The use of aquifers as thermal energy storage (TES) systems

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5.1 Introduction

Using the ground as a seasonal thermal energy store is referred to as underground thermal energy storage (UTES). In the vast majority of cases there are only two basic methods of exchanging thermal energy with the ground: through advection in aquifers using wells, and conduction using boreholes. They are referred to as aquifer thermal energy storage (ATES), and borehole thermal energy storage (BTES). While heat pumps (HPs) or chillers are not always used in conjunction with UTES, it is the most common application since most buildings have both heating and cooling loads. In designing HP systems for moderate to large size buildings, it is often the case that the cooling demand is larger than the heating thermal energy demand over the year for large buildings; occasionally it is reversed. In addition, community systems with single family houses and small residential buildings might have a heating-dominated energy demand. This chapter is largely devoted to the former; however, some notable exceptions are discussed as well.

Diurnal thermal energy storage coupled with chillers is a well-known practice that is used to move cooling load from the peak daytime to evening hours when electrical costs are lower and the air temperatures are lower, resulting in lower energy cost without compromising the energy efficiency. Seasonal energy storage likewise is a natural way to shift peak demands but also to provide thermal energy at much higher efficiencies. ATES systems are used to store cold from the winter for use to cool buildings in the warmer months of the year and to store heat from the summer to heat buildings in the colder months. In many cooling dominated applications, these systems can eliminate the need for compressors completely. ATES systems appear, at times, as open loop geothermal systems since they might incorporate heat pumps in the winter to supply heating demand and at the same time store cold thermal energy.

The principle of energy storage in aquifers is very simple. If there is natural cold in the winter, this can be stored in an aquifer. In summer the stored cold can be used for cooling purposes. It requires a minimum of two wells, a warm well and a cold well. In larger systems it requires several warm and cold wells. When cooling is demanded by the user, cold water is extracted from the cold well(s) and utilized to meet the cooling demand. The water is then returned to a warm well(s) at an elevated temperature. When there is a demand for heating, water is extracted from

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the warm well(s) to provide the heating load. The water is then injected into the cold well(s) at a low temperature. In this manner thermal energy is stored seasonally. The great advantage of this technique is that in some cases chillers (or heat pumps) are unnecessary to generate cold in summer when the outside temperatures are high. In other cases the use of chillers can be drastically reduced. Chillers use large quantities of electric energy so that aquifer cold storage can produce a major saving of electricity. The main elements are the wells, the connecting piping, the heat exchanger and the cold supplier. Aquifers in unconsolidated sands/gravels as well as fractured rock aquifers can be utilized.

5.1.1 Background

Early application of aquifers for cooling lead to gradual heat buildup in the aquifer due to higher temperature water being re-injected into the aquifer. As a result there were many industrial applications that either became untenable due to a rise in temperature or similarly affected downstream users. The technology of storing thermal energy in aquifers was probably first applied more than fifty years ago in the People's Republic of China. They were abandoned in the 1990s (Tian Sang, 1980, Sun Yongfu, 1986). ATES was developed independently in the West. Pilot projects were installed in Denmark (at Hørsholm), France (at Plaisir Thiverval), Switzerland (at Dorigny) and the US (at St. Paul, Minnesota). There was clogging of recharge warm wells and heat exchangers for high temperature storage (above 50°C). The result was that these operational problems needed to be overcome and that environmentally sound water treatment methods needed to be developed. While progress was made, the general interest in aquifer storage shifted from high temperature heat storage to cold storage and low temperature heat storage, since fewer problems were encountered. Much of this work occurred in the context of the IEA's Energy Conservation through Energy Storage Implementing Agreement (Snijders, 1994).

Other pilot projects during this time include two cold storage projects in the US: in Tuscaloosa, Alabama, and another in Holbrook, New York. Aquifer cold storage has developed into a generally accepted technology in the Netherlands and Sweden, commencing in the early 1990s. At the beginning of 2011, over 1000 projects in which ATES is applied had been realized in the Netherlands, mostly in sand aquifers. Almost every major city has a number of projects in operation. In Sweden there are approximately 100 plants, though its geology limits the use of ATES to small areas in the south of the country. Some ATES systems are built in eskers, while others in highly fractured limestone aquifers. Many of these systems are in the MWt power range.

5.1.2 Current status

Currently, aquifer thermal energy storage projects are largely designed to store cold energy in winter for cooling purposes in summer time. In most cases the stored chilled water is utilized directly to cool. Chillers or heat pumps are utilized only for supplementary purposes during peak conditions. Typically the cooling capacity supplied from storage is between 500 kWt (140 tons) and 2000 kWt (570 tons). This requires a groundwater flow rate in the ATES system between 50m^3/h (200 gpm) and 200m^3/h (800 gpm). It is possible when heat pumps are included that they can be used for heating purposes in the winter. In this case it is referred to as 'cold storage and low temperature heat storage'. A very large ATES project supplies cooling and low temperature heating to the buildings and laboratories on the campus of the Eindhoven University of Technology (Holdsworth, 2003). More details can be found in Section 5.7. Of the more than 1000 ATES projects which are in operation in the Netherlands, about 70% are commercial and public buildings and the remaining 30% are housing developments, and industrial and agricultural applications.

5.2 Thermal sources

In the combined heating/cooling system there is usually a seasonal mismatch. Basically the ideal is to charge heat in the summer and/or 'cold' in the winter, to maintain the desired ATES temperature. In many cases it is possible to store both heat and cold, which is discussed in a later section. However, it is unusual for a building heating and cooling load on the aquifer to balance over a year in such a manner that the total heat and cold stored balance each other out. In an unbalanced case, additional measures are taken to restore thermal balance.

5.2.1 Cold sources

The most common thermal source is cold outside air in winter. It is collected with a cooling tower, dry cooler, and/or heat exchanger from fresh air intake on a building. Also common is waste cold water from a heat pump (while generating heat). Less common is cold water from a harbor, ocean, estuary, river or lake or melting of snow in more northern climates. In practice the minimum stored temperature is ~5°C (41°F) for ATES. Any lower temperature might result in freezing water in parts of the system leading up to the minimum storage temperature. It is not as large a limitation in the case of BTES since it can be stored at a lower temperature with the use of antifreeze, if the cold source can provide lower temperatures, such as in the case of outside air.

5.2.2 Hot or warm sources

The source of heat is most commonly waste heat from heat pumps which are being employed to cool in summer months. Less common are thermal solar and waste heat from co-generators or industrial processes. Thermal solar tied to UTES is an example where heat in the summer months is stored to be used in the heating season. Direct heating is not as easily achieved as in the case of direct cooling since high temperatures are required by the building distribution system. Even if the high temperatures are available, there are very high losses due to a larger differential temperature between the ambient ground temperature and the stored high temperature water stored in the aquifer. In many cases additional heat sources are required to boost the temperature, such as heat pumps. In this case heat pumps are operating at a higher coefficient of performance (COP) than if the system were a traditional ground-coupled heat pump (GCHP) system.

5.3 Aquifier thermal energy storage (ATES)

The basic elements of an ATES system are the source of thermal energy, the delivery system, the underground store, and the thermal loads, shown in Figure 5.1.

5.3.1 Thermal loads

As previously mentioned, the most common application of ATES is cooling buildings. Even in more northern climates many large buildings are cooling load dominated. Even if the building cooling and heating loads over the year balance, there is a possible net increase in heating of the aquifer due to the fact that the condensation heat adds to the heat into the building in winter, requiring less from the ground but is injected into the ground in summer adding to that extracted from the building. To understand this more fully, it can be shown that the ratio of heat into the aquifer to that extracted over a year's time is given by:

$$\text{heat injected/heat extracted} = (Q_c/Q_h)*(\mathrm{COP}_h/\mathrm{COP}_c) * ((\mathrm{COP}_c+1)/(\mathrm{COP}_h-1)) \tag{5.1}$$

where Q_c is the total cooling energy demanded by the building over a year's period, Q_h is the total heat energy demanded by the building over a year's period, COP_h is the coefficient of performance in heating mode, and COP_c is the coefficient of performance in the cooling mode.

