INTERNATIONAL SUMMER SCHOOL on Direct Application of Geothermal Energy

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Chapter 2.6

GROUNDWATER AS A HEAT SOURCE FOR GEOTHERMAL HEAT PUMPS

B. Drijver and A. Willemsen

IF Technology, P.O. Box 605, 6800 AP Arnhem, The Netherlands
phone +31 26 4431541, fax +31 26 4460153, email info@iftechnology.nl

1. Abstract

To abstract thermal energy from the subsoil, two different technologies can be used: closed loop heat exchangers and open loop systems. The latter system uses groundwater that is pumped up and that is used to deliver heat or cold to the user. Open loop systems are best designed as an Aquifer Thermal Energy Storage (ATES), because this has the least impact on the environment, because the risk of short circuiting between wells is reduced and because it improves the energy efficiency of the system. The design of an ATES is mainly concentrated on reaching a high thermal efficiency and the minimisation of the environmental impact and cost of the system. This paper presents some practical guidelines and examples to optimise a well field configuration for ATES based on experiences with Dutch ATES projects.

2. Introduction

To abstract thermal energy from the subsoil, two different technologies can be used: closed loop heat exchangers and open loop systems. The latter system uses groundwater that is pumped up from an aquifer and that is used to deliver heat or cold to the user.

In many parts of the world the shallow subsoil (<200 m below surface level) contains aquifers. It is relatively easy and consequently not very expensive to extract groundwater from these layers.

An advantage of using groundwater is the constant temperature throughout the year, which is unlike other heat sources, such as outside air or a ground heat-exchanger system.

Several methods are available for a heat pump to use this groundwater.

a. *Extraction and disposal.* This system is based on groundwater extraction from wells, recovery of thermal energy from it by means of the heat pump, and disposing of it into a sewer or surface water. Many authorities, however do not grant licences for such systems.

b. *Extraction and injection*. A major objection of the authorities can be overcome when the groundwater is re-injected into the subsoil after its thermal energy has been absorbed. This means that groundwater is no longer consumed but merely used. An important drawback of the system is a strong cooling of the subsoil surrounding the injection well. Though this does not have any direct physical and chemical consequences for the subsoil system, certain disadvantages are still involved. First, injected groundwater may flow towards the extraction well, lowering the temperature of extracted water and reducing the heat-pump efficiency. Continuously lowering the extraction temperature may eventually result in the groundwater freezing. A second disadvantage is that potential groundwater users in the immediate surroundings of systems that have already been installed, will be confronted with groundwater that is less suitable as a heat source. in densely populated countries (like the Netherlands) this disadvantage should not be underestimated.

c. *Extraction and injection with thermal equilibrium.* Though re-injection of groundwater does dispel the main objection of the authorities, they are still very reticent when licences are requested for the systems described above. Within the framework of “sustainable utilization” of groundwater (which means that present utilization shall not be a barrier to future utilization) they would prefer the restoration of the thermal equilibrium in the subsoil. This can be achieved by extracting groundwater from the extraction well in summer, heating it by means of outside air (dry heaters), the sun (solar collectors), surface water or surplus heat from buildings. The groundwater with raised temperature is then re-injected and mixes in the subsoil with the cold groundwater from the previous winter season.

d. *Energy storage*. The energy savings may be improved in summer, by utilizing cold energy which had been injected in winter. To achieve this, groundwater can be extracted from the injection well used in winter (the “cold well”) and then be used for cooling, e.g. with handling unit. The then warmer groundwater is injected into the well used for extraction in winter (the “warm well”). This system is called an Aquifer Thermal Energy (ATES).
In addition to the advantages for the subsoil system, such storage systems improve the heat-pump efficiency. This is caused by the raised supply temperature from the warm well. It should be noted here that such systems supply cold energy in summer without using the heat pump. If the cold groundwater were only used to cool the condensor of the chiller (heat pump), a considerable part of the energy saving that can be achieved with such systems, would not be realized.

The heat pump with energy-storage system is especially practicable in situations with a clear demand for cold energy.

Because of the advantages of the ATES concept above more simple extraction and injection systems (open loop systems), we will focus on ATES systems in the rest of this paper.

