



DEPARTMENT OF BIOLOGICAL AND  
ENVIRONMENTAL SCIENCES

# DEVELOPMENT OF ENERGY EFFICIENCY AT THE GEO ENERGY SYSTEM AT SKARABORG HOSPITAL, SKÖVDE

Investigation of how to measure efficiency at a low  
temperature ATEs system

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## Abstract

In connection with the expansion of Skaraborg hospital in Skövde their requirement of energy increased and in dealing with their climate impact they wanted an alternative that was better from the energy and emission point of view. The alternative that was chosen for the hospital was the low temperature aquifer system (ATES) which utilizes the heat and cold in the groundwater to warm up and cool down a facility. WSP began consulting and working on this project in 2014, starting with an investigation to determine if the area were suitable for the ATES system and it had an appropriate hydrological profile. Actual drilling started during fall 2023 with the plan to be ready for operation by the summer 2024. The system consists of 18 wells and the hospital's total requirement is 14000 MWh for heating and 7000 MWh for cooling. The aim of this report is to investigate how a model could be formed to assist in monitoring the system, preventing energy losses and assess the environmental advantage that will follow from different scenarios. Data from Sweco has been used and they have proposed three reasonable scenarios based on varying amounts of available energy in the ground water. Two main equations found in earlier studies describes the relation between injected and extracted temperature, flow and energy content of the groundwater used. Because of expired available extracted data, probable outcomes have been taken from earlier studies and integrated with data from Skaraborg hospital. Possible efficiency for this volume and energy demand range from 0.7-0.9 and varies depending on fraction of loss due to conduction, dispersion and buoyancy driven flow. These factors will fluctuate over the years as the system drifts and due to variations in weather, demand. and the variation in underground thermal hydraulic conductivity. With different results for the efficiency there will be different result for the reduction of CO<sub>2</sub> emissions, in the range of 30-40%. The final conclusion highlighted the importance of controlled monitoring of the system while doing regular measurements to ensure that fraction loss remains as small as possible. The optimal scenario for the CO<sub>2</sub> emissions is also best from energy point of view and it all depends on the drifting. Overall is the use of ATES system beneficial for reduction in CO<sub>2</sub> emissions and with the ongoing trend of increasing worldwide application, the system would positively impact the climate.

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# Introduction

The goal to avoid reaching a 2 °C global increase in temperature is more urgent than ever because climate change is progressing faster than earlier predicted (IPCC, 2023). To decrease the total carbon dioxide emissions, every part of the energy sector must make changes to incorporate more renewable sources. In 2022 the building sector accounted for 30% of the total energy consumption worldwide, but only 15% came from renewable sources. Compared to the agricultural, transport, and industrial sectors, the transition to renewables is slowest in the building sector. Space heating and cooling accounted for 75% of the total energy consumption in the building sector, and the demand for cooling has increased by 6.5%. (Global status report, 2023) The request for cooling is predicted to have increased by 33 times globally by the end of the century (IPCC, 2023).

To address the expected demand for space heating and cooling, a potential technology utilizing thermal energy could be the key (Rostampour et al., 2019). Aquifer Thermal Energy Storage (ATES) has become more attractive lately due to the usage of thermal energy storage in groundwater through temperature varied well system, leading to energy savings and emission reductions (Vanhoudt et al., 2011). For larger buildings requiring space heating/cooling, ATES proves to be an effective choice since it is capable of saving up to 50% of energy use. In ATES it is important to dynamically control thermal interactions which means monitoring of the transfer of heat from water to the surrounding materials like water, air, rock and with that decrease the risk of unwanted heat exchange. By this method greenhouse gas savings can increase by up to 40% for each unit of subsurface volume allocated (Rostampour et al., 2019). The energy savings and reduction in greenhouse gas emissions align well with climate goals aiming for a 45% reduction in emissions by 2030 compared to 2010 levels and to reach net zero emissions by 2050 (IPCC, 2023). The energy savings are associated with the consumption of primary energy resulting from temperature differences between the cold and warm wells, along with the advantage of free cooling without the need for a heat pump. With a larger temperature difference between the cold and the warm side the effect of the system is better because there is less need for electricity to drive a heat pump or cooling machines. Then a bigger share of the input is used in the output, which is a measure of efficiency.

Presently district heating is the most common form of heating in Sweden with approximately half of all heating coming from this source. The heat in the district heating system can

originate from a district heating plant that only produces heat through combustion, a combined heat and power plant where both electricity and heat are produced through combustion or from a local industry that supplies waste heat that can be integrated into the district heating network (Rydberg, 2023). For the latter two options there is production during summer because of the persistent electricity demand and the industries operate continuously producing heat as a byproduct regardless of the heat demand. The heat from the district heating plant is not required in the same amounts during the summer, with some produced heat being released into the atmosphere. There are advantages in using ATES systems instead of district heating because the CO<sub>2</sub> emissions are higher with district heating (Schuppler et al., 2019), and hopefully the amount of waste energy can be decreased in the future. For district cooling there are some alternatives such as using water from a lake or to produce cooling from district heating with heating driven cooling. That is doable due to the absorption refrigeration which uses the heat produced by district heating to drive the cooling machine that produces the district cooling (Rydegren, 2017). In the case with district cooling using the absorption combustion is still ongoing which means that the CO<sub>2</sub> emissions are higher, and it is not as effective as the ATES free cooling. There is significant potential in leveraging ATES and consume energy wisely to meet societal needs and therefore consideration for transitions may become more common in the future.

### **Low aquifer thermal energy storage system**

The ATES system takes advantage of the thermal energy in groundwater to both warm up and cool down buildings. This is possible through the injection and withdrawal of groundwater via different wells, constituting an open-loop system (Sommer et al., 2015). In the open-loop system groundwater is pumped up from wells and with the assistance of a heat exchanger the energy can be utilized. Two types of wells are essential for this process, the warm and the cold (Figure 1).

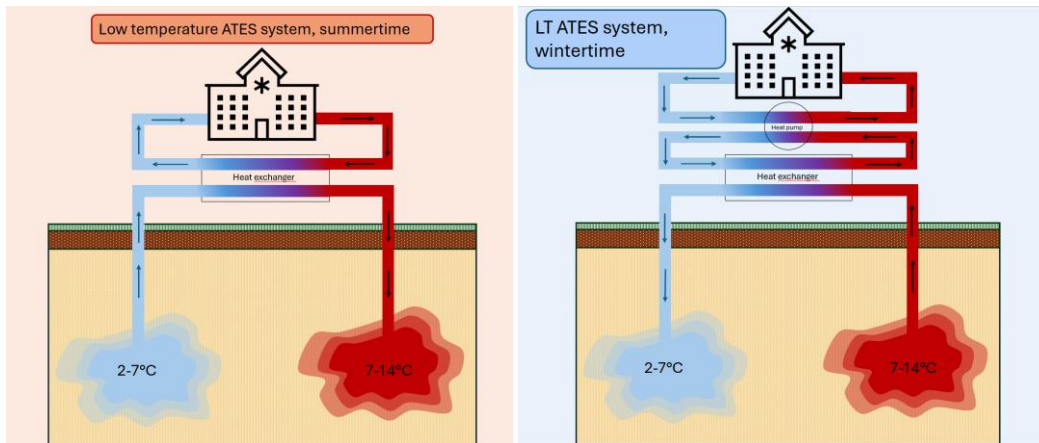


Figure 1: Schematic presentation of the ATES system during the summer (a) and winter (b). The illustrated blue well represents cold well and the red represent the warm well. During winter an additional circuit is used because of the heat pump.

In a low-temperature ATES system, which is most common globally (constituting 99% of ATES systems), the temperature should not exceed 25 °C (Fleuchaus et al., 2018). During the winter when the system is used to warm up buildings, two additional systems must be added. The secondary system is a closed heat/cold carrying system within the building. Heat transfer occurs in the heat exchanger where the warm water is transferred to the cold water. Additionally, a third system is required during the winter which raises the water temperature to 58 °C with the help of a heat pump. The heat pump is using thermal energy in bedrock, soil, or water together with vapor compression and a condenser resulting in an output of higher temperature. For this process electricity is required and with a higher incoming temperature less electricity is needed. The effectiveness of a heat pump can be explained by the coefficient of performance (COP). It can be defined as the proportion of useable energy delivered to the total amount of external energy the heat pump uses and a normal COP value in ATES system is 3.5 (Sommer et al., 2015). The elevated temperature that comes with a heat pump enables heating the building through ventilation. During the winter, warm water from the warm pool passes through the heat exchanger, heat is utilized in the heat pump and cold water returns to the cold pool.

The opposite is the case for the summer, the cold groundwater from the cold pool will go into the heat exchanger where it will increase in temperature (because of the absorption of energy) while cooling down the building/facility and in this situation, there is no need of a heat pump. Then, the warmed-up water will return to the warm pool.

## Hydrogeological requirements for an ATEs system

The usage of the ATEs system requires specific geological condition to function, and these properties depend on the effectiveness of mechanisms such as conduction, radiation, convection, and vapor diffusion. Parameters that affect the conduction include water content and porosity influencing the heat transport and higher water content allowing for heat transfer up to 20 times better than in air. Silt and clay are both fine-grained soil types with small pores and they exhibit good water-bearing characteristics and stable conduction  $2.5\text{-}3\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$  (Sundberg, 1991).

The most common soil type in Sweden is moraine, composed of varying sizes of sand and gravel which results in a wide range of conduction capacities  $0.5\text{ - }3\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$  (Wickström et al., 2021). The variation in conduction with larger particles is due to improved water drainage and moraine typically has good water-bearing characteristics depending on the sand and gravel content. Areas with moraine formations, such as eskers and ridges originating from glaciofluvial deposits, are suitable for ground water abstraction for drinking water and accommodates geohydrological requirements beneficial for ATEs system usage (Andersson et al., 2015; Knutsson et al., 2002).

An ATEs system relies on a good ground water flow and therefore areas with favourable conditions for groundwater extraction suitable for ATEs. It is crucial that the groundwater reservoir has a sufficient capacity to avoid risks of flooding and draining. This is because water moves seasonally back and forth between the cold and warm sides and that constitutes potential risks (Erlström et al., 2016). For the sustainable use of groundwater as an energy carrier it should be exploited at a rate that prevents future resource depletion (Stauffer et al., 2013). The ground water flow can be the main cause for thermal loss together with conduction losses across the storage volumes boundaries (Bloemendal et al., 2018). Since the ratio between the interface area and the storage volume reduces with increasing volume, increasing the storage volume improves the system's thermal recovery with reference to conduction losses from the border of the storage volume (Houben et al., 2011).

Bedrock is also decisive for where an ATEs system could be installed, sandstone and limestone being beneficial (Geoenergicentrum, 2016). Limestone has a conduction capacity of  $1.5\text{ - }3.5\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$  and sandstone  $2\text{ - }6\text{ W m}^{-1}\text{ }^{\circ}\text{C}^{-1}$ . The hydrogeological conditions should also be beneficial for ground water flow, high permeability, and geochemical conditions as forestall clogging and corrosion of wells (Fleuchaus et al., 2018). Clogging occurs more often

with an increase in temperature which accelerates chemical reaction and modifies the geochemical balance of minerals, oxygen saturation and gas solubility (Sauffer et al., 2014). The chemical reaction that occurs through an increase in temperature is the precipitation of calcium carbonate at the surface, which can lead to clogging. One example of corrosion is oxidation of metals that could leach out of pipes and equipment when getting in contact with air. The so-called corrosion index shows if water has the ability to form or dissolve calcium carbonate depending on whether the water is unsaturated, saturated or supersaturated regarding calcium carbonate. The chemical reaction depends on the content of  $\text{CO}_2$ ,  $\text{HCO}_3^-$ ,  $\text{Ca}^{2+}$  and the pH (Lund, 2014).

Sandstone is composed of fragments, quartz grains, feldspar grains, matrix and cement and has a grain size of 0.06 – 2 mm. The size of the grain together with the form and composition is giving the sandstone their physical and technical properties, such as porosity, permeability, hardness and thermal conductivity. Sandstone with larger grainsize has higher porosity and permeability and with that comes a better condition for groundwater use in an ATEs system. Because the sandstone is porous, cracks form more easily and they are decisive for the water flow and the conduction, since the heat can be transported in the direction of the water flow. Crack zones oriented vertically to the heat flow instead reduce the heat transport because they act as a barrier to heat flow (Sundberg, 1991). Limestones also have crack formation because it is a soft and porous material and can therefor also be good for groundwater use. A study done by Iscan et al. (2009) showed that limestone has lower permeability and porosity compared to sandstone. There is a range for porosity in limestone, spanning from 0,1% up to 40%, which affect the variability in permeability (Oates, 2010). If the sandstone is denser, which it will be if it is more quartz rich, the thermal conductivity gets higher. Then the transfer of heat and cold gets higher which could be beneficial for an ATEs system (Wickström et al., 2017).

