500.000 m^3/season.
  - A HT-ATES with a temperature of 50 °C needs a <u>minimum</u> storage volume between 35.000 and 180.000 m^3/season.
- <u>Always use a test drilling</u>.
  The aquifers that are suitable for heat storage are often subject to limited research. This is mainly because these aquifers have never been attractive for drinking water extraction or low temperature cold / heat storage. Research through a test drilling is necessary to show where layers are located and which water quality they have. It is also desirable to perform a pumping test because the estimation of permeabilities based on grain sizes in such fine-sand packages (this usually concerns permeability <5 m/d) is too inaccurate.

- Calculate the recovery efficiency with a 3D thermal model.
  The model schematization is also important. For example, a 3-dimensional thermal transport model is required to correctly calculate the effects of density-driven groundwater flow (e.g. HSTWIN-3D, Modflow/SEAWAT, FEFLOW).
  The reliability of the predicted effects depends on the reliability of the input in the model. This concerns the usage pattern of the system (pumped water quantities, extraction and infiltration temperatures and variation over time), the properties of the system (locations of wells, screen lengths and screen depths) and the subsurface (heterogeneity, permeability).

System Integration

- Ensure that the usable (cut-off) temperature from the store is as low as possible;
  The recovery efficiency of the storage is determined not only by the heat loss in the subsurface, but also by the minimum usable extraction temperature from the hot well. This is referred to as the "cut-off temperature". At this cut-off temperature the maximum required heating power can be supplied under design conditions. The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency. Lowering the cut-off temperature with 10 º can increase the recovery efficiency significantly (e.g. by 10 to 15 %).

- Use star-shapes well configurations;
  The HT-ATES well configuration normally consists of a doublet (one cold and one warm well). If more capacity is required more doublets were used. In a star-shape; warm wells in the middle and a ring of cold wells. In this configuration the cold wells will insulated the heat around the warm wells and efficiency will increase up to 10 %.

- Put the heat storage system at base load in winter time.
  The heat storage is a slow-reacting system because the heat must come from a large depth (e.g. 150-300 mbgl) and because pipe systems must be heated up. To minimize start-up losses and heating losses, it is recommended to use the heat storage as the base load of the heating system. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat.

2 Introduction

In this report an overview of high (> 30 ºC) temperature aquifer thermal energy storage experience in the Netherlands is presented. It is part of workpackage 1.1 of the Dutch HEATSTORE pilot and serves as starting of the engineering of a new HT-ATES at ECW Middenmeer.

Different technologies for underground thermal energy storage (UTES) exist. ATES (Aquifer Thermal Energy Storage), BTES (Borehole Thermal Energy Storage), PTES (Pit thermal Energy Storage), TTES (Tank Thermal Energy Storage) and MTES (Mine Thermal Energy Storage). In the Netherlands the main applications for high temperature storage are in ATES; other technologies are very rare (BTES and MTES) or do not exist yet (TTES and PTES).

This report describes the existing or former HT-ATES projects and focusses on recovery efficiency, system integration and thermal effects in the subsurface. The microbiology and chemical impact of the temperature changes in the underground is intensively studied and reported in the research program “Meer met Bodemenergie” (IF Technology, 2012). In work package 6 of HEATSTORE on environmental assessment this research will be summarized.

The engineering aspects of the HT-ATES projects are addressed in a separate report for workpackage 1.2.

The information on the performance of the existing/former HT-ATES projects is taken out of existing evaluation reports:

- **Drijver, 2012**. More with underground energy storage, high temperature storage, report nr. 6 (in Dutch), knowledge overview and experiences. IF Technology, Bioclear, Wageningen University and Deltares. Arnhem. Overview of the biological and chemical impact of high (> 30 °C) temperature aquifer thermal energy storage based on modelling and measurement at existing projects. This report is part of the large research program MMB (Meer met Bodemenergie www.meermetbodemenergie.nl) between 2008 and 2012.

- **IF Technology, 2014**. Thermal efficiency of High and medium temperature storage in the Underground (in Dutch). 63112/BP/20141002. Arnhem. Overview of the experience with all the Dutch high (> 30 °C) temperature aquifer thermal energy storage projects over the last 20 years.

This report starts with a general description of the application of HT-ATES. Followed by a more detailed description of the well documented HT-ATES projects which are still in operation and of abandoned projects. Finally, the lessons learned and some design criteria with respect to aquifer selection and system integration are described.

3 High temperature aquifer thermal energy storage technology

Within the HEATSTORE project HT-ATES is defined as storing of water between 30 and 95 °. Based on complexity (water treatment and material selection) of the technology a subdivision is made in the Netherlands for HT-ATES projects between 30 and 60 °C (for the Dutch situation called medium temperature MT-ATES) and 70- 90 °C.

3.1 High temperature aquifer thermal energy storage 70- 90 °C

HT-ATES is a storage technique in which surplus heat with a high temperature (around 70 to 90 ºC) is temporarily stored in an aquifer (in the Netherlands it concerns aquifers consisting of fine-sand). To limit heat losses to overlying layers (and the associated thermal impact in overlying layers) the aquifer has to be confined. The stored heat is withdrawn in a later period and used directly for heating buildings and greenhouses. The temperature of the extracted groundwater typically drops significantly during the recovery period (typically the winter season).
It is therefore important to take this temperature drop into account in the design of the heating system. This means that a relatively low extraction temperature (for example 50 ºC) should still be sufficient/usefull for the heating system.

The high storage temperatures result in change of the chemical composition of the groundwater, therefore chemical treatment of the groundwater is needed to prevent the precipitation of minerals in the system (wells, heat exchanger and pipes).

The most important application for HT-ATES lies in the large-scale storage of residual heat from the industry, waste incineration, power plants or CHPs (Combined Heat and Power). HT-ATES has large potential in district heating networks and geothermal energy. An important condition for HT-ATES is that the residual heat is available at low marginal costs, otherwise it will be difficult to complete the business case (in the current (2018) energy mix in the Netherlands). Furthermore, as this report will demonstrate, the size of the system must be sufficiently large, since small systems have relatively low recovery efficiencies.

HT-ATES is a technique that was developed and researched in the eighties of the last century and of which some pilots have been installed. The first relevant projects in the Netherlands were installed in the Beijum district in Groningen (1985: storage of 60 ºC solar heat using BTES) and at Utrecht University (1991: storage of 90 ºC heat from a CHP installation using ATES). In addition, a project was installed at a health care institution in Zwammerdam in the late nineties (storage of 90 ºC heat from a CHP installation using ATES). The project in Beijum is still running; the Zwammerdam project was stopped since it was not economically profitable to run. The project in Utrecht was stopped due to well problems and a mismatch between the temperature level required for the building heating system and the temperature level that the storage could provide.

The applications of HT-ATES has been limited in the past 20 years. Mainly caused by legal limitations, the poor business case because of the competition with natural gas and the decline of the application of CHP installations. In the future, the use of natural gas is expected to be strongly reduced in the Netherlands. More and more new residential areas are made without a natural gas grid. As a consequence, the interest in alternatives (like HT-ATES) is expected to increase significantly.

3.2 High temperature aquifer thermal energy storage 30- 60 °C

Excess heat with a medium-high temperature (30 to 60 ºC), for example coming from a greenhouse, CHP, cooling machine or solar panels, is temporarily stored in an aquifer. The stored heat can be extracted in a later period and used for heating of buildings or greenhouses. A heat pump can be used to raise the temperature to the desired level. HT-ATES at this temperature level is pre-eminently a technique that is applied locally and in which the residual heat of the user is stored.

An advantage over higher temperature storage is that, due to the lower storage temperatures, there are far fewer thermal losses in the subsurface. Because the storage temperature is lower, there is usually no need for water treatment to prevent precipitation of minerals (in the heat exchanger, pipes and wells). Furthermore, the density difference between the stored warm water and the surrounding (colder) groundwater is less, making the density-driven groundwater flow less strong. This means that aquifers with a higher permeability can be used (there is more experience with these aquifers and the flow rate that can be achieved per well is higher). Another advantage is that at lower temperatures, less stringent requirements are applicable on the materials used (temperature resistance).
A disadvantage of the medium-high temperature storage is that the recovered heat has a lower temperature and therefore has fewer possible applications. Furthermore larger volumes of groundwater must be pumped to provide the same amount of heat.

Medium-high temperature storage is not a new technique. In the early nineties of the last century, the first project was developed at the Heuvelgalerie Shopping Mall in Eindhoven (storage of heat that is released during cooling in the summer period). Projects were also installed at the Dolfinarium in Harderwijk (1998: heat from a CHP installation), 2MW in Haarlem (2002: storage of heat from solar collectors) and NIOO in Wageningen (2012: storage of heat from solar collectors), van Duin in Steenbergen (2016) and Koppert Cress in Monster (2017).

The choice for medium-high temperature is often made for projects that only need low-value heat and that can produce low-value heat themselves. In most cases, it concerns relatively small projects (300 - 1,000 kWt), (50 - 200 houses or 1 hectare of greenhouse).

The applications have been very limited in recent years. This is largely caused by the fact that a higher infiltration temperature than 25 ˚C is, in principle, not permitted from a legal point of view. Furthermore, it has to compete with the low prices of gas fired boilers.

4 The projects

4.1 General overview

If heat supply and heat demand are not simultaneous, (temporary) storage of heat can be used. This for example applies for the heating of buildings or greenhouses. The duration of the heat storage can roughly be divided into short-term storage (day / night) and long-term storage (summer / winter). The latter is also called "seasonal storage". A heat surplus (usually in summer) is stored for use in a period with a heat deficit (usually in winter). In the Netherlands the subsurface is the most used medium for seasonal thermal energy storage.

The heat can be stored and extracted through closed tubes systems or by groundwater wells. A system with closed tubes in the subsurface is also called a borehole heat exchanger system (BTES). In the Netherlands, one project was installed where heat is stored in the subsurface using vertical borehole heat exchangers. In the Beijum in Groningen project, since 1983 heat of 60 ºC has been stored in the ground via 360 borehole heat exchangers of 20 m depth.

To limit heat losses to the atmosphere, an insulation layer has been installed on top of the borehole heat exchanger field. The heat is collected with solar collectors and used for the heating of 100 houses (Wijsman, 1983).
All other (known) heat storage projects installed in the Netherlands use groundwater wells (also known as “open loop systems”). These systems extract and infiltrate groundwater into aquifers (ATES).

In the Netherlands more than 3,000 (licensed) ATES systems have been installed since 1985 (Bakema, 2016). In more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in nine projects.
The main characteristics of these heat storage projects are summarized in Table 1 and are briefly described below. The size of the heat storage varies between approx. 400 MWht and 8,000 MWht; the heating power varies between 6 and 1,5 MW.

Table 1 Overview of MT-ATES and HT-ATES Projects in the Netherlands (>25 °C)

Project	year of installation	Storage temperature [°C]	Storage capacity [MWh_t]	Heat power [MW_t]
Office complex, Bunnik	1985	25-30	370 (?)	unknown
Utrecht University	1991	90	6.000	6,0
Heuvelgalerie Shopping Mall Eindhoven	1992	32	3.300	1,8
Dolfinarium Harderwijk	1997	40	7.650	4,7
Hooge Burch Zwammerdam	1998	88	2.250	1,45
2 MW, Haarlem	2002	43	1.650	2,0

NIOO, Wageningen	2011	45	1.280	1,5
Van Duin, Steenbergen	2016	40	2000	2
Koppert Cress, Monster	2017	40		

In this evaluation the main focus is on recovery efficiency. Recovery efficiency is the recovered heat (recovered volume* (temperature warm well – temperature cold well)) divided by stored heat (stored volume * (temperature warm cold – temperature warm well))

4.2 Medium-high temperature aquifer thermal energy storage

4.2.1 Office complex Bunnik (1985-1994)

In 1985 the first aquifer storage project in the Netherlands was installed in Bunnik. This system was set up for space heating of the Bredero office complex. The heat was supplied by solar collectors and residual heat from cooling. The average storage temperature was 25 to 30 ºC. In the winter, the warm water was extracted from the aquifer and upgraded with a heatpump to a maximum temperature of 42 ºC. The well screens of the storage are placed in a moderately coarse to coarse aquifer between 17 and 50 mbgl.

