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Seasonal energy storage for district heating applications, including simulation and analysis of Borehole Thermal Energy Storage systems

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Abstract

The objective of this thesis is to analyse different energy storage technologies for seasonal energy storage in combination with district heating. Tromsø receives district heating (Kvitebjørn Varme). Their new heating central at Skattøra burn waste from industry and households in Tromsø and this heat is used to heat water. A part of this excess heat is lost to air during summer because of a lower energy demand in summer than in winter, and this work look into the possibility to store this excess heat from summer for use in winter when the demand is higher. A storage could cover peak demands during winter instead of burning oil.

The study looks into ATES systems which stores thermal energy in aquifers in the ground, CTES systems which stores energy as hot water in large underground caverns and BTES systems which exchanges heat with the ground with vertical borehole heat exchangers through a circulating fluid. It also analyse energy storage in PCMs (Phase Change Materials) and chemical storage which stores energy in chemical reactions.

After analysing the different storage technologies, BTES systems shows to be the most economical and most practical alternative for Kvitebjørn. The second part of this thesis uses a simulation program called Earth Energy Designer (EED) to analyse BTES systems of different sizes and with different heat loads. Based on a set of input parameters, EED calculates the mean fluid temperature in the circulating fluid which flows through the boreholes. Because of uncertainties of the amount of excess heat and monthly distribution of this heat, I do many simulations with different heat loads and monthly profiles. Borehole configurations for a limited area where a BTES system for Kvitebjørn could be placed is also analysed. Since thermal response tests have not been taken in the area, I do a sensitivity analysis to see how variations in ground parameters influence on the results. I also look at the possibility of preheating the storage for some years. Finally, I look into project costs and profitability.

The simulations show that large storages have lower heat losses. The amount of energy stored is determined by the number of borehole meters and by the thermal conductivity of the ground. A higher thermal conductivity and more borehole- meters increases the amount of heat that can be stored. Storing the same amount of energy in a large volume leads to less temperature variations in the fluid temperature. The results show that sufficiently high temperatures for the district heating network cannot be reached in the BTES system even when preheating, therefore heat pumps would be needed.

Acknowledgements

Jeg vil takke prof. Tobias Bostrøm for god veiledning og feedback underveis. Jeg vil også takke Driftssjef på Kvitebjørn Petter Lundstrøm for forslag til oppgave og for å komme med gode innspill og datagrunnlag til oppgaven. Takker han også for en interessant omvisning på det nye søppelforbrenningsanlegget på Skattøra.

Det har vært spennende å avslutte studietiden med et større arbeid som jeg syntes var interessant å skrive om.

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Abbreviations

ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
CTES	Cavern thermal energy storage
UTES	Underground thermal energy storage
PCM	Phase change material
STS	Sensible heat storage
LTS	Latent heat storage
COP	Coefficient of performance
SPF	Seasonal performance factor
EED	Earth Energy Designer

1 Introduction

District heating by production of warm water is increasing in Norway, from 3000 GWh in 2007 to about 6000 in 2016 as seen in the figure below (SSB 2017). Ca half of the energy comes from waste burning plants.