Convection is the movements in water and air and it can be either natural or forced and difference in the water density depending on temperature is one of the main reasons for natural convection as it induces water movements. In heavily water conducting materials convection plays a significant role because of their larger circulation of heat when warm less dense water rises and floats up on the cold water. Pumps on the other hand are forcing the convection because of the potential differences that appear (Sundberg, 1991).

## Examples of existing ATES systems

The use of ATES system began in the early 1970 because of the oil crisis and the concept came from north America and Europe (Andersson et al., 1993; Andersson et al., 2013). In China the usage peaked in the early 1980s and even though the interest in ATES system was decreasing in some of the countries initially active in research, the usage of ATES system increased in popularity in other geographical areas (Zhou et al., 2015). The popularity has grown especially in Northern Europe where usage is expected to increase but some countries lag behind, for example Switzerland and France that has zero systems, the USA with two and Canada with four (Anibas et al., 2016; Fleuchaus et al., 2018).

It was more popular with high temperature storage initially which has temperatures at 30-90°C, but it early passed over to low temperature storage to now be dominating by 99%. Presently there are 2800 ATES system worldwide that producing a total annual energy of 2.5 TWh. With increasing interest and active systems more research has been carried out to develop the efficiency. The Netherlands lead globally in ATES system usage, 85% of the total usage worldwide with 2500 active systems. Sweden, Denmark and Belgium have together 10% of world usage. In new commercial and institutional buildings, 70% of the total ATES system are utilized in commercial buildings while the remaining 30% is used in industrial or residential buildings. The installation of ATES system is common in new buildings with the rate of 8% in the Netherlands (Bloemendal et al., 2018). In Sweden and Denmark, the usage characteristics are similar to the Netherlands (Andersson et al., 2013). The prediction for 2050 is that half of all city inhabitants worldwide will have climates and subsurface conditions conducive to ATES.

Interest in geo energy system is increasing in several countries like Great Britain, Germany, Japan, Turkey and China (Fleuchaus et al., 2018). The reason why it has not been developed at the same rate everywhere could be because of the market barriers that occurs caused by regulations, socio-economic, technical and political reasons. In many cases the ATES system is not even considered and because of the high investment capital other suggestion seems to be a better choice at first sight. Things like low payback times, the energy efficiency and decreasing greenhouse gases should be highlighted (Dumas et al., 2015). Another challenge that could be a problem is the occupation of underground space. Germany for instance has 350 000 ground source heat pumps (GSHP) which limits the available space for ATES systems (Fleuchaus et al., 2017). The Netherlands have a good solution for the problem and

that is to create a management system for the underground space early in a city's new establishment and planning (Fleuchaus et al., 2018).

In Sweden the development of using ATES system started in the 1980s and one of the first ATES facilities was built in Lomma 1991 (Andersson et al., 1993). High temperature storage was more common by then but because of the issues that appears with high temperature there was a shift towards low temperature storage together with heat pump (Gehlin et al., 2020). The typical user of that time was not the industry, probably due to lack of technical credence along with enlarged payback time, instead the users were the owners of commercial buildings or a district heating network (Andersson et al., 1992).

During the recent decades the interest in ATES has increased in an annually rate of 5% in Sweden. In 2019 there were 190 installed systems with an additionally 320 groundwater heat pumps in the residential sector used only for heat extraction (Gehlin et al., 2020). Examples of facilities in Sweden using the ATES system include Ikea in Malmö (installed 2001), the hospital in Kalmar (installed 2016) and Arlanda Airport (Installed 2009) (Fleuchaus et al., 2018). Arlanda airport has one of the largest ATES systems consisting of 12 wells, 5 warm and 6 cold. In 2022 they extracted 13.7 GWh of cooling and 1.7 GWh heat. The aquifer is utilized to warm up the gates, so they are ice and snow free and to cool down the equipment that cools the terminal during the summer. Arlanda is located close to a lake and an esker which serves as a good source for ground water, and they use water from the lake when the ground water levels are low.

## The ATES system at Skaraborg hospital

When Skaraborg hospital expanded their facility there was a need to enhance the energy demand. They pursued a more sustainable way to heat up and cool down the hospital and therefor the ATES system was an attractive option. In 2014 they decided to implement the ATES system and they got consulting help from WSP. To install this type of system there are certain investigations that must be done to determine if the areas is suitable for an ATES system. The survey focused on soil and water conditions as it makes the requirements of using groundwater as an energy carrier. Understanding groundwater flow requires an examination of the soil and bedrock type. The soil around Skaraborg Hospital in Skövde is dominated by glacial material deposits with occurrences of moraine and peat in the surrounding area. In the westerly direction of the hospital lies Mt Billingen which is a type of table mountain consisting of soft sedimentary rocks overlain by a harder diabase which protects underlying

layers from erosion. Billingen also consists of various rock types with primeval rock in the bottom, followed by 50 m of sandstone, 20 m of alum shale and 50 m of limestone at the top. The sandstone has a porosity of 20% and the water field pores has a heat capacity of  $1.164 \text{ kWh m}^{-3} \text{ }^{\circ}\text{C}^{-1}$  and the enveloping solid material has a lower value of  $0.7 \text{ kWh m}^{-3} \text{ }^{\circ}\text{C}^{-1}$ . Based on the rock- and soil map by SGU, the area has beneficial requirements for an ATES system. To confirm this, knowledge about the rate of formation of new ground water is necessary, and it can be obtained from water balance calculations. These calculations are usually done to investigate if the planned groundwater withdrawal is balanced by the potential inflow to the exploited aquifer. The new formation of groundwater is assumed to be the same as the net precipitation at the area, i.e.  $300 \text{ mm year}^{-1}$ . The net precipitation is the incoming water that does not evaporate. In this case with the highly drainage material, it is expected that all precipitation will infiltrate and therefore form groundwater.

During the fall of 2023 the drilling of wells was started, and it is important that the drilling reaches the primeval rock. This allows water extraction from as large part as possible of the sandstone aquifer existing above the bedrock. There are a total of 36 wells, 17 cold and 18 warm. They should be positioned in north-south directions, with the cold wells in the south and the warm wells in the north. The warm wells have a temperature between  $7\text{-}14 \text{ }^{\circ}\text{C}$  and the cold wells range from  $2\text{-}7 \text{ }^{\circ}\text{C}$ . The maximum water extraction is  $120 \text{ l s}^{-1}$  and the groundwater flows in a northeasterly direction. Each well has its own frequency-controlled, submersible pumps at a depth of 20 m (at least 15 m below the groundwater surface). These pumps activate when there is a cooling or warming demand in the hospital. The water pumped is continuously measured by a flow meter in each well and the total flow from all wells is reconciled with the power demand in the energy centre's heat exchanger. In each well the return flow is measured and compared against the flow in the withdrawal wells and if one well has a low water level for a longer timespan then the water pump is stopped. The wells are also equipped with temperature sensor, flow meter and pressure transmitter on both return and outlet lines. A pressure transmitter supervises the water tables position of the well when the pump is activated and during reversal usage the over pressure is measured. To minimize the risk of clogging a particle filter is installed on the injected line/pipe.

The intended number of operating cases is three, one for warming period and two for the cooling period. During the warming operating case the heat pump is activated, heat is retrieved from the aquifer, and it is loaded with cold water. For the cooling period there are the two cases, free cooling and free cooling together with mechanical cooling. In the free

cooling case the cooling is obtained from the aquifer without mechanical cooling and heat is loaded to the aquifer. Free cooling together with mechanical cooling is at the beginning a similar process obtaining cooling from the aquifer but it occurs together with reloading excess condenser heat from the cooling machines. The condenser heat will then increase the amount energy that will be injected into the aquifer (Klemetz, 2019).

The total energy demand at the hospital is calculated to be 14 000 MWh for heating and 7000 MWh for cooling. This demand varies throughout the year with heating demand from October to April and cooling demand from June to August. The returned energy is higher for the cooling wells compared to the warm in every case.

## Submersion

The extensive part in investigating the suitability of the wells is the geo energy exposition. This type of investigation is managed in several steps with evaluation after each part. When the preliminary investigation has been completed it is time for geo technical exposition with resistivity measurements to evaluate the groundwater level, depth of the aquifer and prevalence and thickness of the glacial deposits. The result from the expositions was used to analyse where the most suitable locations are for drilling the wells. An important parameter during this investigation was that the groundwater flow was not suitable in the soil layer but in the sandstone several cracks were found which were promising for water abstraction. Exploration drilling was placed along the measured geophysical lines to provide better opportunities for analysing the results. The installation was done at a depth of 12 meters which was deeper than the groundwater level. The first 11 drilled wells underwent test pumping along with capacity testing in the next step to determine the characteristic of the aquifer. The measured parameters were the depth of the aquifer, depth of sandstone and assessed water discharge. In context of the capacity test the wells were surveyed to place them in a dimensional 3D cartesian coordinate system. Having them in this system makes it easier to observe how the groundwater levels are affected by withdrawals and to determine if they are recovering. Some of the wells were not able to recuperate as they did not fill up with water and these are not representative for the water level in the area and will not be considered further. The dimensioning of wells resulted in a known groundwater slope and that makes it possible to obtain more information about their function and runoff. The next step in the process was to do different levels of withdraw to investigate the submersion in more detail and how fast it replenishes. Varying amount of water was pumped out to observe the recovery

and the interaction between the wells and how they got affected by each other. The wells were pumped in different rates: 1, 2 and 4 l s<sup>-1</sup> under the process time of 3 hours. There was fluctuating result among the wells, some of them had a faster recovery than others but the water levels in the wells did not stabilise after each step.

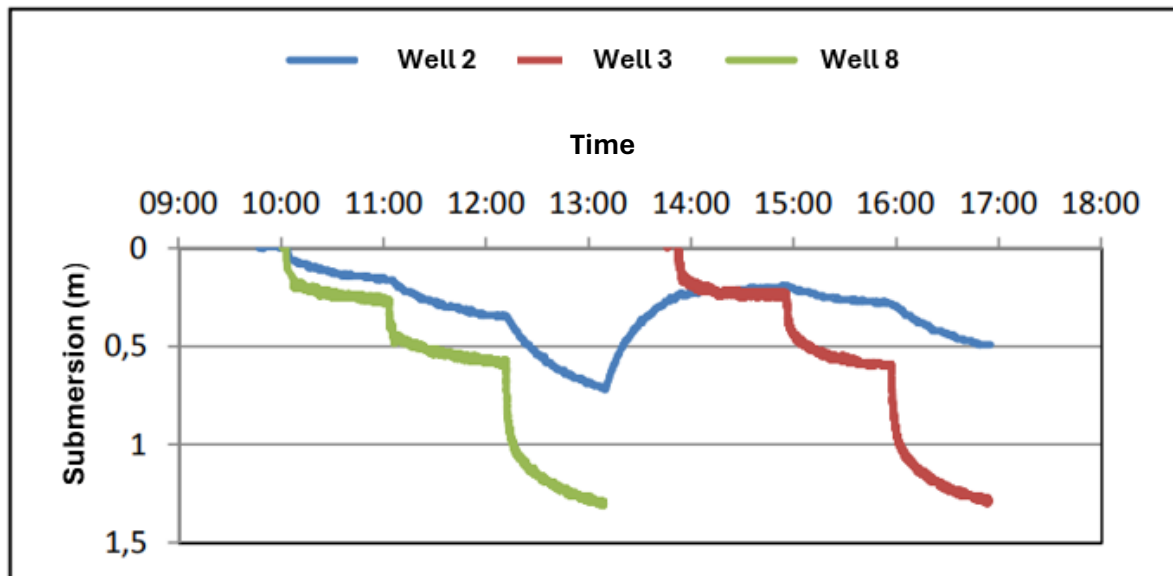


Figure 2. Submersion was followed by testing the capacity of wells 8 and 3 which involved pumping from those wells. Then an observation of well number 2 was conducted to see how it would be affected by pumping from the other wells.

Figure 2 shows that the wells have good connections because when submersion occurs in well 3 and 8, well 2 responds with a lower water level. The result of the capacity test in well 8 was analysed and evaluated to determine the specific capacity.

The outcome was that a withdrawal of 20 l s<sup>-1</sup> could be sustained without a submersion of more than 15 meters in the pumping well. A shorter pumping test was conducted to get the knowledge about how much water could be withdrawn and well number 8 were pumped to observe how the other wells were affected. This test lasted for 19.5 days and a total amount of 13288 m<sup>3</sup> was withdrawn which resulting in a rate of 7.86 l/s. The results were then analysed and the submersion against over time was used to determine the storage capacity.

