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AQUIFER THERMAL ENERGY STORAGE (ATES)

ABSTRACT

Aquifer Thermal Energy Storage uses aquifers as the storage of heat or cold. Thermal energy is transferred by extracting groundwater from the aquifer. ATES is the most economic and energy efficient alternative of the Underground Thermal Energy Storage (UTES) applications.

The paper gives a review of ATES systems and examples and recommendations suitable for Poland.

KEYWORDS

Aquifer Thermal Energy Storage, Geothermal Heat Pumps, Norway

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We need energy for heating and cooling purpose, and often at timeswhere the energy sources are not available. Thermal Energy Storage (TES) can help match energy supply and demand. The most frequently used storage technology for heat and cold is Underground Thermal Energy Storage (UTES). The ground has proved to be an ideal medium for storing heat and cold in large quantities and over several seasons or years. UTES systems is mostly used in combination with Geothermal Heat Pumps (GHP). Several different UTES systems have been developed and tested. Two types of system, Aquifer (ATES) and Borehole (BTES)

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storage, have had a general commercial breakthrough in many countries the last decades ATES requires presence of an aquifer (Midttømme et al. 2008). Further, the operating of an ATES is more challenging than a BTES due to potential problems with clogging, corrosion and water quality issues due to ATES being an open system (as opposed to closed loop BTES systems). This leads to higher operating costs, but on the other hand the installation cost is significantly lower and total cost per kWh extracted energy is typically significantly lower for ATES than for BTES over the life span of an installation.

The power (kW) output from ATES and groundwater is a linear relationship between the extraction rate of groundwater (Q) and extraction of temperature (ΔT) multiplied with the specific heat of water (C_{H_2O}),

$$Power(kW) = Q \cdot \Delta T \cdot C_{H_2O} \tag{1}$$

Here the specific heat of water, C_{H_2O}, is 4,2 kJ/kg·K ≈ 1,17 kWh/m^3·K at 5°C. The linearity demonstrates the flexibility and potential in ATES by varying either the extraction rate Q, the temperature difference ΔT or both.

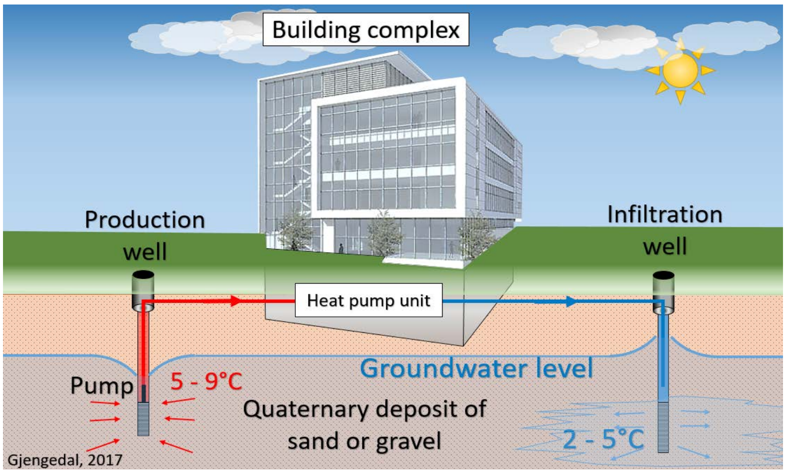


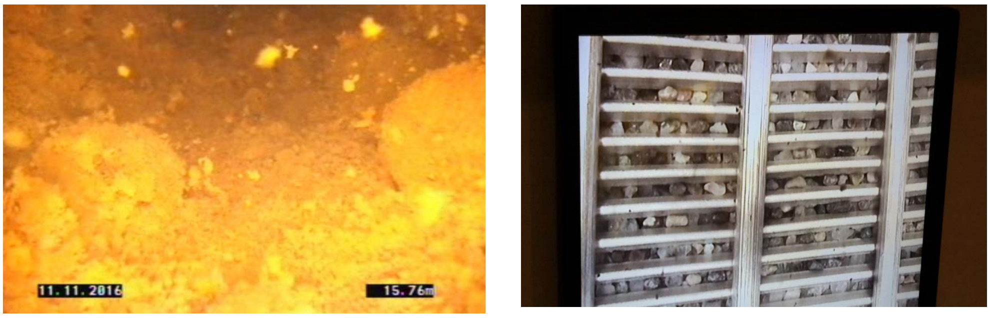
Fig. 1. Principle drawing showing the typical layout for a building using groundwater for heating in Norway