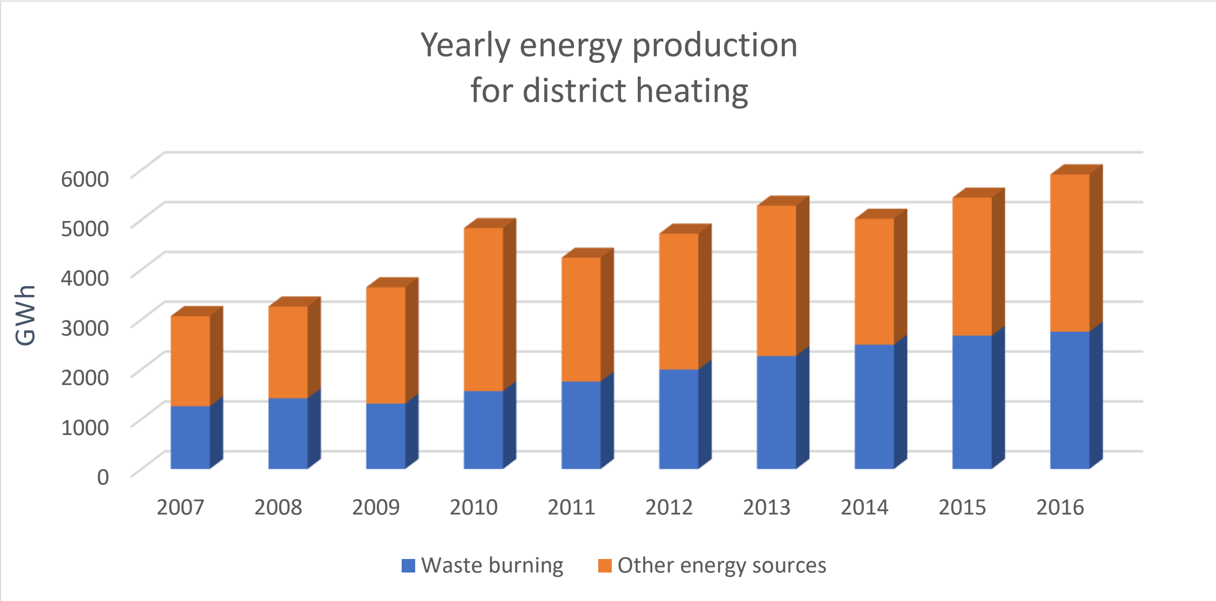

Figure 1.1 Yearly energy production for district heating in GWh (SSB 2017)

As we can see from Figure 1.2 below about 25 % of the waste burning energy is lost to air. This is a great energy source and should be taken better care of.

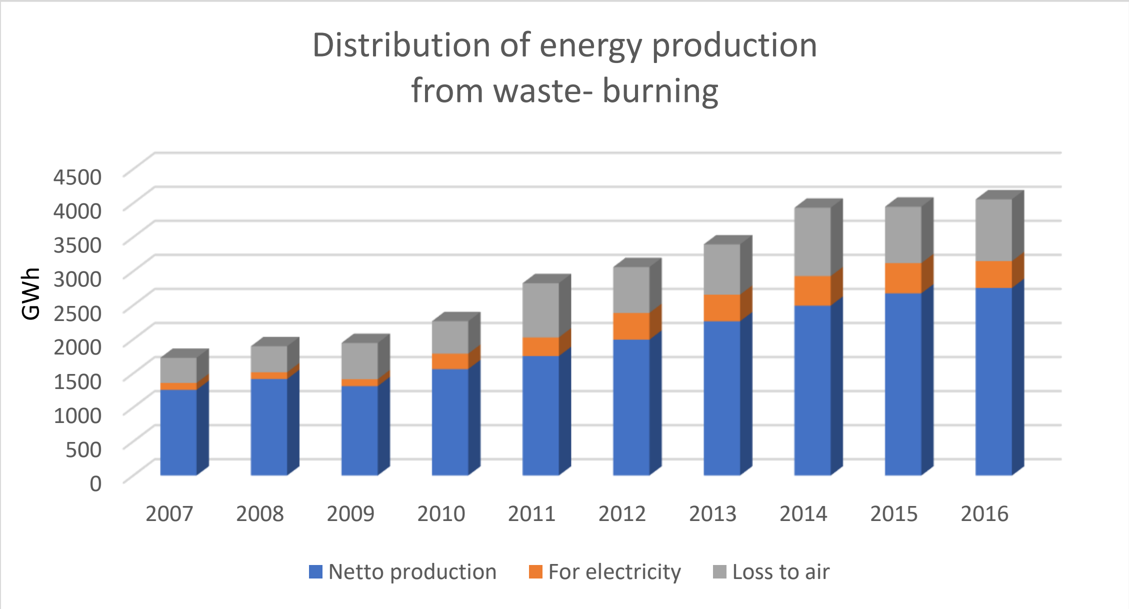

Figure 1.2: Distribution of energy production from waste- burning in GWh (SSB 2017)

Tromsø receives district heating (Kvitebjørn varme AS). Kvitebjørn has several central heating plants which uses several energy sources to heat up water that then is distributed through underground pipes to their customers (kvitebjornvarme.no). The newest heating plant is the one at Skattøra, where the water is heated by burning waste from industry and households in Tromsø.

The need for heating is higher in winter than in summer. The waste is burned during the whole year because of the need to get rid of it, so in summer there is a lot of excess heat (Kvitebjørn). There are several ways this excess heat could be stored for use during the winter. The amount of energy to be stored is relatively high, and the method to store it must be suitable to store energy for a long time (a whole season).

