Chapter 4
Aquifer Thermal Energy Storage

4.1 Definition

In general, groundwater temperatures remain relatively stable at temperatures typically 1–2 °C higher than local mean annual temperatures between depths of 10–20 m. Below these depths, groundwater temperatures gradually increase at a rate of geothermal gradient. As a result, in areas where a supply of groundwater is readily available from an aquifer, a reliable source of low temperature geothermal energy exists.

Open-loop geothermal systems use this resource by extracting groundwater from an aquifer using a water well, and passing it across a heat exchanger to allow transfer of energy for direct use in the HVAC system of a building, typically in combination with a heat pump. The majority of open-loop systems subsequently dispose of the used groundwater either by discharging to a surface water body or reinjecting into the aquifer. These types of open-loop systems, known as pump-and-release or pump-and-dump systems, are relatively simple to implement. For commercial or institutional applications, they offer energy efficiencies comparable to closed-loop systems at substantially reduced capital costs (Bridger and Allen 2005).

In the open-loop systems, energy is typically transferred to and from the building's heating and cooling system via a heat exchanger. Conversely, closed-loop systems exchange energy directly in the ground using ground heat exchanges, which are commonly installed in adapted trenches at relatively shallow depth or in vertical boreholes. Other variations allow for the transfer of energy through heat exchanger pipe work installed in foundation structures (Dickinson et al. 2009).

It is useful to understand a difference between higher and lower enthalpy systems. Higher enthalpy systems take advantage of higher temperature geothermal resource generated from a heat flux originating from decaying radioactive isotopes of uranium, potassium, and thorium in the deeper formation of the earth's crust. Lower enthalpy systems utilize the net solar energy absorbed and stored in the subsurface. In the lower enthalpy systems, the groundwater temperature near

K. S. Lee, *Underground Thermal Energy Storage*, Green Energy and Technology,
DOI: 10.1007/978-1-4471-4273-7_4, © Springer-Verlag London 2013

the surface is inherently associated to the surface temperatures throughout the year. There are seasonal fluctuations in temperatures within a few meters below ground surface. This effect is reduced with greater depth, so the prevailing temperature gradient relating to the thermal flux.

Open-loop systems are a particular type of low temperature geothermal system. A particular type of open-loop system using aquifers for energy storage, is referred as aquifer thermal energy storage (ATES) systems. Aquifer thermal energy storage is an approach used to enhance the efficiency in comparison with other ground energy system. ATES installation actively store cooled and heated groundwater in the ground from respective heating and cooling mode cycles (Dickinson et al. 2009).

Goundwater is used to transfer the thermal energy into and out of an aquifer in ATES systems. ATES systems utilize aquifers for the storage of low-grade thermal energy such as solar heat or waste heat during off-peak periods. The low-grade energy is used to heat or chill water which is injected into an aquifer for storage. Later, the water is withdrawn for space heating or cooling during a period of high demand.

Water wells are used for the connection to the aquifer. However, these wells are normally designed with double functions, both as production and infiltration wells, as shown in Fig. 4.1 (Andersson 2007). The energy is partly stored in the groundwater itself but partly also in the grains (or rocks mass) forming the aquifer. The storage process in the rocks mass takes place when the groundwater is passing the grains and will lead to the development of a thermal front with different temperatures. This front will move in a radial direction from the well during charging of the store and then turn back during discharging.

Practically all systems are designed for low temperature applications where both heat and cold are seasonally stored. However, the systems are sometimes also applied for short-term storage.

ATES open-loop systems can offer increased energy efficiency and long-term cost savings over pump and dump systems and closed-loop systems by using an aquifer as a seasonal storage reservoir for waste or excess thermal energy generated in off-peak seasons or periods of low demand such as solar energy in summer months or cold air in winter months. ATES systems are operated by transferring heat or cold mass to or from groundwater through a heat exchanger. The groundwater that is injected back into the aquifer is heated or chilled. The reinjected groundwater may hold a temperature higher or lower than the undisturbed ground temperature, depending on the thermal properties of the ground and flow characteristics of the aquifer. During periods of high heating or cooling demand, water is pumped from the aquifer and used as an energy source or sink.

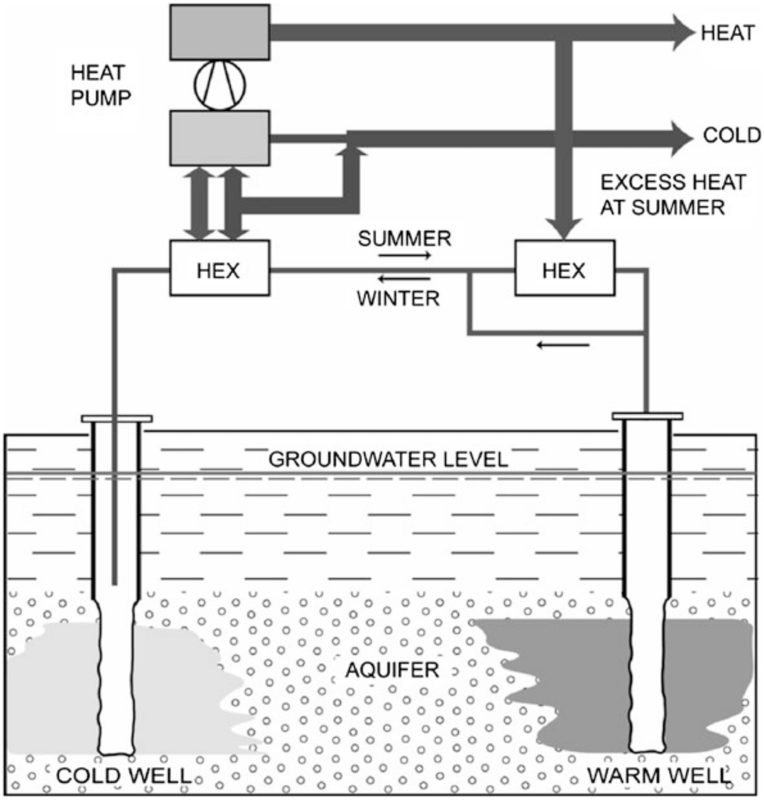

Fig. 4.1 Principal ATES configuration (from Andersson 2007)

4.2 Types of ATES

4.2.1 Operation

Two groups of wells which are hydraulically coupled and separated by a suitable distance are used for ATES purpose (Paksoy et al. 2000). There are two basic principles for aquifer thermal storage: cyclic regime (bidirectional) and continuous regime as illustrated in Fig. 4.2 (Nielsen 2003). A plant can also be made with groups of wells instead of just two single wells.

With a cyclic regime, cold and heat can be stored below/above the natural ground temperature, whereas the continuous regime can only be used where the load can be met with temperatures close to natural (existing) ground temperatures. The storage part is therefore an enhanced recovery of natural ground temperatures. Some pros and cons of the two regimes are:

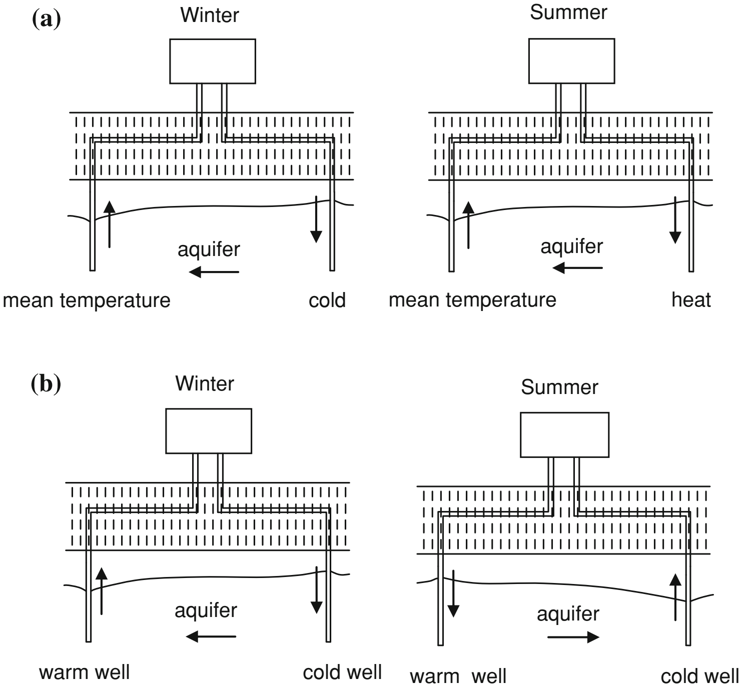

Fig. 4.2 Basic operational regimes for aquifer thermal energy storage (**a**) continuous regime, (**b**) cyclic regime (from Nielsen 2003)

- Cyclic flow will create a definite cold and heat reservoir around each well or group of wells. Cold can be stored around one of the well groups heat can be stored and around the other. Groundwater is pumped from one of the well groups, and then heated or cooled within the building before being injected back into the aquifer in the other well group. The groundwater circuit is closed in the sense that the water is produced from a number of warm wells and then injected through the cold wells at the same flow rate and without being exposed to air. It is possible to maintain a ground volume above or below the natural ground temperature all the time. One disadvantage is a more complicated well design and control system with each well being able to both produce and inject groundwater.
- Continuous flow is simpler with regard to system design and well control, and only one well or group of well need to be equipped with pumps. The disadvantage is the limited temperature range.