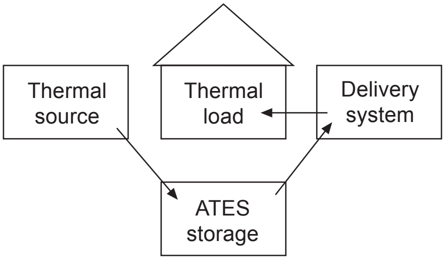


Figure 5.1 Basic elements of ATES.

For example, if both COPs = 4, then the ratio of heat injected to extracted would be 1.67 when the building heating and cooling loads over the year balance. If the cooling load is larger, then this ratio increases.

In another example, in the case of ATES with direct cooling, the COP_c could be 20 and COP_h for heating 4. In this case the ratio of heat injected to heat extracted is 1.4, again for a balanced building load. These examples demonstrate that it is usually necessary to find means to reject more heat efficiently over the year to balance the thermal load on the ground, since in most cases the annual building cooling demand is larger than the heating demand. Clearly if the annual heating load over the year exceeds the cooling load as is the case in very northern climates, then it is possible the effect could be a balanced thermal load on the aquifer or in more extreme cases the aquifer would be cooled. There are a significant, albeit minority number of building loads for large (commercial and institutional) buildings that require more heating energy over a year than cooling, even in more northern climates. The reason that more buildings are becoming cooling dominated is the new 'green energy' designed buildings. In very well-designed (green) buildings, the reduced heating demand is fractionally more substantial than the cooling demand due to remaining interior gains, making the imbalance shift toward putting more thermal energy into the aquifer than is extracted on an annual basis.

If both heating and cooling are required, systems can be designed for optimal efficiency. While any range is technically possible, because of financial considerations, in practice at least a thermal demand of ~200 kWt (~50 tons) is the smallest that can be matched with seasonal thermal storage. More recently thermal utilities are expanding the use of seasonal thermal storage. They provide thermal energy to small buildings as part of a small district heating/cooling system, thus combining the loads.

5.3.2 Delivery system

The most effective and efficient HVAC system for ATES is one which separately handles latent and sensible loads during the cooling season. Fresh air intakes for most climates produce a substantial latent cooling load. To effectively reduce the wet bulb temperature of incoming outside air, the coolant needs to be below 12°C (54°F). To realize the required wet bulb temperature and utilize the stored thermal energy effectively, a larger heat exchanger (HEX) than normally applied in the air handling unit is required. A second HEX can utilize the warm water for reheat when needed. This typically results in a discharge temperature of aquifer water at 18°C (65°F). The sensible heat and cooling demand is typically delivered by a radiant system, air beams or fan coils. More recently radiant ceilings are becoming popular. The ATES system typically serves both for heating and cooling. Including HPs, part of the cooling load is delivered directly with the HP for short peak periods when the ATES system can not provide the full short-term load.

5.3.3 ATES store

The entire system, including the ATES store, needs to supply not only the thermal energy for the year but also the peak thermal power. The later criterion cannot always be cost justified. An optimum ATES system can supply the vast majority of thermal energy demand utilizing the ATES store when designed to serve as a thermal base load plant.

The most important aspect of the well field design is to ensure that groundwater and surrounding properties are not adversely affected by the ATES store. A careful configuration of wells is required to ensure that the hydraulic head does not extend substantially onto adjacent properties (e.g., change in hydraulic head no more than 30 cm (1 ft) at the property boundary). Another requirement is that the temperature change would not reduce the possibility of a neighboring property owner utilizing ATES (e.g., change in temperature not larger than 0.5°C (1°F) at the boundary). Finally, it is critical that there is not a thermal breakthrough between warm (hot) and cold wells in the long run (e.g. over a twenty-year period). To achieve these conditions requires very sophisticated and careful modeling, which is discussed later.

5.3.4 Optimum systems

An example of an optimum system is one that delivers heat during the winter at the same time generating cold water as a byproduct. Thus no extra energy is utilized to generate this chilled water. In the case shown in Figures 5.2(a) and 5.2(b), cold water is being generated by the GHP as a byproduct, and also by the use of water from the warm wells to preheat fresh air during very cold periods. However, it may be necessary to supplement this with additional cold water generated actively by a cooling tower or dry cooler in the winter.

In the winter the GHP utilizes ~18°C (65°F) water stored in the summer operating at a relatively high efficiency, delivering the base load heating for the building and at the same time storing cold water in the ATES cold wells. When the outside temperature is below 0°C (32°F), it is possible for warm ATES water to be utilized to preheat incoming fresh air. Additionally, to achieve a thermally balanced system, cold water from a dry cooler or cooling tower, when air temperature is below 2°C (36°F), might be stored in the ATES cold wells. When the heating demand cannot be fully supplied by the heat pump, then a gas boiler serves as a ‘peaker’. The amount of gas energy is typically less than 10% of total annual energy demand while typically about 50% of peak thermal demand.

In the summer operation the base load cooling is supplied directly by the ATES cold wells to both the building fan coils and the fresh air intake. When the cooling load cannot be met by the ATES cold wells, the GHP serves as a ‘peaker’. Again the ATES cold wells supply the vast majority of the cooling load. The system is designed to financially optimize by trading off peak load from the ATES system with traditional sources for short periods of time, reducing up-front investment with conventional peakers.

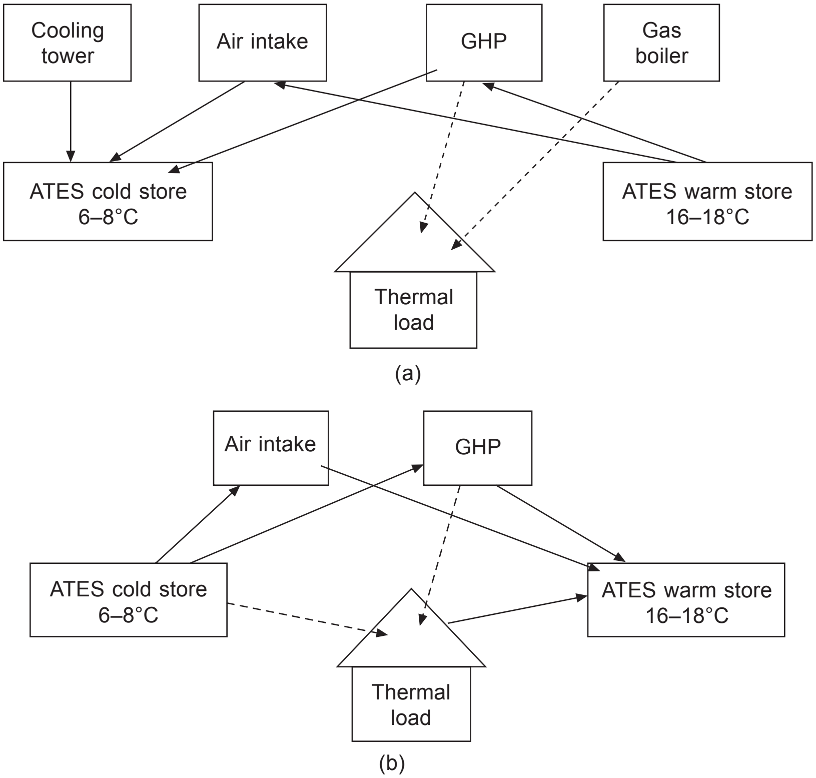


Figure 5.2 (a) Winter operation of optimum ATES system. Dotted arrows indicate heat supply to building; (b) summer operation of optimum ATES system. Dotted arrows indicate cold supply to building.

5.4 Thermal and geophysical aspects

It is essential that short-circuiting between the warm and cold wells does not occur over the lifetime of the project. The design needs to ensure that only a minimum interference between the warm and cold wells occurs. Unlike some open loop geothermal systems, these wells are alternated seasonally from injection to extraction. As a result the ATES system is a complex system to model. Thermal dispersion, the interactions between the warm and cold wells, heat conduction to confining layers, regional groundwater flow and buoyancy flow all must be considered.