Rys. 1. Schemat typowego układu budynku, korzystającego z wody gruntowej dla celów ogrzewania w Norwegii

1. TECHNICAL ASPECTS

Some technical aspects related to ATES installations based on experience from Norway are included here *Settling damages and clogging.* Special precautions need to be made in order to avoid settling damages and clogging. Both the production and infiltration well consists of a con-slot well screen. The slot opening is designed based on sediment sample analysis (grain size distribution analysis from pre-investigations) in such a way that the grain size in the formation match the slot opening. Improper design can cause production of fine sand, and over time causing settling damages around the production well and clogging the infiltration well. To create a natural formation filter outside the well screen just after installation, the well is flushed thoroughly to remove the fine particles. As a precaution to avoid air (oxygen) into the well screen, the submersible pump is recommended to be placed above the upper end of the well screen. Intrusion of oxygen in the system should be avoided due to precipitation of iron and manganese hydroxides, and sometimes iron bacteria, which is a common problem. When ions of iron and/or manganese are solved in the groundwater (anoxic conditions), and the intrusion of oxygen in the groundwater leads to precipitation and clogging of one or more parts (well screens, pump, pipes and heat exchanger) in the plant. For the same reason, these open groundwater system always has an extra heat exchanger before the heat pump.

- *Airtight closed loop between heat exchanger and evaporator.* The maintenance of, repair or replacement of a heat exchanger has lower cost than solving problems in the evaporator in the heat pump. The closed loop between the heat exchanger and the evaporator in the heat pump is often filled with glycol. To avoid intrusion of oxygen and iron and manganese problems, the system should be operated free of oxygen. To keep the system airtight, special precautions must be taken in order to always have the submersible pump and infiltration pipe several meters below the groundwater level, and also designing all the remaining parts (valves, filters, fittings and heat exchanger etc.) in such a way that oxygen is prevented from getting into the system. It is often difficult to get rid of iron- and manganese precipitation when the problem is once present. Thus the effort is related to avoid the precipitation challenges to arise. To some extent, physical-chemical groundwater analysis in the pre-investigation phase reveals the potential for iron- and manganese precipitation as well as corrosion and precipitation of other minerals, e.g. carbonates.
- *Sensors with alarm functionality.* Both the production and infiltration well should also have sensors logging the groundwater level and alarm functions for low or high groundwater level in the production and infiltration well, respectively. The aim of monitoring the groundwater level is to avoid problems by detecting potential deviations from normal operation occurring over time, such as lower extraction and infiltration rates, lowered groundwater level etc., which in turn can be caused by clogging somewhere in the system. Video inspections of the groundwater wells is also recommended with respect to documentation and for troubleshooting when the wells have a deviating behavior. Figure 4 shows an example of video inspections with clogging caused by iron precipitation and bacteria (a), and a new well screen without any clogging (b).



(a) (b)

Fig. 2. Video inspection of two well screens. Here the slot opening is 1 mm
(a) The well screen is clogged with iron oxides and iron bacteria; (b) A new well screenwhere the sand and gravel particles in the natural formation filter outside the screen can easily be seen. Pictures by Gjøvaag AS in the ORMEL-project

Rys. 2. Kontrola wizualna dwóch filtrów za pomocą kamery. Prześwit filtra wynosi 1 mm
(a) filtr zakolmatowany tlenkami żelaza i bakteriami utleniającymi żelazo; (b) nowy filtr, przez który widać piasek i żwir (fot. Gjøvaag AS, Projekt ORMEL)

2. EXPERIENCE OF ATES IN EUROPE

The Netherlands, Sweden and Belgium are the countries with the largest number of ATES-installations in Europe, with some installations also in Norway, Germany, Denmark and the UK (Lee 2013).

The Netherlands has the largest number of ATES-installations in Europe with more than 3500 systems installed per 2015 which together save up to 3500 TJ of Energy (Heekeren and Bakema 2015). The Netherlands has very favorable ground conditions for ATES installations, with sand aquifers that can typically produce up to 250 cubic meters per hour (m^3/h), and typical temperature ranges for storing energy are between 7–17°C. Heating is done in combination with heat pumps. Around 70% of the ATES-installations in the Netherlands are commercial and public buildings while the remaining 30% are housing developments, and industrial and agricultural applications (Cabeza 2015). The largest ATES project supplies cooling and low temperature heating to the buildings and laboratories on the campus of the Eindhoven University of Technology. In neighbor country Belgium the number of ATES-installations was estimated to be around 1200 as of 2015 (Loveless et al. 2015).