Evaluation of the performance of the storage in the first 5 years shows that a great deal of knowledge has been gained regarding the design and management of heat storage (Heidemij and Bredero Energy Systems, 1990). The project was less successful regarding the functioning of the energy system because the new technologies, such as solar collectors and heat pump, did not function properly yet. The storage itself has functioned well technically. Around 1994 the heat storage was converted to a cold storage system.

4.2.2 Heuvelgalerie Eindhoven (1992)

Heuvelgalerie is a shopping mall in the centre of Eindhoven (Figure 1). At the end of 1992, a medium temperature heat storage system (30 ºC) was established and is in use since spring of 1993. The system consists of one cold well and one warm well. In addition, four monitoring wells have been placed. To limit the heat losses due to regional groundwater flow, the cold well is located downstream of the warm well. The locations of the wells and monitoring wells are shown in Figure 2.

Figure 1 Shopping mall Heuvelgalerie Eindhoven (in 2015 the name Heuvelgalerie was changed in Heuvel)

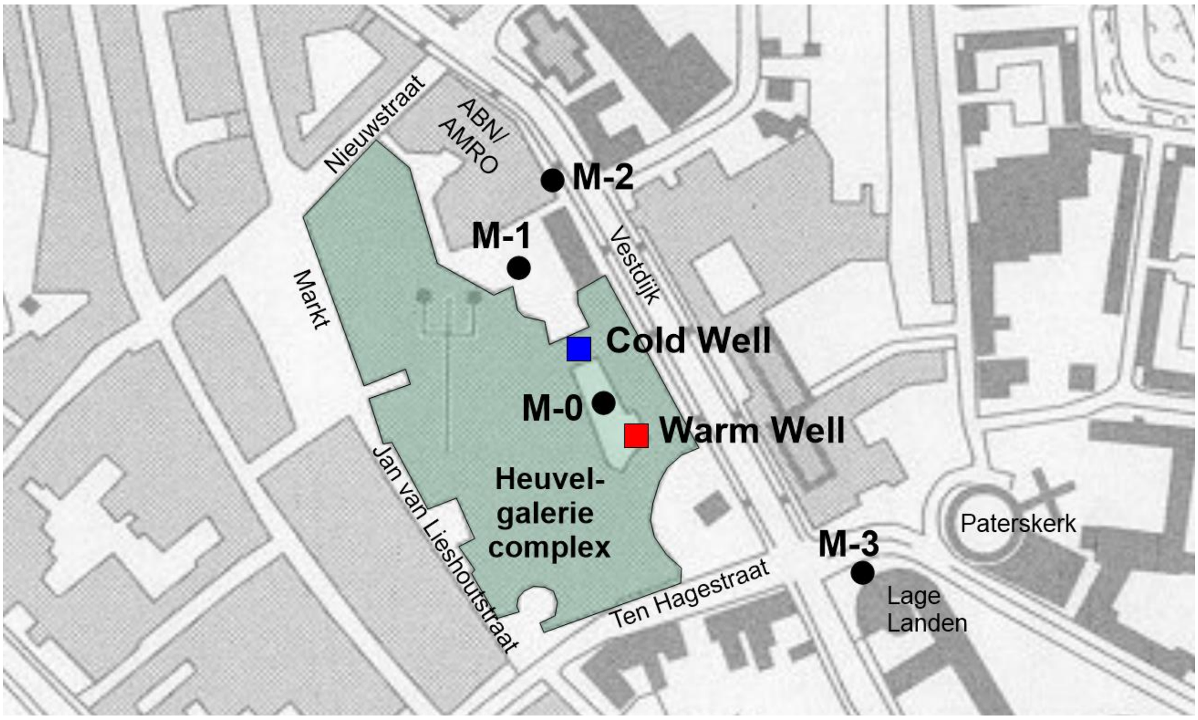

Figure 2 Position of wells and monitoring wells Heuvelgalerie Eindhoven

Recovery efficiency

The storage was designed for storage of 200,000 m³ (and a maximum of 275,000 m³) of groundwater of 32 ºC in the warm well in the summer period. In the winter the warm water is extracted and used for heating the ventilation air. Use of the heat is possible as long as the temperature of the extracted groundwater is at least 24 ºC (cut-off temperature = 24 ºC). After use for heating, the cooled groundwater is infiltrated at 18 ºC in the cold well.

When applying for the license in 1990, a storage efficiency of 50- 55 % was calculated in the fourth year (Table 2). During the period 2006 and 2011 the average storage efficiency is comparable with this number. Large differences over the years occur due to climate differences and occupancy rate of the mall.

Table 2 Recovery efficiency Heuvelgalerie Eindhoven

Year	Stored volume m^3	Recovered volume m^3	Stored heat MWh_t	Recovered heat MWh_t	Recovery Efficiency %
Design	200.000	150.000	3.250	1.740	54
2006	46.000	168.700	1.554	398	26
2007	48.300	115.200	1.027	299	29
2008	124.200	101.900	832	501	60
2009	95.700	128.000	1.354	488	36
2010	213.100	233.500	1.046	1.431	136
2011	57.600	79.700	667	318	48
Average	97.500	137.800	1.080	573	53

Temperature measurements

The heat storage system was installed at the end of 1992 and is in operation since the spring of 1993. In the first 5 years there was a pilot permit and monitoring of the groundwater composition (chemical and microbiological) and the subsurface temperature (measured in the warm and cold well and the four monitoring wells around the site).

The results of the subsurface temperature measurements in the cold and hot well and in the monitoring wells M0 and M1 are shown in Figure 3 (no changes were measured in the monitoring wells M2 and M3). Several graphs have also been made for monitoring well M0, in which several successive measurements have been added, so that it is clearer which changes have been measured successively.

The warm well and M0 show lower temperatures between 30 and 45 m-mv at the end of 1993 - early 1994. The reason for this is the interruption of the screen in the warm well of 35-40 mbgl because of the presence of a clay layer (also visible at M0, but not at the cold well). In the first quarter of 1994, the subsurface temperature in M0 is clearly higher than that in the warm well (on average about 22 °C and 15 °C respectively); this is possibly due to infiltration of warm water with different temperature levels during the summer period.

In the last quarter of 1994 both M0 and the warm well showed higher subsurface temperatures than in the first quarter of 1994. This is a logical consequence of the storage of heat in the previous summer period.

In the graphs of M0 and M1 the heat concentrates in the upper part (at less than 65 m depth at M0 and less than 55 m depth at M1). This can be explained by the occurrence of density-driven groundwater flow because of the increased storage temperatures. The screen of the warm well is between 24 and 81 m-mv, so at the warm well the heat will be injected in this depth interval. The groundwater takes some time to reach monitoring well M0 and even more time to reach monitoring well M1. In time, the warmer groundwater can flow in the upward direction because of the lower density, which explains the heat is shallower at monitoring well M1 than at M0 and at M0 shallower than at the warm well.

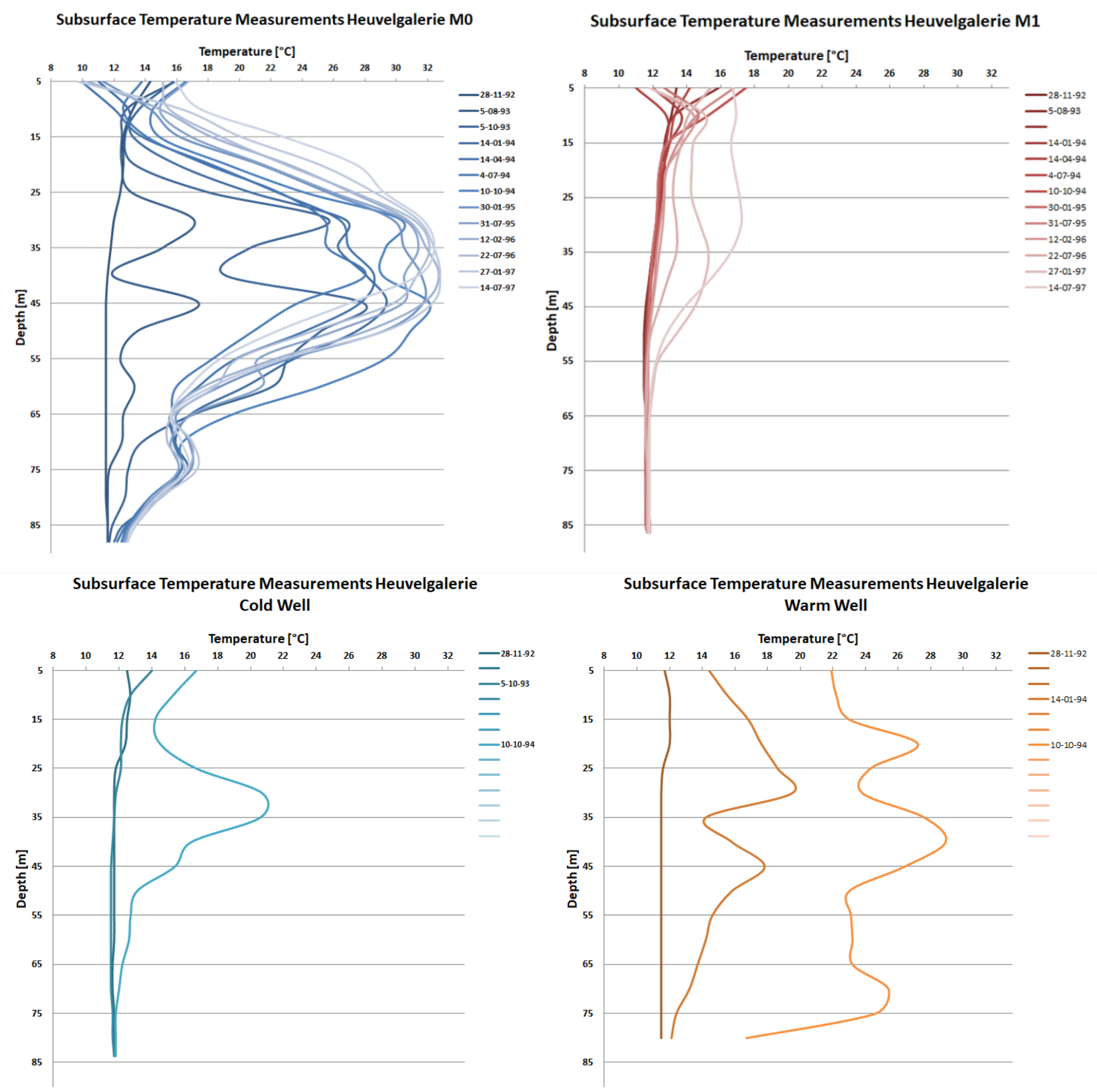

Figure 3 Results of subsurface temperature measurements Heuvelgalerie Eindhoven

4.2.3 Dolfinarium Harderwijk (1997)

At the sea animal park Harderwijk (Dolfinarium Harderwijk) combined heat and power units (CHP units) are used for generating electricity and supplying heat for space heating of offices, buildings (at a high temperature) and basins (at a low temperature) (Figure 6). In the summer period, in which the visitor's peak traditionally falls, the CHP units produce a large surplus of heat, while the demand for heat is concentrated in the winter months.
In the summer situation, the excess heat from the CHP units is therefore stored in the subsurface using an ATES system.

In the summer season, on average 244,000 m³ of water is stored with a maximum temperature level of 40 ºC. During the winter season, on average 366,000 m³ of groundwater is extracted from the warm well and infiltrated at a temperature of 13 ºC in the cold well. This recovered heat is used for the heating of the basins (which are suitable for this because of the low temperature heating).