The water is heated up to 140ºC and circulates through a closed loop, and the energy is then transferred to the district heating network through a heat exchanger. The water in the district heating network is heated up to 100ºC and the return temperature of the water after energy is extracted from the customers is normally 70ºC, but it depends on the time of the year and the amount of energy delivered to the customers (Kvitebjørn). An energy storage will transfer energy to the district heating network through a heat exchanger. Therefore the temperature must be high enough, at least higher than 70ºC.

In this thesis the theory chapter focuses on different storage technologies for storing thermal energy. After comparing and discussing what it most relevant for Kvitebjørn, Borehole Thermal Energy Storage (BTES) systems shows to be the best and most economic alternative for Kvitebjørn for storing large amounts of energy of several GWh. BTES systems stores and exchanges heat with the ground through borehole heat exchangers. The heat is exchanged through a circulating fluid which flows through vertical boreholes.

Next an area (Strandkanten) where a BTES system can be built is analysed, and the simulation program Earth Energy Designer (EED) is used to do simulations. In the program the input parameters are ground properties like thermal conductivity and volumetric heat capacity, and monthly profiles of stored and extracted heat from the BTES system. The program calculates the mean fluid temperature of the circulating fluid based on the input parameters.

Since the heating central at Skattøra has been operated for just about 1 year and since Kvitebjørn continue to extend the district heating network, it is difficult to estimate the exact amount of excess heat and monthly distribution of this heat. Therefore I do many different simulations to find out how different load profiles and borehole configurations affect the mean fluid temperature. The possibility to preheat the ground to a higher medium temperature than the average ground temperature is also analysed. High temperatures is preferable, since heat pumps is needed to raise the temperature up to 80°C and the efficiency of heat pumps is dependent on the temperature lift.

For storage sizes I focus on modules for storing 1 GWh. It is and advantage to keep the heat loads fixed when analysing how changes in other input parameters influence the behavior of the system. This work also look into larger storage sizes and a storage inside a limited area where it probably would be placed.

2 Energy storage technologies

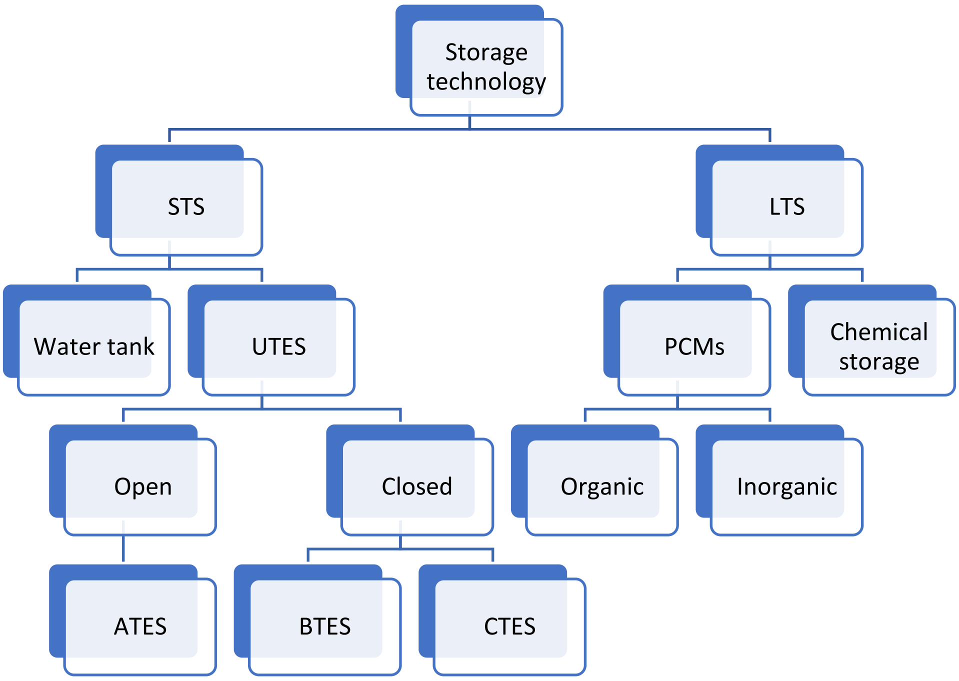

Figure 2.1: Overview of different storage technologies.