## Fraction loss

Fraction loss is heat loss that could occur in a ATEs system. It can be divided into 3 different categories which is dispersion, conduction and buoyancy driven flow. Dispersion is explained as the thermal loss of energy that could be spread from the wells when the heat or cold energy is transported through the subsurface aquifer. The amount of dispersion depends on the

variation in pore flow velocity variation that appears due to asymmetry in the material both at the grain level and on a larger scale. In calculation for dispersion, it essentially only to look at the longitudinal dispersion and not the vertical because vertical flow is trivial compared to radial flow velocity (Beernink at al., 2024)

The conduction loss of thermal energy occurs because of the difference in temperature between the edge of the stored thermal volume and the surrounding groundwater. The amount of conduction losses is controlled by the thermal conductivity of the material in the aquifer, consists of the water bearing sandstone and aquitard which is the surrounding solid material without water. Buoyancy driven flow is the natural convection that occurs because of the difference in water density due to varying temperatures. For low temperature aquifers losses due to dispersion and conduction is more common. The reason why buoyancy driven flow is more common in HT aquifer storage is because of the greater differences in temperature between the wells and the ambient ground water flow. The heat loss due to ambient groundwater flow could be seen as a fourth factor of that will be decisive for the overall fraction loss. When the wells are extracted, submersion will occur and while the wells recuperate with refilled ambient ground water the amount of heat and cooling would affect the thermal efficiency outcome. The ambient ground water flow will also affect the already injected wells, as the stored energy could risk being flushed away. Earlier studies have shown that the velocity of transported heat in the ambient ground water will be approximately 50 % of the flow velocity ( $u$ ) (Bloemedal et la., 2018).

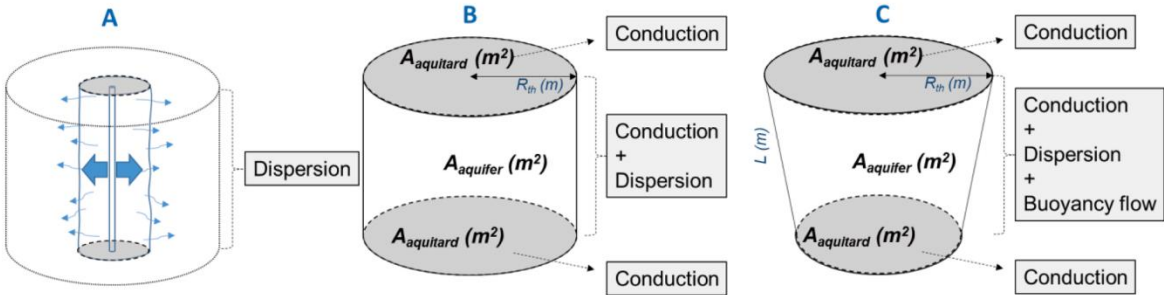


Figure 3. Illustration of how the different types of fraction loss, conduction, dispersion and buoyancy driven flow is function within a well and the surrounding thermal radius and aquitard. From Beernik et al. (2024)

As illustrated in Figure 3 the surrounding thermal area is the one around the well and inside the outer cylinder, the thermal radius ( $R_{th}$ ) is the radius of the thermal cylinder.  $L$  represent the thickness of the aquifer and the  $L/R_{th}$  becomes the ratio of the boundary layer and the volume. When the diameter of the thermal cylinder is equal to the height (as the case for b), then the  $L/R_{th}= 2$  and the ratio between the total boundary area and the volume is at its smallest,

resulting in decrease in conduction. Dispersion is closest to the well and decreases with distance from the thermal front. Natural convection only appears in the thermal front and causes the front to tilt as shown by the cylinder in Figure 3. Compared to the thermal area that is described in Figure 3, the hydraulic area the enveloping surface outside the thermal area. The hydraulic area has one-third the radius of the total, and when the thermal area stops and the hydraulic area begins, only the movement of water continuous without heat being transported. To understand how ambient groundwater will affect the dispersion of heat the function  $R_{th}/u$  function could be used. It describes how the heat will be transported through a specific material and a higher value will result in slower transfer (Bloemedal et al., 2018).

## Research question and aim

The general aim of this thesis is to study how effective the ATEs system at Skaraborg Hospital, Skövde is according to different factors that can affect the outcome of the efficiency. The different factors that can influence the system is the fractions loss along the system, the energy demand of the hospital and the flow rate. Information about the efficiency and energy losses should be created by several equations. To obtain the environmental advantage there is a need of an equation that calculates the CO<sub>2</sub> emissions.

1. What are the environmental advantages of a low temperature ATEs system?
2. How will the energy demand affect the efficiency of an ATEs system?
3. How much energy will vanish through the groundwater?
4. How can a model to monitor the effectiveness of the system be developed?
5. What can be done to prevent energy losses?

## Methods

Information about ATEs systems have been researched in articles, document from the WSP and Sweco and directly from employees within SWECO. The majority of the information has been obtained from investigations and research by the companies. The methodology has been both qualitative and quantitative depending on the research questions. The research question regarding how the ATEs system can prevent energy losses falls under the qualitative part. This is because the information has been interpreted to reach conclusions about these questions and get different perspectives. The remaining research questions about the model

for efficiency, the energy demand affecting the efficiency, how much energy will vanish through the groundwater and the environmental advantage the quantitative ones. For these questions quantitative data analysis was needed.

The introduction introduced the ATES system and includes climate change, its function, hydrogeological advantage, distribution of ATES and the current ATES system at Skaraborg Hospital in Skövde. Information about climate change was sourced from IPCC and while the function and hydrological advantages were found in earlier studies about ATES system and books about the physical effects of soil and rocks. Regarding the distribution of ATES system most of the information was collected from earlier research on worldwide applications of thermal aquifer systems. Some of the research about ATES system in Sweden was obtained from an interview with a technical manager at Arlanda airport. Questions were prepared and sent to the technical manager before the meeting to make the interview more effective. The questions were about how their system worked in terms of efficiency, the number of wells, energy demand and how to prevent energy losses. Information about the system at Skaraborg hospital in Skövde was assessed from their feasibility investigations and technical description of the system. More specific hydrogeological information and operating cases was found in the attachments. Additional specific knowledge about the system such as the secondary and tertiary circuit was achieved from an employee at Sweco.

## Equations

The research question about obtaining an equation to calculate the efficiency of the system was addressed with help from the article by Sommer et al. (2015). In that article different models about thermal efficiency, reduced emissions, electrical power use and volume ratio are presented. The expression for thermal efficiency ( $\eta_{t,i}$ ) per year  $i$  is expressed as:

$$\eta_{t,i} = \frac{\int_{extraction,i} |T_{extraction} - T_{injection}| \cdot dt}{\Delta T \cdot \Delta t} \quad (1)$$

The *extraction* is the normalized extracted energy compared to the amount that would be extracted without any subsurface loss. The  $T_{extraction}$  is the water temperature extracted from the wells while the  $T_{injection}$  is the water temperature that returns to the wells. Whether the extracted and injected water comes from a warm or cold well depends on the seasons.  $\Delta T$  is the difference between the average temperature for cold wells and the average temperature for warm wells. The  $\Delta t$  is the number of months the cold or warm side is operational for the ATES system. At Skaraborg hospital in Skövde it is five and seven months, respectively. The

warming season in this case is seven months while the cooling is five. The  $dt$  is the time step and in this case, it is 1 month and  $i$  is the number of seasons.

The variation in total energy has been calculated by Sweco and they have three different cases with variation in energy and the withdrawal speed. To get these variations into the model, Beernink et al. (2024) has developed a model that depends on the pumping rate.

$$\eta = \frac{E_{extracted}}{E_{injected}} = \frac{\int (T_{extracted} - T_{amb}) Q_{extracted} c_w dt}{\int (T_{injected} - T_{amb}) Q_{injected} c_w dt} \quad (2)$$

The  $Q_{extracted}$  is the pumping rate which is the amount of  $m^3 \text{ day}^{-1}$  of groundwater extracted from the system and the  $Q_{injected}$  is the volume per day of groundwater that is returned to the wells. There could be applications of variation which gives different outcomes. The  $T_{amb}$  is the temperature of the ambient flow, which is the temperature of the ambient water that flows into the wells while extracting groundwater. This can vary due to the energy demand at the hospital. The  $c_w$  is the volumetric heat capacity. The  $E_{extracted}$  and  $E_{injected}$  represent the energy (heating during winter, cooling during summer) that is extracted and injected respectively. The fraction loss that is generated from the system into the surrounding aquitards could be calculated by using the efficiency from the equation:

$$f_{loss} = 1 - \eta \quad (3)$$

The  $f_{loss}$  is the percentual loss from the system and it is predicted to be highest in the first year and then decrease and stabilize in the fifth year (Beernink et al., 2024).

The fraction loss that is depending on the different thermal losses and that could be described as a cylindrical tube enclosing the well. To know that area the following equation could be used to get the thermal radius describes as  $R_{th}$ :

$$R_{th} = \sqrt{\frac{c_w V_{in}}{c_{aq} \pi L}} \quad (4)$$

With the volumetric heat capacity of water  $c_w$  at  $4.18 \times 10^6 \text{ J m}^{-3} \text{ }^\circ\text{C}^{-1}$  as a constant,  $V$  as the total volume of the aquifer,  $c_{aq}$  is the bulk volumetric heat capacity.  $L$  is the aquifer thickness.

To able to assess how much emissions of  $\text{CO}_2$  are saved by using the ATES system there is a need for knowing the total emissions before and after the system was installed. The model for total emissions that are released from the hospital with the ATES system can be expressed as:

$$C_{i,ATES} = E_{i,ATES} \cdot C_{elec} \quad (5)$$

$C_{i,ATES}$  is the total emissions of CO<sub>2</sub>,  $E_{i,ATES}$  is the total electrical energy and  $C_{elec}$  is emissions in kg CO<sub>2</sub> MWh<sup>-1</sup> from the electricity production. To determine the total electrical energy used it is necessary to know the management and dimension of the system as well as the electricity use by the heat pump (Sommer et al., 2015).

$$E_{i,ATES} = q_{max} \cdot u_{eq} \cdot L \cdot E_p + \frac{E_i}{COP_H - 1} \quad (6)$$

The  $q_{max}$  is the maximum flow rate per meter well screen which is the maximum flow rate of water that could pass through the well pipes,  $u_{eq}$  the equivalent time while the aquifer is at full load, and  $L$  is the thickness of the aquifer. For the electricity use there are several factors included in the total energy use,  $E_p$  is the electrical energy required to pump 1 m<sup>3</sup> of groundwater.  $E_i$  is the amount of energy extracted from the subsurface and the  $COP_H$  is the coefficient of performance of the heat pump and then the electricity used by the heat pump becomes  $E_i/(COP_H - 1)$ . During the winter the full equation has been used but for the summer the end part is not needed because the cooling is done with free cooling meaning there is no use of the heat pump.

The emissions that were released before the ATES system was installed has to be known because a comparison between the emissions before and after the system installation is necessary to define the total reduction of emissions:

$$E_{i,conv} = \frac{E_i}{COP_c} \quad (7)$$

The  $E_{i,conv}$  is the total electrical energy use,  $E_i$  is the total consumption of electricity and the  $COP_c$  is the coefficient of performance for the cooling system indicating how much energy is used to drive the heat pump. For Skaraborg hospital the emissions from using district heating are used to calculate the total emissions for the winter. Concluding the relative CO<sub>2</sub> emissions the following model is used.

$$Relative\ CO_2\ emissions = 1 - \frac{C_{i,ates}}{C_{i,conv}} \quad (8)$$

The  $C_{i,ates}$  is the total emissions from the ATES system and the  $C_{i,conv}$  is the total emissions from the system previously used by the hospital that also includes district heating.

## Data

The data that is required to use in the model for efficiency includes the injection and extraction temperature for the warm and the cold wells, the time increment, and the difference in the cold injected and the warm injected groundwater. These data come from the energy compilation document and is based on a typically year of warming and cooling demand for Skaraborg hospital considering the energy demand from the hospital (Sweco, 2024). The total energy demand for heating and cooling is compiled as the total warming and cooling effect (kW) based on the outdoor temperature. The outdoor temperature data has been taken from SMHI and is for a typical year at Skaraborg hospital (Sveby, 2022). From the warming and cooling effect it is possible to define the required temperature of the water to achieve the intended indoor temperature. During the period when using the warm wells, the heat pump is needed and therefore the temperature of the water that is heating up the ventilation is added.