4.2.2 Form of Energy

On the basis of the form of energy being stored, three main types of ATES systems can be defined. These are chilled water storage systems (or cold storage), heat storage systems, and integrated heat and cold storage systems.

Cold storage involves the injection, storage, and recovery of chilled (or cold) water at temperatures between 6 and 12 °C in a suitable storage aquifer for storage periods from several hours to several months. One or more wells are used depending on energy requirements and the properties of the aquifer.

Applications of cold storage include primarily air conditioning and equipment cooling in institutional and commercial buildings, and industrial process cooling. These systems are best applied when a demand for cooling exists for significant portion of the year. Presently, many cold storage systems operate in Europe and North America, particularly in The Netherlands. The storage efficiency of a cold storage system is equivalent to the amount of energy injected into an aquifer (e.g., energy injected to the aquifer while cooling a building) divided by the amount of energy taken from an aquifer (e.g., energy rejected from the aquifer using a fluid cooler to passively refrigerate the aquifer during cold spells). It should be calculated over an entire charge/discharge cycle where the aquifer reaches the same bulk temperature at the end of each cycle, which is ideal for environmental sustainability considerations. It can reach 70–100 % for most long-term cold storage projects. The cold storage efficiency decreases as the heat transfer from the surroundings to the storage aquifer increases.

Heat storage involves the injection, storage, and recovery of heated water in a suitable storage aquifer. Heat storage systems can be classified on the basis of low to moderate temperature heat (10–40 °C) or high temperature heat (40–150 °C). The components, well configurations, and storage periods of heat storage ATES systems are similar to cold storage systems. Applications of aquifer heat storage exist in space heating, industrial heating, heating for agricultural purposes (e.g., greenhouses), and roadway de-icing and snow-melting. Because convective heat losses (buoyancy effects) are greater for heat storage than for cold storage, the storage efficiency is typically less than that of cold storage and ranges from 50 to 80 %.

To counter the effects of higher heat losses due to convection currents, the storage wells for high temperature heat storage are preferably drilled to greater depths. This minimizes heat losses by using the overburden formation above the storage aquifer as an insulator between the warm aquifer and the cooler ambient air, and by choosing a storage medium that is surrounded by warmer materials due to the geothermal gradient, thereby reducing losses.

Integrated or combined heat and cold ATES systems may offer an improved efficiency over cold- or heat-only storage systems, particularly in large-scale applications. These systems are most commonly used in combination with a heat pump to provide heating and cooling in commercial or institutional buildings.

The components of combined systems are virtually the same as for cold or warm mass storage alone. However, the design of above-ground and below-ground components of integrated systems is more complicated. For underground components, the positioning of the wells become more important as the aquifer is used as a heat source or sink. Specifically, storage of warm and cold mass results in the development of thermal plumes around the wells and there is increased risk of heat transfer between them.

From an economic perspective, integrated ATES systems for combined space heating/cooling applications using a heat pump, with no other sources of waste heat or chilled water, may be more sensitive to costs associated with aquifer characterization and other design costs compared to ATES systems with higher grade waste heat sources. In smaller applications, it will be challenging to rely on a relatively small increase in heat pump coefficient of performance (COP) to generate sufficiently attractive returns on the incremental capital investment. The increased complexity of the system, in addition to the effort for aquifer characterization, may add significant cost to the project. In the cooling mode application of an integrated ATES system, an opportunity may exist for direct cooling (without the use of a heat pump) where direct cooling might otherwise not be possible. In this case, substantial energy savings could result.

COP is the classic parameter that has been used to describe the performance of a heat pump. A simple definition of the coefficient of performance adequate for our purposes is The COP is a dimensionless parameter on which upper bounds can be found using the laws of thermodynamics. It is common in the U.S. air-conditioning industry to report the cooling performance in terms of what is called the “energy efficiency ratio” or EER. The EER is not a dimensionless parameter, as the energy input rate is in watts and the output thermal effect is in Btu/h. The EER can be readily determined by multiplying the COP by 3.413. While COPs will vary, depending on the quality of the heat pump unit and its operating conditions, in the heating mode, COPs in the range of 3–4.5 can be expected for GSHPs. In the cooling mode, performance will generally be lower; a net COP of 2–3.5 can be expected when the heat load within the conditioned space that is generated by the fans, compressors, and parasitics is subtracted from the gross cooling effect. When comparing GSHP system performance to conventional system performance the designer must be careful to also include all the parasitic losses of the conventional systems if a legitimate comparison is to be achieved (Phetteplace 2007).

4.3 Aquifer and Groundwater

4.3.1 Aquifer

To be able to construct an ATES systems a suitable aquifer has to at hand at or close to the site where the ATES user is located. As explained in Chap. 2, “aquifer” is defined as a geologic formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs. An aquifer is in practice defined to be a geological formation from which groundwater can be pumped by using water wells.

Groundwater refers to subsurface water found beneath the water table in the void spaces of unconsolidated (i.e., sands and gravels) and consolidated (i.e., sandstone and volcanic rocks) geologic formations. A groundwater aquifer exists in geologic formations which are sufficiently permeable to store and yield large quantities of groundwater.

By definition groundwater can be found almost anywhere. The groundwater table is defined as the level under which all pores or fractures are water saturated. Above the water table lies the unsaturated zone, where voids between rocks are mostly filled with air. Some water is held in the unsaturated zone by molecular attraction, and it will not flow toward or enter a well. In the saturated zone, which lies below the water table, all the openings in the rocks are full of water that may move through the aquifer to streams, springs, or wells from which water is being withdrawn.

There are two major types of aquifers. If the groundwater stands in direct contact with the atmosphere, the aquifer is regarded as unconfined. If, on the other hand a permeable formation below the groundwater table is covered by a less permeable layer, the aquifer is regarded as confined.

The confined type of aquifer has a hydraulic pressure (static head) that is on a higher level than the top of the aquifer. This artesian pressure can sometimes reach above the surface level resulting in self-flowing wells or artesian wells. In nature, the groundwater is a part of the hydrological cycle. Hence, groundwater is naturally recharged and drained. Sometimes the draining is shown up as springs, but more common it flows out to a lake or a river.

4.3.2 Aquifer Properties

To determine the suitability of an aquifer for thermal energy storage, a characterization of the aquifer must be performed. Aquifer characterization for an ATES project usually involves a detailed assessment of the aquifer in terms of its geology, physical properties, flow characteristics, and water chemistry. These characteristics are similar to those assessed for most environmental investigations or water supply studies.

Any ATES application will require a good knowledge on the properties of the aquifer being the target to use (Andersson 2007). The most important properties for ATES application include geometry (surface area and thickness), stratigraphy (different layers of strata), static head (groundwater or pressure level), groundwater table gradient (natural flow direction), hydraulic conductivity (permeability), transmissivity (hydraulic conductivity × thickness), storage coefficient (yield as a function of volume), leakage factor (vertical leakage to the aquifer), and boundary conditions (surrounding limits, positive or negative). The first four items are studied by using topographical, geological and hydrogeological maps and descriptions, data from existing wells and older site investigations. The latter ones may contain geophysical data as well as pumping tests and so forth. Any information on groundwater chemistry is of importance as well as information of the natural groundwater temperature (Bridger and Allen 2005)

4.3.2.1 Geology and Aquifer Thickness

The physical makeup of the sediments or rocks and depth, aerial extent, and thickness of permeable and impermeable geological units both at a regional scale and locally at the proposed ATES site, are important factors in determining the nature and distribution of aquifers in the subsurface. The majority of thermal storage projects use unconsolidated aquifers as storage media. However, unfractured and highly fractured bedrock aquifers also can be used for thermal energy storage. In these aquifers, the mapping of structural features, such as fractures and faults that strongly influence fluid flow, will be also important.

4.3.2.2 Hydraulic Properties and Groundwater Flow

The effective porosity and the hydraulic properties such as hydraulic conductivity and specific storage are important to the design and evaluation of ATES systems. The effective porosity refers to the system of interconnected void space in the porous aquifer media. It is important in determining the amount of heated or chilled water that can be stored per unit volume of the aquifer.

The hydraulic conductivity is a measure of the ability of the porous medium to transmit water. High hydraulic conductivities are required for large flow rates of water to be withdrawn or injected from or to the aquifer with the least change to the hydraulic and temperature gradients around the production wells. Specific storage is a measure of the water storage capacity of an aquifer and is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. These properties, along with the hydraulic gradient, control the velocity, and direction of groundwater flow or the flow regime in an aquifer.

4.3.2.3 Thermal Properties and Ground Temperature Field

The physical processes of conduction and convection govern the transport and storage of heat in an aquifer. Conductive heat transport refers to the movement of heat along a thermal gradient. Convective heat transport refers to the movement of heat by flowing groundwater. In an ATES system, conductive heat transport occurs due to the temperature gradients induced by warmer or cooler storage water coming into contact with the surrounding aquifer water. The conduction of heat in the aquifer is governed by the thermal properties of aquifer such as the volumetric heat capacity and the effective thermal conductivity. Heat capacity indicates the amount of temperature change that occurs when the aquifer media absorbs or loses a specific amount of energy and thermal conductivity represents the ability of the aquifer media to transmit heat. Since water has a higher heat capacity but lower thermal conductivity than rock, the storage of thermal energy in aquifers is best suited to a high porosity formation to minimize conductive energy losses and increase the efficiency of the thermal store.