In Sweden there were around 150 ATES system plants in operation per 2015 (Gehlin et al. 2015). The systems are described as highly efficient, and have generally low pay-back times, often less than 3 years. The wells are normally designed with a double function – both as production – and injection wells. Energy is stored in the groundwater and in the grains (or rocks mass) that form the aquifer. Typical Swedish ATES operation temperatures are

12–16°C on the warm side and 4–8°C on the cold side of the aquifer. The largest ATES system in Sweden is the Stockholm Arlanda Airport ATES plant, used for direct cooling and pre-heating of ventilation, and for de-icing of gates. It has been designed to a capacity of 10 MW and uses no heat pumps. There is a steady market growth for larger systems for residential buildings as well as for larger ATES and BTES systems in the commercial and institutional sector in Sweden.

The number of ATES-installations in other parts of Europe are more limited, partly due to ground conditions and partly due to regulations. One of the ATES-installation in Germany is noteworthy; the district heating and cooling scheme the renovated Reichstag building and of the connected neighboring large office buildings of the Parliament include a shallow and a deep aquifer, with a cold store in a depth of about 60 meters and a heat store in a depth of about 300 meters (Lee 2013). 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.

In Denmark there are a few ATES used for heating, cooling or seasonal storage (Røgen et al. 2016). However, the three geothermal plants with wells of depth between 1.2 km and 2.6 km producing heat for district heating from aquifers with temperature between 43°C and 74°C (Røgen et al. 2016) may be more interesting for Polish conditions, although these installations are not actually ATES as they are only used to pump up heat with no storage component. These three installations which are in operation since 1984, 2005 and 2013, respectively, have several features in common with the type of geothermal installations which could be built up in Poland from the aquifers with temperatures of around 60°C. The plants have capacity of 7–12 MHw, with one production and one injection well producing heat from the sandstone reservoirs through heat exchangers and/or LiBr based absorption heat pumps, where the driving heat primarily comes from biomass boilers for heat and/or combined heat and power production.

In Norway Gardermoen is the largest groundwater reservoir. The groundwater in the glaciofluvial delta fan deposited 10 000 years ago is used for heating and cooling of Oslo Airport, the largest airport in Norway The total building floor is 180.000 m^2, and the buildings are equipped with large glass walls which increase the cooling demand in summer and the heating demand in winter. The ATES system consists of 18 wells, 9 warm and 9 cold wells, each with diameter of 450 mm and depth 45 m. Each well is supplied with its own ground water pump and its own injection pipe. The cold wells are located 150 m east of the warm wells. The wells are connected to the heat pump / refrigeration system.

Oslo Gardermoen Airport was opened in 1998, and the ATES system has been in operation since then. There have been significant problems connected to clogging in the wells due to iron precipitation and iron bacterias in longer periods, which in turn was initiated by the presence of oxygen in the system. The presence of oxygen in the system is suspected to be a result of too intense pumping in periods, and/or mixing of oxic and anoxic groundwater in the upper and lower part of the aquifer, respectively. Due to the problems with clogging, the airport hasa regular cleaning process for the wells at regular intervals, with well screen washing and airlift pumping. Only 12 of 18 wells were in operation part of the year 5-6 years after the Gardermoen system was set into operation, and several of the wells are currently not in operation due to these issues.