5.4.1 Modeling and calculating thermal effects in ATES systems

Vertical movement of water within an aquifer can occur due to the density difference between warm and cold water. A mathematical criterion is given by Hellström *et al.*

(1988). Specifically it is usually not a problem when the temperature differences are less than 30°C (50°F) and permeabilities up to 30 m/d (100 ft/d). Robust numerical transport models are necessary to ensure thermal breakthroughs do not occur. Examples of models include METROPOL, MOCDENSE, NAMMU, SUTRA, FEFLOW, and HST3D (Kipp, 1997).

In most of the modeling work by the authors, HST3D has been chosen for availability (source code, price), and capabilities (heat and solute transport simultaneously, and 3D instead of only 2D). HST3D is based on the SWIP model (Intercomp Inc., 1976). As an example, Figure 5.3 shows the calculated isotherms for a common hypothetical situation. The main input data for this can be found in Table 5.1.

In general the designer has many parameters that can be adjusted to obtain an effective design. Usually the energy requirement of the building or end user is fixed as well as the background groundwater temperature. Parameters that are available are: the aquifer that is chosen (in case there are more aquifers at the location), the number of wells, the position of the wells with respect to each other and with respect to the regional flow and the length and depth of the well screen in case the aquifer allows a partial penetration. Due to heat buildup around the warm well and cold buildup around the cold well, the groundwater temperatures are gradually changed during use. Dispersion and conduction to upper and lower confining layers are the main reasons for this. The dispersivity is not usually known and an approximation is necessary. In this case one tenth of the distance traveled, or a value of 3 m was used for the dispersivity.

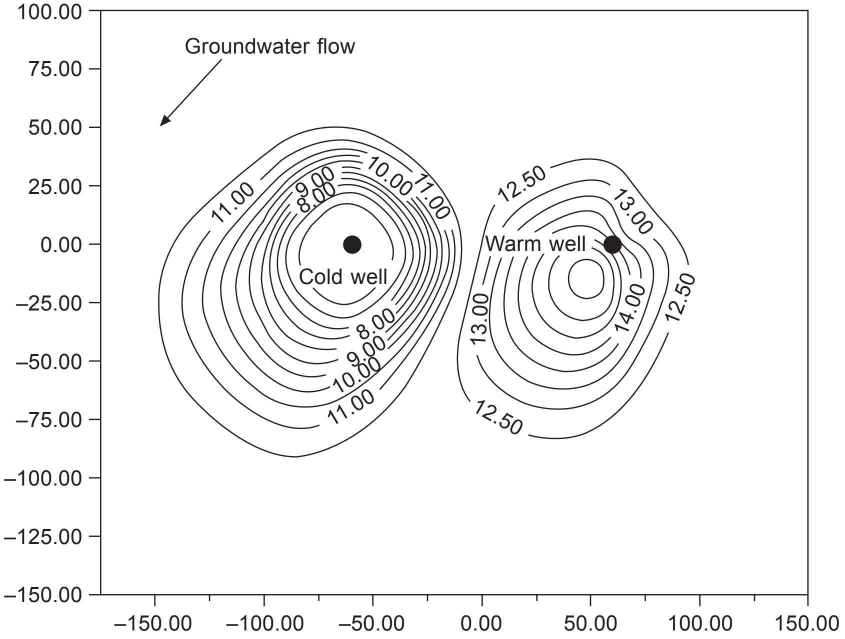


Figure 5.3 Calculated isotherms in the aquifer after the fifth winter. Contours are in °C, X- and Y-axis are in m (Pyne, 2005, by permission from D. Pyne).

Table 5.1 Data for example calculation using HST3D

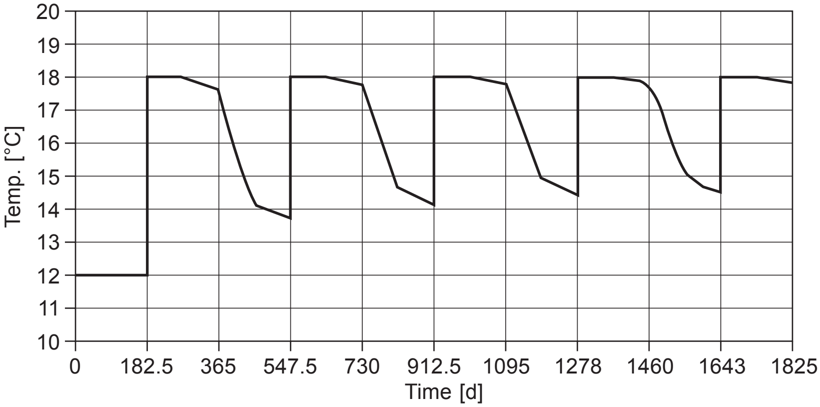
Parameter	Value
Storage volume per season [m^3]	100,000
Injection temperature in summer [°C]	18
Injection temperature in winter [°C]	6
Natural groundwater temperature [°C]	12
Aquifer thickness [m]	30
Regional groundwater flow velocity [m/year]	30
Distance between warm and cold well [m]	120
Angle between regional flow and line connecting wells [degrees]	45

Source: Pyne, 2005, with permission from D. Pyne.

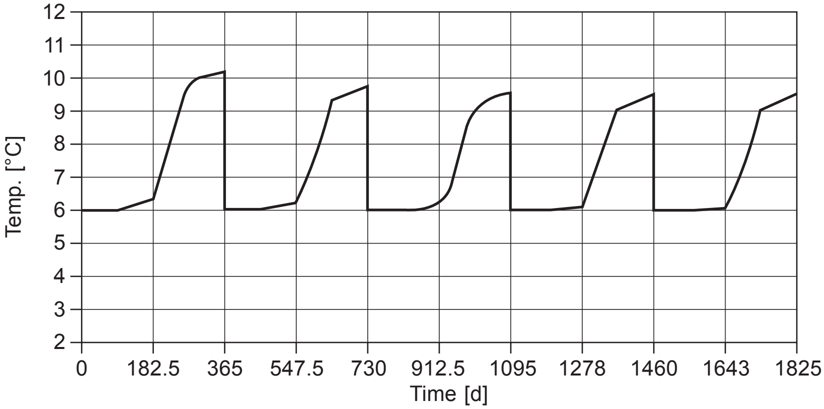
For the first five cycles, the calculated production temperatures from the cold and the warm wells are shown in Figures 5.4(a) and (b). The largest effect of the temperature change around the injection and production wells is observed in the first few cycles and diminishes after that. In this case the maximum production temperature from the cold well should not exceed 9°C, which results from a design supply temperature for the cooling circuit of 10°C and a ΔT of 1°C over the heat exchanger between groundwater and building circuit (Pyne, 2005). Note that the relaxation temperatures in the warm well are rising over time. The cold well maximum extraction temperature falls over time. This is to be expected and is demonstrating little thermal interference.

5.4.2 Geochemical aspects

Geochemical property requirements for long-term viability of wells is presented by Jenne *et al.* (1992). Of importance are the presence of dissolved gas, the use of reduced, iron-containing water, and the possible presence of a water quality boundary (so called redox interface) in the aquifer so that both aerobic (O_2 or NO_3-containing water) and anaerobic (Fe or Mn-containing) water are present. If groundwater contains high concentrations of dissolved gas, there is a risk of degassing that can rapidly clog the infiltration well. Maintaining sufficient overpressure may prevent this type of well clogging. Groundwater is often anaerobic, and contains 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. This suggests utilizing variable speed pumping. However, this will not prevent iron and manganese precipitation when a redox interface is found in the middle of a fully screened aquifer.



(a)



(b)

Figure 5.4(a) Calculated temperatures in the warm well for 5 years (Pyne, 2005, by permission from D. Pyne); (b) Calculated temperatures in the cold well for 5 years (Pyne, 2005, by permission from D. Pyne).

5.5 ATES design

Aquifers that can be utilized for cooling and low temperature thermal energy storage with ATES are limited to deposits of sands and gravels and highly fractured rock, preferably within about 150 m (500 ft) of the surface. Water quality further limits useful aquifers to those with consistent concentrations of dissolved oxygen, limited mineral content and relatively high porosity and hydraulic conductivity. These conditions make ATES less universally applicable than borehole thermal energy storage (BTES), which can be applied in almost all geological formations. There are many advantages of ATES compared to BTES. While aquifers are geographically limited in area around the world, they are typically located under large population areas such as the east coast of the US and new river deltas such as the Netherlands.