Convective heat transport results from groundwater flow driven by hydraulic head and temperature differentials, which exist both locally in the vicinity of the well field as a result of pumping/injection of groundwater and regionally within the aquifer. Convective heat transport has both advective and dispersive components.

Advection describes the movement of thermal energy directly due to the average linear flow of groundwater through the porous medium. Thermal dispersion refers to the microscopic dispersal or spreading of thermal energy in three dimensions beyond the regions it normally would occupy as a result of advection alone. Dispersion can be regarded as a zone of mixing, which travels in advance of the thermal energy front defined by advection. In addition, free convection also occurs when groundwater movement is driven by density variations due to temperature gradients. In high temperature ATES systems, the effects of free convection will become important, as the thermal energy will rise due to a lowered density of the heated water. In lower temperature ATES systems, including heat storage and cold storage, the density differences between the stored water and the ambient groundwater will be small enough so that free convection is limited.

Regional groundwater flow is an important consideration in the design of ATES systems as higher groundwater flow regimes can lead to advection or down-gradient ‘drift’ of stored energy beyond potential recovery regions. In the presence of a steep regional gradient in hydraulic head, which would correspond to faster groundwater flows, a lower permeability aquifer is required to minimize convective losses (dispersion reduces the thermal intensity of the recovered plume). In addition, small-scale vertical and horizontal variations in hydraulic conductivity or heterogeneity in the aquifer that result from changes in geology are important, as these will affect the dispersion of the thermal plume.

4.3.2.4 Groundwater Chemistry

The chemistry of aquifers often represents a significant problem in the design of ATES systems. The primary problems related to groundwater chemistry include (1) the scaling of heat exchangers and clogging of wells resulting from the precipitation of minerals such as calcium carbonate and iron or manganese oxides, (2) the corrosion of piping and heat exchangers by ambient and heated groundwater, (3) biofouling of the well intake area; and (4) the clogging of the aquifer as a result of precipitation of minerals within the aquifer or the transport of precipitates into the aquifer.

These problems are avoidable if consideration of the potential for geochemistry problems is considered in advance of the system design phase. Many design strategies and water treatment technologies have been used to mitigate these problems.

4.3.3 Aquifer Characterization

Aquifer characterization for an ATES project typically involves phases of desktop review, drilling, hydraulic testing, and modeling, although the level of complexity of these characterization steps can vary considerably depending on how much information is known about the local geology/hydrogeology and how large the ATES system will be.

A simple review can be performed as a preliminary data gathering or prefeasibility study step to determine whether an ATES system is feasible. If the area is well developed and much is known already about the hydrogeology of the area, then geological/hydrogeological investigative costs can be kept to a minimum. In unexplored areas, more effort may be needed.

In a prefeasibility study, information regarding the site geology and groundwater potential often can be obtained from various sources such as existing nearby water wells, previous hydrogeological investigations, aerial photographs, topographic and geologic maps. If there is a suitable aquifer being capable of yielding the amount of water required for the project, one need to determine the number of wells needed to meet the demand, bearing in mind peak demand, average demand, and the fact that injection wells are often less efficient at receiving water. Ultimately, a well (or wells) will have to be hydraulically tested to ensure that they are capable of producing and receiving water. The spacing of the wells only can be estimated by a hydrogeologist in a preliminary sense. A decision then can be made concerning space availability, piping costs, etc.

If the prefeasibility study suggests that ATES is feasible, then a preliminary test well should be drilled to confirm the information collected to that point. It is not recommended that an expensive production size well be drilled initially, particularly if large diameter wells are needed. A test well can later be over-drilled to a production diameter. Logging of borehole cuttings/sediments should be undertaken to verify the geology, and identify permeable zones and target aquifers. In unconsolidated aquifers, grain size analyses should be performed on these sediments to select an appropriate slot size for a well screen. Sampling and analysis of groundwater should be carried out to assess groundwater chemistry.

To determine the hydraulic properties of the aquifer, and to assess the response of the aquifer to pumping and injection during operation of the ATES system, hydraulic testing of the aquifer should follow test drilling. Constant discharge pumping tests, step-injection tests, step-drawdown tests, and tracer tests are examples of tests performed for ATES aquifer characterization, although not all of these need to be done. Thermal conductivity can be calculated using values for known minerals and porosity, measured in a laboratory using either a needle probe (sediments) or divided bar apparatus (rock core or chips), or measured in situ using a formation thermal conductivity testing unit.

For borehole thermal energy storage (BTES) systems, in situ measurements of thermal conductivity should be conducted because these systems rely solely on conductive heat transport. In cases where thermal conductivity is high, the length of the loop can be shortened leading to lower costs for installation of the system. For ATES systems, thermal conductivity can be estimated because heat conduction is not significant. Therefore, the additional expense to perform an in situ thermal conductivity test would not have as significant a payback as for a closed-loop borehole system. The volumetric heat capacity typically is calculated.

For larger systems, borehole geophysical logging is very useful for identifying geologic units and permeable zones, particularly fractures in the bedrock, and to determine the temperature-depth profile in the aquifer. A monitoring well network, installed around the production wells and in background areas, can be used to determine the hydraulic gradient and direction of groundwater flow at the site. Later, they can be used to monitor the movement of the thermal front during operation of the system. Maps showing temperature isotherms, lines of equal temperature, of the thermal plume subsequently can be produced.

The geologic and hydraulic data collected from desktop studies, site investigations, and aquifer testing subsequently can be input into simulation models that can predict the movement of the thermal plume and calculate the heat balance of the thermal energy store. These thermo-hydraulic codes provide either analytical or numerical solutions to heat transport and storage problems posed by ATES systems. Complex three-dimensional models, combining groundwater and heat flow within the aquifer and heat conduction to surrounding layers, can be used to calculate the temperature of the water recovered from the store.

4.3.4 Groundwater Chemistry

The chemical composition of the groundwater is of extreme importance when it comes to the design of any ATES system. It may be related to the potential risks for functional problems with wells and other components in the system.

The most common technical problem is clogging of wells. Clogging is defined as an increased flow resistance for water to enter the well (or be disposed through the well). The clogging process normally gets more evident with time and will result in a lower well capacity. Clogging can easily be traced and dealt with in an early stage by monitoring flow rates and drawdown as shown in Fig. 4.3 (Andersson 2007).

The figure illustration shows occurrence of clogging by plotting data from an observation well (OW) and compare that to the production well (PW). In this case, the production well shows a decreased specific capacity while the observation well shows a steady level versus time. This observation reveals that the resistance for water to enter the production well is increasing. The increased resistance will

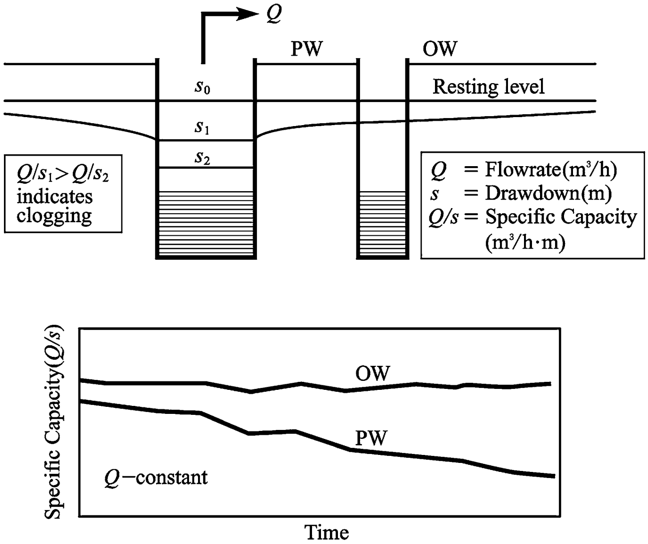

Fig. 4.3 Detection of clogging by using a monitoring program in an early stage (from Andersson 2007)

lower the drawdown inside the well, while the groundwater table outside the well is kept constant. This will increase the hydraulic gradient between the well and the aquifer and hence maintain a constant flow rate.

"False clogging" sometimes occurs. Such events are either explained by a general lowering of the groundwater table or by failure of the submersible pumps cutting down the flow rate. However, by monitoring both the production wells and the aquifer in observation wells or pipes such events can be excluded as a result of clogging.

4.4 Problems of Aquifer Thermal Energy Storages

4.4.1 Clogging

Scaling is precipitation within the above-ground portion of an ATES system and clogging of wells, gravel pack, adjacent aquifer represents reduced aquifer permeability caused by precipitation within the aquifer. Both are caused by chemical precipitates and has been frequently encountered in existing ATES systems, especially the precipitation of carbonates in the systems operating above 85 °C and Fe and Mn oxides in low temperature (<40 °C) systems (Jenne et al. 1992).

The precipitation of Fe and Mn oxides is caused by a change in water chemistry. Precipitation of Fe III oxides can be induced by increasing either the redox potential (Eh) or the pH. As illustrated in the Fe stability field diagram shown in Fig. 4.4, if either the Eh or pH of slightly reduced water (point A in the diagram) is increased, precipitation of Fe oxides is likely. Not shown on this figure is the effect of Fe concentration; as Fe concentration increases, its oxide will precipitate at progressively lower Eh and pH values. In practice, there are at least three processes involved to create the Eh and pH changes. Those are (1) oxygen is added from some source and the Eh value is increased (displacement from *A* to *B* in Fig. 4.4); (2) waters differing in their Eh status are mixed upon entering the well causing either an increase or decrease in Eh and possibly pH (*A* to *B* or *B* to *A*); or (3) carbon dioxide escapes from the water, increasing the pH-value (*A* to *C*). The latter process is also believed to be one of the main factors causing the precipitation of carbonates in a well with little or no scaling in the heat exchanger. Where there are significant Fe concentrations, Fe carbonate rather than Ca carbonate may precipitate. The Fe carbonate precipitate is not readily solubilized by acid treatment of the well.