The extracted groundwater can be used for heating when the extraction temperature is at least 17 ºC (cut-off temperature = 17 ºC).

The locations of the wells and the monitoring wells are shown in Figure 4. The screens of the wells are placed in the combined 1st, 2nd and 3rd aquifer between 75 and 125 mbgl.

The calculated extraction temperatures show that approximately 55% of the heat, that is stored in the warm well during the summer period, is recovered during the winter period. This storage efficiency hardly increases over the years due to the relatively large thermal losses caused by the natural groundwater flow and the influence of density-driven groundwater flow.

Table 3 shows the measurement data for the period 1997-2010 (pumped water quantities and stored and recovered amounts of energy for each year). These data apply to calendar years (heat supply in the first months and the last months of the year and in the interim period heat storage takes place).

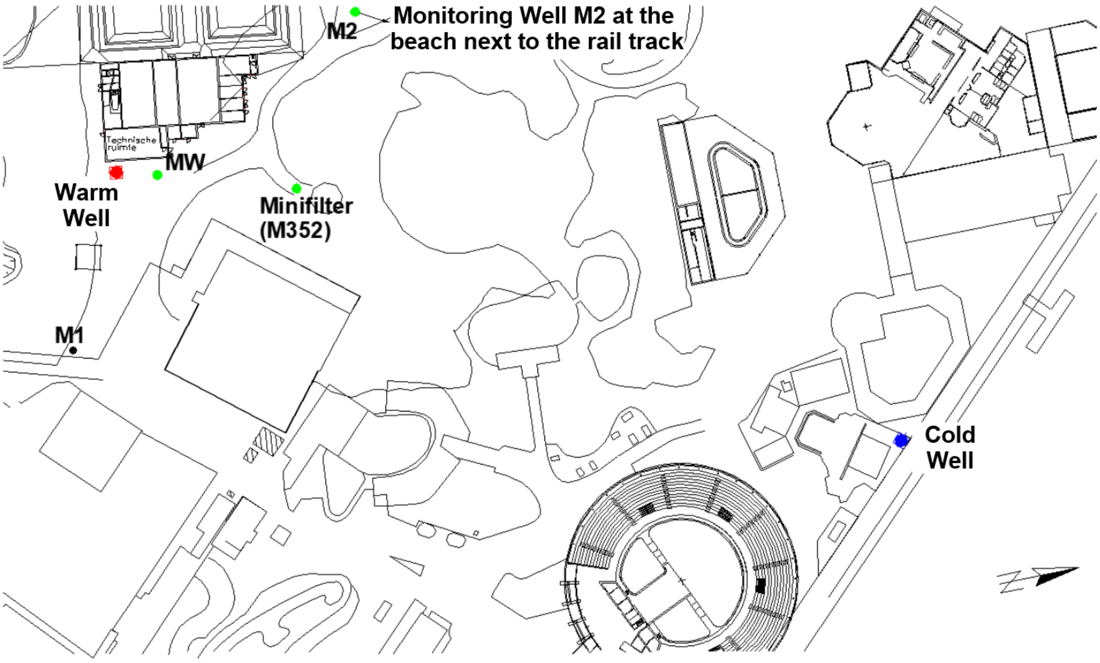

Figure 4 Locations of the wells and the monitoring wells at the Dolfinarium in Harderwijk

The long-term average efficiency is about 40%. The most important explanation for this relatively low average efficiency (compared to the 55% that was calculated in the design phase) is that on average significantly more water is pumped for heat storage than is withdrawn for heat supply, while in the design phase the opposite was assumed (system integration issue).

Table 3 Measured water and energy volumes Dolfinarium Harderwijk

	Recovered water volume [m³]	Stored water volume [m³]	Recovered heat [GJ]	Stored heat [GJ]	Recovery Efficiency
1998	237.606	108.118	9.244	13.224	70%
1999	65.076	277.755	3.012	34.097	9%
2000	108.192	139.317	3.670	15.712	23%*

2001	295.478	305.810	17.896	34.724	52%
2002	223.685	324.488	17.110	38.018	45%
2003	254.765	268.448	14.494	27.659	52%
2004	185.296	240.732	12.433	23.643	53%
2005	182.564	286.988	11.072	33.417	33%
2006	188.496	319.085	17.553	37.875	46%
2007	126.066	203.239	3.079	6.729	46%
2008	175.286	405.693	14.902	45.912	32%
2009	178.092	365.741	12.741	40.099	32%
2010	226.371	334.721	16.974	38.585	44%
average	188.229	275.395	11.860	29.976	40%

Temperature measurements

In the measurement wells MW (near the warm wells) and M2 (downstream of the warm well), subsurface temperature measurements are performed twice a year. The results of the measurements performed in both wells are shown in Figure 5.

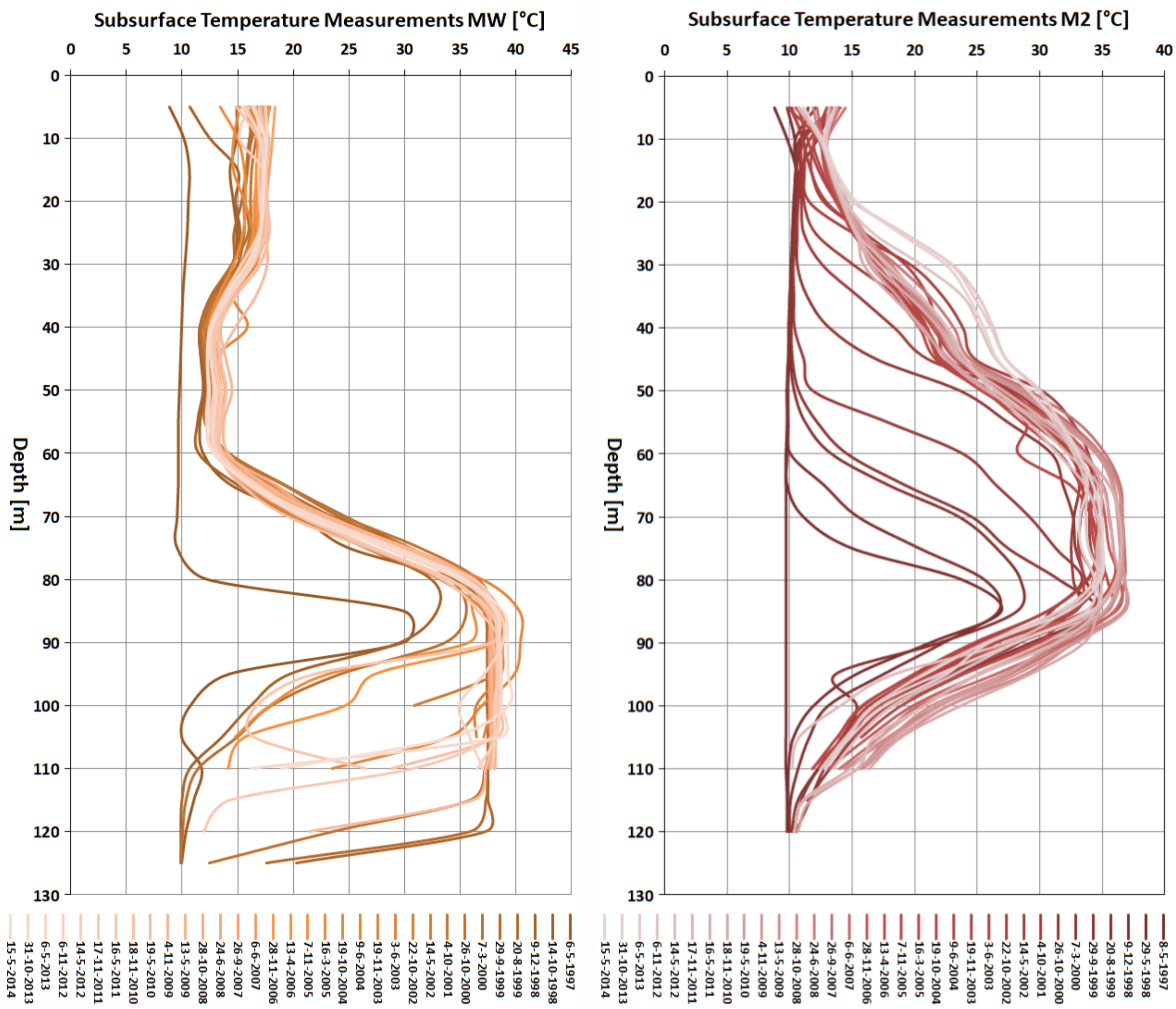

Figure 5 Results of subsurface temperature measurements monitoring wells MW and M2 Dolfinarium Harderwijk

At monitoring well MW, which is a short distance from the warm well, the temperature increases are concentrated in the depth range of the screen of the warm well (75-125 mbgl).
At monitoring well M2, located downstream of the warm well, there is a more gradual temperature gradient in the depth, with the highest temperatures occurring between approximately 50 and 90 mbgl. The centre of the heat bubble is thus shifted from 100 mbgl at the warm well (corresponds to the centre of the well screen) to 70 mbgl. Apparently upward transport of the heated groundwater occurs between the warm well and monitoring well M2, which can be attributed to density-driven groundwater flow as a result of the elevated temperature. In this case, density-driven groundwater flow has little impact on the storage efficiency (at the warm well the heat remains concentrated at the depth of the well screen) but is important for the spatial distribution of the heat in the long term (downstream of the heat store).

In monitoring well M2 it is also striking that the oldest measurements show warming at about 85 mbgl and that the warmest zone gradually spreads to more shallow depths in the successive measurements. Approximately 5 years after commissioning (from 2002), a virtually stable situation is reached: all temperature profiles that have been measured afterwards show a very similar pattern and further heating does not occur or only to a limited extent.

4.2.4 NIOO Wageningen (2011)

The headquarters of the Netherlands Institute of Ecology of the Royal Netherlands Academy of Sciences (NIOO-KNAW) in Wageningen has a high sustainability level (Figure 6).

To enable a sustainable climate control system, two ATES systems have been installed. The first (shallow) groundwater system is a regular (low temperature) ATES system in a coarse sand aquifer. The second (deep) ATES system is a medium-temperature heat storage system in a low permeability aquifer. The medium temperature heat storage system of NIOO consists of a cold and a warm well with infiltration temperatures of respectively 26 ºC and 45 ºC. Figure 7 shows the locations of the wells. The well screens are placed in the depth range of 220 to 295 mbgl.