3. Aquifer Thermal Energy Storage (ATES)

The development of ATES in the Netherlands started in the early 1980s. Initially, seasonal heat storage was considered a suitable method for space heating in winter. It soon became apparent that seasonal storage in aquifers is also very useful for storing cold and waste heat. During the second half of the decade the first projects of thermal energy storage were realised. Better understanding of the economic aspects and environmental advantages of ATES, plus the success of the first projects, resulted in rapid development in the 1990s.

A new development is the concept winnerway. By installing heat exchangers just below the surface of asphalt roads, heat can be stored in the summer and the road can be de-iced in the winter. The excess heat can be used for heating residential areas or other buildings along the road. Advantage of this technology is that the degradation of the road is slowed down, because of the cooling of the road surface in the summer and the lack of damage due to frost in the winter. The first projects with this concept are being realised at the moment.

Presently ATES is a widely used technology. More than 150 ATES systems have been realized or are in progress, of which 90 % provide cold storage or the combination of cold and low-temperature heat storage. Approximately 80 % of the applications are found in the building sector, mainly office blocks, hospitals and shopping centres. Recently, thanks to the introduction of the heat pump, ATES is applied for heating houses.

The main reasons for the success of ATES in the Netherlands are (Bakema and Snijders, 1998):

- aquifers are available under every major city and 95% of the shallow subsoil (< 200 m below surface level) consists of aquifers;
- the government has responded positively towards ATES, by subsidising feasibility and market studies;
- the relatively high price of electricity;
- the prohibition of CFCs;
- the positive attitude of licensing authorities;
- a permit to build a new building can only be obtained if this building satisfies a minimal energy efficiency.
- as a result of the absence of altitude differences the velocity of the groundwater flow is normally limited to 5 to 50 m per year.

Most systems have injection temperatures between 6 and 9 °C in the winter and 15 to 25 °C in the summer. Generally, ATES systems are single doublet systems (one cold and one warm well) with an average yield between 10 and 250 m^3/h per well, and the amount of pumped/reinjected water ranges between 10 000 to 500 000 m^3 per well per season (i.e. summer or winter). More recently, larger ATES systems have been designed and constructed. These systems comprise multiple well systems with yields of 300 to 3 000 m^3/h, and approximately 0.5 to 5 million m^3 water is pumped/reinjected per season.

The major advantage of ATES over borehole heat exchangers is the larger capacity. Furthermore open systems are more economic than borehole heat exchangers, except for small systems (< 100 kW_{th}). Disadvantages are the potential larger environmental impact and the fact that a permit is needed.

With an ATES system groundwater is extracted from the “warm wells” in the winter. After the extraction of heat the groundwater is injected in the “cold wells”. During the summer water is extracted from the cold wells. The extracted water is used for cooling while absorbing superfluous heat and subsequently reinjected in the warm wells.

There are a number of conditions that must be satisfied to be able to realise an ATES system.

a. The presence of a suitable aquifer is required. Aquifers which consist of coarse sand and have a high transmissivity are favoured, because the number of wells needed for an ATES system in such aquifers is relatively low. Fine grained clayey aquifers are not suitable because of the risk of clogging the wells. Aquifers that have mainly a secondary transmissivity (like fractured rocks and karstic aquifers) may be less suitable for ATES. In case a high regional flow is present, these aquifers may be suitable for ‘conventional’ open loop systems.

b. The aquifer choice may be limited by water quality. Water quality limited systems can be split up into three categories:

b1. High dissolved gas content in groundwater. If groundwater contains high concentrations of dissolved gas, there is a risk of degassing which can rapidly lead to clogging of the infiltration well. Maintaining sufficient over-pressure may prevent this type of well clogging. This is only possible if the gas pressure is not close to the hydrostatic pressure in the aquifer. In case the gas pressure is close to the hydrostatic pressure in the aquifer, a different aquifer should preferably be chosen.