The data for extracted and in injected temperature in the (Eq 2) is the same as the first and the value for  $Q$  is also from that data but the extracted temperature is not known and therefore that kind of calculation is done with help of the literature. The  $c_w$  constant was taken from the same article as the model (Beernink et al., 2024). The values for the thermal radius as calculated by (eq 4) is taken from the compilation document and the  $V$  is defined as  $u_{eq} \cdot q_{max} \cdot H$ . The  $q_{max}$  is divided into two parts, the volume of the wells and the hydrological permeability ( $K$ ).  $K$  assessed from the pre-investigation document about capacity tests and test pumping measuring both the aquifer material and the water flow passing through the aquitard. The  $c_{aq}$  is the bulk volumetric capacity which demonstrate the volumetric heat capacity for the whole aquifer and that value gets from both the volumetric heat capacity if the aquifer and it is expressed as:  $c_{aq} = n_{c_w} + (1 - n)c_s$  with  $n$  as the porosity which is 20% for this sandstone aquifer and  $c_s$  is the volumetric capacity of the surrounding solid material. The  $c_s$  in this case was take from the technical description document from WSP.

The  $COP_H$  value describes how efficient the heat pump is by providing the ratio between incoming and outgoing energy passing through the heat pump. The data for the model calculating the  $CO_2$  emissions partly comes from the energy compilation document and including data with effect and pumping rate. The same  $q_{max}$  was used for the calculate of the  $CO_2$  values as for the previous volume calculations. The dimension, depth and water level for the wells were taken from technical description (Klemetz, 2018). The  $u_{eq}$  describes the equivalent number of hours when the pumping is at full load indicating how many hours the

system has a flow of  $120 \text{ l s}^{-1}$ . The data for the hours that the system is at full load is taken from the energy compilation document which presents the flow for each hours/day/year during a typical year for Skaraborg hospital.  $H$ , which is the depth of the aquifer, is the same number that has been used to calculate the depth of the well. The  $E_p$  unit was partly based on the effect required to pump  $120 \text{ l s}^{-1}$  and for the number of hours it takes to pump  $1 \text{ m}^3$  of water at that withdrawal speed. The  $COP_H$  value reflects the temperature returned from the evaporator and the temperature of the water that is forwarded to the heat pump. The total energy consumption by the heat pump is calculated as  $E_i/(COP_H-1)$  where  $E_i$  is the total energy provided by the groundwater, which can be expressed as:

$$E_i = c_w \cdot V \cdot n_{t,i} \cdot \Delta T \quad (9)$$

With  $c_w$  at  $4.18 \times 10^6 \text{ J m}^{-3} \text{ }^\circ\text{C}^{-1}$  as a constant, the  $V$  is expressed as  $u_{eq} \cdot q_{max} \cdot H$ . The  $n_{t,i}$  is from the efficiency model and the  $\Delta T$  is the difference between the warm and the cold extracted temperatures. The same data is used as to calculate the thermal efficiency. The total electrical power that is required is taken from the (eq 4) and the  $C_{elec}$  is taken from Hallen (2018) and the type of electricity they use generates  $5 \text{ kg CO}_2 \text{ MWh}^{-1}$ . The amount of  $\text{CO}_2$  that the district heating system generates is also from the report geo energy and district heating (Hallen, 2018). Skaraborg hospital used district heating during the cold months and that type of heating system corresponds to  $65 \text{ kg CO}_2 \text{ kg MWh}^{-1}$ . During the summertime, cooling machines were used before installing the ATEs system and to determine how much electricity they needed to fulfil the total cooling demand for the building during the summer the value for the total energy demand for summer was used along with the  $COP_C$  values for the cooling machines. The  $COP_c$  was taken from previous studies (Sommer et al., 2015). The relative  $\text{CO}_2$  emission reduction is then given by (eq 5) which shows the reduction in percent. The data used for this calculation includes  $C_{i,ates}$  and  $C_{iconv}$  which are the emissions in  $\text{kg CO}_2 \text{ MWh}^{-1}$  from the ATEs system and the system used before respectively.

Table 1. Description of the used variables and what values that are present in the equations.

Abbreviation (unit)	Description	Values
$n_{t,i}$	Thermal efficiency	0.7, 0.75, 0.78, 0.8, 0.85, 0.9
$T_{\text{extracted}}, T_{\text{injected}}$	Temperature of the extracted and injected groundwater (monthly)	
$\Delta T$	Difference in extracted temperature during summer, winter ( $^{\circ}\text{C}$ )	6
$\Delta t$	Durational mode (month)	5 and 7
$T_{\text{amb}}$	Temperature of the ambient ground water	7.5
$Q_{\text{extracted}}, Q_{\text{injected}}$	Pumping rate ( $\text{m}^3/\text{day}$ )	1050-7050
$c_w$	Volumetric heat capacity for water ( $\text{J m}^{-3} \text{ }^{\circ}\text{C}^{-1}$ )	4.18
$c_s$	Volumetric heat capacity sandstone ( $\text{J m}^{-3} \text{ }^{\circ}\text{C}^{-1}$ )	0.7
$c_{\text{aq}}$	Volumetric heat capacity aquifer ( $\text{J m}^{-3} \text{ }^{\circ}\text{C}^{-1}$ )	1.16
$dt$	Time increment (monthly)	1
$f_{\text{loss}}$	Fraction loss %	10-30
$E_{i,\text{ATES}}, E_{i,\text{CONV}}$	Obtained energy kWh	7000 summer, 14000 winter
$C_{\text{elec}}$	Electricity production emissions ( $\text{kg CO}_2 \text{ MWh}^{-1}$ )	0.5
$q_{\text{max}}$	Maximum pumping rate ( $\text{m}^3 \text{ m}^{-1} \text{ h}^{-1}$ )	5.32
$u_{\text{eq}}$	Equivalent full load hours per season	3771, 2307
$L$	Aquifer thickness (m)	30
$E_p$	The electrical energy needed to pump $1 \text{ m}^3$ of groundwater ( $\text{kWh m}^{-3}$ )	0.00257
$E_i$	Obtained energy (MWh)	4450-5340
$\text{COP}_H \text{ COP}_C$	Coefficient of performance for heat pump	4
$\text{COP}_c$	Coefficient of performance for cooling	3.5
$V$	Volume of the aquifer, $\text{m}^3$	$3.7 \times 10^5$ summer, $6 \times 10^5$ winter

## Analysis

Information from articles, reports, previous studies and interviews has been compiled and interpreted to find both similarities and differences. The meaningful units have then been extracted to highlight the most essential information. For the quantitative part the data has

been used to calculate both the efficiency and when having that value the emissions could be calculated. The results from the chosen equations (1-9) have been analyzed and compared to other studies that used similar models and analyses. There were some limitations due to the predicted data and energy losses. The actual system has not been in operation yet so there is some uncertainty about how the real data will affect the assessment both in terms of efficiency and the emissions. Sweco had developed three different scenarios that was used to see how it would affect the efficiency and CO<sub>2</sub> emission, but there were no values for the extracted energy and flow. Therefore, already made analysis occurring efficiency was used. Then the actual efficiency could be analysed but instead with reversed use of the (eq 2) it was possible to get an anticipated extracted energy and CO<sub>2</sub> emissions. These results were analysed together with earlier studies on different parts of thermal losses to gain an overview of how a possible case could be for the ATES system at Skaraborg hospital in Skövde. How the distribution between dispersion, conduction and convection was analysed with help of earlier studies and the ATES system at Skaraborg hospital was implemented (Beernink et al., 2024). The discussion and analysis were then ending in a conclusion for how to manage the system and optimising the drift.

## Result

### Thermal efficiency

The effectiveness of the ATES system is important to understand because it informs how much energy it generates and how much energy the water could hold. The hospital wanted a model to be able to monitor how effective the system is and have control over its operation. Equation 1 has been developed by Sommer (2015) and it measures the efficiency of an ATES system while taking into account the injection and extraction temperature, the length of the withdrawal season and the difference in injection temperature in the summer and winter seasons.

The required data is available from the hospital and makes possible future monitoring by the hospital (Sweco, 2024). With help from the equation it is possible to make predictions and use the efficiency to measure how much CO<sub>2</sub> emissions it will save. This equation does not consider the flow rate of the water and how the demand can affect the temperature outcomes in the wells. Equation 2 takes this into account and it is from new study by Beernink et al.

(2024) which concludes using the injected, extracted and the ambient flow and the velocity of the flow.

By applying different scenarios for the hospital's cooling and heating demand depending on the outdoor temperature it is possible to assess the flowrate ( $Q$ ) extraction and injection which allows for the use of this equation for efficiency. They have also concluded the possible energy losses for different types of ATEs system. For a system in the specific size and well temperature Skaraborg hospital falls into the category where energy losses are projected to be 20-25 % in the first year and 10-15% after five years.

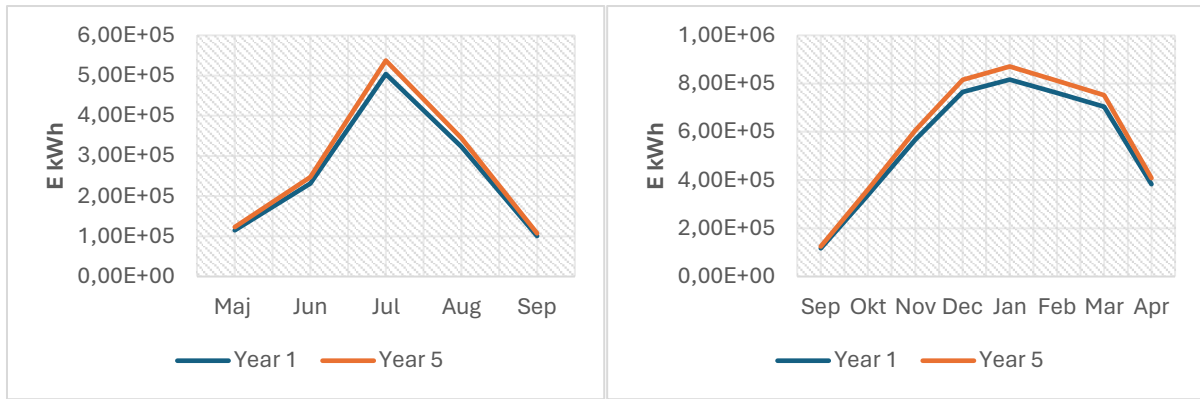
Using (eq 2) and incorporating it into (eq 3) for fraction loss they could do their own follow ups for the fraction loss.

## Energy use and pumping rate

The predictions of extracted energy ( $E$ ) and pumping rate ( $Q$ ) based on calculations of injected water ( $m^3$ ) and energy (MWh) by Sweco has been categorized into three different scenarios which is referred to as scenario 1, 2, and 3. These three scenarios is based on different variation in both injected energy into the wells and the injected groundwater. In scenario 1 the total amount of injected energy is 6383 MWh, scenario 2 is 3933 MWh and scenario 3 is 1770 MWh. The total amount of injected cold water for scenario 1 is  $1.3 \times 10^6 m^3$ , scenario 2 it is 850 000  $m^3$  and for scenario 3 it is 385 071  $m^3$ . Sweco have only predicted the variation for the warm wells which assumed for the cold wells has monthly  $V$  and  $E$  that remains the same based on the total injected volume 508 571  $m^3$  and energy 1745 MWh. Within the scenarios there are different predictions included of efficiency assessed from Beernink et al., (2024). There are also comparisons between year 1 and 5. In scenario 1 the cold wells are also included but they are only shown once because there is only one scenario for them. Each scenario and efficiency scenario are divided into two groups, one with the x-axis showing the  $E$  and the other group  $E$  per extracted amount of water ( $V_{extracted}$ ).

### Scenario 1

Figure 4-6 illustrate the variation in extracted energy for the cold wells between May and September and the warm wells between September and April for three different assumptions of efficiency. It is divided into two different assumptions of efficiency for year 1 and 5. Year 5 has bit higher  $E$  but the difference between the year is not that big.