Figure 6 NIOO Wageningen

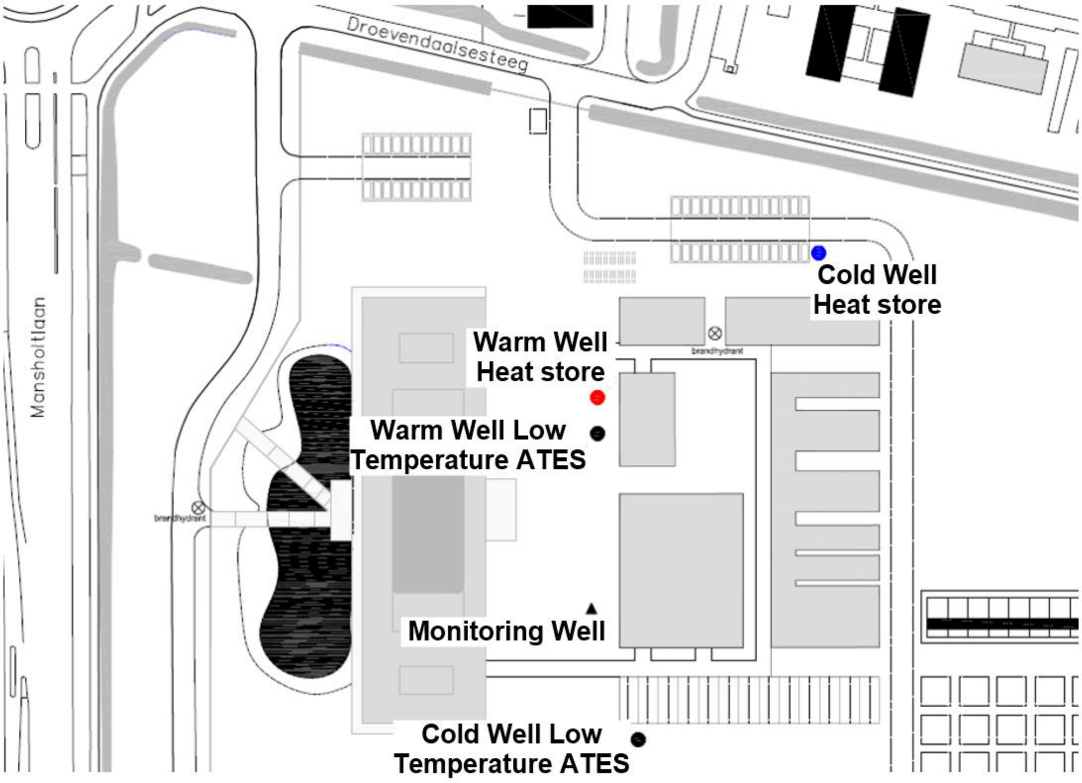

Figure 7 Positions of the wells and monitoring wells NIOO Wageningen

Recovery efficiency

The system was designed with a recovery efficiency of 45 % (Table 4). Untill now the efficiency is between 10 and 20 % and the recovered heat is only 5 % of what was expected (Table 4). The latter is mainly caused by the installation of less solar collectors and the lower capacity of the groundwater system. The recovery efficiency is negatively influenced by:

- The subsurface temperature at storage depth is lower (14 °C) than assumed in the design (18 °C).
- The stored water temperature (45 °C) is too close to the cut-off temperature (40 °C). In 2016 the cut-off temperature is lowered to 30 °C)
- A much smaller stored volume.

Table 4 Amounts of energy displaced per year

	Recovered heat [MWht]	**Stored heat [MWht]**	**Recovery efficiency [%]**
designed	**578**	**1.283**	**45 %**
2011	18,5	100,4	18%
2012	0,0	182,7	0%
2013	0,6	305,6	0%
2014	34,3	271,4	13%
2015	7,9	232,1	3%
2016	55,5	320,4	17%
average	19,5	235,4	8%

Temperature measurements

The subsurface temperature was measured in the monitoring wells every five meters. Figure 8 shows the results for the warm and the cold wells up to 2016. In the subsurface temperature measurements, the effects of both the regular ATES (up to about 65 mbgl) and the medium-temperature heat storage system (from around 220 mbgl) are visible.

The temperature in the warm well has been increased to approximately 36 ºC due to the storage of heat in 2016 (was 30 ºC in 2013). The deepest measurement was measured at 220 meters. Currently, the monitoring well is obstructed, and measuring is no longer possible. The temperature in the cold well is comparable with the measurements in 2013 (relatively warm in autumn). In the monitoring well (Figure 8) the seasonal influence of the shallow ATES is clearly visible: the temperature decreases in the spring (after injection of cold in the winter period), and in the autumn (after injection of heat in the summer period). The monitoring well lies outside the thermal influence area of the medium-temperature heat storage

Extensive analyses of the NIOO project is made in workpackage 5 of the HEATSTORE project.

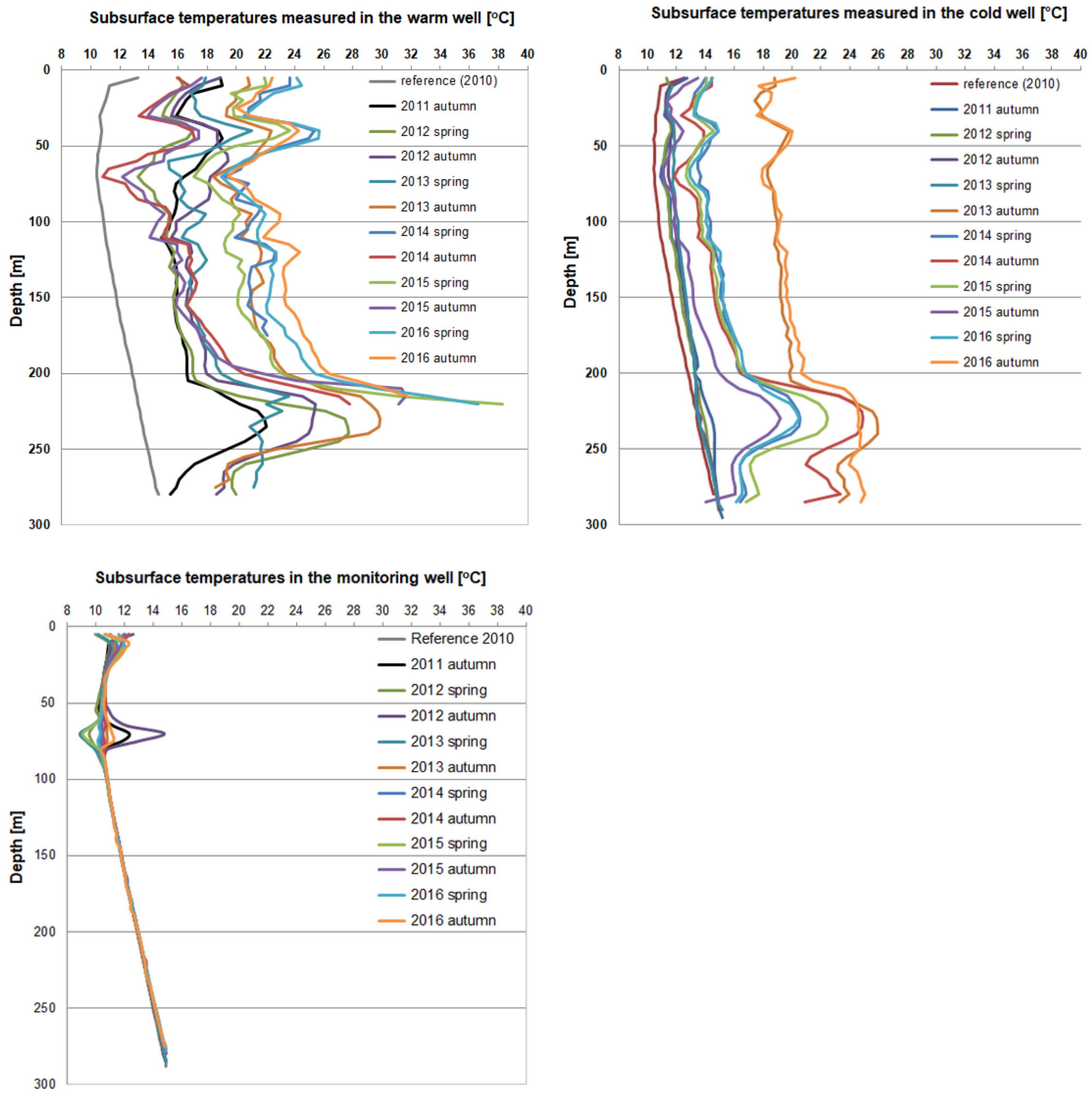

Figure 8 Results of subsurface temperature measurements NIOO Wageningen

4.3 High temperature aquifer thermal energy storage

4.3.1 Utrecht University (1991-1999)

Figure 9 Campus Utrecht University

The heat storage at Utrecht University has been unique in the world as the only high temperature ATES system. The heat storage was commissioned in 1991. In 1999 the warm well was damaged, and the storage was taken out of service. The functioning of the heat storage has been extensively evaluated (IF Technology, 2001)

The ATES stored residual heat from the university's combined heat and power (CHP) plants in the summer period. The heat storage consisted of a cold and a warm well, both in the third aquifer at a depth of 220 to 260 mbgl (Figure 10). The storage was designed for a storage capacity of 6 MW_t and a storage quantity of 6,000 MWh/year (21,600 GJ); the predicted recovery efficiency was 59 %.

Recovery efficiency

The measured average recovery efficiency of the storage was 33 % during the nine years the system operated (see Table 5). In the period 1994-1997 efficiency was 53 %. The low recovery efficiency was partly caused by failures of the CHPs (less heat stored). More importantly, the return temperature (= cut-off temperature) from the building was far too high. As a consequence, the heat storage could add little heat to the central heating system the cut-off temperature was reached after extraction of a limited amount of water. As a result, the storage still contained a lot of heat at the end of the winter. Conclusion is that the low average recovery efficiency of 33 % was mainly caused by the high return temperatures from the building and not by losses in the subsurface.

Table 5 Recovery efficiency University Utrecht

year	Stored heat GJ	Recovered heat GJ	Recovery Efficiency %

design	21.600	12.660	59
1991	18.979	1.927	10
1992	9.836	3.503	37
1993	19.380	3.350	17
1994	15.225	6.301	41
1995	20.792	4.765	23
1996	8.330	5.670	68
1997	4.648	3.729	80
1998	2.903	435	15
1999	13.079	765	6
average			33

Temperature measurements
After the first storage cycle the measured temperatures were use the calibrate the hydrothermal model HST-3D (see Figure 11) (Heidemij, 1996). This calibrated model was used to predict the thermal efficiency and thermal impact after the fourth cycles (see Figure 12)