Shallow, unconfined aquifers generally have levels of Fe and Mn that are likely to yield oxyhydroxide precipitates if air is allowed to enter the ATES system. An air leak in the ATES system caused Fe and Mn scaling of the well screen.

However, none of the processes causing Fe oxide precipitation need occur during injection if the system is airtight, and the aquifer is selected or the hydrology is controlled to eliminate the mixing of dissimilar waters near the well. For these reasons, the likelihood of Fe oxide clogging during injection is low in a properly designed system. If for any reason an airtight system is not feasible, any one of a number of iron removal methods may be used.

Clogging by biofilm or microbial slime is a well-known phenomenon in the water-well industry. The most frequent biologically caused well clogging is that associated with iron bacteria, especially the ones belonging to the Gallionella family. However, in a highly reduced environment, clogging can also be associated with sulfur bacteria. In ATES applications, clogging by iron bacteria slime will is a potential risk mainly in low-temperature systems (less than 25 °C) and in waters with an iron content of at least 1 mg/L. Other conditions that favor major bacterial growth are Eh values between 200 and 400 mV and pH values between 5.5 and 7.5.

Gas clogging may occur as a result of the exsolution of gases present in excess of the amount that would be present at equilibrium with air at atmospheric pressure.

Swelling and dispersion of clays contained within the aquifer sediment occurs when the Na saturation exceeds an amount determined by the ionic strength (i.e., conductivity) of the water. Clay swelling and dispersion are unlikely to pose a problem in consolidated or silica-cemented aquifers even when the water is passed through a Na ion exchanger repetitively. Clay swelling and/or dispersion has been avoided by treating the minimum fraction of the water necessary to prevent carbonate scaling; no scaling is observed at a calcite saturation indices of 0.6–0.7.

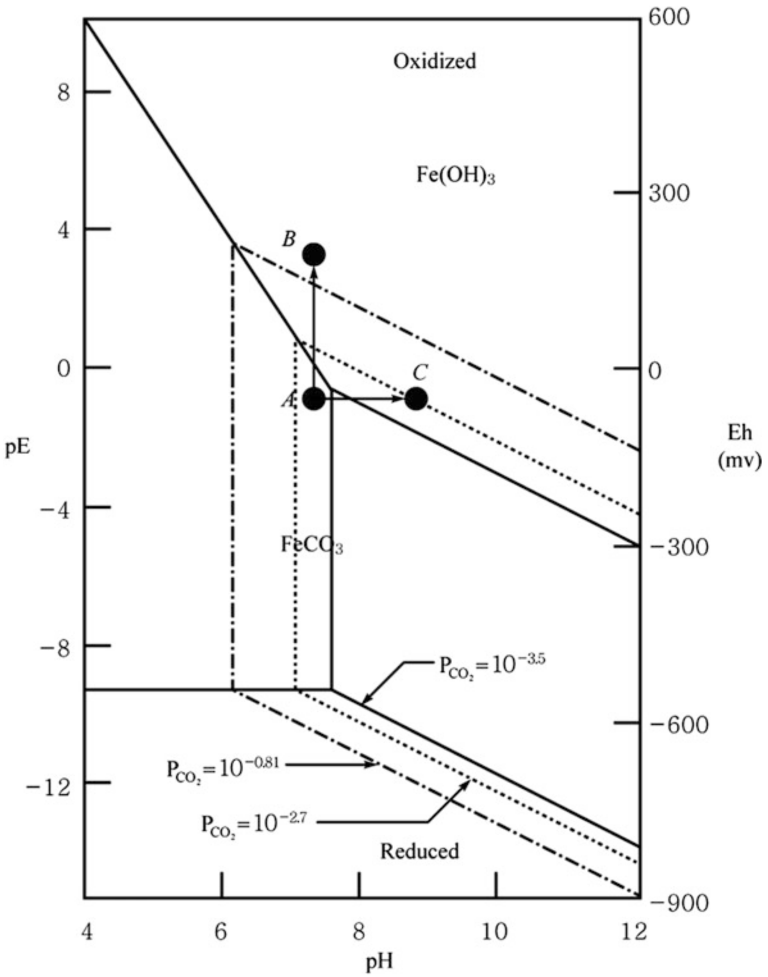

Fig. 4.4 A portion of the Eh (or pE) versus pH stability field for iron illustrating the likely precipitation of ferric hydroxide and/or ferrous carbonate (siderite) as result of a change in Eh or pH ($a_{Fe} = 10^{-4}$ M, temperature = 25 °C; redrawn from Jenne et al. 1992)

The amount of suspended sediment may have been increased by the use of foreign water (i.e., local surface water) into the aquifer and/or the inadequacy of the gravel pack.

Research makes clear that clogging of recharge wells (ATES and ASR) by suspended solids is very common and, despite advances in infiltration well technology, remains a key determinant of infiltration well performance. The clogging potential of suspended solids in water is not just a function of concentration, but also of particle size and composition. Since 2000 in the Netherlands the MFI is used to estimate the clogging potential of water that has to be infiltrated using recharge wells (Buik and Snijders 2006). The MFI gives no detailed information about each individual particle, instead it gives a direct value of the clogging potential of the water. In 2000, a quantitative relation between clogging rate and MFI was developed. In the years between 2000 and 2005, the relation was used to design over 250 ATES systems. During these years the relation has proven itself as reliable and as a useful tool to predict clogging rates of recharge wells satisfactory, especially considering the uncertainties in measured parameters like MFI and permeability. Further an easy, cheap (fast) and reliable apparatus was developed to measure the MFI of the water that has to be infiltrated.

Clogging caused by both straining and physical–chemical filtration can be described by the following equation:

$$\Delta h_v = \left(\frac{1}{\rho_w g}\right)\left(\frac{c\mu_d}{K_c}\right)v^2 t \tag{4.1}$$

where Δh_v = increment of pressure caused by clogging (m_w); ρ_w = density of the infiltrated water (kg/m^3); g = gravity acceleration (m/s^2); c = concentration of suspended matter in the infiltration water (kg/m^3); μ_d = dynamic viscosity (Ns/m^2); K_c = intrinsic hydraulic conductivity of the filter cake on the borehole wall (m^2); v = infiltration rate on the borehole wall (m/s); t = infiltration time (s).

One of the best parameters to predict the clogging potential of infiltration water, is the MFI. The MFI is a variation of the Silting Index (SI) and Silt Density Index (SDI). Both indices were developed to characterize the fouling potential of reverse osmosis feed water on RO membranes. The SI and the SDI have week theoretical foundations and do not vary linearly with the concentration of colloidal and suspended solids in water. The MFI, on the other hand, has a strong theoretical foundation and exhibits a linear correlation with the concentration of colloidal and suspended solids in water.

The MFI is equal to the slope of the line that describes the inverse of the flow rate versus the amount of water that passes a membrane filter with 0.45 μm pores under a constant pressure drop for standard conditions and can be described with Eq. (4.2):

$$\mathrm{MFI} = \frac{\mu_d}{2pA_f^2}\frac{c}{K_c} \tag{4.2}$$

where MFI = membrane filter index (s/l^2); p = pressure loss (N/m^2); A_f = area of the filter (m^2).

If an MFI of 1 s/l^2 is directly translated [with Eqs. (4.1 and 4.2)] into a clogging rate for an infiltration well under standard conditions ($A_f = 1.38 \times 10^{-3}$ m^2 for a standard membrane filter; $p = 2 \times 10^5$ Pa; $\mu_d = 1.3 \times 10^{-3}$ Ns/m^2 and $v = 1$ m/h on the borehole wall, a 'common' value for infiltration wells), the calculated clogging rate of more than 2,000 m/y is not compatible with measured clogging rates of around 0.1 m/y in the field. This demonstrates that a clogging rate derived using a filter with a pore size of 0.45 μm cannot be translated directly into a clogging rate for an infiltration well. The calculated clogging rates were found to be more compatible to clogging rates for water flood wells in oil fields. The difference was attributed to the fact that the pore size of the receiving formation in an oil field is closer to that of the MFI-membrane than the pore size in groundwater environments.

The MFI measured with a standard membrane filter can now be translated into an MFI that is valid for other pore sizes.

$$\mathrm{MFI}_{\mathrm{cor}} = \mathrm{MFI}_{\mathrm{mea}} \frac{A_{fp}}{A_p} \tag{4.3}$$

where $\mathrm{MFI}_{\mathrm{cor}}$ = corrected MFI; $\mathrm{MFI}_{\mathrm{mea}}$ = measured MFI; A_{fp} = area of a pore of the applied filter; A_p = area of a pore for which the MFI must be corrected.

To calculate the ratio between the pore size of the aquifer and the pore size of the filter, it is necessary to estimate the pore size of the aquifer. The effective pore size is about a sixth of the median grain size of the sand (D_{50}).