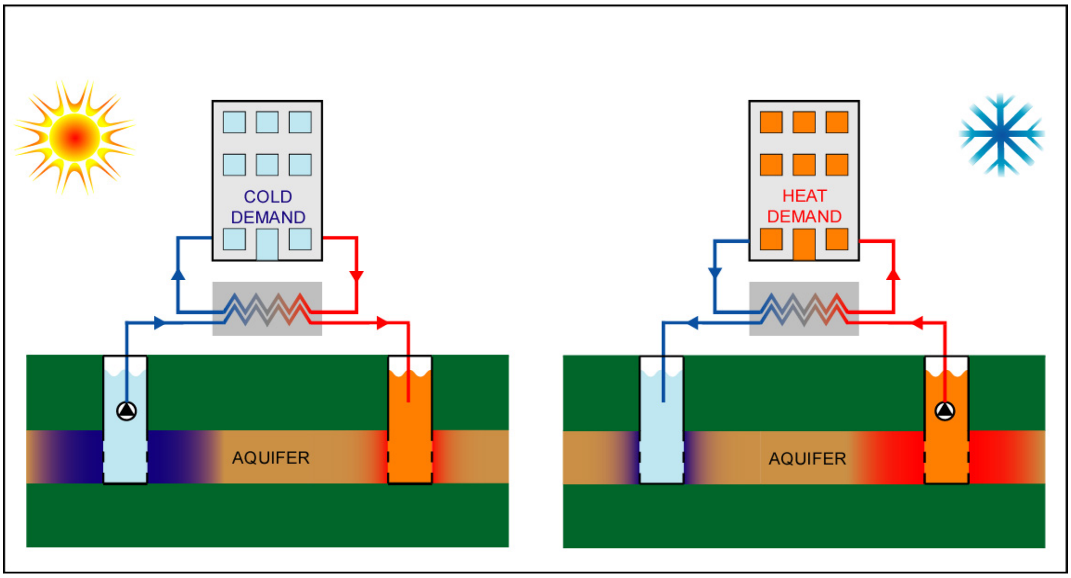

Figure 1: Aquifer Thermal Energy Storage

b2. Vertical water quality interface (e.g. salt/fresh, iron/oxygen)
In these cases, it is important to avoid vertical displacement of groundwater near the water quality interface or mixing of the different water types in the wells. This may be realised by:

- Screening of the ATES in an aquifer or part of an aquifer so that there is a high hydraulic resistance between the interface and the well screens. Its important to prevent screens that extract water with different redox properties. When for example iron-containing water is mixed with oxygen- or nitrate-containing water, this will result in precipitation of iron-oxyhydroxides and clogging of the wells.;
- Balancing the amounts of water that are pumped/reinjected in summer and winter;
- Reducing the hydraulic impact of the ATES (see design).

b3. Horizontal water quality interface (e.g. polluted groundwater)
Extra displacement of polluted groundwater is mostly not allowed. The extra costs that are involved with the cleaning of the site must be paid by the one who caused the extra costs. Because of the fact that natural attenuation is becoming the most popular technology to deal with polluted plumes in groundwater, a small extra displacement is often acceptable. Horizontal displacement can be minimized by the above mentioned parameters and in addition by the positioning of the wells with respect to the flow directions. It should be noted that an ATES system may also have positive contributions to the natural attenuation of contaminants. Positioning of the warm wells near the polluted plume may increase the rate of decomposition of contaminants.

c. Regional groundwater flow

Where regional gradients in pressure head in the aquifer are relatively large and the permeability of the aquifer is high, there will be a significant regional groundwater flow that will cause part of the stored energy to be lost. There are several ways to cope with this problem. The easiest way is to change the system in a extraction/injection concept (open loop) that can use groundwater with the natural temperature for both cooling and heating. Other, more expensive, solutions are creation of a bypass to reduce the groundwater flow at the site to zero or the injection upstream and extraction downstream (Jenne et al, 1992). In both cases this implies drilling up to twice the amount of wells compared to a low flow system.

d. Permit

In most countries a permit is required for the realisation of an ATES. To apply for a permit the impact of the ATES on the environment must be reported with the application.

The most important issues are the hydraulic and thermal impact. Nature, fresh groundwater, other ATES systems and existing groundwater extractions should be protected. Furthermore compaction and influence on polluted groundwater are issues of interest.

4. Design of ATES systems

For the design of ATES systems some general rules apply that have to be considered if the system is to function without problems for many years. Some of these general rules are described by Jenne et. al. (1992) . They can be summarized as follows.