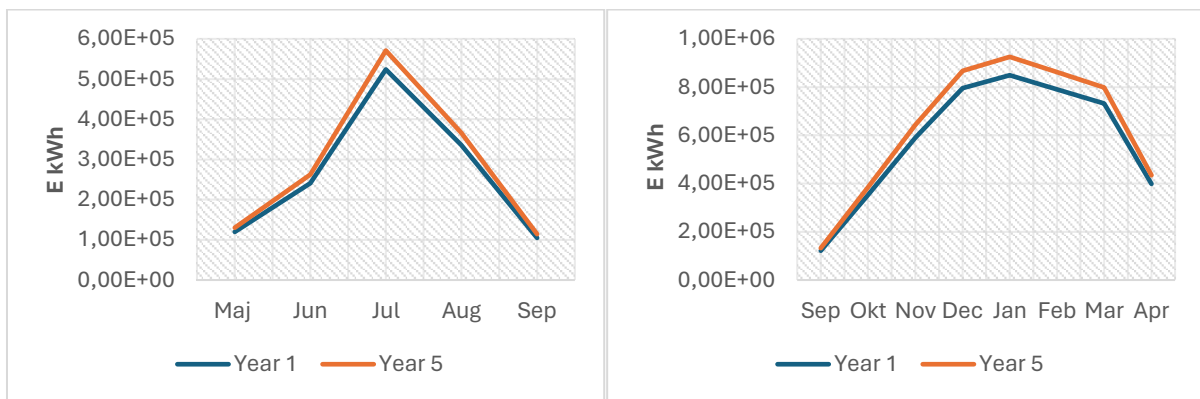


a.

b.

Figure 4. Variation in  $E_{\text{extracted}}$  with the efficiency is 0.75 for year 1 and 0.8 for year 5. The cold wells operate May to September (a) and warm wells September to April (b).

Figure 4 shows similarly how the energy demand peaks at the middle of the season and the beginning and end of the season remains similar. For the cold wells the peak is in July with 0.51 GWh year 1 and 0.5 GWh year 5. The warm wells had higher peaks in December and January at 0.78 and 0.82 GWh respectively for year 1 and 0,82 and 0,87 GWh for year 5. The end of the warm seasons has same values as the cold but for the warm season there was a higher value for April with 0.38 and 0.41 GWh, respectively.

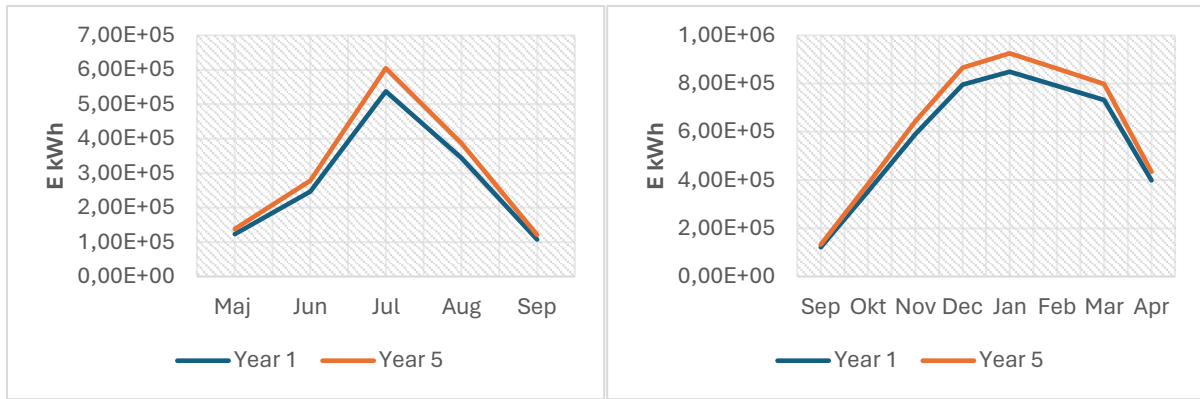


a.

b.

Figure 5. Variation in  $E_{\text{extracted}}$  with the efficiency is 0.78 for year 1 and 0.85 for year 5. The cold wells operate May to September (a) and warm wells September to April (b).

As for the Figure 3 and 5 also peaked in July and January with similarly values at 0.52 and 0.85 GWh in for the cold and warm season respectively.



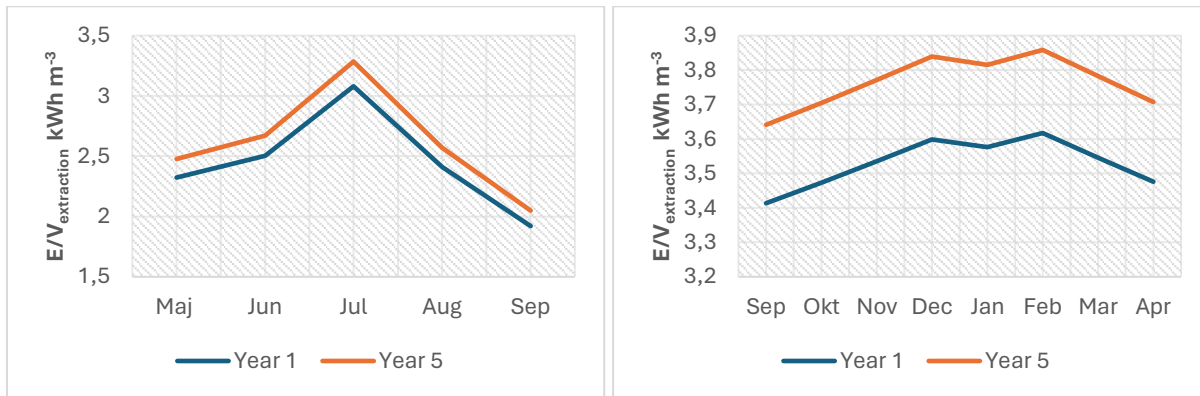
a.

b.

Figure 6. Variation in  $E_{\text{extracted}}$  with the efficiency is 0.8 for year 1 and 0.9 for year 5. The cold wells operate May to September (a) and warm wells September to April (b).

The difference between year 1 and year 5 becomes larger with higher assumed efficiency. It also depends on the flow, initially and at the end of the cooling and warming seasons the difference is smaller but becomes larger with a higher energy demand and flow as is the case for the month in the middle. With higher energy demand and flow the difference between year 1 and 5 increases. The results are based on an ideal situation, showing the same efficiency throughout cooling and warming seasons which means that it always will be the same percentage difference between year 1 and 5.

In Figure 7-9 the y represents the  $E/V_{\text{extraction}}$  for each assumed efficiency.



a.

b.

Figure 7. Variation in  $E_{\text{extracted}}/V_{\text{extracted}}$  with the efficiency is 0.75 for year 1 and 0.8 for year 5. The cold wells operate May to September (a) and warm wells September to April (b).

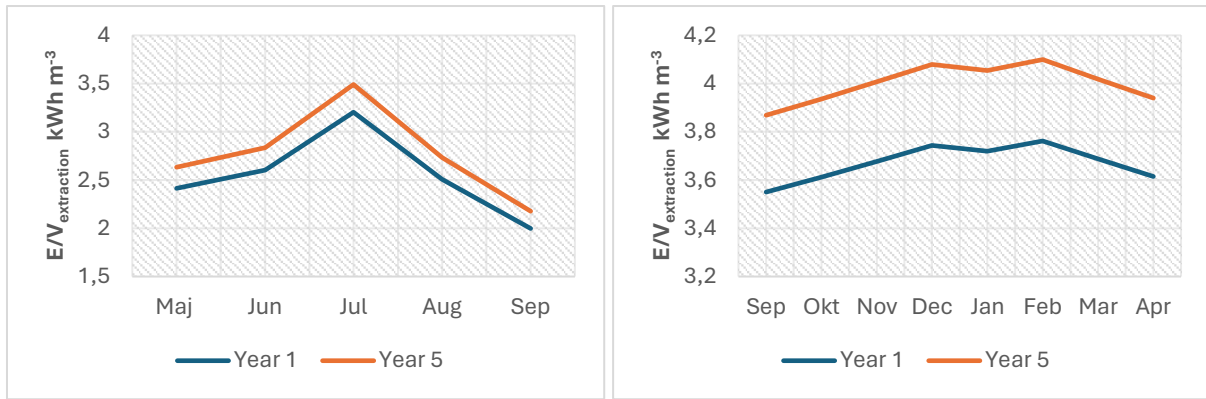


Figure 8. Variation in  $E_{\text{extracted}}/V_{\text{extracted}}$  with the efficiency is 0.78 for year 1 and 0.85 for year 5. The cold wells operate May to September (a) and warm wells September April (b).

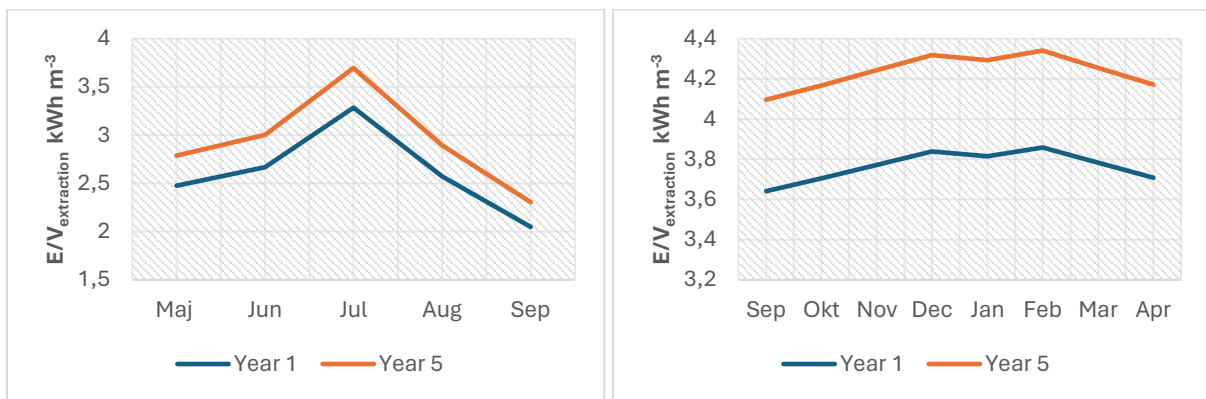


Figure 9. Variation in  $E_{\text{extracted}}/V_{\text{extracted}}$  with the efficiency is 0.8 for year 1 and 0.9 for year 5. The cold wells operate May to September (a) and warm wells September to April (b).

The variation within the warming and cooling seasons presented in Figures 7-9, both for year 1 and 5, is smaller compared to Figures 3-5 which show the total energy extracted. The total difference between year 1 and 5 gets slightly larger for each efficiency, from 6% for Figure 6, 8.2% for Figure 7 and for Figure 8 1.1%. The peak is the same for the summer with the highest  $E/V_{\text{extracted}}$  in Juli with 2,7 MWh<sup>2</sup> m<sup>-3</sup>. The variations in  $E/V_{\text{extracted}}$  is more consistent throughout the seasons because there are similar amount of energy per m<sup>3</sup> compared to the amount of total extracted water. The highest in February with 3.75-3.82 MWh m<sup>3</sup> for year 1 and 3.85-4.3 MWh m<sup>3</sup> kWh for year 5.

## Scenario 2

In scenario 2 the warm wells have different values for the  $E_{\text{extracted}}$  and  $V_{\text{extracted}}$ .

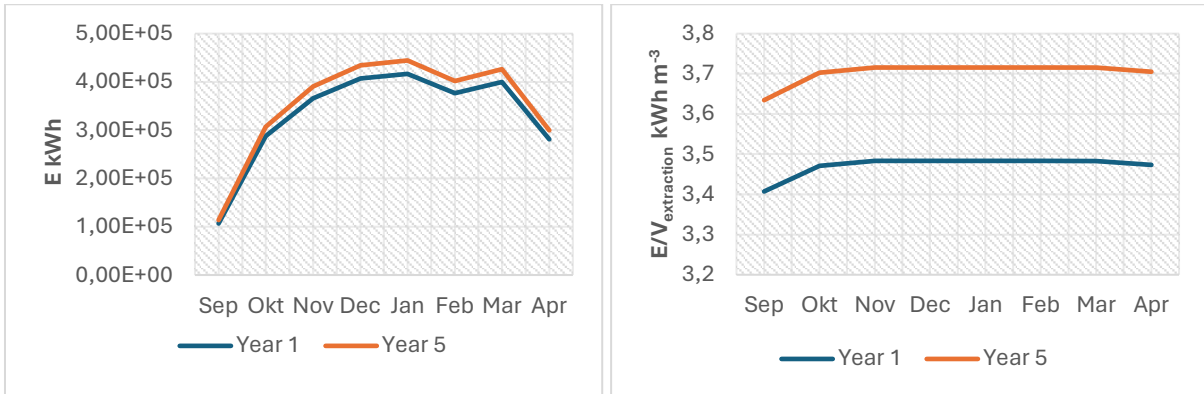


Figure 10. Efficiency is 0.75 for year 1 and 0.8 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy and amount water.