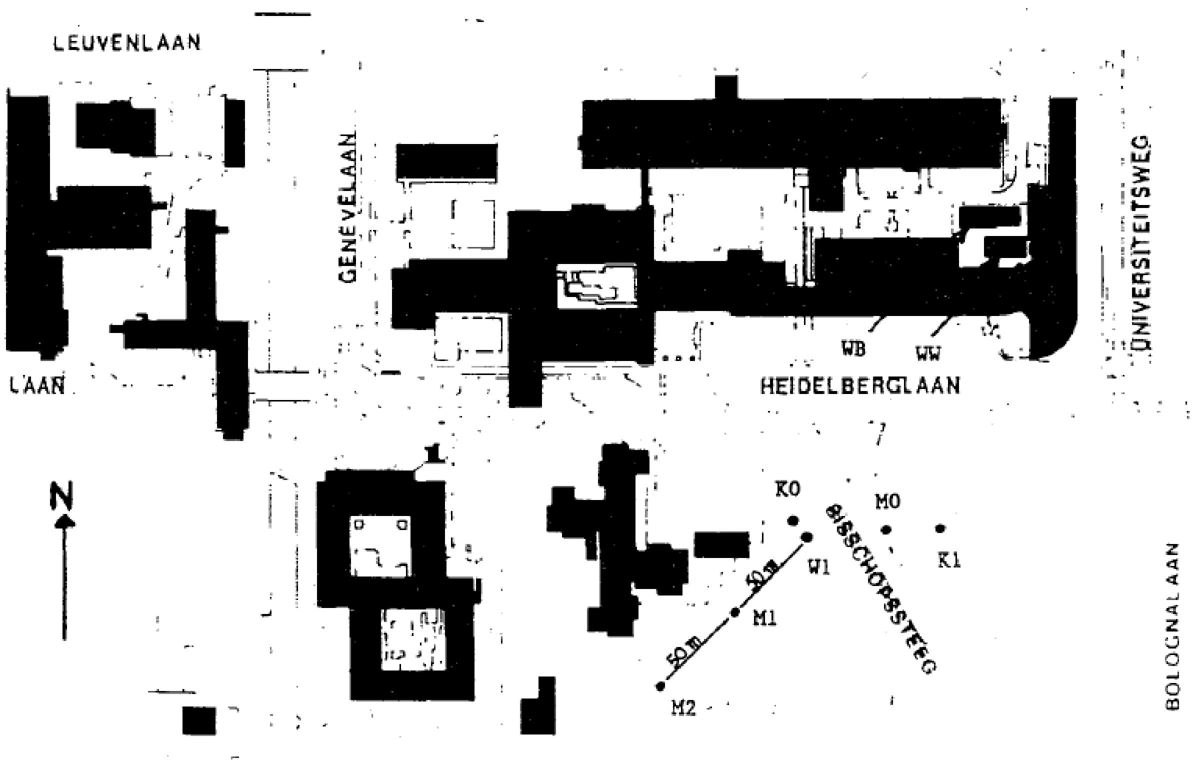

Figure 10 Location of wells and monitoring wells at HT-ATES University Utrecht

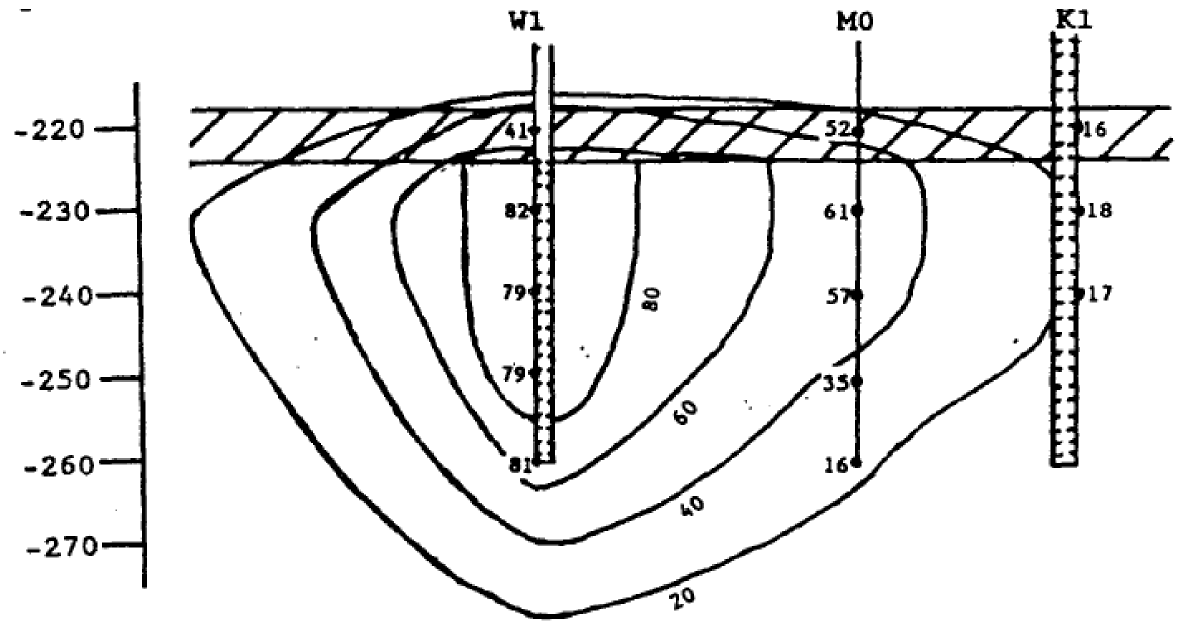

Figure 21 Measured and calculated temperatures after the first storages cycle at HT-ATES University Utrecht

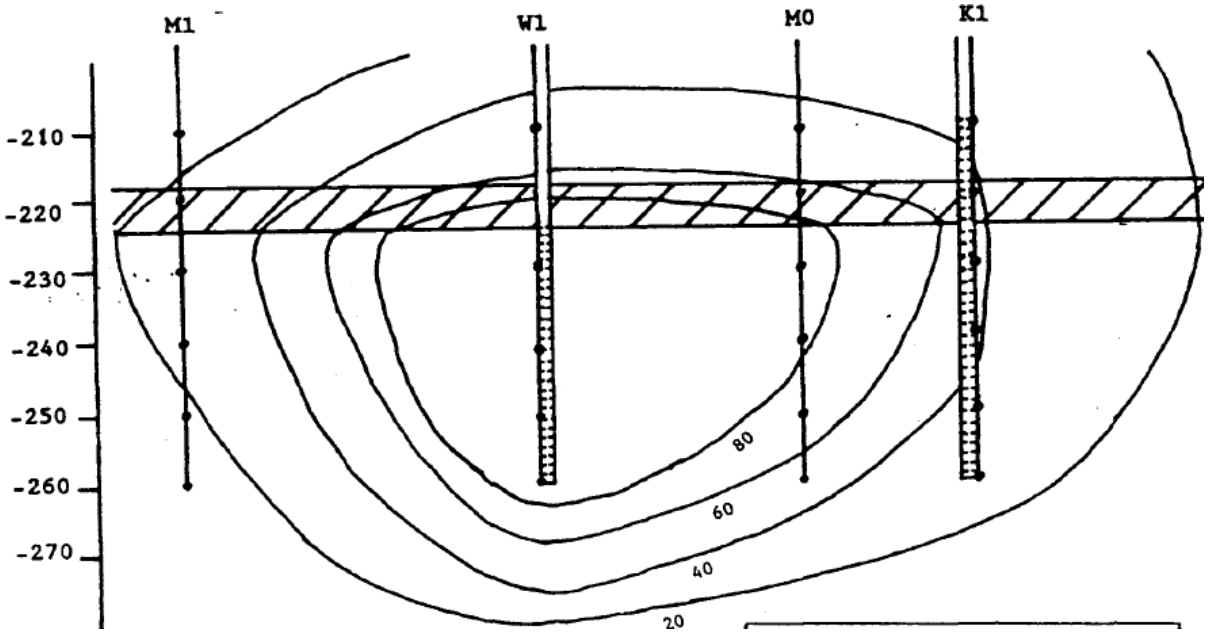

Figure 32 Modelled temperatures profile after the fourth cycle at HT-ATES University Utrecht

4.3.2 Hooge Burgh Zwammerdam (1998-2009)

The Hooge Burgh health care institution in Zwammerdam has a combined heat power plant (CHP) for electricity production and heating. The installation was also equipped with a high temperature heat storage system at a depth of approximately 180 mbgl. Heat is stored at 90 ºC when the CHP runs for electricity production and the heat demand is smaller than the heat production. The stored heat can be used later for heat supply to the health care institution. The heat storage consists of a cold and a warm well, both in an aquifer at a depth of 135 to 151 mbgl. The distance between the cold and the warm well is approximately 67 m. The storage was designed for storage of 2,250 MWh_t of heat per year. The expected recovery efficiency was 49 %.

The heat storage has been carefully managed for 5 years. After that, the heat storage has been taken out of operation for financial reasons. The reason was that the CHP is the main source of heat. The CHP is controlled by electricity demand. The electricity is then returned to the grid at a favourable rate. Monitoring data have shown that the feed-in fee for electricity production and heat storage profits were financially unattainable. It was decided to reduce the CHP in operating hours and not to use the heat storage anymore.

The system was put into operation in 1998. In 2003, hardly any water was pumped and in the following years the system was no longer used. In 2009, the license was withdrawn on request. Three monitoring wells are present at the heat store system. Figure 13 shows the locations of the wells and monitoring wells. As prescribed in the Groundwater Act license, measurements were performed on chemistry, microbiology, hydraulic head and subsurface temperature.

Recovery efficiency

The expected recovery efficiency is determined for the initial situation in which an average of 41,000 m^3 of groundwater is pumped in summer and winter; this is therefore 82,000 m^3 per year (see Table 6). The measurement data shows that less groundwater is pumped than expected: for the years 1999 to 2001, an average of approx. 47,500 m^3 per year has been pumped; this is 58% of the expected quantity.

The expected amount of energy stored in the summer period was 2,250 MWh (charging) and the amount of heat to be recovered in the winter period was 1,100 MWh in winter (discharging). In the period 1999-2001, an average of 1,561 MWh per year was charged and 167 MWh discharged. So 69% of the expected amount of energy was charged, and only 15% of the expected amount of energy was discharged (IF Technology,2002).

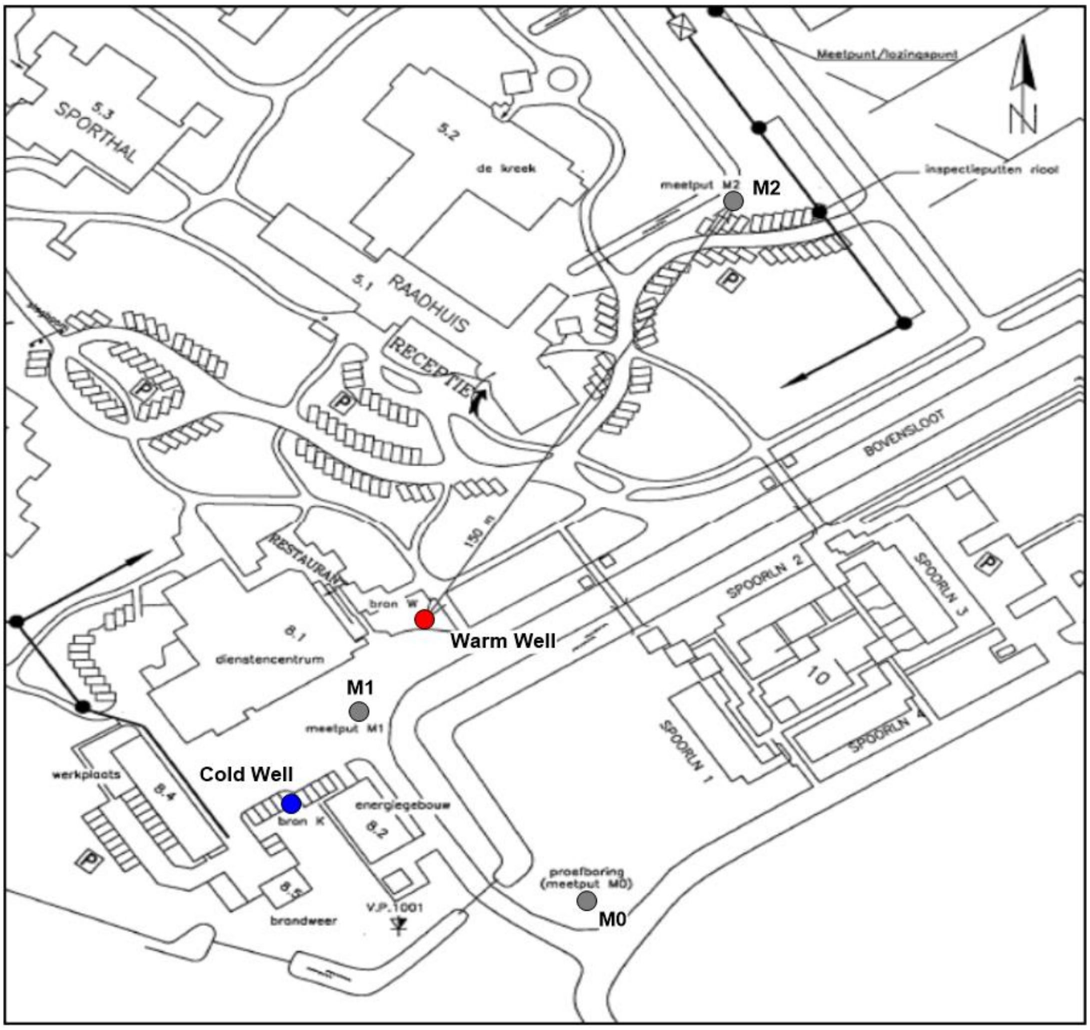

Figure 43 Wells Hooge Burch Zwammerdam

Table 6 shows the pumped water and energy quantities and the average extraction and infiltration temperatures.

Table 6 Water and energy volumes Hooge Burch Zwammerdam

year	Charging (heat storage)			Discharging (heat recovery)		
	pumped water volume [m³]	average extraction temperature [°C]	average infiltration temperature [°C]	pumped water volume [m³]	average extraction temperature [°C]	average infiltration temperature [°C]
1998	19,226	13	71	2,513	54	44
1999	18,923	25	81	4,944	72	62
2000	24,662	37	86	21,097	59	55
2001	22,424	44	82	21,162	58	54

Table 7 Recovery efficiency Hooge Burch Zwammerdam

Year	1998	1999	2000	2001
Recovery efficiency	3,45%	10,3%	11,3%	10,4%

Table 7 shows that the expected recovery efficiency has not been achieved. This can be explained by the fact that annually less groundwater is pumped than expected (58% of the expected amount) and from the high cut-off temperature combined with the rapid decrease of the extraction temperature during discharging (resulting in a small temperature difference during heat supply and only a small amount of heat supplied to the building).