Figure 1 show that the different storage technologies can be divided into STS (sensible heat storage), storage in PCM (phase change materials) and chemical storage. ATES (aquifer thermal energy storage)- systems, BTES (borehole thermal energy storage)- systems and CTES (Cavern thermal energy storage) systems are sensible heat storage systems. These systems store energy by changing the temperature of the storage material. They are also considered UTES (underground thermal energy storage)- systems, since they store thermal energy underground. Storage in water tanks will be considered as STS- storages but not as UTES- storages. An ATES- system is considered an open system whereas BTES and CTES systems are considered closed systems. PCM storages absorb or release energy when a material changes phase, whereas in chemical storages energy is absorbed or released during chemical reactions. Both PCM and chemical storages can be considered as LTS (latent heat storages), but often LTS refers to PCM while chemical storage is considered a group by itself. PCM- materials can be divided into organic and inorganic materials.

2.1 Sensible heat storage (STS)

Sensible heat storage is based on the concept that increasing the temperature of a material increases its energy content. The energy can be stored in water, rock/soil etc. The greatest concern with sensible heat storage are heat losses. The losses will depend on factors like storage medium, temperature gradient and volume of storage. A low temperature storage, for example with temperatures lower than 30ºC will have lower losses than a high temperature storage. A system with low surface to volume ratio also results in lower losses (Herazaki, Holmberg, Haghighat- 2014).

The thermal energy stored is given by the formula:

$$E = mC(T_2 - T_1) = \rho VC(T_2 - T_1) \qquad (2.1)$$

Here E is the energy required to heat a substance of volume V with density ρ from a temperature T_1 to a temperature T_2 and C is the specific heat of the substance (Lee, 2014).

Below a certain level under the earth's surface (more than about 10 meters), temperatures are relatively stable during the whole year. The temperature fluctuations on the surface affect the temperature below this level to a small extent. Systems using natural underground storage sites are called underground thermal energy storage (UTES) systems (Lee, 2014). In a low temperature UTES, storage temperatures range from around 0ºC to a maximum of 40- 50ºC. A high temperature UTES, use storage temperatures higher than 40- 50ºC (Lee, 2014).

UTES systems are usually divided into open systems and closed systems. Borehole thermal energy storage systems are called closed systems and aquifer thermal energy storage systems are called open systems. Open systems generally have the advantage of higher heat transfer capacity than closed systems (Lee 2010).

2.1.1 Borehole thermal energy storage

A borehole thermal energy storage (BTES) system consists of vertical ground heat exchangers, also called borehole heat exchangers. A standard borehole is between 20- 300 meters deep with a width of 10- 15 cm in standard applications. A BTES system consists of an array of boreholes, drilled in a quadratic or hexagonal pattern. The quadratic pattern is easier to drill and the connection between the boreholes is easier, but the hexagonal pattern gives lower heat losses. (Lee, 2014). Each borehole contains a U- tube which links together with a central piping system on the surface, so the boreholes are interconnected. The fluid flows down and then up again through each borehole. The boreholes require some kind of filling- material to fill the spaces between the borehole- walls and the flow channels (U- tube) (Lee, 2014). The filling material is usually bentonite, quartz with sand or a water mixture (Northern Europe) (Rad, Fung, Rosen, 2014). The boreholes are the heat exchangers of the system. The fluid usually consists of water, mixed with glycol or alcohol to allow the system to work below the freezing point (Lee, 2014). In summer heat is transferred from the water to the ground by conduction when the water flows through the U- pipes. In winter the flow is reversed and heat is extracted from the ground (Lee, 2014).

For a BTES system the ground should have high thermal conductivity, high heat capacity, and low hydraulic conductivity. Groundwater is favourable because it gives a higher heat capacity, but low groundwater flow is preferable. The ground material can be soil or rock. Heat capacity of a BTES system varies between 15- 30 kW/m^3 (J.Xu, R.Z. Wang, Y.Li, 2013).

The thermal conductivity of the ground can be measured by thermal response tests which measures the ability of the ground to absorb heat (Sintef, 2016)

A BTES system uses a long time to reach typical performance. A system with high temperature storage would need to operate for 3-4 years to achieve typical performance so that the ground reaches the designed temperature level. In soil the heat transfer is much slower than in water, so it takes time to charge the storage to the designed temperature level (J.Xu, R.Z. Wang, Y.Li, 2013).