In an aquifer with a D_{50} of 300 µm the effective pore size is then about 50 µm. A measured MFI of 1 s/l^2 (pore size 0.45 µm) will give a corrected MFI of 8.1×10^{-5} s/l^2 (Eq. 4.3). The calculated clogging rate (for an MFI of 1 s/l^2 and v = 1 m/h) is now about 0.20 m/y, which is a realistic value.

Equations (4.1, 4.2 and 4.3) can be combined and rewritten as:

$$\frac{\Delta h}{t} = \frac{2\mathrm{MFI}_{\mathrm{mea}} p A_f^2}{\rho_w g} \frac{t}{t_o} \frac{\mu}{\mu_o} \frac{A_{fp}}{A_p} v^2 \tag{4.4}$$

The ratios $\frac{t}{t_o}$ and $\frac{\mu}{\mu_o}$ are added to make corrections for the amount of equivalent full load hours per year ($t_o = 8{,}760\,\mathrm{h}$) and temperature influences (μ_o = viscosity at 10 °C), and the ratio $\frac{A_{fp}}{A_p}$ is added to translate a measured MFI to an MFI for the aquifer.

For practical use the D_{50} is translated into hydraulic conductivity K;

$$K = 150\left(D_{50} 10^3\right)^{1.65} \tag{4.5}$$

with D_{50} in m and K in m/d. Equation 4.5 can be rewritten as:

$$D_{50} = 10^{-3}\left(\frac{K}{150}\right)^{0.6} \tag{4.6}$$

If the standard circumstances for the MFI measurement are substituted in 4.5, the equation can be simplified and rewritten to (t is replaced by u_{eq} and $\frac{\Delta h_v}{t}$ is replaced by v_v i.e. the clogging rate):

$$v_v = 2 \times 10^{-6}\, \mathrm{MFI}_{\mathrm{mea}} u_{\mathrm{eq}} \frac{v_b^2}{\left(\frac{K}{150}\right)^{1.2}} \tag{4.7}$$

where u_{eq} = amount of equivalent full load hours per year (h) (m^3 infiltrated per year divided by max. flow rate in (m^3/h)); v_v = clogging rate (mw/y); v_b = infiltration rate on the borehole wall (m/h).

The water that is infiltrated will not be distributed equally over the height of the aquifer but it is divided over the well screen in relation to the hydraulic conductivity of the aquifer. This means that layers with a high hydraulic conductivity are receiving more water than layers with a low hydraulic conductivity. The infiltration rate in layers with a high hydraulic conductivity is therefore higher than in layers with a low hydraulic conductivity, and because the clogging rate is quadratically related to the infiltration rate (and linear to the MFI), these layers with a high hydraulic conductivity will clog faster than layers with a low hydraulic conductivity.

4.4.2 Corrosion

Both chemical and electrochemical corrosions may occur in ATES systems. Chemical corrosion is induced by constituents, such as CO_2, O_2, H_2S, dissolved sulfide, chloride, and sulfate. Corrosion was also experienced when a pipe connection was not sufficiently tight and allowed a small amount of air to diffuse through the threaded joint and react with reduced groundwater. Electrochemical corrosion appears to be more frequent than chemical corrosion. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials but electrochemical corrosion also occurs on monometallic components that have been stressed, e.g., welded joints, cut surfaces, or damaged coatings. Further, it seems that electrochemical corrosion causes loss of material only on parts of well screens and casings. Usually it occurs in water that is slightly acidic and with total dissolved solids greater than about 1,000 mg/L.

Protection against corrosion is in most cases dependent upon the choice of materials for each specific system. For instance, different steel alloys may cope with expected corrosion, as well as plastic materials, ceramics, or corrosion-resistant coatings. A world-wide method for galvanic corrosion protection of wells is to use a cathodic protection system, normally accomplished by connecting a sacrificial anode to the well casing.

4.4.3 Other Problems

Some of the problems and future issues with ATES may include:

- Interference between wells, especially between group of "warm" wells and group of "cold" wells. Detailed investigation, calculation, and simulation should be conducted to establish the optimal well density, interval, and interactions before the practical implementation. Some of simulation programs can be used to predict the spread of thermal fonts under different well plannings.

- Better combination of heat pump and ATES. It is better to find the optimal ways to combine heat pumps and ATES, because different combination methods will influence the design value of warm/cold well temperature and heating/cooling effect of the whole system. Furthermore, it is very useful and significant to investigate the compatibility between ATES, heat pumps, and the whole distribution system. Their individual viable and vulnerable features need to be checked when the other components fail. For example, for the ATES heating system in Rostock introduced in (Bauer et al. 2010), the failure of heat pumps lead directly to the poor performance of ATES after 2006. If this problem can be solved, ATES will be more desirable.
- Currently, very few researches are focusing on the environmental impact of ATES to the surrounding aquifer and soil layers, such as (1) influences of the increased or decreased temperatures around the warm or cold wells on the local biological communities, (2) influences of the varied temperatures on the chemistry composition and properties of the local aquifer water, and (3) influences of the varied temperatures and the well operations on the geological structures of the local soils. All these questions are lacking enough investigations, simulations, research and references.

4.5 Construction of ATES

Construction of ATES is summarized by AEE Institute for Sustainable Technologies (2006). Aquifers are below-ground widely distributed and water filled permeable formations with high hydraulic conductivity, such as sand, gravel, sandstone, or limestone layers. If there are impervious layers above and below and no or only limited natural groundwater flow, they can be used for thermal energy storage. In this case, two wells or groups of wells are drilled into the aquifer formation and served for extraction or injection of groundwater. As seen in Fig. 4.5, cold groundwater is extracted from the cold well during charging periods, heated up by the heat source (e.g. solar or waste heat), and injected into the warm well. In discharging-periods the flow direction is reversed. Warm water is extracted from the warm well, cooled down by the heat sink, and injected into the cold well. Because of the different flow direction during each flow period, both wells are equipped with pumps, production, and injection pipes.

Because the storage volume of an ATES cannot be thermally insulated against the surroundings, heat storage at high temperatures (above 50 °C) is normally only efficient for large storage volumes (more than 20,000 m^3) with a favorable surface to volume ratio. However, for low temperature or cooling applications also smaller storages can be feasible.

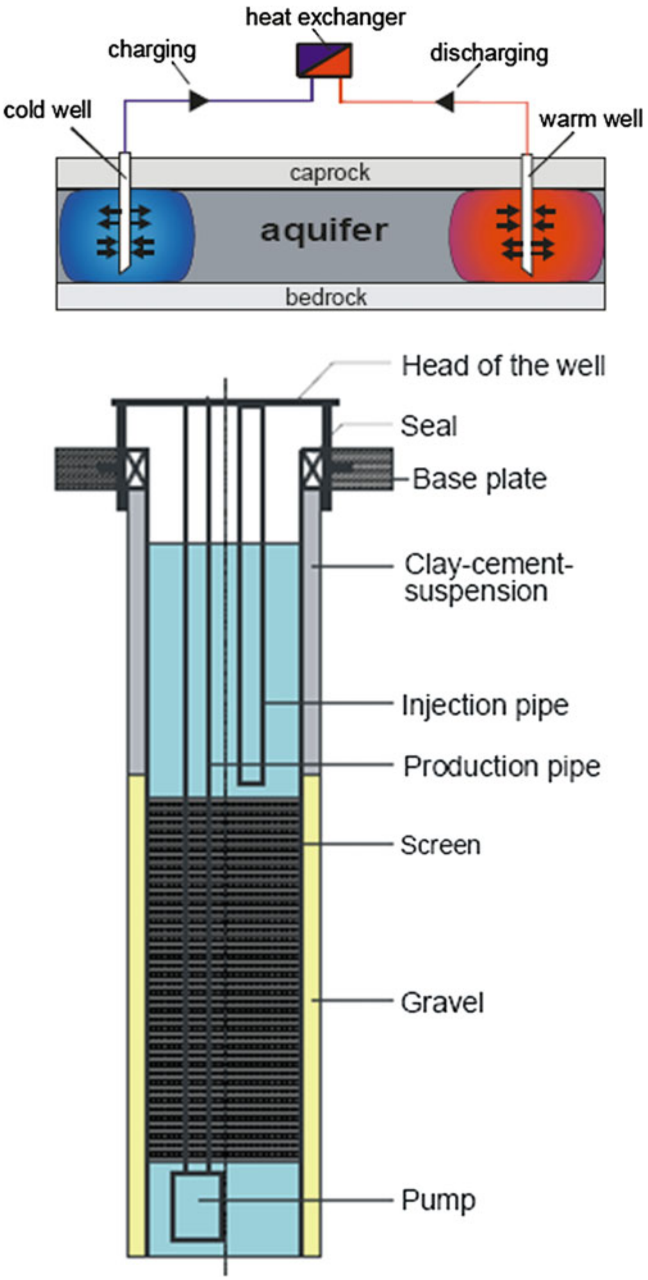

Fig. 4.5 Schematics of an Aquifer thermal energy storage (ATES) and layout of a well for charging and discharging (from AEE Institute for Sustainable Technologies 2006)

ATES systems are not as easy to realize as BTES systems, and need more maintenance and pre-investigations, but if the conditions are favorable, payback times are typically short (EU Commission SAVE Programme and Nordic Energy Research 2004). ATES systems cannot be constructed in all geological conditions, and hence they sometimes require extensive pre-investigations, which have to be taken into account and budgeted already from the early design phase. The process of obtaining a permit for installation can be complex and time-consuming for the first plant in the region. Many restrictions in relation to protection of groundwater resources and environmental impact assessment may reduce possibilities. Some ATES plants have shown various kinds of operational problems, most of which can be controlled with simple measures. One major identified problem is clogging of wells. In most cases, the clogging processes can be avoided by a proper design of well and total system.