- Groundwater can contain dissolved iron and manganese. When this water comes into contact with air, the iron and manganese will precipitate, which will cause clogging of the wells. Prevention of entrance of air is therefore essential. This is best achieved by keeping the whole groundwater circuit airtight and by maintaining a positive pressure with respect to the outside air at all points in the circuit, at all times.
- Groundwater often contains dissolved gasses. When the groundwater is pumped up, gas bubbles can form, which can clog the infiltration wells. This is best prevented by maintaining a pressure in the groundwater circuit that is higher then the bubble pressure. Throttling of the pressure to control the flow is not advisable. It is better to use frequency converters.
- Groundwater contains small particles (clay, silt, sand). These particles will clog the injection wells with time. The clogging rate depends on the well design (flow rate on the bore hole wall) and on the amount and type of particles present. Therefore the wells have to be designed and realised such that they: 1. produce a minimum amount of particles, 2. have a low clogging rate, 3. can handle a certain amount of clogging, 4. can be cleaned.
- Use materials that show a low corrosion rate like plastics and stainless steel. Do not use carbon steel or cast iron.
- The injection pressure in the wells has to remain below a certain level. This maximum level is defined by the risk of breaching of the confining layer.

Apart from these general rules the design of the store has to be such that the system functions optimal. The overall objective of the optimisation procedure is to design a well field configuration of an ATES which results in (1) minimum initial and running costs, (2) maximum thermal efficiency and exergy and (3) minimum environmental impact. There are many degrees of freedom (i.e. parameters) to optimise the well field configuration. The most important parameters are: (1) aquifer choice, (2) section to screen, (3) distance between cold and warm wells, (4) positions of wells with respect to the direction of regional groundwater flow and (5) positions of multiple cold and warm wells with respect to each other. Table 1 shows how the optimisation parameters may be related to costs, thermal efficiency and environmental impact.

From Table 1 can be concluded that:

- Initial costs are mainly determined by the number (and diameter) of wells, the depth of the wells and the distances between the wells. Preventing clogging of wells and cracking of the soil near the wells require a minimum number of wells. Therefore, the number of wells is related to the required maximum flow rate, the total amount of reinjected water, the transmissivity of the aquifer and the permissible injection pressure (see e.g. Olsthoorn, 1982; Driscoll, 1989). The distance between a cold and a warm well must be sufficient to avoid thermal break-through of the wells. Lowest costs are gained with a minimum number of (shallow) wells and a minimum distance between the wells. In general, the number of wells is the main factor determining the costs, so it will mostly be cheaper to have less wells in a deeper aquifer than to have many shallow wells. If the injection pressure determines the number of wells, it is generally cheaper to intersperse cold and warm wells than to cluster cold and warm wells.

- Highest thermal efficiency is gained in aquifers with the lowest regional groundwater flow velocities, sufficient spacing between warm and cold wells in order to prevent thermal break-through, large thermal volume and an optimal ratio between thermal radius and the thickness of the storage (see Doughty et al., 1982). From a thermal point of view, it is better to concentrate all the cold wells in a cluster and the warm wells in a different cluster instead of interspersing cold and warm wells.
- Lowest environmental impact will generally be caused by a storage in deep aquifers and short distances between cold and warm wells. Alternating positions of warm and cold wells will result in the lowest hydraulic and thermal impact.
- Optimising one objective may deteriorate one of the other objectives. It is recommended that the optimisation procedure is started with a well field configuration with the lowest costs and the highest thermal efficiency. If the environmental impact is not acceptable, alternative configurations must be considered. These configurations will probably have higher costs and a lower thermal efficiency.

<u>General cases</u>

Possibilities of optimising ATES well field configurations are shown for different cases. In each case the well field design has to be optimised with respect to one of the following limitations: (a) induced pressure changes (= hydraulic limitations), (b) induced thermal changes and (c) storage space. Each case shows how optimisation parameters can be used to optimise a well field design.

a. Hydraulically limited systems

Hydraulic limitations may occur due to different causes, e.g: cracking (as a result of an excessive injection pressure), a large drawdown, consolidation and land subsidence, crop growth reduction due to draught and/or wetness and reduced stability in civil works (tunnels, cellars, etc.).