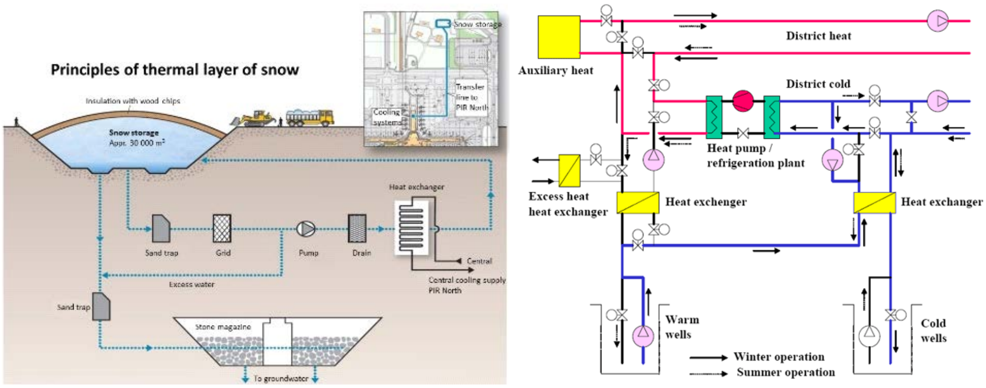
The ATES system covers the total cooling needs of the airport, of which 25% (2.8 GWh/yr) is direct cooling via direct heat exchange with cold groundwater and 75% (8.5 GWh/yr) is active cooling via the use of heat pumps. The annual heating provision from the heat pump is typically 11 GWh. Additional heat is supplied from a heat energy central with four oil heated boilers (12 GWh) and the district heating plant of Gardermoen with biofuels as the primary energy source (17 GWh). The total cost of the ATES system was 2.65 USD and the payback time compared to traditional heating and cooling system was estimated to be less than four years.

In summer, ground water is pumped from the cold wells for cooling the airport buildings. The heated water is returned to the warm wells. In winter, the direction of the heat pump is reversed, so the heat is extracted from the groundwater and transferred to a warm space –heating fluid. The cold from the building is returned to the cold wellsThe heat and cold from the energy central is transported through insulated district heat and cooling pipelines to the terminal building and other buildings including a hotel and a conference centre. In addition, heat is used for snow melting at the airplane setback areas. The heat is distributed as low -temperature fluid through a 40.000 m^2 floor heating system. Most of these systems are also used for cooling in summer.

Ammonia was chosen as working fluid for the heat pump. It is a natural, environmental friendly and with excellent thermodynamic properties, but since it is poisonous, the energy plant was built in a separate building 1 km from the terminal building.

The largest ATES-installation in the Netherlands is found at the Eindhoven University of Technology where an ATES-based district heating and cooling system was installed in 2001. The ATES-system supplies 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 technical 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 (Cabeza 2015).

The ATES-based district heating and cooling 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. The installation has a seasonal imbalance problem due to higher cooling demand than heating demand.



(a) *(b)*

Fig. 3. (a) Revised energy system at the Gardermoen international airport which includes snow storage insulated with wood chips, (b) Functional description of the Gardermoen ATES. Illustration: COWI

Rys. 3. (a) zmodernizowany system energetyczny w międzynarodowym porcie lotniczym Gardermoen, z magazynem śniegu izolowanym wiórami, (b) schemat funkcjonowania magazynu energii cieplnej ATES. Ilustracja: COWI

The soil conditions on the campus show a top layer of approximately 28 m thickness in which a shallow phreatic aquifer is present. At a depth between 28 m and approximately 80 m below the surface, the "first aquifer" (most shallow) 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. The groundwater is fresh with a chloride content of 10–40 mg/l.

3. SUCCESS AND CHALLENGES BY ATES

ATES-systems are the UTES-systems with lowest installation cost for a given installed capacity, making it possible to get short return of investment – the four year payback-time of the Gardermoen ATES-system is not an exceptional case. Thus if the ground conditions are suitable for ATES, the installation of an ATES is a very good investment, even with relatively low temperatures as is the case for Norwegian conditions (below 10°C). However, the number of locations for which ATES-systems are suitable is small in Norway, leading to relatively few ATES-installations, and none in the same order of magnitude as the Gardermoen ATES.

A challenge related to ATES-systems is that there may be significant and unpredictable costs in the operational phase related to clogging, growth and corrosion. Potential problems with respect to these issues may be identified and handled already in the planning and pre-investigation phase due to e.g. water quality from test drilling. Whereas BTES-systems are nearly maintenance free, significant costs may be expected for ATES-systems for maintenance, and maintenance may also lead to some wells being non-operational for months if one does not apply an active maintenance program. The Gardermoen ATES-installation is an example; only 12 of 18 wells were in operation part of the year 5–6 years after the Gardermoen system was set into operation In an ongoing Norwegian research project, (the ORMEL project) results shows lacking of regular maintenance and monitoring of groundwater level: Allowing a drawdown of the groundwater level to the water intake in the submersible pump introduced air into the system, and following precipitation and clogging problems. However, even including typical maintenance cost, ATES-systems are often favourable compared to BTES-systems.