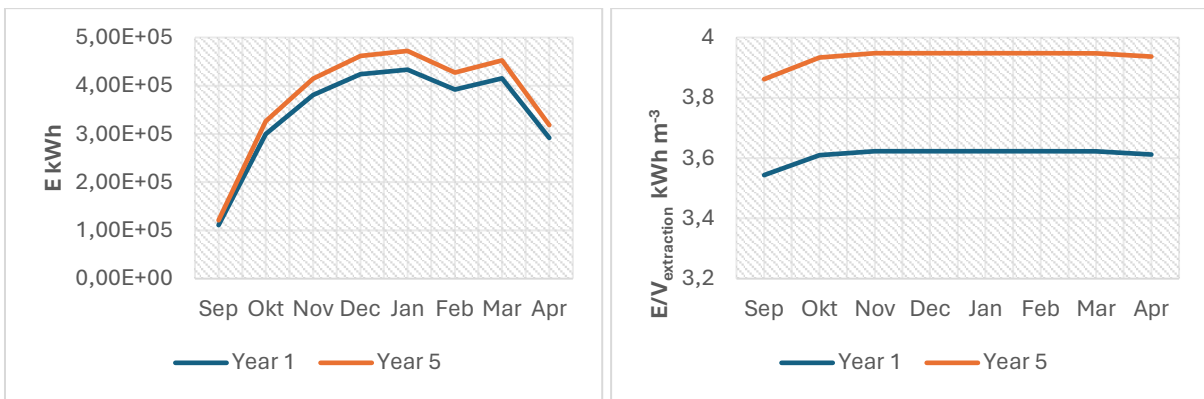


Figure 11. Efficiency is 0.78 for year 1 and 0.85 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy to the amount water.

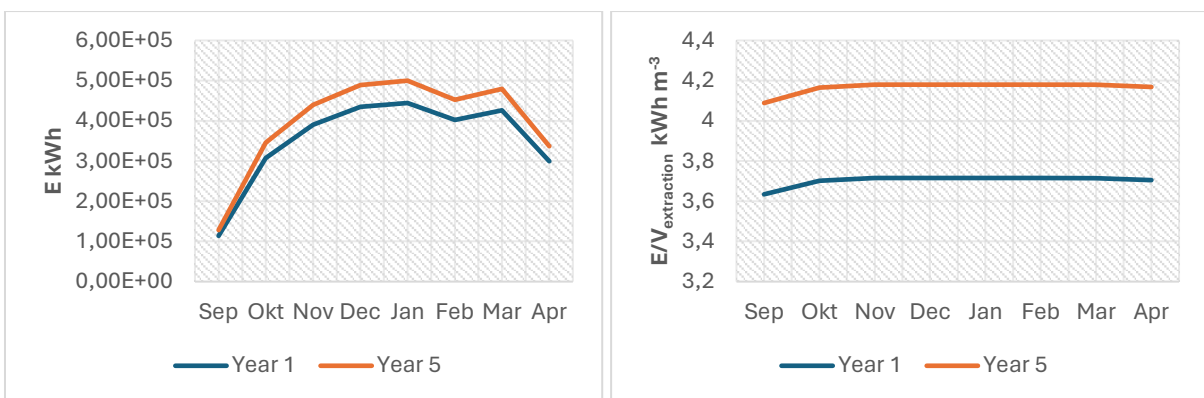


Figure 12. Efficiency is 0,8 for year 1 and 0,9 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy to the amount of water.

Figure 9a, 10a and 11a that that measures the extracted energy shows smaller gap between year 1 and 5 with smaller amount of extracted energy and higher gap between the years with higher amount of extracted energy. For the 9b, 10b and 11b the difference between year 1 and

two remains the same throughout the period, and it only depends on the amount of extracted energy per extracted volume of water and the percentage increase is the same as for figure 6, 7 and 8. The peak for the E is in January with 0.42-0.44 GWh for year 1 and 0.44-0.5 GWh in year 2. The  $E/V_{extracted}$  had the peak is between November and February with values between 3.5-3.7  $MWh\ m^{-3}$  for year 1 and 3.7- 4.2  $MWh\ m^{-3}$  for year 5.

### Scenario 3

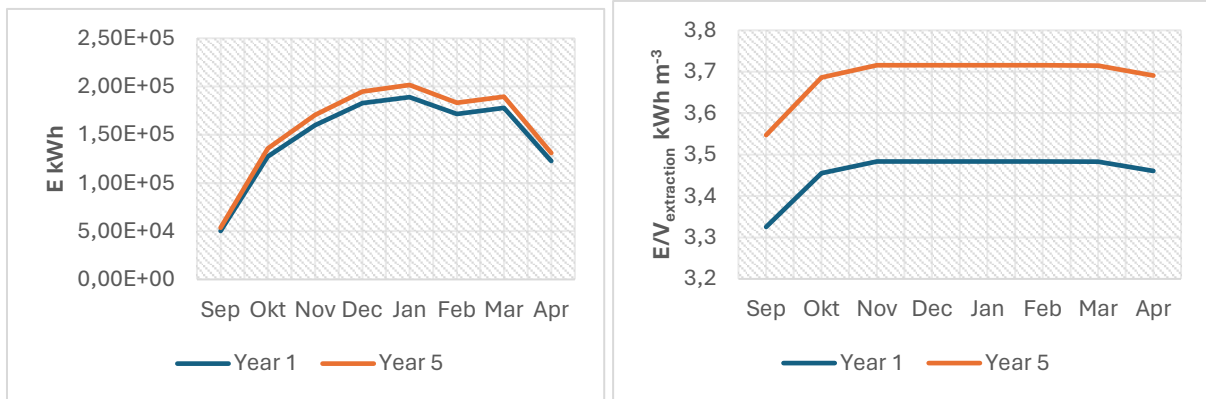


Figure 13. Efficiency is 0.75 for year 1 and 0.8 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy to the amount of water.

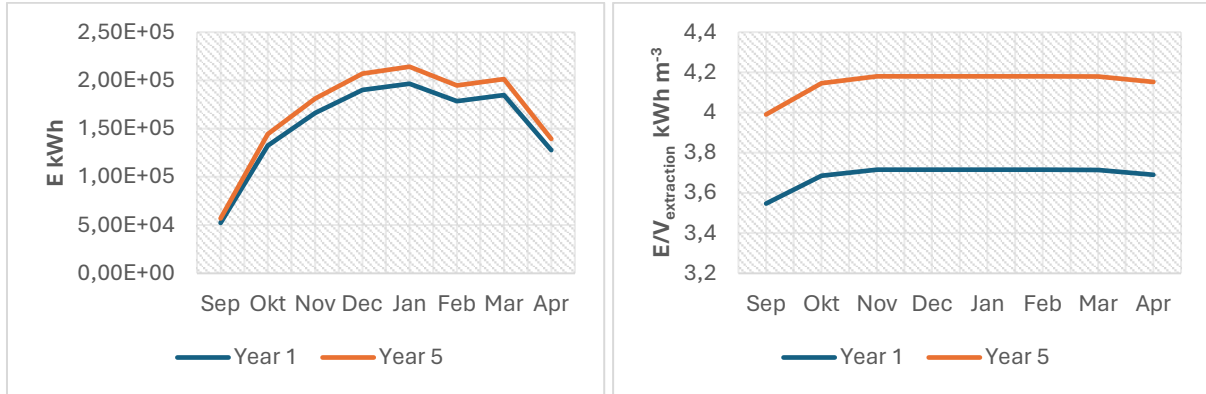


Figure 14. Efficiency is 0.78 for year 1 and 0.85 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy to the amount of water.

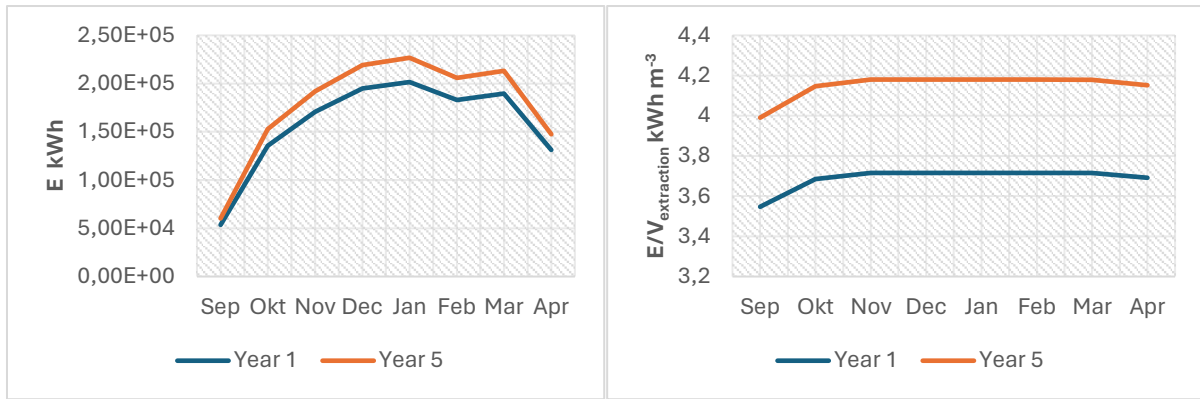


Figure 15. Efficiency is 0.8 for year 1 and 0.9 for year 5, with (a) representing the variation in extracted energy and (b) representing the ratio of extracted energy to the amount of water.

The third scenario has smaller variation in flowrate compared to scenario 1 and 2 and has a much smaller extracted energy during September compared to the other and a lower energy coming from water. There is a larger difference between the start of the season to the end compared to the other scenarios. The peak for  $E$  is in Januari with values between 0.19-0.22 GWh for year 1 and 0.2-0.23 GWh for year 5. For  $E/V_{\text{extracted}}$  the peak is similar to scenario 1 and 2 with higher values for November to Mars.

## Fraction loss

The fraction loss is divided into three different group, dispersion, conduction and buoyancy driven flow. To estimate how much of the total loss is due to the different groups, there is a need to know how the thermal radius of the ATES system at Skaraborg hospital in Skövde. The total  $R_{th}$  for the system calculated by using (eq 4).

Tabel 2. The variables needed for describe conduction, dispersion and buoyancy driven flow.

Variables	Unit	Value
$R_{th}$	m	96, 22
$L/R_{th}$	-	0.3, 1.3
$A/V$	-	0.08, 0.18

From the thermal radius it is possible to get the relative area of the aquifer compared to the aquitard surface describe as  $L/R_{th}$ . The  $L/R_{th}$  for the aquifer is 0.3 and the  $A/V$  as expresses as  $2/L + 2/R_{th}$  is 0.08. When divided the  $u_{eq}$  for the number of existing wells in the aquifer and not the total volume of the whole aquifer the values differ. The thermal radius becomes lower at 22 m, the  $L/R_{th}$  1.3 and the  $A/V$  0.18.

# CO<sub>2</sub> emissions

The total emissions from the ATEs system were calculated using (eq 5,6,7,8) and their results were combined. The predicted efficiency from previous studies was used to assess how it affected the outcomes for the CO<sub>2</sub> emissions (Beernink et al., 2024). First the data for cooling was used to determine the potential free cooling available and the fluctuations depending on the differences in efficiency and presented in Figure 16.

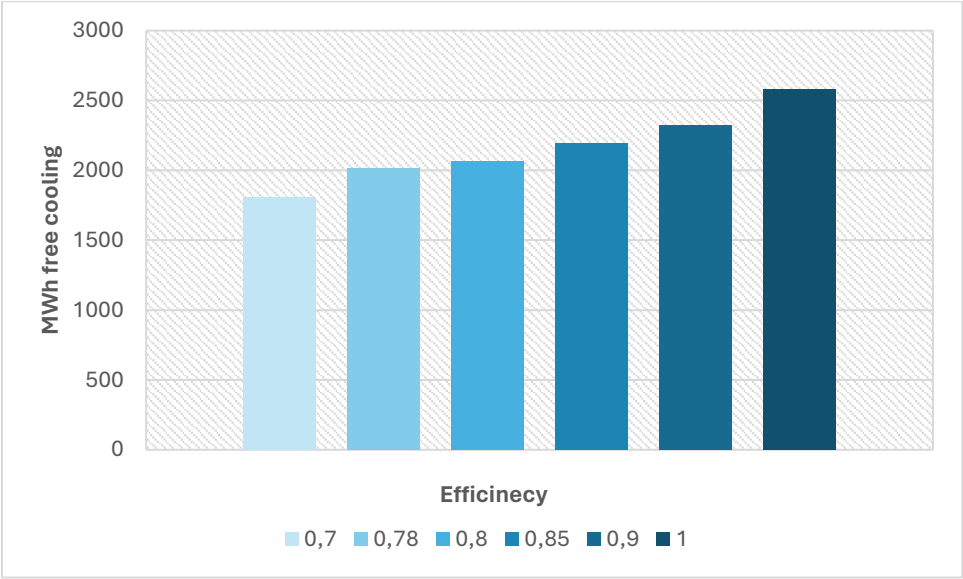


Figure 16: Free cooling (MWh) from the ATEs at Skaraborg Hospital at different efficiency outcomes.