In all cases it is desirable to reduce the hydraulic impact of the ATES system. There are several possibilities to reduce the hydraulic impact of the system, e.g. by: (1) longer well screens; (2) a larger number of wells; (3) a larger well diameter; (4) a smaller distance between cold and warm wells; and for multiple well fields: (5) a larger intermediate distance between the cold (or warm) wells and (6) interspersing cold and warm wells. The effectiveness of the proposed changes can be illustrated with the simple equation to calculate the pressure changes for a single and a double doublet:

$$\Delta h(x,y) = \frac{Q}{2\pi T} \ln \frac{r_{i1} \cdot r_{i2}}{r_{p1} \cdot r_{p2}} \qquad (1)$$

Where: h = Pressure change [m]

Q = Amount of pumped/reinjected water [m^3/d]

T = Transmissivity of the aquifer [m^2/d]

r_{i1}, r_{i2} = Distance from observed point (x,y) to infiltration wells i1 and i2 [m]

r_{p1},r_{p2} = Distance from observed point (x,y) to production wells p1 and p2 [m]

Table 1: Relationships between costs, thermal efficiency, environmental impact and optimisation parameters.

	Choice of aquifer **(shallow vs. deep)**	**Section to screen (within an aquifer)** **(shallow vs. deep or short vs. long)**	**Distance between cold and warm wells** **(short vs. long)**	**Position of wells with respect to direction of regional flow**	**Positioning of multiple cold and warm wells (clustered vs. interspersed)**
Costs	depends mainly on required number of wells for each aquifer; shallow wells are cheaper, but have a smaller permissible injection pressure	shallow: cheaper, but with smaller permissible injection pressure long: higher flow per well possible	short: cheaper and injection pressure decreases	-	If no. of wells is determined by flow injection velocity, clustering of wells is cheaper than interspersing of cold and warm wells due to less length of connecting pipes between wells. If no. of wells is determined by injection presssure: interspersed cold and warm wells are cheaper.
Thermal efficiency and 1exergy	depends on regional flow velocity; a larger flow velocity results in lower thermal efficiency and exergy	longer screens lead to a smaller radius of stored water around the wells, which in turn results in a smaller minimally required distance between a cold and warm well in order to prevent thermal break-through;	short: possibly more thermal interaction between cold and warm wells	In case heat or cold is the most important energy stored: place the most important wells upstream. In case both are equally important: an angle of 90° between the position of wells with respect to direction of regional flow. This results in less risk of thermal break-through of the	clustered: higher thermal efficiency

		there may be more thermal losses due to regional flow		wells.	
Environ -mental impact	shallow: larger impact near ground level (thermal, hydraulic and soil consolidation)	shallow: larger environmental impact; short: larger horizontal thermal impact and higher hydraulic impact	short: smaller hydraulic impact	Parameter to minimize interaction with pollution or other ATES system. Water balance on an annual basis is important.	clustered: higher environment al impact (thermal and hydraulic)

For a single doublet the values of r_{i2} and r_{p2} can be omitted. From this equation can be deduced that T and Q are linearly related to the pressure change in the aquifer. The well configuration is, however, not linear. To illustrate the effect of the well configuration an example is presented. In this example the maximum pressure changes for an ATES system are calculated with 2 and 4 wells (with T = 1 000 m^2/d and well radius = 0.5 m). The results are presented in Table 2.

Table 2 Maximum pressure changes for different well configurations

				20 m	100 m	100 m
100 m		∃I1 ∃P1	∃I1 ∃P1	I1∃ ∃I2 P1∃ ∃P2	I1∃ ∃I2 P1∃ ∃P2	I1∃ ∃P2 P1∃ ∃I2
Q per well (m^3/h)		100	200	100	100	100
Q total prod. (m^3/h)		100	200	200	200	200
Max)h (m)		2.03	4.06	2.65	2.16	1.89

The results show that due to alternating positions of the injection and the production wells in a multiple well configuration smaller pressure changes are induced than with the original single doublet. This example illustrates that multiple doublet systems can offer very good possibilities to reduce the pressure changes and that an extension of an existing system does not necessarily lead to an increased impact.

b. Temperature limited systems

Examples of temperature limited systems are: (1) system with presence of high regional flows (discussed below) and (2) system in the vicinity of an existing ATES system or a pumping station for drinking water (not discussed).