Temperature measurements

During the “Meer met Bodemenergie” research project, this HT-ATES system has been hydrothermally modelled (Drijver, 2012).

The calculation of the thermal effects of the heat storage was carried out with the program HstWin-3D. With the HstWin-3D program heat and solute transport can be simulated in a saturated 3-dimensional groundwater system.

Based on the extraction / infiltration pattern shown in Table 6, the groundwater system was modelled. The calculations assumed that the storage was stopped after 2001 (insufficient data available for 2002). Subsequently another 96 years were simulated (so 100 years has been calculated) to see how the thermal effects develop in time after stopping the HT-ATES.

Figure 14 shows cross sections of the calculated temperatures after the first and fourth heat storage season.

After stopping the heat storage (in the model after 2001), the residual heat will spread gradually and at the same time the temperature level will decrease. The calculated temperatures in 2005, 2011, 2020 and 2038 are shown in cross sections in Figure 15. The temperature in the subsurface does not deviate more than 2 ºC from the natural groundwater temperature approximately 35 years after storage has ceased. From the calculations it follows that about 70 years after the storage is stopped the temperature in the subsurface does not deviate by more than 0.5 ºC from the natural groundwater temperature. It has to be noted, that in this project relatively small amounts of heat have been stored. Therefore, the residual heat “dilutes” relatively rapid. For a larger scale HT-ATES, the thermal effects are expected to be much more pronounced and last much longer after ending the project.

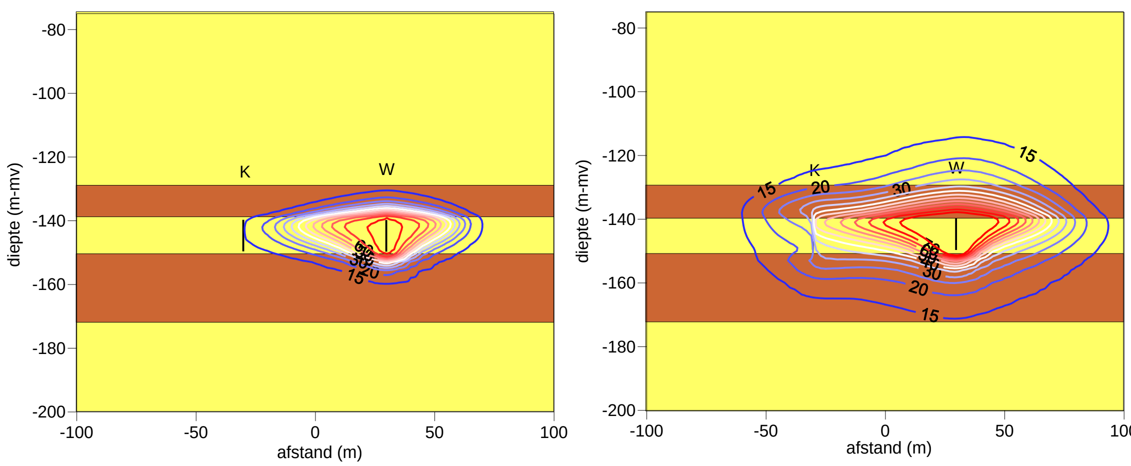

Figure 14 Calculated temperature first and fourth storage season

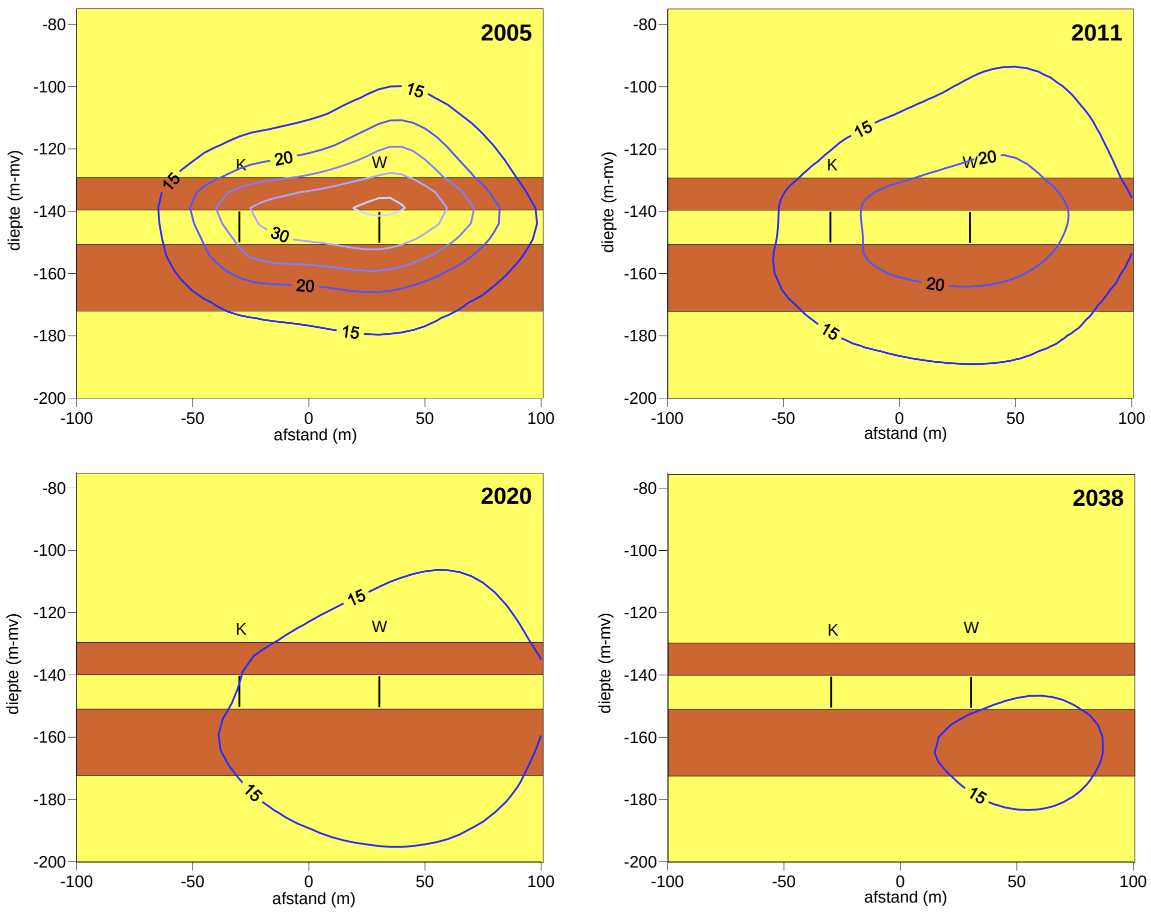

Figure 15 Calculated temperature after stopping the heat storage

4.4 Conclusions on project experiences

The measured recovery efficiency for all the HT-ATES is lower than designed (Table 8). The main reasons are:

- The storage volumes of the projects are lower than designed. This makes them extra vulnerable for high thermal losses;
- Some low temperature projects (Harderwijk and Eindhoven) are made in formations with very course sand. Buoyancy flow will decrease efficiency;
- The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in the building was not adapted to the extraction temperatures from the heat store.

Table 8 Recovery efficiency (designed versus measured)

Project	Year of installing	Storage temperature [°C]	Design recovery efficiency (%)	Measured Recovery efficiency (%)
Utrecht University	1991	90	59	33
Heuvelgalerie Shopping Mall Eindhoven	1992	32	60	55
Dolfinarium Harderwijk	1997	40	55	40
Hooge Burch Zwammerdam	1998	88	49	10
NIOO, Wageningen	2011	45	45	15

All the projects were evaluated with the HSTWIN-3D-software. The modelled recovery efficiency and temperature fields show good similarity with the measured values.

5 Design criteria on recovery efficiency for future HT-ATES projects

In general more than 50 % of the stored energy in the existing HT-ATES projects was not used for heating. Besides the negative influence on the profitability of the HT-ATES project, also the authorities and other subsurface stakeholders will have their concerns about thermal and environmental impact of HT-ATES. For future projects the recovery efficient will have to be increased. In this chapter some suggestions based on validated models are made for improving recovery efficiency.

5.1 Subsurface design rules

Make HT-ATES of sufficient size.

Because water with a high temperature has a lower density than the ambient groundwater in the used aquifers, the warm water tends to flow to the upper part of the aquifer. This process can have major negative consequences for the storage efficiency. For high-temperature heat storage systems (seasonal storage), based on a large number of model calculations, a relationship has been derived (IF Technology/SKB, 2012 ; Schout et al., 2014) between the recovery efficiency and the following parameters:
• the stored volume of hot groundwater (V);
• the well screen length / thickness of the aquifer (H) used;
• the temperatures of the natural groundwater in the storage aquifer (T_a) and the stored water (T_i);
• the horizontal and vertical permeability (k_h and k_v) of the aquifer used.

Figure 56 shows the recovery efficiencies that were calculated with this relationship as a function of the storage volume at different hydraulic conductivities, storage temperatures and well screen lengths. These tables are based on a number of assumptions:

1) the volumes of water that are pumped during storage and recovery are equal;
2) the cold well temperature of the is equal to the ambient groundwater temperature in the storage aquifer (assumed to be 12 ºC);
3) the efficiency is given for the fourth year;
4) interaction between the warm and cold well is insignificant;
5) heat losses by regional groundwater flow are negligible.

Since at least some of these assumptions will not be true in a real case, the recovery efficiency in practice may differ. The derived relation is especially useful to make a selection of the best aquifer for storage. For a proper assessment of the recovery efficiency in practice, numerical simulations are required.

Storage Temperature 30°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	75%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%
10	2	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	2	70%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
20	2	67%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
30	2	62%	64%	66%	68%	69%	71%	72%	73%	73%	74%	74%	74%
40	2	57%	60%	62%	65%	66%	68%	70%	71%	71%	72%	73%	73%
50	2	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%
5	5	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
10	5	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%
15	5	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%	78%	78%
20	5	74%	74%	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%
30	5	71%	72%	73%	74%	75%	75%	76%	76%	76%	76%	77%	77%
40	5	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
50	5	67%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
5	10	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
10	10	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
15	10	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%	78%	78%
20	10	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%
30	10	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%	78%	78%
40	10	74%	74%	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%
50	10	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%

Storage Temperature 30°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
10	2	70%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
15	2	66%	68%	70%	71%	73%	74%	75%	75%	76%	76%	77%	77%
20	2	62%	64%	67%	69%	70%	72%	73%	74%	74%	75%	75%	76%
30	2	54%	57%	61%	63%	66%	68%	69%	71%	72%	72%	73%	74%
40	2	47%	51%	55%	59%	61%	64%	66%	68%	69%	70%	71%	71%
50	2	41%	46%	50%	54%	57%	60%	63%	65%	66%	68%	69%	69%
5	5	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%	80%	80%
10	5	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%	79%
15	5	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%
20	5	72%	74%	75%	75%	76%	77%	77%	78%	78%	78%	78%	79%
30	5	69%	70%	72%	73%	74%	75%	76%	76%	77%	77%	77%	78%
40	5	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
50	5	62%	64%	67%	69%	70%	72%	73%	74%	74%	75%	75%	76%
5	10	79%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
10	10	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%	80%	80%
15	10	77%	78%	78%	79%	79%	79%	79%	79%	80%	80%	80%	80%
20	10	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%	79%
30	10	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%
40	10	72%	74%	75%	75%	76%	77%	77%	78%	78%	78%	78%	79%
50	10	70%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%