Free cooling refers to cooling achieved without the need for heating or cooling pump. It varies with the efficiency of the of the system. If there were no fraction loss at all, the scenario with efficiency 1 would be the case and then the amount of available free cooling would be 2579 MWh. The other efficiencies are used because they may represent reasonable scenarios based on earlier studies (Beernink et al., 2024). The best-case scenario is the one with the highest efficiency which is 0.9 and it generates the most energy at 2321 MWh. The scenario with lowest efficiency of 0.7 has the lowest amount available energy at 1805 MWh. The emission for the free cooling remains the same for all scenarios because the same amount of water is pumped. While having lower free cooling available at the lower efficiency there is also a higher demand for other sources of cooling from cooling machines, leading to higher emissions.

In figure 17, the amount of CO<sub>2</sub> emissions was calculated by using (eq 8) with the efficiency ranging from 0.7-0.9, with number 1 presenting the perfect scenario with no fraction loss. The emissions from conventional system comes from cooling machines while the emissions

representing the ATES system includes the ATES system energy use in pumping ground water with additional use of cooling machine because free cooling alone does not cover the hospitals demand.

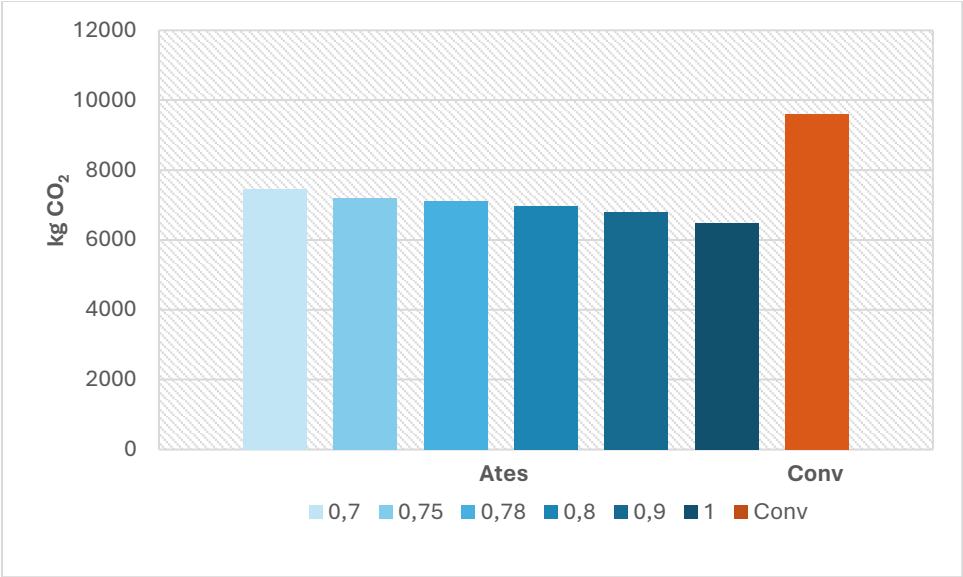


Figure 17: Emissions realised by the system during summer depending on different efficiency of the system and the emissions from the conventional system with the same energy demand.

The cooling part of the ATES system has the same amount of extracted water throughout the different scenarios and therefore it has the same electrical energy need for pumping the water. In these scenarios the ATES system realizes the highest emissions for the lowest efficiency with 0.7 resulting in 7447 kg CO<sub>2</sub> MWh<sup>-1</sup> and 0.9 resulting in 6802 CO<sub>2</sub> MWh<sup>-1</sup>. The emission for the conventional system is highest at 9609 CO<sub>2</sub> MWh<sup>-1</sup>.

During the winter the district heating is used instead of the cooling machines and is the only source of heat for the conventional system. The total warming required by the hospital is 14000 MWh and depending on the efficiency of the ATES system, different amounts of energy will be available from the ATES system. The remaining amount of energy required to meet the demand of the hospital is obtained from district heating. Figure 18 shows how much CO<sub>2</sub> MWh<sup>-1</sup> the ATES system and the conventional system realises.

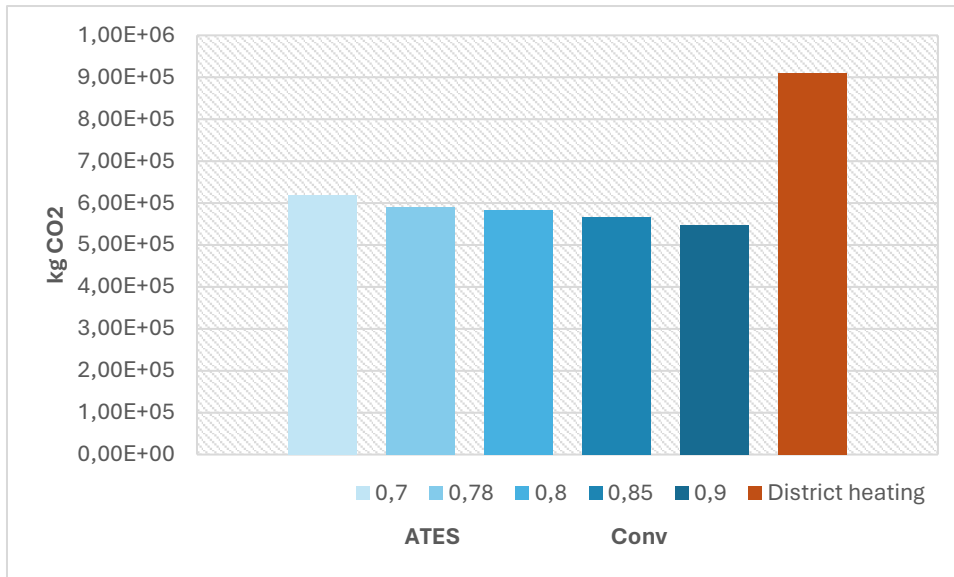


Figure 18: Emissions realised by the ATES system for 5 different scenarios with different efficiency and the emissions from the Conv consisting of district heating.

The conventional part had the largest amount of CO<sub>2</sub> emissions at 9.1 kg CO<sub>2</sub> MWh<sup>-1</sup> and the lowest at 5.8 CO<sub>2</sub> kg MWh<sup>-1</sup>. The variation in ATES system depends on the efficiency, ranging between 5.5 and 6.2 kg CO<sub>2</sub> MWh<sup>-1</sup>. The higher the rate of energy needed from the district heating, the higher is the CO<sub>2</sub> emissions.

The first part of the (eq 5) has been used to obtain the emissions for the free cooling part while the rest represents the emissions for the cooling machines for which (eq 6) has been used. To calculate the total reduction emissions for the cooling part the (eq 7) has been used.

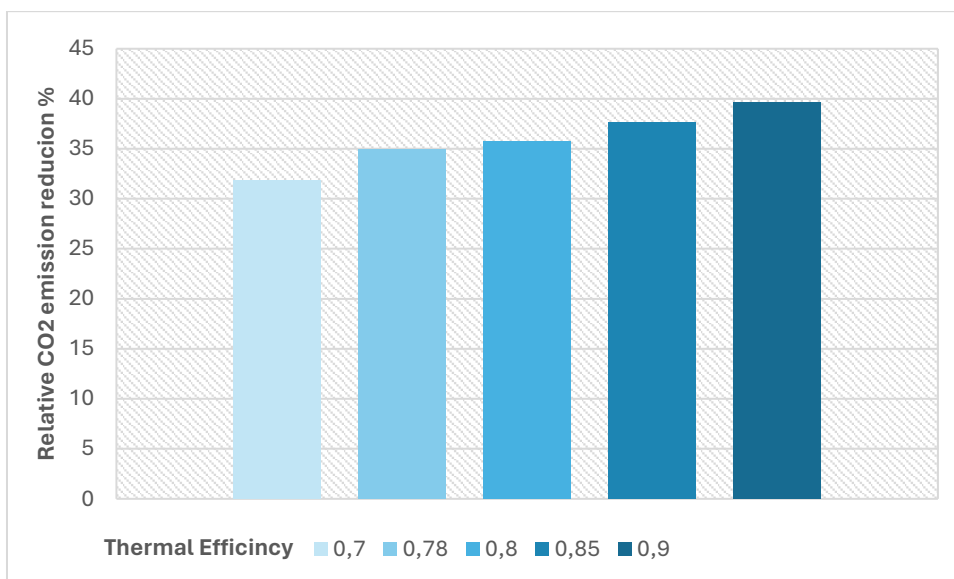


Figure 19: The relative CO<sub>2</sub> emissions reduction for each thermal efficiency scenario.

The reduction of CO<sub>2</sub> emissions increases with higher system efficiency, both for cooling and heating although emissions from heating were dominating. The proportion between the use of the ATES system and the additional cooling or heating is uneven and with electric power use of the ATES system contributing only a small part of the total emissions. This contribution is even smaller for the heating because of the higher amount of emission from district heating. The emission from the system becomes negligible and the efficiency that determine the amount of added cooling or heating becomes important. When the highest efficiency of 0.9 is used the relative CO<sub>2</sub> emissions are 40% and the lowest for 0.7 is 31%. For an ATES system of the same size as Skaraborg hospital the scenario for the first years could be as those presented in Figure 19, with a smaller reduction initially and then increasing until 5 years after the start when they stabilize for the lifetime of the system (Beernink et al., 2024).

## Discussion

### Thermal efficiency

The most crucial parameter for the ATES system is the thermal efficiency and the thermal efficiency recovery. It shows how the temperature of the extracted water in relation to the injected water and how much of the injected energy that has recovered when it gets extracted. If there would be a perfect scenario with the efficiency 1 there would be no difference between  $T_{warm\ injection} - T_{cold\ injection}$  and the  $T_{extracted} - T_{injected}$ . Equation 1 can be used by Skaraborg hospital to get information about the thermal efficiency when it comes to documentation (Sommer et al., 2015). While the system is in operation it could be a better alternative to use the (eq 2) because it also takes into account the ambient ground water flow considering both temperature and flowrate. That could be used to monitor the system and regulate out- and inflow before the direct thermal recovery get affected. Identifying areas with a significantly higher energy demand while considering the capacity of the aquifer volume is important. The hospital should therefore with help of (eq 2) and regular measurements to optimize energy savings. Bloemdahl et al. (2018) shows that the efficiency of the ATES system is notably impacted by the presence of elevated ambient groundwater flow. The wells within the ATES system will get affected differently due to the location of the well. If the location is more upstream they are going to have more losses because of the ambient ground water flow. (Bloemdahl et al., 2018) The placement of wells should therefore be strategically placed in alignment with the flow direction to optimize the efficiency. This will increase the

heat infiltration upstream and enhance heat extraction downstream and mitigate losses associated with groundwater flow (Groot, 2013).

## Energy use and pumping rate

The data used obtained from Sweco according to pumping rate had some limitations because of the absence of variation in the summer season. The variation has been divided into three scenarios with difference in energy extraction ( $E$ ) and extracted volume of water ( $V_{extracted}$ ) for the use of warm wells in the winter. These variations as shown in Figures 3-16 are divided into these three scenarios but also in total extracted energy (MWh) and extracted energy in relation to the extracted water volume ( $\text{MWh m}^{-3}$ ) while showing difference in efficiency for the first year of using the system and the 5<sup>th</sup> year. Showing the results for both  $E$  and  $E/V_{extracted}$  was necessary determine not only the total amount of extracted energy that the system can provide overall, but also to observe the variation in energy per  $\text{m}^3$ . With that insight it is possible to assess how much energy comes from each  $\text{m}^3$  which would provide more information about the actual amount of energy per volume of water. While the extracted energy shows the total  $E$  it does not provide the information about any increase in  $V_{extracted}$ . For the scenario 1 it was clear that with higher efficiency the available energy to extract increase from 4452 to 4784 MWh for year 1 and 4749-5342 MWh for year 5. The  $E/V_{extracted}$  ranges from 3.4-4.2  $\text{MWh m}^{-3}$ .

For scenario 2,  $E$  is slightly lower than scenario 1 ranging from 2641-2817 MWh for year one and 2817-3117 MWh for year 5. The  $E/V_{extracted}$  is also a bit lower here ranging 3.4-3.7  $\text{MWh m}^{-3}$  for year 1 and from 3.6-4.2  $\text{MWh m}^{-3}$  for year 5. Scenario 3 has the lowest amount of extracted energy, with 1181-1259 MWh for year 1 and 1259 to 1417 MWh for year 5. The  $E/V_{extracted}$  for year 1 ranges from 3.3– 3.7  $\text{MWh m}^{-3}$  and for year 5 it ranges from 3.5-4.2  $\text{MWh m}^{-3}$ . The reason for the difference in the amount of available energy there is to use in the different scenarios could be variations in weather and the previous season, resulting in changes in the amount of absorbed heat injected into the system.