Those factors affecting ATES design are: stratigraphy, grain size distribution, structures and fracture distribution, aquifer depth and geometry, storage coefficient, permeability, leakage factor of confining layers, degree of consolidation, natural temperature, static head, natural groundwater flow, direction of flow, and water chemistry. Table 5.2 summarizes the range of parameters normally required for a successful application in an unconsolidated aquifer.

Flow control is a serious issue in ATES projects. The complexity is caused by the additional requirement to maintain an overpressure in the groundwater system under all operating conditions. This is achieved with variable speed frequency drive submersible pumps in combination with either multiple injection tubes in the recharge well, which are taken into or out of operation depending on the desired groundwater flow, or pressure controlled automatic valves located in the well (Figure 5.5).

Table 5.2 **Major criteria for unconsolidated aquifer**

Aspect	Lower limit	Typical	Upper limit
Aquifer thickness (m)	2–5	25	None (partial use)
Aquifer depth (mbgs)	5 (injection pressure)	50	150 (economic)
Aquifer permeability (m/s)	3×10^{-5}	3×10^{-4}	1×10^{-3}
Groundwater flow (m/d)	0	0.1	0.3
Static head (mbgs)	50	10	–5

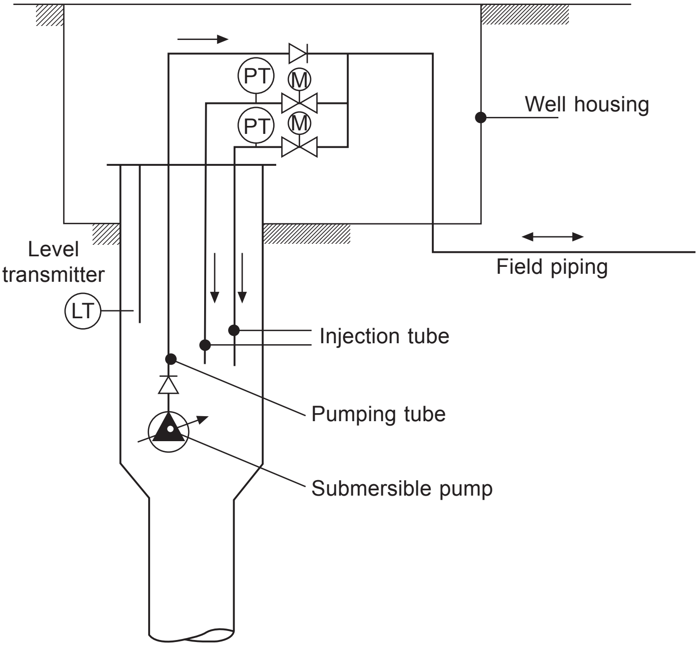


Figure 5.5 Well piping scheme of extraction/injection well with multiple injection pipes.

5.5.1 Well design

Reverse rotary drilling to create a controlled borehole diameter is required in order to obtain good quality ground samples, and to reduce the need for bentonite in the drilling fluid. This is to prevent clogging of pores in the formation, which would lead to high pressures for infiltration. Similarly, in rock drilling, care is required to prevent closing off of the pores or fractures. In unconsolidated formations and some types of consolidated formations, a thick gravel pack surrounds the screen which is carefully located in formations with good hydraulic conductivity (i.e., very low concentrations of silt and/or clay).

The basic design criterion is to keep the flow velocity of the water around the production and infiltration well low enough for fines to stay in the aquifer (production well) and to collect fines that moved from the production well to the infiltration well in the gravel pack. Thus wells can be back-flushed readily at the end of each season to maintain low injection resistance. This ensures the longevity of the wells as well as reducing pumping energy. Variable speed pumps are used to match load conditions and to ensure water is sufficiently chilled during storage. These design criteria result in much larger diameter wells than would normally be expected for a standard water extraction supply well. For production wells a maximum approach velocity is used. Several equations have been developed over time to relate the maximum approach velocity to aquifer characteristics (Pyne, 2005, p. 443).

A measurement technique to determine the suitability of water for infiltration is the membrane filter index (MFI) measurement, giving a measure for the 'plugging capacity' of the water. The technique has been developed during research on clogging of infiltration wells in The Netherlands. It is used to check the water quality of wells for ATES systems in The Netherlands and it has been applied for ASR systems in the US (Pyne, 1995, p. 232). The clogging rate of an injection well can be estimated based on the MFI value, the approach velocity in the well and the aquifer characteristics (Pyne, 2005, pp. 444–445). A smaller diameter well (higher approach velocity) will result in a higher clogging rate and thus higher maintenance cost. This implies that economic criteria, such as total cost of ownership, determine the design of infiltration wells. For injection wells the maximum injection pressure that can be applied also limits the flow. This maximum injection pressure can be derived from the depth of the aquifer and the characteristics of the strata covering the aquifer.

Given the aim to remove drilling mud from the aquifer and to minimize the movement of fines present in the aquifer, much attention should be paid to well drilling, well completion and well development. Where required, wells are gravel packed with the thickness of the gravel pack varying between a minimum of 100 mm to a maximum of 300 mm. Wells are developed (cleaned) using a variety of methods to remove any drilling mud and fines from the wells and the surrounding formation and sometimes requiring a couple of weeks of development time. The cost of well development for wells for ATES projects is in general considerably higher than for wells that are only used for production. The requirements are more severe, because water has to be infiltrated for many years without significant clogging.

5.5.2 Well field layout

Well field layout is dependent on several factors including geomorphology, location of end user and other competing uses for the available surface area. Three of the issues to be taken into account while designing a larger well field are described in the following.

5.5.2.1 Clustering strategies

For larger ATES well fields, there is the possibility of induced changes in hydraulic head (pressure changes in the aquifer and the covering layers). Large changes in hydraulic head are to be carefully avoided since land subsidence is a possibility. In addition it might result in reduced stability in civil works (tunnels, cellars, etc.). There are several options to reduce the hydraulic impacts of an ATES system. For larger well fields, interspersing of cold and warm wells is very effective. This implies that, instead of making a cluster of warm wells and a separate cluster of cold wells, the well field layout is arranged in a number of doublets, each doublet consisting of one warm and one cold well. This well field layout offers very good possibilities to reduce the changes in hydraulic head. The drawback of interspersing of wells will be higher cost for piping and a reduction of thermal efficiency of the ATES system.

5.5.2.2 Distance between warm and cold well

When the temperature of the warm and that of the cold well are on both sides of the natural temperature (i.e., the warm well injection temperature above, and the cold well injection temperature below the natural temperature), short-circuiting between the wells should be avoided. A minimum distance between a warm and a cold well of three times the thermal radius of the stored cold or heat is normally sufficient to prevent thermal breakthrough between wells. However, in other cases breakthrough might be more likely and more careful modeling will be necessary. This becomes apparent when utilizing software discussed in Section 5.4.1. An equation (5.2) for the thermal radius r_{th} is:

$$r_{th} = \sqrt{\frac{c_w Q}{c_a H \pi}} \tag{5.2}$$

where r_{th} is the thermal radius of the stored cold or heat [m], $c_{w,} c_a$ are the Heat capacity of water and aquifer material (water and sediment together) [J/(m^{3}K)], Q is the amount of pumped/reinjected water per season [m^3], and H is the length of the screen [m].

When the temperatures of the warm and cold wells are on one side of the natural groundwater temperature, some short-circuiting will increase the thermal efficiency. For instance, if a cold storage system is made using a warm well at an average injection temperature of 10°C and a cold well with an injection temperature of 4°C, while the natural temperature is 12°C, then the warm well (10°C) should be placed preferably on the 10°C isotherm around the cold well. This means that the distance between the wells should in this case be around 1–2 times the thermal radius, depending on temperature levels and regional flow (size and angle).