The key to successful design and operation of an ATES-system is to use skilled personnel all the way from the pre-investigation phase to the construction phase, operation phase and regular maintenance phase. It is also important to employ the experience from earlier installations in all phases, drawing on the experience from e.g. the Netherlands, Sweden and Norway. It should also be emphasized that ATES needs a multidisciplinary approach involving expertise in multiple fields like hydrogeology, drilling, heat pump technology and automation. Documentation of the installation as well as follow up on critical operational parameters such as groundwater extraction and infiltration, groundwater level, groundwater chemistry, energy production, groundwater temperatures, COP etc. is also important. A recommended approach is to set up a periodic maintenance program in order to reduce the risk of problems, e.g. the Gardermoen ATES has a cleaning process of the wells which is performed at regular intervals to avoid problems with clogging caused by iron precipitation and iron bacteria. Systematic monitoring with alarm functions should also be used to understand when cleaning is necessary and to prevent oxygen getting into the system. Even though the groundwater quality can be challenging with high content of dissolved ions of iron, manganese and sometimes carbonates, keeping the system free of oxygen seems to be a success criteria in most ATES systems in Norway.

Another potential challenge for ATES-systems is to avoid thermal shortcut between the production and infiltration wells. Thermal shortcut could be as a result of high hydraulic conductivity in the aquifer. The groundwater flow (velocity and direction) should also be mapped thoroughly. Results from a test pumping and infiltration program performed in the pre-investigation phase will be sufficient to design the ATES with minimal risk of thermal shortcut.

4. RECOMMENDATIONS FOR POLAND

Poland has very high potential for widespread usage of ATES with excellent ground conditions in large parts of the country. However, only a minor part of the potential has been exploited. In addition to low temperature aquifers which can be used for combined heating and cooling following the approach used in Norway, Poland has higher temperature aquifers with temperatures up to 60°C which depending on groundwater flow rate in the aquifer can be used either as high temperature storage or to only extract heat (see examples for Denmark. A combination of high temperature heat extraction from a deep aquifer and cooling from a shallow aquifer following the approach used in the Reichstag in Germany may also be a viable approach.

Equation (1) shows that the heat output in kW is linear the extraction of groundwater. Thus the extraction of as much heat as possible per m^3 of groundwater is recommended. A maximum temperature reduction for heat production will save huge volumes of groundwater from being extracted from the aquifers. Extraction of groundwater is usually a limiting factor with respect to a sustainable exploitation of the aquifer to maintain the water balance. In addition to direct use of the warm groundwater, the remaining heat extraction, i.e. temperature reduction of the groundwater, should be done by using a heat pump. Today the electricity in Poland is mostly produced by coal fired power plants. Thus in the near future and according to the decarbonisation and introduction of more renewable power, the use of electricity driven heat pumps will be acceptable with respect to CO_2-emissions from the electricity generation. To reduce the CO_2-emissions and dust as much as possible, the focus should be holistic and on system level. E.g. the potential for the use of heat pumps driven by electricity from solar cells should be considered and evaluated. Another important perspective on system level, is the investment needs in the electricity grid. Local energy solutions and seasonal and short term storage of energy in ATES (as well as BTES) can potentially reduce peak electricity demand and the need for investment, and should be investigated further. In some cases however, ad- or absorption heat pumps might be a right solution.

The need for skilled personnel in all phases (pre-investigation phase, building phase, operation phase and regular maintenance phase) of ATES systems should be emphasized. ATES requires a multidisciplinary approach involving expertise in many fields as discussed in the previous section. In order to ensure that more of the ATES potential in Poland is exploited in the future, one should focus on relatively large installations where one can have a short return of the investment. To exploit the resource fully, ATES should be used for both heating and cooling purposes, direct cooling included. The use of ATES must be according to the groundwater regulations.

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STRESZCZENIE

Metoda ATES polega na magazynowaniu ciepła lub chłodu w podziemnych zbiornikach wodnych. Energia cieplna jest następnie odzyskiwana podczas eksploatowania wody z takich zbiorników. Pod względem ekonomicznym i energetycznym ATES jest najbardziej efektywną metodą podziemnego magazynowania energii cieplnej (ang. UTES – *Underground Thermal Energy Storage*). Artykuł zawiera przegląd systemów ATES, przykłady i rekomendacje przydatne dla Polski.

SŁOWA KLUCZOWE

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