An ATES system has a high demand on ground conditions at the construction site. A suitable hydrogeology is a prerequisite. The ground properties have a strong effect on feasibility, design, and operation of an ATES system (number and location of wells, production rate, thermal losses, etc.). The hydraulic conductivity K of the aquifer layer is the most important parameter. For a water exchange between aquifer layer and production/injection well, values of $K > 10^{-5}$ m/s are necessary.

According to AEE Institute for Sustainable Technologies (2006), it is not possible to give exact criteria for the feasibility of an ATES system. It depends strongly on the total system concept. The requirements on the aquifer properties from the system side depend on the size of the storage project, which is related to the flow rate that has to be handled and volume of energy that will be stored.

In general the aquifer porosity will govern the volume needed. This will normally be much less for an aquifer with a primary porosity than for an aquifer that mainly consists of fractured rock. The flow rate, that means the volume of water that can be extracted and reinjected from and into the aquifer as a function of time, will be related to the aquifer transmissivity (the hydraulic conductivity times the aquifer thickness). Although there is no transmissivity limit in theory, the limit for primary porosity aquifers is determined by the possibilities to construct functional wells in practice. This limit can be defined as a situation where the dominating grain size is less than 0.06 mm and corresponds to a transmissivity less than 10^{-5} m^2/s. The latter figure may also be relevant for the fractured aquifer type, but in that case without any well-designed restrictions.

Other properties and conditions that have to be considered are:

- stratigraphy (sequence of layers)
- grain size distribution (mainly for primary porosity aquifers)
- structures and fracture distribution (mainly for fractured aquifers)
- aquifer depth and geometry including hydraulic boundaries
- storage coefficient (hydraulic storage capacity)
- leakage factor (vertical hydraulic influence)
- degree of consolidation (hardness)

Table 4.1 Site-specific prerequisites for ATES systems (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Parameter	Small project ($25\ m^3/h$)	Big project ($500\ m^3/h$)
Thickness of confining layer	$d > 5$ m	$d > 20$ m
Thickness of aquifer	$D > 10$ m	$D = 50–100$ m
Transmissivity	$T > 5 \times 10^{-4}\ m^2/s$	$T = 1 \times 10^{-2}$ to $3 \times 10^{-2}\ m^2/s$
Natural groundwater flow	$v < 3$ cm/d	$v < 11$ cm/d
Danger of ground depression	Not relevant	Prefer deep aquifer

- thermal gradient (temperature increases with depth)
- static head (groundwater level)
- natural groundwater flow and direction of flow
- water chemistry

Table 4.1 gives recommendations for values of hydrogeological parameters for small and big ATES systems for the Netherlands. Table 4.2 shows typical general values for ATES systems which are also valid as a general reference for Germany and central Europe.

The suitability of the ground conditions at a specific site has to be evaluated during pre-design step by a geological investigation. In a first step, a ground profile for the interesting range of depths is adequate. If a suitable ground layer is assumed based on this information the hydrogeological parameters like hydraulic conductivity and natural groundwater gradient should be identified by pumping tests.

4.5.1 Design Steps and Permit Procedure

Any ATES realization is a quite complex procedure and has to follow a certain pattern to be properly developed. Typical designing steps are suggested by Andersson (2007).

- prefeasibility studies (to describe the principal issues)
- feasibility study (to identify the technical and economical feasibilities and environmental impact compared to one or several reference systems)
- the first permit applications (local authorities)
- definition of hydrogeological conditions by complementary site investigations and measurements of loads and temperatures, etc.
- evaluation of results and modeling (used for technical, legal, and environmental purposes)
- final design (used for tender documents)
- final permit application (for court procedures)

Table 4.2 Typical values of ATES system for heat storage application (from EU Commission SAVE Programme and Nordic Energy Research 2004)

Flow pumped per well (m^3/h)	10–100	Capacity per well at 25 m^3/h and $\Delta T = 30$ K (kW)	870
Flow re-infiltration per well (m^3/h)	10–75	Min./max. re-infiltration temperature (°C)	3/80
Borehole diameter (mm)	200–600	Transmissivity of aquifer (m^2/s)	10^{-3} to 10^{-4}
Borehole depth (m)	10–300	Typical total cost of ATES storage (€/kW)	100–200

The technical issues are general, but the permit procedure may be different from country to country. However, in most countries the use of groundwater for energy purposes will be restricted and will be an issue for application according to different kind of acts.

4.5.2 Elements of System Design

The basic elements of an ATES system are the source of thermal energy, the delivery system, the aquifer store, and the thermal loads. Paksoy et al. (2009) provided an extensive summary on the each element.

Thermal Loads. The most common application of ATES is cooling buildings. Most large buildings are cooling load dominated even in more northern climates. With very well-designed (green) buildings becoming more common, the reduced heating demand is more substantial than the reduced cooling demand due to interior gains, making the imbalance even greater.

Another common application is heating of buildings. If both heating and cooling are required, systems can be designed for optimal efficiency. The most common applications within the building sector are buildings with long hours of operation, such as hospitals, academic buildings, shopping malls, hotels, multiple family housing, and office buildings which have a high level of utilization. Less common applications are greenhouses and industrial heating and cooling. While small buildings and single family housing might benefit, the problem is that storage volume may be too low resulting in too high a loss factor of seasonal stored energy. In practice, at least a thermal demand of 200 kWt ($\sim$50 tons) is the smallest that can be matched with seasonal thermal storage. More recently thermal utilities which provide thermal energy to small buildings as part of a small district heating/cooling system are expanding the use of seasonal thermal storage.

Thermal Cold Source. The most common thermal source is cold outside air in winter. It is collected by 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. If chilled water is being stored, for most applications it is optimum to store as cold as possible for direct use. In practice, the minimum is ~5 °C (41 °F). Any lower temperature might result in freezing water.

Thermal Heat Source. The source of heat is most commonly waste heat from heat pumps which are being used to cool in summer months. Less common is waste heat from cogenerators or industrial processes. Another heat source is solar thermal collected in the summer months. Direct application is not as easily achieved since high temperatures are required by the delivery system. In these cases, additional traditional sources are required to boast the temperature such as boilers and heat pumps.

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. To realize the required wet bulb temperature and utilize the stored thermal energy effectively, a larger heat exchanger than normally applied in the air handling unit is required with a counterflow configuration. A second HEX can utilize the warm water for reheating when needed. This typically results in a discharge temperature of aquifer water at 18 °C.

In any event an air-to-air heat recovery system with both latent and sensible heat recovery reduces the fresh air thermal demand and is typically included in the ATES delivery system design. The sensible heat and cooling demand is often delivered by a radiant system or fan coil. Radiant ceilings are becoming more popular in these cases. In this case, that the ATES system serves both for heating and cooling, the HVAC system often includes heat pumps. In this case, the cooling load is often delivered directly with the heat pump for short peak periods when the ATES system cannot provide the full load.

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 thermal plant.

The most important aspect of the design of wells is to ensure that 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 of hydraulic head not more than 30 cm 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., temperature change not larger than 0.5 °C at the boundary.) Finally, it is critical that there is not a thermal breakthrough between warm (hot) and cold stores over the long-time operation. To achieve these conditions requires a very sophisticated and careful modeling.

The simplest system for ATES cold seasonal thermal storage utilizes a cooling tower (or dry cooler) during the winter months to charge cold wells. The cold aquifer store is then used to directly cool a building or buildings in the summer.

Such a system requires a peaking chiller to supply cold when the ATES system is not adequate.

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 winter, the water source heat pump utilizes 18 °C water stored in the summer operating at a relative high efficiency, delivering the base load heating for the building. In addition, when the outside temperature is below 0 °C, warm ATES water is utilized to preheat incoming fresh air and at the same time the cold water from an eventual dry cooler is stored in the ATES cold wells. When the heating demand cannot be fully supplied by the heat pump then a gas boiler comes on. The amount of gas energy is typically less than 10 % of total energy demand while about 50 % of peak thermal demand. The dry cooler is utilized to make additional cold water when air temperature is below 2 °C.

In the summer operation, the base load cooling is supplied directly by the ATES cold wells to both the building including the fresh air intake. When the cooling load cannot be met by the ATES cold wells the heat pump comes on. Again the ATES cold wells supply the vast majority of the cooling load.

The system is designed to optimize, financially, by trading off peak load from the ATES system with traditional sources for short periods of time-reducing up-front investment with conventional peakers.

4.5.3 Field Investigations

One essential part in developing an ATES project is to perform site investigations. The more knowledge that is obtained of the underground properties, the better basis for design is achieved.

The site investigations will most commonly cover the following procedure:

- geological mapping
- geophysical investigations
- test drillings
- pumping tests

The test drillings will define the stratigraphical units in the area while the geophysics and geological mapping are used for extrapolation of the layers and for definition of geometry.

Test drillings may be a part of the final system and can be looked upon as an early investment in system. However, more commonly they are drilled in a small dimension and do not fit into the final system after design. In these cases, they still can serve as observation wells.

For shallow aquifers in the overburden it is common to drive slim steel pipes that are perforated in the lower meter or so. This method has proven to be an excellent way of taking samples for the design of screened production wells.