Equation (5.3) describes changes in hydraulic heads for a single and a double doublet:

$$\Delta h(x, y) = \frac{Q}{2\pi T} \ln \frac{r_{i1} \cdot r_{i2}}{r_{p1} \cdot r_{p2}} \tag{5.3}$$

where Δh is the change in hydraulic head [m]; Q is the amount of pumped and re-injected water [m^3/d]; T is the transmissivity of the aquifer [m^2/d]; $r_{\mathrm{i}1}$, $r_{\mathrm{i}2}$ is the distance from observed point (x,y) to infiltration wells $i1$ and $i2$ [m]; r_{p1}, r_{p2} is the distance from observed point (x,y) to production wells $p1$ and $p2$ [m]

For a single doublet the values of r_{i2} and r_{p2} can be omitted. The injection wells and production wells are reversed seasonally. From this equation it can be deduced that T and Q are linearly related to the pressure change in the aquifer. However, this is not true of the well configuration. Alternating warm and cold wells can result in reducing pressure changes (Pyne, 2005, p. 449).

5.5.2.3 Angle with respect to regional flow

Since high regional aquifer flow can result in large thermal losses, the orientation of the wells must be chosen carefully. The optimal positions will depend also on the type of storage that is designed: heating only, cooling only or for both heating and cooling. The dominant load determines the location of the corresponding well which should be on the upside of regional flow. Thus losses can be captured from the downstream well and improve overall efficiency. When the thermal loads on the aquifer are fairly balanced, then placing the wells at an angle perpendicular to the regional flow direction will minimize short-circuiting. When there are more wells, then the same rule applies to the clusters keeping them inline. In this way losses from the upstream well may be partially recovered from the downstream wells.

The results also show that by alternating positions of the injection and the production wells in a multiple well configuration, smaller pressure changes result. Interspersing wells with multiple doublet systems reduces the changes in hydraulic heads. The downside is higher costs for piping (approximately double the cost) and to lower thermal efficiencies compared to a clustered configuration.

5.6 ATES cooling only case study: Richard Stockton College of New Jersey

Stockton College is located in the United States near the southeastern edge of the New Jersey Coastal Plain. At this location, the total thickness of unconsolidated sediments is estimated to be approximately 1.35 km (4500 ft) with multiple layers of sand and clay formations. The upper formation, Kirkwood, combined with the generally permeable sediments of the Miocene Cohansey Sand, makes up the Kirkwood–Cohansey aquifer system, a highly productive regional aquifer found throughout a large portion of the Coastal Plain of New Jersey. The formation properties can be found in Table 5.3.

The energy supply system with ATES uses a cooling tower to charge the aquifer with chilled water during the winter months. In the summer, this stored cold energy is withdrawn from the aquifer to provide cooling to a chilled water loop connected to several buildings. Since a significant cooling capacity is delivered by the aquifer, chillers in a new building were avoided. Cold water wells and warm water wells are connected to building loads through two heat exchangers, one to direct cold and heat between a campus cooling loop and the aquifer storage and one to direct cold from the cooling tower to the aquifer storage.

During the winter months the cooling tower runs whenever the outdoor wet bulb temperature is low enough to generate 5°C (41°F) water. On the groundwater side of the heat exchanger a temperature of 6.1°C (43°F) is generated. This water is injected into the aquifer cold storage. During summer water is withdrawn from cold wells to cool the buildings. The maximum flow rate in the groundwater circuit is 272 m^3/h (1200 gpm). As long as the flow rate required for cooling does not exceed 272 m^3/h, all cooling is provided from the aquifer storage. In case the flow rate would exceed 272 m^3/h, the cooling of a new building is provided from the aquifer storage and the base load cooling of four existing buildings connected through a common chilled water loop is taken over by the existing chillers located on those buildings. No chillers and cooling towers are installed in the new academic building, thus saving the cost of 900 kWt (250 T) of chiller capacity. In addition, this system replaces the

Table 5.3 Major aquifer properties of Kirkwood – Cohansey aquifer system

Aquifer property	Metric unit value	English unit value
Depth below surface	35–60 m	115–200 ft
Transmissivity	750–775 m^2/d	9200–9400 ft^2/d
Hydraulic conductivity	31–32 m/d	102–104 ft/d
Vertical hydraulic conductivity	0.006–0.027 m/d	.02–.09 ft/d
Hydraulic gradient	0.0019–0.0024	0.0019–0.0024
Direction hydraulic gradient	ENE	ENE
pH	5.1	5.1
Iron	0.78 mg/l	
Alkalinity as $CaCO_3$	1.0 mg/l	
Chloride	1.4 mg/l	
Ammonia nitrogen	9.5 mg/l	
Nitrate nitrogen	<0.1 mg/l	
Sulfate	1.9 mg/l	

need for redundant cooling capacity, which would have been added and/or capacity for other new buildings including a new Student Center added to the system more recently.

While cold storage is charged in winter with a temperature of 6.1°C (43°F), in summer the first water extracted will be 6.1°C, but the extraction temperature from the storage will gradually rise during the course of the summer, to at most 8.9°C (48°F). Under design conditions, with a maximum extraction temperature of 8.9°C, the maximum injection temperature in the warm wells will be 18.3°C (65°F). The average injection temperature in the warm wells is estimated at approximately 15.1°C (59.2°F). About 427,000 m^3 (113 million gallons) of cold water can be charged into the aquifer, providing a total of 1025 MWh/annum (575 000 ton hours).

5.6.1 Aquifer storage system

The groundwater system extracts stored chilled or warm water from the sand aquifers and re-injects it into the sand aquifer after it has lost its energy. The aquifer storage system consists of three cold wells and three warm wells. The dimensions of the wells are given in Table 5.4. For this dimensioning, it was assumed that it would not be possible to screen the Lower Cohansey aquifer over the full height and that the MFI value of the groundwater in the aquifer is $2s^2/l$; criteria that were met (Paksoy *et al.*, 2009b).

The down-the-well piping includes a wire-wrap screen at the level of the storage aquifer. The space around this screen is filled with a fine gravel pack. A riser pipe and a pump chamber are located, successively, between the top of the screen and the ground surface. The pump chamber consists of a plastic casing with a sufficiently large diameter to accommodate the submersible pump (see Figure 5.5). The resulting layout of the well field and the piping is presented in Figure 5.6.

To determine the hydraulic impact of the extraction and infiltration of groundwater from/into the lower Cohansey aquifer, calculations have been made with the software program MLPU. The maximum change of head in the storage aquifer is calculated to be about 5.2 m (17 ft). This change of head occurs in the direct surrounding of the wells.

Table 5.4 **Well dimensions of the Kirkwood – Cohansey aquifer storage system**

Design parameter	Dimensions
Number of wells	2 × 3
Diameter cold and warm wells	0.70m (28″)
Depth	60.9m (200 ft)
Screen depth	35.1–61.0m (115–200 ft)
Effective length of screen	19.8m (65 ft)

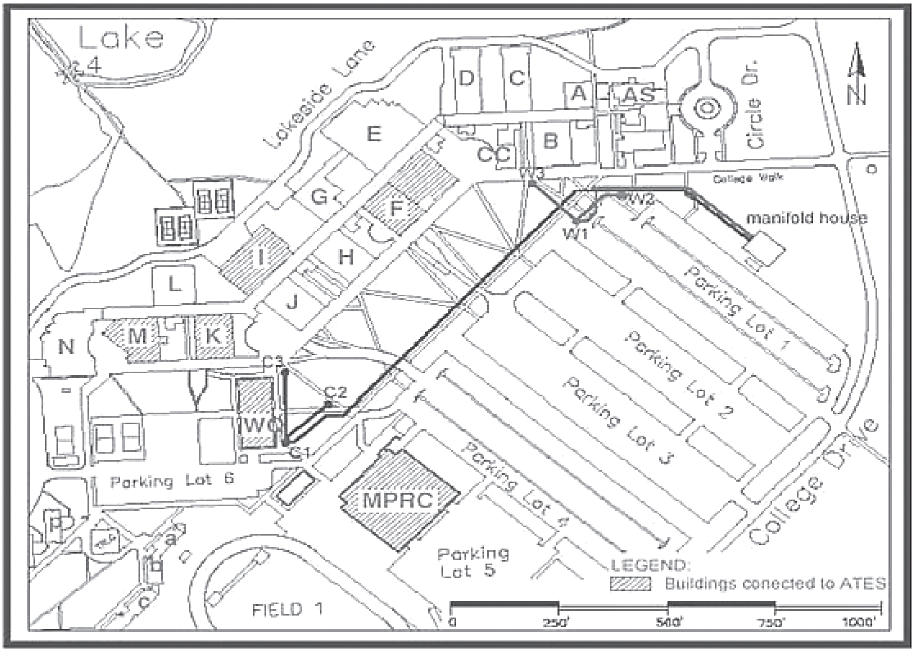


Figure 5.6 Transit piping between wells and buildings served by ATES.