High regional flow may result in significant losses of the stored energy. The positions of the wells with respect to the flow direction will be important for the performance of the ATES. The thermal efficiency of the ATES may be improved by:

- Positioning the favourable type of wells (cold or warm) upstream from the less favourable type of wells. This reduces the risk that the favourable type of energy is affected by energy losses of the other (type of) wells.

- Positioning the cold and warm wells in the direction of the regional flow for single cold and heat storage. As mentioned above, the favourable energy is stored upstream and the other type of energy is stored downstream. Consequently, upstream energy losses will be recovered at the downstream well. This improves the thermal efficiency of the single cold or heat ATES system. For a combined cold and heat storage system, it is better to position the wells perpendicular to the direction of flow in order to minimize the risk of thermal break-through of the wells.

c. Storage space limited systems

Storage space limited systems may be caused by the presence of a thin aquifer and a limited property area without the possibility to place the wells outside the property area. This may cause thermal break-through between cold and warm wells. For thermal balanced systems, a minimum distance between a warm and a cold well of 3 times the thermal radius of the stored cold or heat is sufficient to prevent thermal break-through between wells. The thermal radius r_{th} can be calculated from:

$$r_{th} = \sqrt{\frac{c_w Q}{c_a H \pi}} \qquad (2)$$

Where:

r_{th} = Thermal radius of the stored cold or heat [m]

c_w, c_a = Heat capacity of water and aquifer material [J/(m^{3}K)]

Q = Amount of pumped/reinjected water per season [m^3]

H = Length of the screens [m]

If the actual distance between the cold and warm well is less than $3r_{th}$, a thermal calculation should be carried out in order to determine the interflow component. Storage space limited systems may be optimised as follows:

- Reduction of the hydraulic radius of the stored energy.

From Formula 2 it can be deduced that the thermal radius can be reduced by decreasing the amount of stored cold and warm water or by increasing the length of the screens. The amount of pumped/reinjected water reduces for a certain amount of energy when the temperature of the infiltrated water is decreased in the winter and increased in the summer. Alternatively, clustering of the cold and warm wells will lead to a smaller r_{th} than alternating positions of cold and warm wells , since r_{th} is as a square-root related to Q.

- Allowing thermal short-circuiting

In case there is not enough space for an optimal distance between the wells, thermal short circuiting between the warm and cold wells will occur. This will decrease the energetic and exergetic efficiency of the system, but it might still be acceptable. When short circuiting happens, it may be necessary to store more heat (and cold) than required for a certain amount of heat production (and cold production) than in case of a proper distance between the wells. If a significant regional groundwater flow exists, this flow may be used to reduce short-circuiting of the upstream well and will in turn increase short-circuiting of the downstream well (see below).

5. Example of an ATES with heat pumps (Paleiskwartier Den Bosch)

Paleiskwartier is a district in the centre of the city of Den Bosch in the Netherlands, where new office buildings and apartments are being realised. For the heating and cooling of these buildings an ATES system in combination with heat pumps will be constructed.

Each winter the ATES system will have to provide 10 000 MWh of thermal energy. This amount must be stored in the summer period. Part of the stored heat is the waste-product of cooling the office buildings. The rest is extracted from a shallow pond which is situated in the centre of the district. In the summer the pond acts like a huge sun-collector.

The cooling capacity will be over 6 000 kW during the summer. To be able to provide this capacity 5 warm wells and 5 cold wells are required. The maximum rate of extraction is 750 m^3/h during the summer period. The maximum amount of water that is pumped in a year is nearly 3 000 000 m^3.

The screens are placed in the first aquifer. In the covering layer a large spot of contaminated groundwater is present. South of the location two nature reserves are present. These are the main reasons the hydraulic impact of the system had to be minimised. Furthermore the hydraulic pressure should not rise too much, because of the risk of cracking the soil. The best way to minimize the hydraulic impact would be to realise the ATES in the second aquifer. The provincial authorities however, have reserved the second aquifer for drinking water supply and ATES in this aquifer is not permitted.