Based on the results a conceptual model is created and the hydraulic properties of the aquifer and its surrounding layers are derived from the pumping test. The final outcome will be a geological model that is more or less accurate and that can be used for the final design using simulation models.

To be able to make model simulations, the loads of heat and cold have to be known. For this reason, it is common to perform measurements on how the loads are varied at different outdoor temperatures.

Such investigations that also covers supply and return temperatures in the distribution systems are often done prior to or in parallel with the underground site investigations. The results are key factors as basis for design in order to calculate flow rates and size of the ATES storage.

4.5.4 Model Simulations

Simulations are used for several reasons, but preferably to study how different flow rates and different number and distances between the wells are functioning. The results will then guide the decision where to place the wells and with what flow rate they should be operated.

The outcomes of such simulations are of two kinds, namely

- the hydraulic impact shown as cones of depression and uplift around the wells
- configuration of the thermal front around the wells

4.6 History and Current Status

4.6.1 Belgium

Desmedt and Hoes (2007) and Desmedt et al. (2006) summarized the status of ATES in Belgium. ATES was introduced on the Belgian market since 1995. Since 1998, many companies showed interest in the technology, but this is not translated into a steady increase of realized projects. This is mainly caused by the hydrogeological circumstances. In Belgium, the North-eastern part of the country has very good technical and economical potentials for ATES applications. However, the most interesting economical and industrial areas are located outside this region. A thick clay layer covers the Western part of Belgium; the southern part mainly exists of Silurian schist and Devonian rock. At this time, 15 large ATES-systems (>300 kW) are operational and most installations are monitored.

A number of ATES projects are monitored within the framework of a subsidy program for the stimulation of innovative energy technologies, called

"Energy Demonstration Program". For ATES system the monitoring is three years in order to have representative results for steady-state performance. Enterprises can get financial support (35 % of the extra investment of the innovative investment in comparison to a traditional installation).

The implementation of the ATES technology in Belgium went unarguable together with some unavoidable growing pains. Some of these problems were caused by the unusual combination of technologies and working parties. Especially the knowledge of hydrogeological and technical issues of ATES applications is not well understood or not existing with engineering companies. Drilling companies get involved in the process of HVAC installation. Most critical are the connection points between the traditional and innovative installation part, defined as the boundary zone between the underground and aboveground installation. As typical example, the communication between the control systems of HVAC and ATES system can be mentioned. Other common problems are the treating of the wells from time to time by the owner of the installation, the energy balance in the ground (cold storage), control problems, etc.

4.6.2 Norway

Accroding to Midttømme et al. (2008, 2009), there are about ten large Aquifer Thermal Energy Storage (ATES) installations. In 1987, the first known ATES system in Norway was established in Seljord. A 10 m-deep well was drilled for heating and cooling of Seljord lysfabrikk. The largest UTES system in Norway is at Oslo's Gardermoen international airport. This ATES system has been in operation since the airport opened in 1998 and comprises an 8 MW heat pump array, coupled to 18 wells of 45 m depth, 9 for extraction of groundwater, and 9 for re-injection. The wells are sunk into the Øvre Romerike glaciofluvial sand and gravel aquifer. This system covers the total cooling needs of the airport, of which 25 % (2.8 GWh/y) is free cooling via direct heat exchange with cold groundwater, and 75 % (8.5 GWh/y) is active cooling via the use of the heat pumps. The annual heating provision is typically 11 GWh. There have been some problems with clogging of the groundwater loop, and the groundwater wells and heat exchangers require cleaning every few years. Because of a lack of knowledge of ATES systems in Norway, Dutch consultancies were hired to design the ATES system and GSHP installations. The total cost of the system was 17 million NOK and the payback time, compared to traditional heating and cooling systems, is estimated to be less than 4 years.

Oslo Centre for Interdisciplinary Environmental and Social Research, a component of the Oslo Innovation Centre in Oslo, is a 13,500 m^2 office building with laboratories. An ATES system, extracting groundwater from the underlying limestone and shale rock, provides both heating and cooling to the building. A closed-loop BTES system was originally intended for the site, but extremely difficult ground conditions were encountered during initial drilling: namely, zones of remarkably high groundwater flow associated with a Permian syenite dyke structure several meters thick. It became clear that it would be both more feasible and cheaper to drill a small number of groundwater wells (using the dyke as an aquifer) than a large number of closed-loop boreholes. Thus, a total of nine wells were drilled. These wells are typically located in extraction-injection pairs, one well drilled to 100 m depth and the second to 100–200 m depth. Using this arrangement, it is possible to access enough groundwater and rock volume to cover the seasonal cooling and heating demands of the building.

4.6.3 Sweden

The ATES systems being used in Sweden can be divided into four basic configurations (Andersson et al. 2003). In the simplest system (A), groundwater is directly used for preheating of ventilation air during the winter and for cooling during the summer season. In this case, heat and cold from ambient air is seasonally stored in the aquifer at a temperature level of approximately +5 °C (winter) and +15 °C (summer). More commonly used is the heat pump supported system (B) that works the same way as system A. However, the production of heat is much larger and the temperature change is somewhat greater. System C represents an early type of ATES applications where surface water is used as a source of energy for the heat pump. This heat, at a temperature of 15–20 °C, is stored during the summer and used during the heating season. The fourth system (D) is similar, but in this case cold from the winter is stored to be used for district cooling.

Of these systems, heat pump supported combined heating and cooling applications (system B) are dominating (65 %). However, in recent years, there is a growing interest for storage of natural cold (system D), which is used for district cooling applications or for industrial cooling. In Table 4.1 the recent statistics of ATES utilization are presented. It is seen that the technology is preferably used for commercial and institutional buildings from small-scale applications to large-scale utilization in district heating and cooling. In the industry sector only a couple of systems are applied for manufacturing industries. The rest represents cooling of telecommunication installations.

The currently designed total storage capacities are in the order of 40 MW for heating and 70 MW for cooling. A rough calculation on the yearly energy turnover, based on designed values, indicates a storage heat utilization of 120 GWh while the utilization of cold is about 80 GWh (Nordell et al. 2007).

Still, high temperature ATES projects are lacking in Sweden. However, recent feasibility studies of two large-scale applications have yielded promising results. In both cases these projects are related to storage of waste heat.

A survey within Annex 13 of IEA ECES IA revealed that 40 % of the plants have had or have operational problems or failures. The major part of these has been solved by fairly simple measures. However, approximately 15 % have continued difficulties with well capacities. The dominating reason is clogging of the wells mainly caused by iron precipitation. These wells have to be treated from time to time. Other common problems are corrosion and malfunctioning control systems. In general, these types of problems are now clearly identified and understood, and are therefore less common in newer plants. The research in Sweden has been focused on geodata collection by test drilling as one important part for proper well and system design. The objective with this work, which was carried out at the Lund Institute of Technology, was to create guidelines for site investigations related to ATES design. These guidelines are part of a more extensive work with UTES guidelines that takes place within Annex 13 of IEA ECES IA. These covers all aspects of design, construction, and maintenance of UTES wells and boreholes and will be published during the autumn 2003.

From 1999, a new legislation (The New Act of Environment) was applied. This Act has complicated the ATES permit procedures in Sweden and it has become an obstacle for some potential ATES projects. However, the environmental benefits in terms of energy conservation and economics will probably still favor a further growth of ATES projects in Sweden, especially for large-scale systems.

4.6.4 Germany

Lottner and Mangold (2000), Schmidt et al. (2003, 2004), and Sanner et al. (2005) reported the status of ATES in Germany. In Germany, two aquifer heat stores are in operation in Rostock-Brinckmanshöhe and in Berlin.

In the solar assisted district heating plant of the new housing project in Rostock-Brinckmanshöhe, an aquifer is used as a low temperature seasonal store. Due to the small size of the plant, the shallow 30 m deep aquifer has to be operated in a temperature range between 10 and 50 °C. Model calculations for the design of the plant showed that a maximal fraction of the stored solar heat can be recovered by a 100 kW heat pump. The aquifer is charged with solar heat from a 1,000 m^2 solar collector roof. A long-term monitoring program has been started in early 2000.

The district heating and cooling scheme of the renovated Reichstag building and of the connected neighboring large office buildings of the Parliament include a shallow and a deep aquifer, where a cold store in a depth of about 60 m and a heat store in a depth of about 300 m. The deep aquifer is charged in summer with surplus heat of 70 °C from the combined heat and power plants. These plants are operated dependent on the electricity demand of the connected buildings. According to the design calculations, about 60 % of the stored heat can be recovered during the heating period from the aquifer in the temperature range between 55 and 70 °C and can supplement the absorption heat pump system. The groundwater of the shallow aquifer is used at ambient temperature for the air conditioning of the buildings. An extensive long-term monitoring program will examine the technical and economic feasibility of the concept.

4.6.5 The Netherlands

In the Netherlands, Aquifer Thermal Energy Storage started to be implemented in the early 1980s (Snijders 2005). In first instance, the objective was to store solar energy for space heating in winter. R&D activities and the first demonstration projects were financed within the framework of the National Research Programme on Solar Energy (National Onderzoek Programma Zonne-energie).