To calculate the impact of the storage system on the phreatic groundwater level, it is assumed that the groundwater extraction and infiltration during wintertime takes place at maximum flow rate during one period without interruption. This approach results in the worst case situation with respect to the impact on the phreatic groundwater level. It is also assumed that the hydraulic resistance of the intermediate layer covering the Lower Cohansey aquifer is 1000 d. The resulting modeling suggests that the hydraulic impact of the storage system on the phreatic groundwater level at the wetlands northwest of the College site will be less than 5 cm (2″). This result is significant in determining that the impact of the system would not adversely affect the surrounding wetlands.

Calculations with the computer code HST2/3D have been made to determine the volume of cold groundwater to be stored during the winter in order to meet the cold demand during summertime. The calculations have been made assuming a gradient of the groundwater head (groundwater flow) of 0.0022 in the direction east-north-east. Input assumptions are found in Table 5.5.

The results from the calculations are summarized in Table 5.6 for the fifth year of operation. From comparing the amount of cold groundwater that should be charged in winter to meet the cooling demand in summer with the amount that actually can be charged with the cooling tower in an average winter, it can be concluded that the cooling tower capacity is adequate for this project.

Figure 5.7 shows the calculated temperature of the injected and extracted

Table 5.5 Assumptions for the HST2/3D calculations

Parameter	Charging (winter)	Discharging (summer)
Injection temperature	6.1°C (43°F)	15.1°C (59.2°F)
Maximum useable temperature		8.9°C (48°F)
Required cooling capacity		2025 MWh (575,000 ton hours)

Table 5.6 Results of hydrothermal calculations (year 5)

Water to be charged in cold wells in winter	325,000 m^3 (86 MGallons)
Water to be produced from cold wells in summer	245,000 m^3 (65 MGallons)
Average production temperature from cold wells	7.6°C (45.7°F)
Max. production temperature from cold wells	8.9°C (48.0°F)
Storage thermal efficiency	68%

water temperatures from the wells over a 20-year period. It is clear that the cold wells get colder and warm wells warmer over this period of time. The average extracted and delivered temperatures are a mixture of the three cold and three warm wells.

5.6.2 Cost effectiveness

5.6.2.1 Fuel costs

A combination of the building simulation program, micro-AXCESS Energy analysis Program, Version 10.01, and actual measured demand of the existing buildings provides the basic information for determining electrical use demand. Table 5.7 gives the electrical demand for the ATES system and the reference chiller system. At 2007 electrical rates, the estimated savings for the ATES system is approximately US$90,000/annum.

5.6.2.2 Maintenance

The only major maintenance item that is different between the traditional and the ATES systems is that there is an avoided 900 kWt (250 T) chiller and cooling tower for the ATES system and subsequent reduced maintenance. This is estimated at US$4000/annum. There is also a possibility that there will be deferred maintenance required on the existing chillers and cooling towers since they will not be used as heavily. This benefit has not been quantified.

The second major difference is that preventative maintenance of the wells occurs during seasonal backflushing during the change-over period between charging and discharging of ‘cold’.

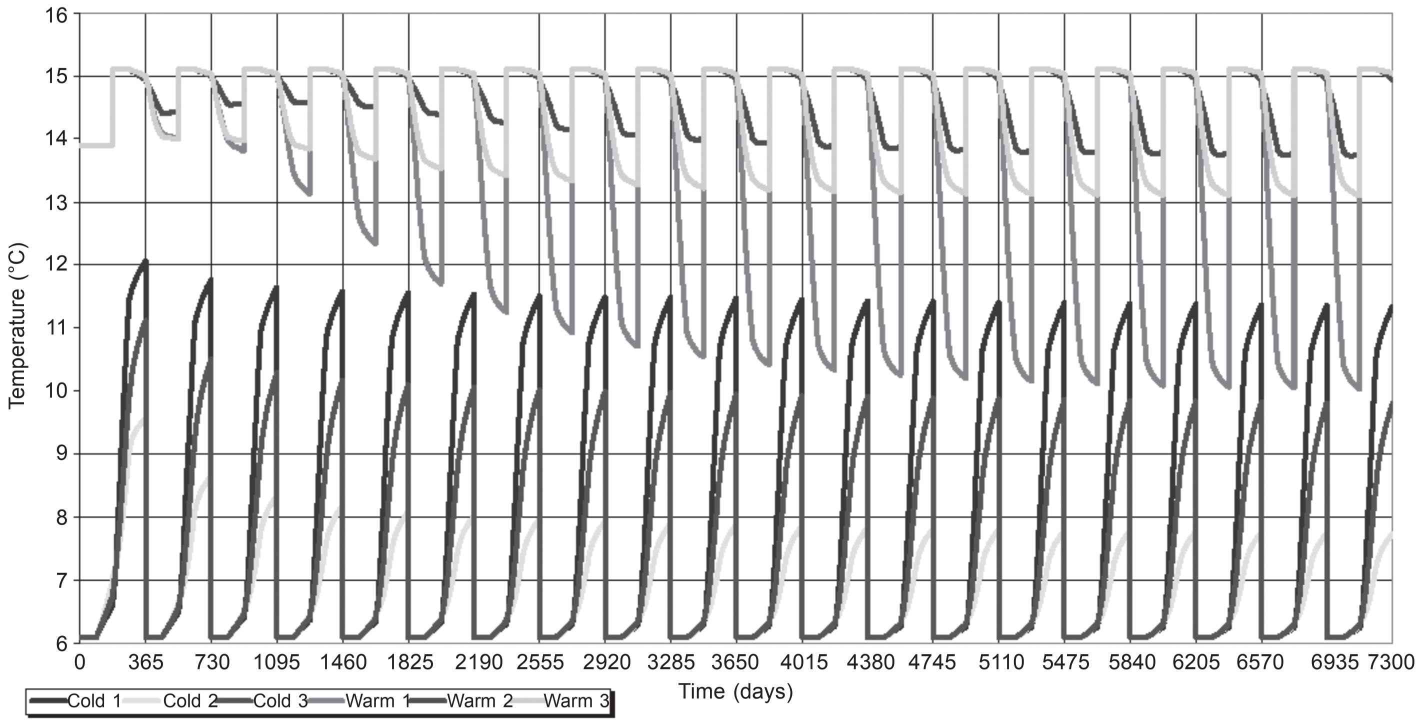


Figure 5.7 Temperatures of water extraction from cold and hot wells over a 20-year period.

Table 5.7 **Electrical demand for the ATES system**

Standard chiller		ATES system		Electrical savings	
kWh	**kW peak**	**kWh**	**kW peak**	**kWh**	**kW peak**
770,862	594	344,288	202	426,574	445

5.6.2.3 Replacement

The existing cooling towers and chillers will have a much lower use. However, they were fairly new (approximately 6 years old) and this saving will only be realized in 15 years or more. This is also treated as an unquantifiable benefit. If this project were entirely for new buildings, then the avoided cost of chillers and cooling towers would be realized immediately.

5.6.2.4 Avoided costs

The College will be able to utilize the approximate 3000 kWt (850 ton) capacity of the system and will, over the short term, realize a savings in reduced need for 850 tons of chillers. This credit offsets a substantial cost of the project.

5.6.2.5 Installation costs

The total incremental cost of the project is US$1.5 million after taking into account the avoided cost of chillers on the new buildings.

5.6.2.6 Financial analysis

As an example of an expected rate of return on a US$1.5 million investment, if fuel inflates at 5%/annum and our first year savings is US$90,000, the internal rate of return over 20 years is 7%. Since the bonds utilized to pay for this project are at about 4%, the College will receive a net positive cash flow. Alternatively, the value of cash flow discounted at 4% after 20 years has a present value of approximately US$2 million.