According to earlier studies by Bloemdahl et al. (2018) it is more rational to consider different scenarios than to assume equal infiltration and extraction volume for every season because that does not reflect how it would look in practice. Assumption of different scenarios is crucial to get the knowledge how the system will perform. The reason way there are differences in extracted and injected energy, according to Bloemdahl et al. (2018), is because

of variations in energy demand of the buildings and the seasonal fluctuations. These factors can lead to temporal imbalance in the system, such as the one observed in scenario 3. A possible example could be that cold summers with lower energy demand followed by a cold winter with higher energy demand can deplete the warm wells. Bloemdahl et al. (2018) illustrates this difference between the assumed constant storage volume and the actual weather dependent storage in following figure:

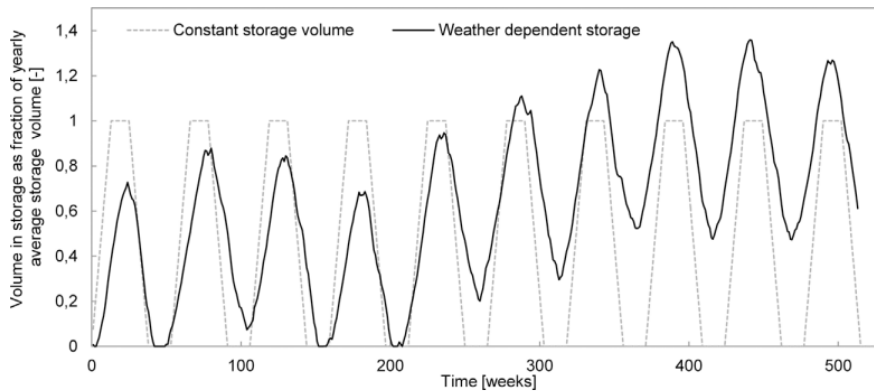


Figure 20: Illustration of the assumed fraction of yearly average storage volume and (broken lines) and the weather dependent fraction of yearly average storage volume (solid line) (Bloemdahl et al. 2018).

Comparisons between the scenarios already include the efficiency and therefore make it easier to observe how the system is affected within scenarios with the same efficiency. Therefore it does not depend on fraction loss and it is more a question of above surface factors such as temperature and system operation. However, it is clear that over time the system would be more resistant to variation in demand (during extreme weather events) because of the adapted temperatures in the surrounding aquitard.

## Fraction loss

There is a strong relationship between the area and the volume of the aquifer due to the conduction loss which dominates in low temperature aquifer storage (Beernik et al., 2024). When the  $L/R_{th}$  decreases with a larger aquifer volume, earlier study has shown that conduction loss increases while dispersion decreasing (Beernik et al., 2024). Skaraborg Hospital in Skövde is beneficial when it comes to limiting dispersion loss because of the large size of the aquifer with an  $L/R_{th}$  of 0.3. But because of the high number of wells included in Skaraborg Hospital there could be some uncertainties about whether that method could be applied. The uncertainties are based on the fact that each well does not cover the same amount of injected water  $m^3$  as the equation for the  $V$  assume. Therefore the thermal radius that envelops the wells is calculated as if the total volume of the aquifer would go into each well,

or on the other hand just be injected in one well. It would be more reasonable if the stored heat were divided among the number of wells because all injected heat does not spread from one well, there should be interaction between the wells. According to earlier studies is it not clear if they divided the equal number of hours depending on the number of wells, but if that method with divided equivalent hour applies to Skaraborg hospital in Skövde, the  $R_{th}$  is 22 m. One other factor that could affect the result of the  $R_{th}$  is that the rate of submersion differs among the wells, which is also something that has not been taken to account in earlier studies. Previous research has only examined how the permeability affects the difference in fraction loss between the aquifers but not between the well within the aquifer (Bloemendal et al 2018; Beernink et al 2024).

The decrease in dispersion at a low  $L/R_{th}$  results from the relative area at thermal front where the dispersion occurs becoming smaller. This area includes both the surface area into the aquifer and the surface area into the aquitard. Dispersion comes in two types: thermal and the mechanical. The mechanical dispersion has shown by earlier studies to increase with increasing  $R_{th}$  and that occurs when the thermal radius ranging between 50-150 m (Sheldon et al., 2021). The ATES system at Skaraborg hospital falls within the range with an  $R_{th}$  at 96, so there is a risk for increasing dispersion loss. But when using the second  $R_{th}$  it does not fall within that range. This risk only occurs during extraction when there is an advective flow when operating the specific warm or cold wells. The loss from the mechanical dispersion appears only in waterflow directed into the aquifer at the thermal front. Larger radius will result in larger circumference and that in turn increases the thermal front and in dispersion. During the rest of the year when the system is not actively extracting, there is no mechanical dispersion while the other side is operation. With  $L/R_{th}$  below 2 which is the case for the aquifer at Skaraborg hospital, there was an increase in conduction losses. This increase in conduction loss is associated with a decreasing ratio of  $A/V$ . Skaraborg hospital has a low value for  $A/V$  at 0.08 and 0.17. But with the  $L/R_{th}$  under 0.5, which is the case for this ATES, the total thermal loss increases even though overall dispersion decreases and the conduction increases. The reason for this is that the increase in conduction loss is higher than the decrease in dispersion loss. The loss for the buoyancy driven flow i.e., natural convection, is larger with a larger value for the  $L/R_{th}$  which comes with a smaller aquifer and also increases with higher temperature and hydraulic conduction. When the  $L/R_{th}$  is lower, the thermal front tilts at considerable distance from the injection well which entails the impact from a strong buoyancy driven flow.

The tilting angle is not static due to changes in the width of the thermal front zone which also expands throughout the year. This means that it could be difficult to know the exact impact of the tilting angle. Beernink et al. (2015) demonstrated that for a system with an  $R_{th}$  of 0.3, variations in tilting angle between  $10^{\circ}$ - $70^{\circ}$  does not affect the fraction loss of natural convection because the thermal front remains at considerable distance from the well screen. But with the  $R_{th}$  of 1.3 the proportions look a bit different and the tilting range affects in higher extent with higher risk for buoyancy driven flow. The changes in thermal front throughout the year is a consequence of the conduction and dispersion, which in turn changes because of the advective movement from the well during injection and extraction. Even for aquifers with temperatures above  $60^{\circ}\text{C}$  the effects of loss depending on the natural convection could be relatively small but there may also be cases with up to 80% of the total loss.

In conclusion the size of the ATEs system at Skaraborg hospital is beneficial regarding dispersion but not when it comes to conduction for either of the two cases. Understanding the underground hydrogeological and thermal conduction could be challenging before the system has been in operation. Natural convection could vary throughout the seasons partly depending on the thermal front and the advective movement which increase with extraction. Therefore the operation of the system has a big role in how the outcomes of different fraction loss components are distributed, whether looking from the scenario with smaller or larger  $R_{th}$ . It could be beneficial to know the maximum of mechanical dispersion that will set the limit for when it is more useful to use the district heat instead. Regular temperature monitoring is essential to provide an overview of the temperature conditions within the aquifer, both in the thermal and hydraulic area. The temperature measurements can therefore prevent unnecessary losses due to mechanical dispersion and convection which only become apparent during system operation.

## CO<sub>2</sub> emissions

The evaluation of how much the ATEs system reduces CO<sub>2</sub> emissions compared to conventional heating and cooling methods, such as district heating and mechanical cooling machines has been predicted with some uncertainties and limitations. There is no exact efficiency measure for Skaraborg hospital because (eq 1) requires data on the extracted temperature and that data was not available in this case (Sommer et al., 2015). Without the extracted temperature is it impossible to determine the systems efficiency due to the lack of temperature variation. Then the variation in CO<sub>2</sub> emissions is not possible to quantify because

of its sensitivity to temperature differences between the warm and the cold wells. The efficiency has instead been predicted using earlier studies by Beernink et al., (2024). This has been used for the calculating the pumping rate which in turn depends on different rates of fraction loss over the system of that specific size. The difference in CO<sub>2</sub> emissions between the ATES system and the conventional system is more significant for heating (Figure 17) than for cooling (Figure 18). The reason for this is that the district heating has higher emission of kg CO<sub>2</sub> MWh<sup>-1</sup>, 65 compared to electrical energy that is only 5. The use of value 5 kg CO<sub>2</sub> MWh<sup>-1</sup> could be seen as relatively low value, normally the use of Swedish electric mix is 90 kg CO<sub>2</sub> MWh<sup>-1</sup>(SMED). Secondly, the amount of equivalent full load hours is higher for winter compared to summer with 3771 and 2307 hours, respectively and it also has a higher energy demand in total. That could make a decisive difference because with a smaller rate between equivalent full load hours and the total energy demand the external sources requirements of the total use of the ATES system decreases which in turn leads to smaller amount of district heating or cooling machines. According to Sommer et al. (2015) who have examined different ATES system in The Netherlands, a usage of 2000 equivalent full load hours is an intensive use. Therefore the already high demand for Skaraborg hospital would be classified as an intensive use. The total energy demand for the hospital is also decisive because with larger energy demand the proportion of external energy use increases if the full load hours remain the same. The most recent calculations by Sweco differ from these results. Their predicted energy use from the ATES system is much higher compared to the results obtained using (eq 5,6,7 and 8). The reason for the difference could be because the utilization of different values for  $COP_H$  and  $COP_C$  and the assumed number of equivalent full load hours. The  $COP_C$  for cooling machines was taken from Sommer et al. (2015) because there were no available values for it in Swecos documents.

The full load hours taken from the energy compilation include data for using cold wells even during the winter and warm wells during the summer, which is not the intended operation of switching warm and cold wells more than between seasons (Sweco, 2024). Therefore, the equivalent full load hours used for the (eq 5) only account for the intended summer and winter months. The energy demand for heating during winter is consistent between the new calculation from Sweco and the documents (Klemetz, 2019). There is a discrepancy in the summer cooling demand. In this case has the cooling demand from the hospital is calculated as 7000 MWh whereas Sweco's calculations indicate 5339 MWh. There was no clarity about how much cooling comes from the free cooling ATES source system or from the cooling

machines, but new calculation by Sweco indicate that the system could deliver at least 1688 MWh of cooling.

The relative CO<sub>2</sub> emission reductions realized from the hospital range between 30-40 % depending on the efficiency of the system. Compared to earlier studies by Sommer et al., (2015) and Vandhout et al. (2011) where the relative CO<sub>2</sub> emissions reduction was 69% and 69-70% respectively, the relative CO<sub>2</sub> emissions reduction for Skaraborg hospital appears to be low. But there are several factors that could influence in this outcome. These two studies were conducted in the Netherlands and Belgium which the kg CO<sub>2</sub> emissions MWh<sup>-1</sup> electricity is much higher compared to Sweden, at 460 (370-550) (Sommer et al, 2015). This result in a larger difference in CO<sub>2</sub> emissions between using free cooling and electrical energy. The high energy demand from Skaraborg hospital plays a significant role because then they need more energy from district heating. The depth of that aquifer system was twice as big in studies by Sommer et al. (2015) which provides more energy.

## Conclusion

The intention of installing the ATES system at Skaraborg hospital in Skövde was to lower the energy consumption and make an environmental advantage by decreasing the total CO<sub>2</sub> emissions. Managing the best possible outcome of energy consumption they required a method to assess the performance of the system. With help of earlier studies, the equation 1 and 2 were available and could be useful for the assessment. While using the equations for monitoring it is possible to control the energy extraction by regularly making temperature measurements of the aquifer, because the energy demand will affect the efficiency of the system. Variations between the seasons will make the extraction of energy vary and therefore the following year will get affected by the energy demand from the previous. That is more of big picture while looking in yearly variation but to prevent the energy loss through the groundwater a continuous monitoring would be beneficial. The amount of energy that will vanish through the groundwater is depending on conduction, dispersion and buoyancy driven flow and it will be dominated by conduction. The dispersion and buoyancy driven flow can be regulated while monitoring the system and controlling the energy extraction from different wells, temperature, and flow inside and outside aquifer. Prevention of energy losses could then be managed by having control over the operation of system and knowing when to change

to the conventional heating and cooling. How big the environmental advantage would be is in this case described by the relative CO<sub>2</sub> reduction. That depends on the energy losses, which in turn depend on the weather varieties, energy demand and how the system is operated. The relative CO<sub>2</sub> reduction is in the range 30-40% depending on the efficiency of the system, which in turn depend on the level of the fraction losses. Good regular monitoring methods would be the key for having the best possible outcome while using the ATEs system.

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