Storage Temperature 50°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%	77%
10	2	63%	66%	68%	69%	70%	71%	72%	73%	74%	74%	75%	75%
15	2	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
20	2	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	71%	71%
30	2	42%	46%	50%	54%	57%	59%	62%	64%	65%	66%	67%	68%
40	2	34%	38%	43%	47%	51%	54%	57%	60%	61%	63%	64%	65%
50	2	27%	32%	37%	42%	46%	49%	53%	56%	58%	59%	61%	62%
5	5	75%	76%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%
10	5	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	5	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
20	5	66%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
30	5	61%	63%	66%	67%	69%	70%	71%	72%	73%	73%	74%	74%
40	5	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%	72%	73%
50	5	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	71%	71%
5	10	77%	77%	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%
10	10	75%	76%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%
15	10	74%	74%	75%	76%	76%	76%	77%	77%	77%	77%	77%	77%
20	10	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
30	10	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
40	10	66%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
50	10	63%	66%	68%	69%	70%	71%	72%	73%	74%	74%	75%	75%

Storage Temperature 50°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	68%	69%	71%	72%	74%	75%	75%	76%	76%	77%	77%	77%
10	2	57%	60%	63%	65%	67%	69%	71%	72%	73%	73%	74%	74%
15	2	48%	52%	55%	59%	61%	64%	66%	68%	69%	70%	71%	72%
20	2	40%	45%	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%
30	2	28%	33%	38%	43%	47%	51%	54%	57%	59%	61%	62%	64%
40	2	20%	25%	30%	35%	39%	44%	48%	51%	54%	56%	57%	59%
50	2	14%	18%	23%	28%	33%	37%	42%	46%	49%	51%	53%	54%
5	5	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
10	5	70%	71%	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%
15	5	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
20	5	61%	63%	66%	68%	70%	71%	72%	73%	74%	75%	75%	76%
30	5	53%	56%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
40	5	46%	50%	54%	58%	60%	63%	65%	67%	68%	69%	70%	71%
50	5	40%	45%	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%
5	10	78%	78%	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%
10	10	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
15	10	72%	74%	75%	76%	76%	77%	77%	78%	78%	78%	78%	79%
20	10	70%	71%	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%
30	10	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
40	10	61%	63%	66%	68%	70%	71%	72%	73%	74%	75%	75%	76%
50	10	57%	60%	63%	65%	67%	69%	71%	72%	73%	73%	74%	74%

Storage Temperature 70°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	64%	66%	68%	70%	71%	72%	73%	74%	74%	74%	75%	75%
10	2	53%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%
15	2	44%	48%	52%	55%	58%	61%	63%	65%	66%	67%	68%	69%
20	2	36%	40%	45%	49%	52%	56%	59%	61%	63%	64%	65%	66%
30	2	24%	29%	34%	39%	43%	47%	51%	54%	56%	58%	59%	60%
40	2	16%	21%	26%	31%	35%	39%	44%	47%	50%	52%	54%	55%
50	2	11%	15%	20%	24%	29%	33%	38%	42%	45%	47%	49%	51%
5	5	73%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
10	5	67%	69%	70%	71%	72%	73%	74%	75%	75%	75%	76%	76%
15	5	62%	64%	66%	68%	70%	71%	72%	73%	73%	74%	74%	74%
20	5	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
30	5	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%	70%	71%
40	5	42%	46%	50%	54%	57%	60%	62%	64%	65%	66%	67%	68%
50	5	36%	40%	45%	49%	52%	56%	59%	61%	63%	64%	65%	66%
5	10	75%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%
10	10	73%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	10	70%	71%	72%	73%	74%	74%	75%	76%	76%	76%	76%	76%
20	10	67%	69%	70%	71%	72%	73%	74%	75%	75%	75%	76%	76%
30	10	62%	64%	66%	68%	70%	71%	72%	73%	73%	74%	74%	74%
40	10	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
50	10	53%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%

Storage Temperature 70°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	58%	61%	64%	66%	68%	70%	71%	72%	73%	74%	74%	75%
10	2	42%	47%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%
15	2	30%	35%	40%	45%	49%	53%	56%	59%	61%	62%	64%	65%
20	2	22%	27%	32%	37%	41%	46%	50%	53%	55%	57%	59%	60%
30	2	12%	16%	20%	25%	30%	34%	39%	43%	46%	48%	50%	52%
40	2	6%	9%	13%	17%	21%	26%	31%	35%	38%	41%	43%	45%
50	2	3%	5%	8%	12%	15%	19%	24%	28%	32%	34%	37%	39%
5	5	71%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
10	5	62%	65%	67%	69%	70%	72%	73%	74%	75%	75%	76%	76%
15	5	55%	58%	61%	64%	66%	68%	70%	71%	72%	73%	73%	74%
20	5	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
30	5	37%	42%	46%	51%	54%	57%	60%	63%	64%	66%	67%	68%
40	5	29%	34%	39%	43%	47%	51%	55%	58%	60%	61%	63%	64%
50	5	22%	27%	32%	37%	41%	46%	50%	53%	55%	57%	59%	60%
5	10	75%	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%
10	10	71%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
15	10	66%	68%	70%	72%	73%	74%	75%	76%	76%	76%	77%	77%
20	10	62%	65%	67%	69%	70%	72%	73%	74%	75%	75%	76%	76%
30	10	55%	58%	61%	64%	66%	68%	70%	71%	72%	73%	73%	74%
40	10	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
50	10	42%	47%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%

Storage Temperature 90°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
10	2	42%	46%	50%	54%	57%	60%	62%	64%	65%	67%	67%	68%
15	2	31%	36%	40%	45%	49%	52%	55%	58%	60%	61%	63%	64%
20	2	23%	27%	32%	37%	41%	45%	49%	52%	55%	56%	58%	59%
30	2	12%	16%	21%	26%	30%	35%	39%	43%	46%	48%	50%	52%
40	2	6%	10%	13%	18%	22%	26%	31%	35%	38%	41%	43%	45%
50	2	3%	6%	9%	12%	16%	20%	25%	29%	32%	34%	37%	39%
5	5	69%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
10	5	61%	64%	66%	68%	69%	70%	71%	72%	73%	73%	74%	74%
15	5	54%	57%	60%	63%	65%	67%	68%	69%	70%	71%	72%	72%
20	5	48%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	70%
30	5	37%	42%	46%	50%	53%	56%	59%	62%	63%	64%	65%	66%
40	5	29%	34%	39%	43%	47%	51%	54%	57%	59%	60%	62%	63%
50	5	23%	27%	32%	37%	41%	45%	49%	52%	55%	56%	58%	59%
5	10	74%	74%	75%	76%	76%	76%	77%	77%	77%	77%	77%	77%
10	10	69%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
15	10	65%	67%	69%	70%	71%	72%	73%	74%	74%	75%	75%	75%
20	10	61%	64%	66%	68%	69%	70%	71%	72%	73%	73%	74%	74%
30	10	54%	57%	60%	63%	65%	67%	68%	69%	70%	71%	72%	72%
40	10	48%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	70%
50	10	42%	46%	50%	54%	57%	60%	62%	64%	65%	67%	67%	68%

Storage Temperature 90°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
10	2	29%	34%	39%	43%	47%	51%	55%	58%	60%	61%	63%	64%
15	2	17%	22%	27%	32%	36%	41%	45%	49%	51%	54%	55%	57%
20	2	10%	14%	19%	23%	28%	33%	37%	41%	44%	47%	49%	51%
30	2	4%	6%	9%	13%	16%	21%	25%	30%	33%	36%	38%	40%
40	2	1%	2%	4%	7%	10%	13%	17%	21%	24%	27%	30%	32%
50	2	0%	1%	2%	4%	6%	8%	12%	15%	18%	21%	23%	25%
5	5	65%	68%	70%	71%	72%	73%	74%	75%	76%	76%	77%	77%
10	5	53%	57%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
15	5	43%	48%	52%	56%	59%	61%	64%	66%	67%	68%	69%	70%
20	5	35%	40%	45%	49%	53%	56%	59%	62%	63%	65%	66%	67%
30	5	23%	28%	34%	38%	43%	47%	51%	54%	56%	58%	60%	61%
40	5	15%	20%	25%	30%	34%	39%	43%	47%	50%	52%	54%	56%
50	5	10%	14%	19%	23%	28%	33%	37%	41%	44%	47%	49%	51%
5	10	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%	78%	79%
10	10	65%	68%	70%	71%	72%	73%	74%	75%	76%	76%	77%	77%
15	10	59%	62%	65%	67%	69%	70%	72%	73%	74%	74%	75%	75%
20	10	53%	57%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
30	10	43%	48%	52%	56%	59%	61%	64%	66%	67%	68%	69%	70%
40	10	35%	40%	45%	49%	53%	56%	59%	62%	63%	65%	66%	67%
50	10	29%	34%	39%	43%	47%	51%	55%	58%	60%	61%	63%	64%

Figure 56 Estimated recovery efficiency for different storage temperatures, aquifer thickness values and vertical anisotropy (k_h/k_v) values

Some observation from Figure 5:

- The recovery efficiency is never higher than 80%. This is explained by heat losses caused by heat conduction and dispersion, that also occur at low temperatures.
- The recovery efficiency at low storage temperatures is higher than at high temperatures. At high temperatures, heat losses caused by density driven flow increase (the higher the storage temperature, the bigger the density difference between the ambient groundwater and the stored water).
- When higher temperatures are stored, the recovery efficiency significantly increases with decreasing hydraulic conductivity of the storage aquifer and/or increasing vertical anisotropy. This is because density driven flow is suppressed in less permeable aquifers.
- A small well screen length results in a higher recovery efficiency for the same storage volume, because the relative impact of density driven flow is smaller. A drawback of a small well screen length is that the capacity per well is also smaller (resulting in higher investment costs).
- The recovery efficiency significantly improves when the storage volume is increased, especially at high storage temperatures. When large volumes are stored, the tilting of the thermal front occurs further away from the well and therefore the impact on the recovery efficiency becomes smaller. Furthermore, the surface area/volume ratio of the hot bubble becomes smaller, reducing the relative heat losses by conduction.

When high temperatures are stored (70 and 90 °C), the tendency for density driven flow is strong. As a result, small storage volumes usually lead to low recovery efficiencies. Furthermore, layers of lower hydraulic conductivity and/or higher anisotropy are required to suppress density driven flow. In the Netherlands the Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis formations are the most interesting aquifers for storage of high temperature heat. At most locations these layers are located at a depth of more than 150 mbgl. Although the permeability of these layers is usually not well known, the permeabilities are relatively low compared to the shallower aquifers. The disadvantage of these moderately permeable aquifers is that the current design standards indicate low flow rates per well, which adversely affects the economic feasibility of projects in these aquifers. It is therefore key to find an optimum between recovery efficiency (a lower permeability is favourable to reduce thermal losses by density driven flow) and investment costs (an aquifer with a higher permeability is favourable, since higher flow rates per well can be achieved, which reduces the amount of wells that are required). For each location a consideration has to be made, based on the local hydrogeological conditions (number of aquifers present with associated depths and properties) (e.g. Drijver et al., 2012).

When relatively low temperature heat is stored (30 and 50 °C), the decrease in density is smaller. In that case storage volume is less important and the recovery efficiency can be acceptable in layers with a relatively high hydraulic conductivity. It is important here to also consider any additional losses under the influence of the regional groundwater flow (for the same hydraulic gradient a higher permeability results in a higher groundwater flow velocity).

For the Dutch target formations (Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis) the following design considerations could be defined based on the following assumption: Screen length 50 m (to get economical feasible projects), K horizontal < 10 m/d, minimal recovery rate: 70 %, Anistropie 2-5:

- A HT-ATES with a temperature of 90 °C needs a minimum storage volume between 250.000 and 500.000 m^3/season.
- A HT-ATES with a temperature of 50 °C needs a minimum storage volume between 35.000 and 180.000 m^3/season

Test drilling is always necessary

The aquifers that are suitable for heat storage are often subject to limited research. This is mainly because these aquifers have never been attractive for drinking water extraction or low temperature cold / heat storage. Research through a test drilling is necessary to show where layers are located and which water quality they have. It is also desirable to perform a pumping test because the estimation of permeabilities based on grain sizes in such fine-sand packages (this usually concerns permeability <5 m/d) is too inaccurate. To reduce costs, a test drilling can be used later as a monitoring well (which is usually a requirement in the permit for a heat storage project).