The additional value of ownership is intangible, but clearly of value as the College continues to develop its commitment to reduction of greenhouse gas emissions and its environmental image.

5.7 ATES district heating and cooling with heat pumps case study: Eindhoven University of Technology

Eindhoven University of Technology was established in 1956. In size, it is the second largest university of technology in the Netherlands and hosts about 7000 students and 3000 employees (in 2010). Many buildings on the university campus were erected in the early 1960s. A central gas-fired heating plant in combination with a district heating system delivered heat to the buildings. Cooling to laboratories and offices was provided by groundwater, except when low-temperature cooling was required. The groundwater was pumped from wells on the campus site and had a natural temperature of 11.8°C. After being used for cooling, the groundwater was discharged into the Dommel River, which passes the campus.

In the 1980s the governmental groundwater policy aimed at preserving good-quality groundwater for drinking water purposes. As a result, Eindhoven University started to change from groundwater-based cooling to chiller-based cooling. It is obvious that this resulted in an increase in electricity consumption for cooling. In the 1990s two individual buildings were equipped with aquifer cold storage as an alternative to chiller-based cooling.

Subsequently, the university committed itself to improve its energy efficiency by 20% over the period 1996–2006. This commitment and the fact that many of the 40-year-old buildings had to be refurbished over the next decades, resulted in several studies on the future energy infrastructure of the campus site. As a result of these studies, in 1998 the decision was made by the Board of Directors of the University to realize a heating and cooling infrastructure based on large-scale aquifer thermal energy storage (ATES-based district heating and cooling (DH&C) system).

5.7.1 Project description

The ATES system will supply direct cooling in summer as well as low-temperature heat in winter for the evaporators of the heat pumps. The heat pumps are located in the plant rooms of the buildings and can provide peak load cooling in summer as well. In order to be able to charge enough cold in winter, cooling towers are used to charge additional cold. The ATES system on the campus of Eindhoven University of Technology was completed by 2001 and can serve approximately 20 buildings with a total floor space of about 250,000 m^2.

The ATES-based DH&C system consists of a main distribution network with two distribution rings (one warm and one cold) to which the cold wells and warm wells are connected. By means of this main distribution network, cold and low temperature heat are available all year round. Every building has a so-called delivery station, including a heat exchanger and several mechanical and electrical components to exchange cold and heat between the building and the main distribution network.

The ATES-based DH&C system also enables the users to exchange cold and/or heat by means of the distribution network. In this case the groundwater is functioning as an energy transport medium between the buildings. In the case of a net cooling or heating demand after the energy trade-off between users, groundwater is extracted from the cold or warm wells respectively, and transported to the users by means of the distribution network. As a result of this energy exchange between the buildings, the energy efficiency is further improved. An overview of the most important features of the ATES system at Eindhoven University of Technology is given in Table 5.8.

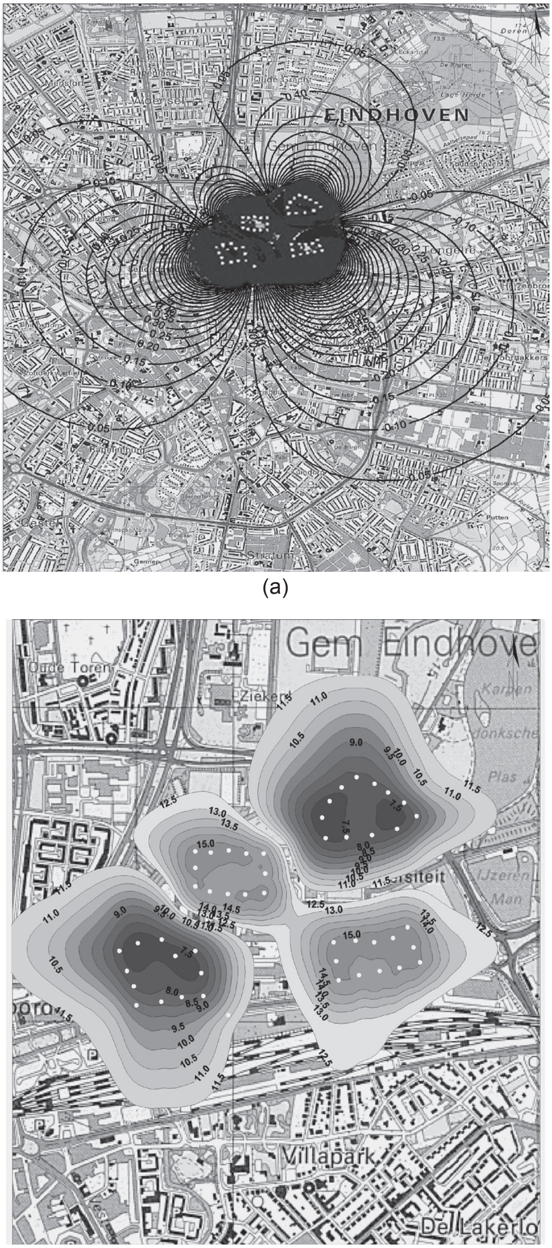
Table 5.8 **Dimensions of the ATES DH&C system at Eindhoven University of Technology**

Dimensions ATES DH&C system		**Summer (cooling)**	**Winter (low-temp. heating)**
Capacity	MW_t	17	17
Maximum energy delivery	GWh_t/y	25–30	25–30
Max. amount of pumped water	m^3/y	3,000,000	3,500,000
Maximum flow rate	m^3/h	2000	2000
Average infiltration temperature	°C	16	6
Dimensions of components			
Number of cold wells	#	16	16
Number of warm wells	#	16	16
Number of wells per cluster	#	5 or 6	5 or 6
Filter screen depth (below surface)	m	between 28 and 80	between 28 and 80
Length of effective filter screen	m	30	30
Diameter of borehole	mm	700	700
Maximum flow rate per well	m^3/h	125	125
Power consumption per well pump	kW_e	25	25
Diameter of main field piping	mm	450	450
Total length of field piping	m	1500	1500

The soil conditions on the campus show a top layer of approximately 28 m in which a shallow phreatic aquifer is present. At a depth between 28 m and approximately 80 m below the surface, the ‘first aquifer’ is found with a transmissivity in the range of 1600 to 2000 m^2/day. Below this aquifer an aquitard is found of 60 m thickness with a hydraulic resistance of 20,000 days. Deeper aquifers are present and protected by the government as drinking water reserves and therefore these aquifers are not available to be used for ATES. The natural temperature of the groundwater in the first aquifer is 11.8°C and the groundwater flow of 15–20 m/a is directed north/ north-west. The groundwater is fresh with a chloride content of 10–40 mg/l.

5.7.2 Environmental impacts

Application of large-scale ATES systems will result in high maximum flow rates and large quantities of groundwater that are extracted and infiltrated. As a result, the possible effects on the surroundings and the environment can be significant. Therefore, special attention should be paid to the configuration of wells (see Section 5.5.2). For Eindhoven University of Technology several options for well configuration were investigated. Figures 5.8(a) and 5.8(b) show the thermal and hydrological impacts

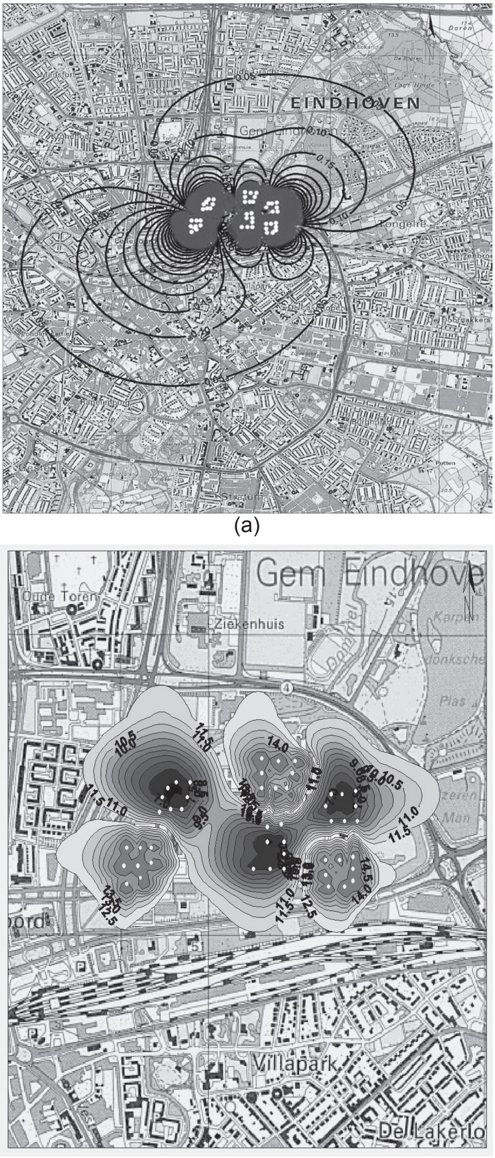


(a)