Because of the amount of wells involved there were a lot of possible configurations in the first aquifer. Thermally the most ideal configuration would be one cluster of cold wells and one cluster of warm wells. To achieve a minimal hydraulic impact, the wells should be interspersed. An interspersed well configuration would however be a relatively expensive one.

Because clustering all the warm and all the cold wells would result in a very large hydraulic impact, this concept was not desirable. Two concepts were worked out:

1) Interspersing all the wells
2) Two clusters of cold wells and two clusters of warm wells, where the clusters are interspersed.

From the hydraulic point of view the first concept is the most optimal. Thermally concept two is more robust. In the end concept two was considered the best one, mainly because of the thermal advantages.

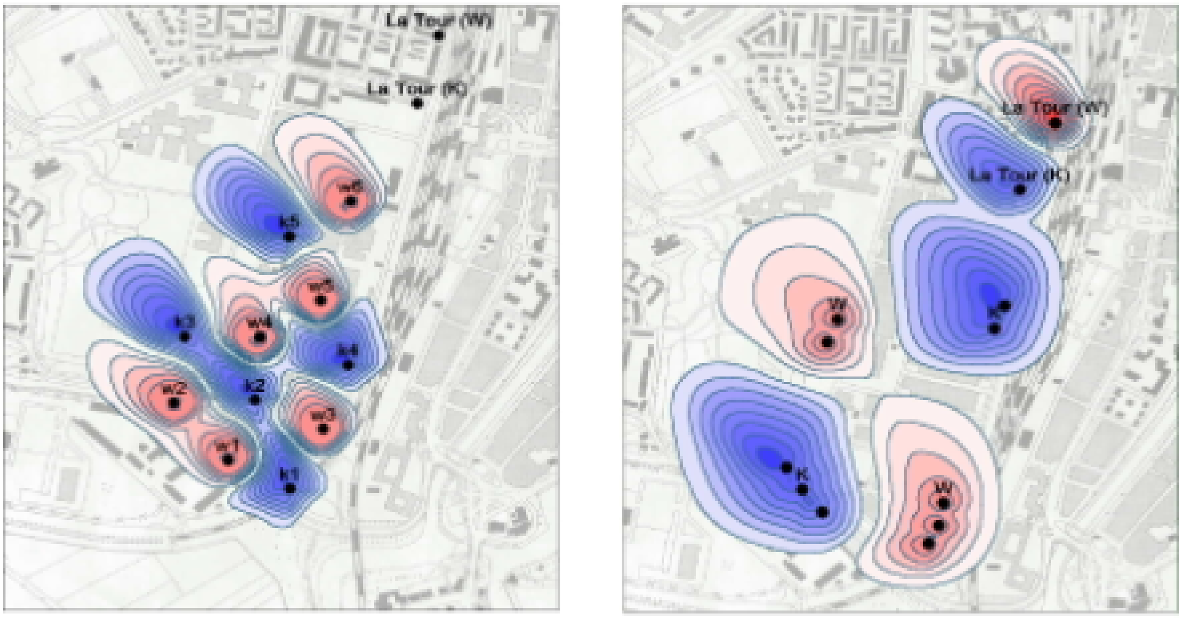

Figure 2: Thermal situation after 20 years of ATES for concept 1 (left) and concept 2 (right). In the right image thermal effect of the neighbouring ATES system (north) is presented too.

At the moment the ATES for the Paleiskwartier is being realised. The wells are connected by a circular double main-pipe-system, one for cold groundwater and one for warm groundwater. In a number of building blocks heat pumps are installed and a (double) connection with the main-pipe-system is made. In this way, if cooling- and heating-demand are equal, cooling and heating of different buildings can occur without extracting or infiltrating groundwater.

6. Conclusion

For Underground Thermal Energy Storage system larger then 100 kW, Aquifer Thermal Energy Storage, if geohydrologically possible, is preferred over Borehole Heat Exchangers. The main disadvantage of ATES with respect to BHE is the environmental impact. The environmental impact can be minimised through the design of the ATES system.

7. References

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