Use 3-D Modelling, with accurate subsurface and time schematization

Reliability predicted effects
The reliability of the predicted effects depends on the reliability of the input in the model. This concerns the usage pattern of the system (pumped water quantities, extraction and infiltration temperatures and variation over time), the properties of the system (locations of wells, screen lengths and screen depths) and the subsurface (heterogeneity, permeability).

The model schematization is also important. For example, a 3-dimensional thermal transport model is required to correctly calculate the effects of density-driven groundwater flow (e.g. HSTWIN-3D, Modflow/SEAWAT, FEFLOW).

Heterogeneity
In groundwater models it is usually assumed that the storage aquifer is homogeneous: this means that it is assumed that the permeability in the entire aquifer is constant. This is not the case in reality, but there is often no good information about the heterogeneity at the location. Heterogeneity affects the distribution of the stored heat in the subsurface. When infiltrating the heated groundwater, a relatively large part of the water will flow into the coarsest sand layers, because they have the highest permeability. In case of groundwater extraction, however, a relatively large proportion of the extracted water is also produced from the same coarse sand layers. As a result, heterogeneity does influence the distribution of the heat in the subsurface, but the influence on the storage efficiency is usually limited. If, however, there is strong heterogeneity or if the cold and warm wells are close to each other, the influence of heterogeneity can be important.

Time scheme
When modelling heat storage in the subsurface, it is usually assumed that there is one period in which heat is stored continuously and one period in which heat is continuously supplied (for example two periods of six months). The average time that the supplied heat is stored is in that case about half a year. Realistically the system is controlled by the supply and the demand for heat, which varies over time. As a result, the flow rate and the pump direction of the heat storage system also varies over time. Due to the fluctuating pump regime (mainly pumped back and forth in the mid-season) the average storage period will in reality be somewhat shorter than half a year. Because heat losses due to processes such as heat conduction, regional groundwater flow and density-driven flow are time-consuming, a somewhat shorter average storage time will result in a somewhat higher average extraction temperature. The modelling therefore gives a slightly less favourable picture. When the cut-off temperature is reached during the winter season, the average storage time is also somewhat shorter. Generally this is favourable for the storage efficiency, but the fact that the cut-off temperature is reached is (obviously) detrimental to the storage efficiency.

Perform a sensitivity analysis for the recovery efficiency

The projects presented in this report indicate that there is a clear difference between the predicted recovery efficiency and the actual recovery efficiency. This can often be explained by the fact that the recovery efficiency of MT-ATES / HT-ATES is sensitive to variations in the storage volume, the storage temperature, the cut-off temperature and the permeability of the aquifer. In the preliminary phase it is therefore important to address the uncertainties in these parameters and the consequences of these uncertainties for the feasibility of the project. For example, the project can be feasible with a large storage volume and a high storage temperature, but not feasible in case of a smaller storage volume and / or a lower storage temperature. In certain cases, it may be useful to carry out additional research to reduce the uncertainties in the key parameters and thus to obtain more certainty about the feasibility in practice.

5.2 System integration design rules

Based on the experience with the current projects, the following design rules have been compiled for the integration with the building system.

Ensure that the usable temperature is as low as possible

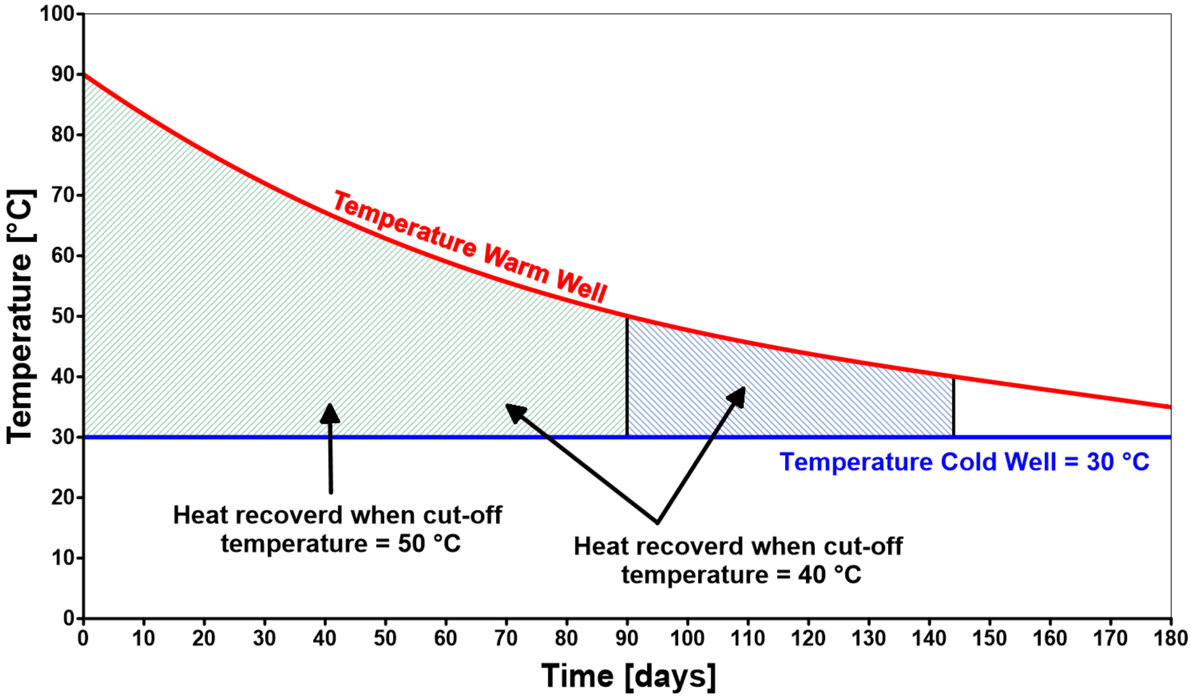

Figure 6 Example of the impact of different cut-off temperatures on the amount of heat that can be extracted

The recovery efficiency of the storage is determined not only by the heat loss in the subsurface, but also by the minimum usable extraction temperature from the hot well. This is referred to as the "cut-off temperature". At this cut-off temperature the maximum required heating power can be supplied under design conditions. The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency. Figure 17 shows the relationship between cut-off temperature and the amount of heat that can be extracted from the subsurface with heat storage at 90 ºC. Lowering the cut-off temperature with 10 º can increase the recovery efficiency significantly (e.g. by 10 to 15 %).

<u>Use STAR well configurations.</u>

The HT-ATES well configuration normally consists of a doublet (one cold and one warm well). If more capacity is required more doublets were used. During the design of the HT-ATES at GEOMEC-4-P (IF technology, 2013) the wells were configurated in a star-shape; warm wells in the middle and a ring of cold wells. In this configuration the cold wells will insulated the heat around the warm wells (see Figure 18) and efficiency will increase up to 10 % (Drijver 2012).

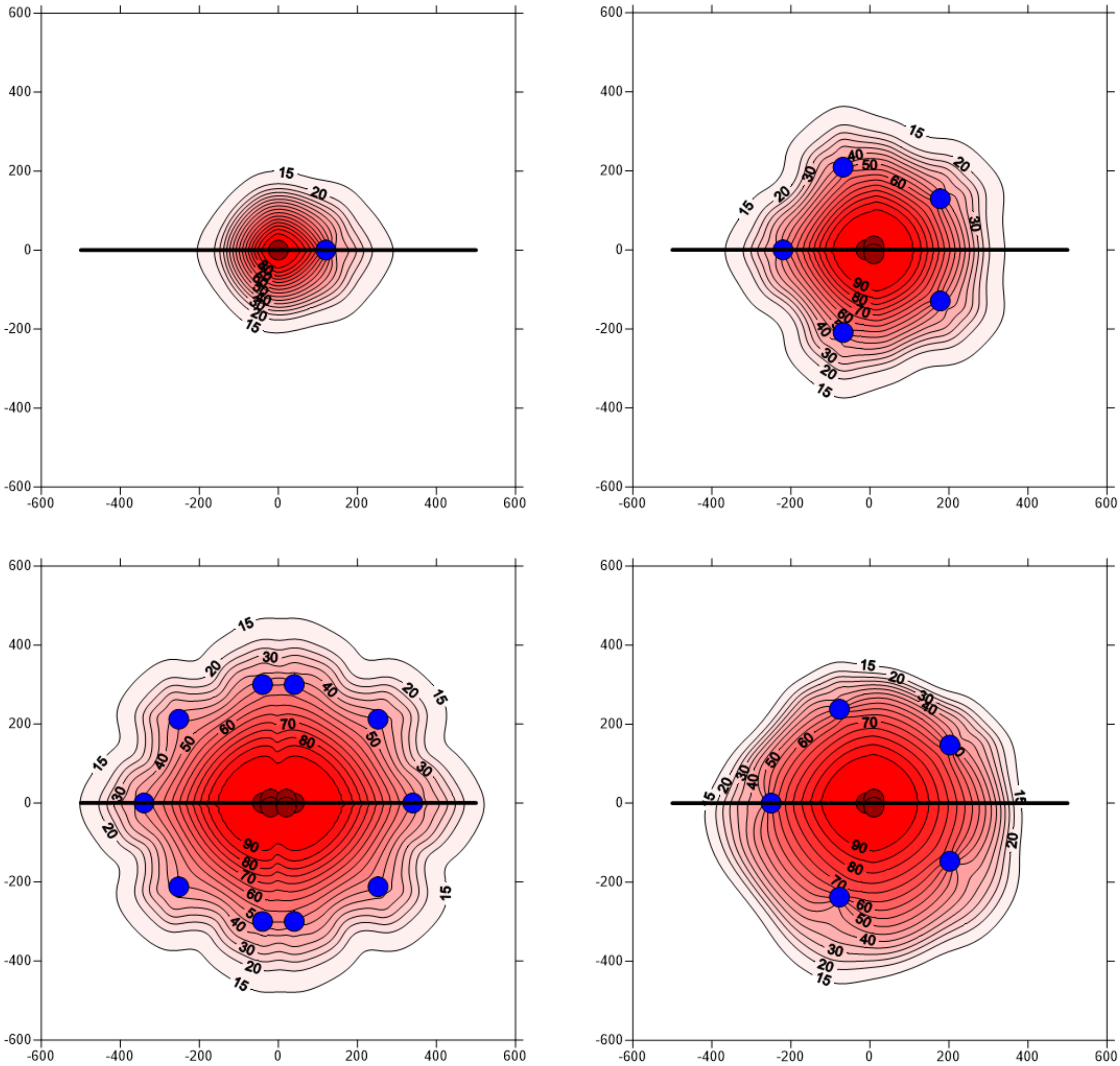

Figure 7 Different star-shape well configurations in comparison with a doublet-shape configuration (up left)

MT-ATES (50 °C) is technically less complicated than HT-ATES (90 °C)

MT-ATES (storing heat up to 50 °C) has significant technical advantages over HT-ATES (less density-driven groundwater flow, it can be used in aquifers with a higher permeability, no special high temperature resistant materials needed, no water treatment required and environmental (temperature) effects are smaller. Disadvantages of MT-ATES are that heat from a lower temperature level is suitable for less applications and a higher flow rates (and larger volumes of water) are needed for the same heating power.

Use heat storage systems in base load

The heat storage is a slow-reacting system because the heat must come from a large depth (e.g. 150-300 mbgl) and because pipe systems must be heated up. To minimize start-up losses and heating losses, it is recommended to use the heat storage as the base load of the heating system. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat. Day/night storage could also increase seasonal recovery efficiency.

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