(b)

Figures 5.8(a) Maximum hydrological effects in the aquifer for an ATES system with two clusters of warm and cold wells. The horizontal distance across the figure is 4500 m and the hydrologic head is in meters. (b) Maximum thermal effects (after 20 years of operation) in the aquifer for an ATES system with two clusters of warm and cold wells. The horizontal distance across the figure is 1700 m and the isotherms are in °C.

in the aquifer for an ATES system with two clusters of warm and cold wells, and Figure 5.9(a) and Figure 5.9(b) show the impacts for a system with three clusters.



(a)

(b)

Figures 5.9(a) Maximum hydrological effects in the aquifer for an ATES system with three clusters of warm and cold wells. The horizontal distance across the figure is 4500 m and the hydrologic head is in meters. (b) Maximum thermal effects (after 20 years of operation) in the aquifer for an ATES system with three clusters of warm and cold wells. The horizontal distance across the figure is 1700 m and the isotherms are in °C.

The latter configuration has been realized. (Note: the figure shows eight wells per cluster, which takes into account a possible expansion of the present system with five or six wells per cluster.)

5.7.3 Evolution of the project

A characteristic of ATES-based DH&C systems is that a major part of investment in infrastructure has to be made up front, i.e. at the moment when the first building requires heating and/or cooling from the system. The major part of the infrastructure at Eindhoven University of Technology was realized by 2002. Ten years later, about 70% of the building area on the campus was connected to the system. Due to changes to the refurbishment and building program, this took more time than envisaged.

New buildings in the framework of the so-called Campus 2020 program are heated and cooled completely by the ATES/HP DH&C system. It is expected that the annual energy saving will increase from about 3 million kWh_e and 600,000 m^3 natural gas in 2012 to about 4 million kWh_e and 1 million m^3 natural gas when all buildings are connected.

5.8 ATES heating and cooling with de-icing case study: ATES plant at Stockholm Arlanda Airport

Stockholm Arlanda airport handles 20 million passengers per year (Swedavia, 2013). About 15,000 people work at the airport, which makes it the largest workplace in Sweden. The airport is owned and operated by the Swedish Civil Aviation Administration (LFV), a government company that operates 16 Swedish airports. Stockholm Arlanda has a cap for carbon dioxide emissions included in its environmental permit. This emission cap includes emissions from take-off and landing of aircraft, ground transports to, from and at the airport and heating and cooling of airport buildings. It states that the net CO_2 emissions from these activities shall not be higher in year 2016 than they were in 1990, regardless of any expansion. Another goal for the airport was a considerable reduction of its energy consumption and also that it should use 100% renewable energy as from 2010 (Andersson, 2012).

5.8.1 ATES plant

Heat and ‘cold’ is seasonally stored in an aquifer close to the airport. In the winter the ATES is used for heating of the ventilation air and for snow melting of the ramps at gates. In this way the aquifer water is cooled down during the winter. In the summer this cold water is used for comfort cooling.

The aquifer is situated in an esker a couple of kilometers away from the terminals (Figure 5.10). The idea of using the esker for seasonal storage of heat and cold took

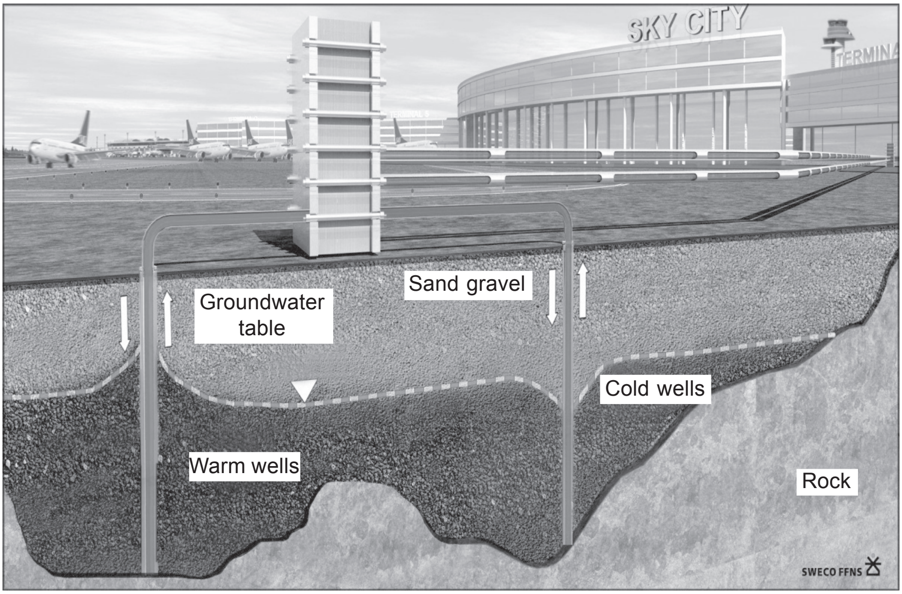


Figure 5.10 Depiction of wells near terminal (provided by Olof Andersson, Sweco FFNS, Malmö, Sweden).

form in 2005. A feasibility study made in 2006 was followed by hydrogeological site investigations. The Swedish Environmental Court gave necessary permits in August 2008 and the construction of the ATES started. The system was designed to cover a cooling and heating load of approximately 6 MW at a maximum ground water flow of 720 m^3/h.

The ATES consists of five cold wells in the northern part of the aquifer and six warm wells in the southern part. The water is pumped from one side of the esker, delivering heat or cold passing the heat exchanger, and then continuously injected back at the other side to the aquifer. The heat or cold is distributed by a local district pipe system to connected buildings.

During winter the heat is used for preheating the ventilation air to the terminals and to the system of ground heating coils at the gates. The waste cold from heating is distributed back and stored at the cold side of the aquifer. The cold storage temperature is estimated to vary between +3 and +5°C under normal conditions. Before this system was taken into operation, heating was supplied by district heating. The plant will annually reduce the amount of district heat by 15 GWh.

In summertime, the flow through the ATES is reversed as it supplies cooling to the terminals where the need for cooling is large. In this way the ATES replaces the old conventional chillers which had an annual electricity consumption of 4 GWh. The return temperature to the ATES is about +15°C, but this temperature can be increased to approximately +25°C by using the ground heating coils at the gates as solar collectors during sunny days.

5.8.2 Cost effectiveness

The ATES plant at Stockholm Arlanda has considerably lowered the energy consumption, with reduced electricity use for cooling production by 4 GWh/year and the district heating use by 15 GWh/year. The cost of energy has thereby been annually reduced by at least €1 million for an investment of approximately €5 million. The system's efficiency is very high since no heat pumps are used and its seasonal performance factor of about 60 means that it is practically insensitive to future energy fluctuations.

5.9 Conclusion

With well over 1000 ATES systems realized by 2013, seasonal thermal storage in aquifers is a well-developed technology. While the vast majority of applications are for institutional and large residential buildings, notable exceptions are for community thermal energy systems for small commercial and industrial applications. The largest limitation on the application of ATES is hydrogeological suitability. Fortuitously coastal regions are most likely to have significant aquifers close to the surface coinciding with the largest population densities. It is clear that with the proper design techniques found in this chapter that ATES is a viable and attractive 'green energy' source. It is a mature technology. Case studies presented are typical of the applications of ATES. Realized coefficients of performances ranging from 8 to 60 demonstrate not only a high level of energy efficiency but also a benefit of reducing the impact of future energy cost escalation.

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