In the first project, (commissioned in 1983) vertical soil heat exchangers were used (BTES application). Given the good experience with aquifer storage in later projects and the fact that in the Netherlands aquifers can be found almost everywhere, in particular the application of ATES has been further developed in the Netherlands. Although, ATES systems can be applied almost everywhere in the Netherlands, geographical proximity between projects and agglomeration is emerging in four provinces: North and South Holland, North Brabant and Gelderland contain over 75 % of all projects.

In 2005, the number of registered ATES projects was 537. In almost every major city a number of ATES projects are in operation. The aim of most ATES projects is to store cold in winter for cooling in summer. In general, cooling is direct, that is to say without using a chiller. In most projects, the cooling capacity supplied from storage lies between 500 and 2000 kWt. This means that by applying cold storage these projects economize on a large chiller.

The heat released during cooling is stored in the aquifer also. If possible, the heat is used for heating during the winter season. This combination is called “Cold storage and low temperature heat storage”. The largest ATES project in operation is for supplying cooling and low temperature heat to the buildings and laboratories on the campus of Eindhoven University. Both the cooling and heating capacity of the store are 20,000 kWt (5,700 tons and 68 MBtu/h respectively).

Until 2000, most ATES applications were for individual buildings like offices and hospitals. However, since about 2000 ATES also started to be applied as a central (collective) system for a number of buildings, mixed developments, and housing projects. At present several utility companies are offering their clients to supply heating and cooling with ATES-based district heating and cooling systems, whereby the system is owned and managed by the utility.

Currently, the expectation is that the number of systems constructed each year can grow from about 100–1000 (Coenen et al. 2009). So in 2008, the Dutch government formed a new actor, an ATES taskforce. This task force was asked to make an inventory of the main barriers for implementing ATES systems. One problem is the increasing geographical proximity in the underground in the Netherlands of other infrastructural systems (cables, pipes, sewers systems, tunnels, storage systems, etc.). Another problem is the lack of a clear regulatory framework for the use of the underground and the groundwater. Moreover, it is not clear how the government should deal with conflicting interests of different users of the underground and groundwater. Because of this, the ATES network expresses confusion and uncertainty about what is permitted and what not. Another barrier is the already mentioned potential interference of systems.

4.6.6 Canada

ATES has been or is currently being implemented in a number of large-scale building projects in Canada (Allen et al. 2000). Existing large installations include, for example, the Carleton University campus in Ottawa, the Sussex Hospital in New Brunswick, and the Scarborough Centre near Toronto. Many of these have been operating since the late 1980s.

The Carleton University project draws its water from fractured limestone aquifers at a temperature of about 9 °C. The project was originally designed for implementation in four phases. Phase 1 (consisting of five wells) opened in February 1990, and was constructed using standard heat-pump technology in combination with aquifer thermal energy storage. The system was designed to provide heating and cooling for approximately 40 % of the campus buildings. The high cost of energy associated by using the heat pumps prompted the university to re-assess the original design. In 1992–1993, a retrofit was undertaken in one building such that it could be directly cooled during the summer months and pre-heated in the winter by a heat exchanger, without the use of heat pumps.

This new design (without heat pumps) formed the basis for an expansion to the system. Additional wells for Phase 2 were drilled during 1994 and were to have been incorporated with the existing five well system. Unfortunately, the system has never been implemented or tested because of non-technical administrative problems. Nevertheless, two wells continue to provide heating and cooling to one building.

New ATES installations are being designed for buildings operated by Environment Canada in Ottawa and by Agriculture Canada in Agassiz, British Columbia. The Environment Canada system consists of a multiple well field, and groundwater is extracted from a fractured sandstone aquifer at an ambient temperature of about 9 °C. To date, the wells have been drilled and hydraulic testing and modeling has been undertaken. Work on the building retrofit is expected to take place this year. At Agriculture Canada's laboratory facility, five wells have been drilled. Four of the wells will be used for ATES, and the fifth well will act as a dump well to dispose of a small amount of excess cold water generated in the building during the winter heating.

Research on ATES in Canada is limited; however, Canadian Scientists have been active participants in several Annexes on Energy Conservation through Energy Storage under the auspices of the International Energy Agency. The most recent Annex (13) is aimed at identifying state of the art techniques for the design construction and maintenance of underground thermal energy storage wells and boreholes.

There are four early ATES systems installed in Canada (Wong et al. 2006). Good amount of information has been published from these studies and this pioneering work in ATES technology led the way in the development of ATES application in Canada. Through these early projects, the technical community has identified many challenges and also provided many learning opportunities in advancing the technology introduction.

The earlier ATES projects included the Scarborough Canada Centre which began in 1986 and studied the application of ATES for office building cooling. Later heat pumps were added to increase peak cooling and also provide some heating. Another important project was the Sussex Health Centre. This project was first commissioned in 1994. It was designed for cooling with limited heating. The Carleton University system has been in operation since 1990. The system was designed for cooling and heating and operated with heat pump in the low temperature range. In 2002, the ATES system at the Pacific Agriculture Research Centre was implemented for cooling and heating using heat pump. These installations helped the scientific and engineering community in getting a better understanding on how the ATES systems work in the low temperature range. The main challenges encountered were in cooling and heating load balance.

4.6.7 Denmark

As far as known, no BTES projects will be operational in Denmark by that time. The majority of the groundwater cooling projects provide direct cooling to industrial applications. In general, the warm groundwater is reinjected into the aquifer without thermal balancing.

Recently, there is a growing interest in the application of ATES for the heating and cooling of buildings (Hendriks et al. 2008). The first project of this kind was operational by the end of 2007. The major reason for this increasing interest is the introduction of the European Energy Performance Directive for Buildings. Lack of awareness is considered to be the major bottleneck to the application of UTES technologies in Denmark.

4.6.8 United Kingdom

There is only one known ATES system installed to date in the UK. The system is for a residential development in West London and has a storage capacity of 250 kW. The system was installed in 2006. By the end of 2007, there were a number of larger scale (>500 kW) ATES and BTES systems under development, and the level of interest in UTES application is increasing. This is to a large extent attributable to recent sustainability requirements for larger scale new developments and retrofits.

UTES technology is only just starting to enter into the UK market and thus is regarded as a “new” technology. The availability of suitable aquifers varies significantly in the UK and therefore certain areas are suitable for ATES systems and others areas are more favorable to closed-loop BTES systems. London, the South East, Birmingham, Liverpool, and East Anglia are examples of areas where ATES systems are viable.

In the UK, the Environment Agency (EA) is the government body which regulates the groundwater industry. Any larger scale open-loop ground source heating and/or cooling system has to go through the EA permitting procedure. The EA is becoming increasingly worried about net heating or cooling effects on the ground of GSHP’s and is therefore in favor of ground coupled systems like ATES and BTES, creating a thermal balance annually.

4.6.9 China

According to Morofsky (1994), Gao et al. (2006), applications of ATES in large-scale projects started in the 1960s, mostly in China. There were three interrelated problems in Shanghai that led to the development of aquifer thermal energy storage—ground subsidence, groundwater pollution, and the lack of summer cooling in factories. Restrictions on groundwater extraction aimed to solve subsidence and pollution. However, large-scale year round injection made the groundwater temperature unsuitable for cooling.

In 1965, cold water injection during winter started for summer cooling and has continued since giving 30 years of experience. Heated water is also injected for winter heating. Experience with heat storage is also extensive with the water volume injected being about 30 % of the cold storage volume.

By 1984, there were 492 cold storage wells in Shanghai accepting 29 million cubic meters of water annually. Of these wells, 90 % were used for both injection and extraction. These cold storage wells supplied textile mills, chemical works, and other industrial plants, but also commercial buildings such as the Shanghai Exhibition Hall where there are five injection wells and 1 extraction well. Most of these cold storage wells are 10–12 inches in diameter. The total annual cooling energy stored in Shanghai is about 1,100 TJ. Hot water storage of waste heat is practiced with injection temperatures as high as 400 °C. Recovery temperatures in winter can be as high as 38 °C.

Recently Applications of ATES are fewer and fewer. The bottleneck of ATES is recharging which is the key point of groundwater resource sustainable utilization. Low temperature ATES and heat pump technology should be combined to improve efficiency and extend development space.

4.6.10 Turkey

According to Paksoy et al. (2000, 2004) and Paksoy and Evliya (2009), R&D activities on the underground thermal energy storage in Turkey started with participation in IEA ECES Annex 8. UTES potential study carried out in Annex 8 revealed that there is significant potential for applications in buildings (residential, commercial, and service), industry and agriculture (greenhouses) sectors. First feasibility study on aquifer thermal energy storage using nearby Seyhan Lake was realized for the new annex of Çukurova University Hospital. 3,250 MWh of electricity for cooling and 1,000 tons of oil for heating were estimated to be saved annually with a calculated payback time of less than two years. In a joint study, carried out with Lulea University of Technology winter air as a cold source for borehole thermal energy storage was investigated. The ground temperature was decreased to 20–15 °C at the end of 3 months of cold storage in 2002–2003.

These activities were followed by a commercial ATES application in a supermarket in Mersin with a heating load of 74 kW and cooling load of 195 kW. This project has been in operation since 2001 with about 60 % annual energy savings. Heating and cooling potential of greenhouses in the Mediterranean climatic zone—using ATES systems was investigated in a 360 m^2 greenhouse for growing tomatoes. "Zero" fossil fuel was consumed for the heating in winter and cooling was a bonus in spring time. The yield of tomatoes was increased by 40 % with a 68 % energy savings. The calculated payback time is two years for this project.

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