An example of a BTES- system

In Canada, Drake Landing Solar Community (DLSC) in Okotoks, Alberta, the first large scale (BTES) designed as part of a solar community was built in 2006 (Rad, Fung, Rosen, 2014). DLSC consists of 52 detached houses having a total annual heating demand of 2120 GJ (ca. 0.59 GWh). A central energy centre with short term energy storage tanks distributes hot water through a two- pipe system to each of the 52 houses (Rad, Fung, Rosen, 2014). A total of $2293m^2$ of flat plate solar- collectors was installed on the roof of the connected garages of the houses, facing south. The energy center contains two storage tanks with a total volume of $240m^3$, pumps, heat exchangers and controls (Rad, Fung, Rosen, 2014). Next to the energy center a borehole thermal energy storage is located, containing 144 boreholes of 35m depth installed in 24 parallel circuits in which used as a seasonal storage (Rad, Fung, Rosen, 2014). Figure 1 shows the system in a simplified schematic. The maximum storage temperature of the DLSC is 80°C. The solar collectors transfer the received energy from the sun to a short-term storage tank through a heat exchanger all year around. In mid- spring and summer with no heat demand from the homes, the thermal energy is transferred to the borehole thermal energy storage. Heat is extracted from the boreholes during the heating season and transferred to the short-term storage tanks when the solar collectors doesn’t produce enough energy to keep the temperature in the tanks at a sufficient level to meet the community heating load (Rad, Fung, Rosen, 2014). There are three loops with pumps (solar, BTES, and community loop). Each loop exchange thermal- energy with the storage tanks through a heat exchanger (Rad, Fung, Rosen, 2014).

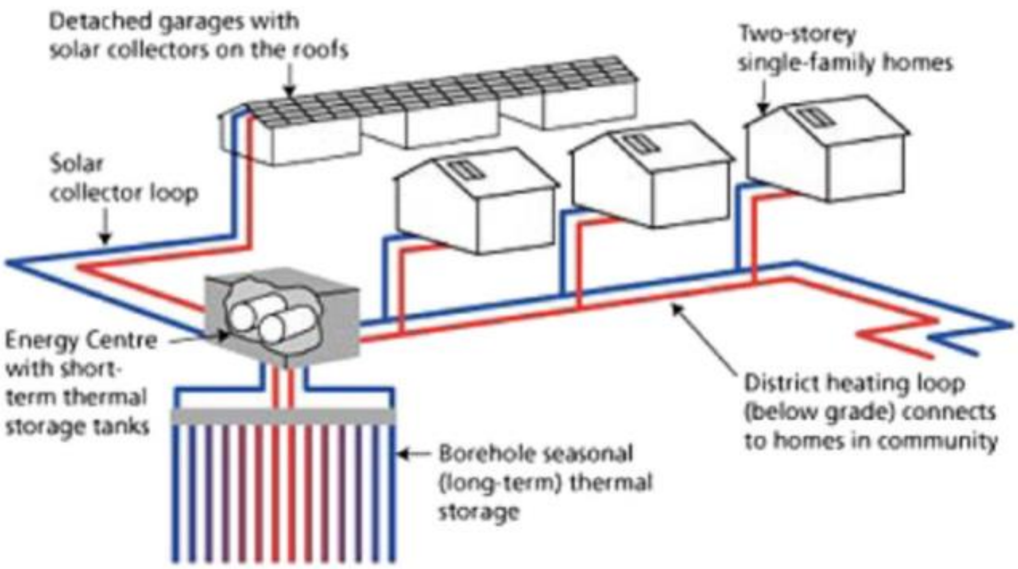

Figure 2.2: Drake landing solar community (DLSC) simplified system schematic (Nordell, 2000), (Rad, Fung, Rosen, 2014).

2.1.2 Aquifer thermal energy storage

An aquifer is a geologic formation that contains sufficient water- saturated permeable material to yield sufficient amount of water to wells and springs (Lee, 2014). An aquifer thermal energy storage system consists of two groups of wells which are hydraulically coupled and separated. In summer water is extracted from the cold well. The water is heated and the warm water is injected into the warm well. During winter the flow is reversed. Warm water is extracted from the warm well. Heat is extracted from the water for use, and the cold water is injected into the cold well (Lee, 2014). Figure 3 below illustrates the principle of an ATES-system.

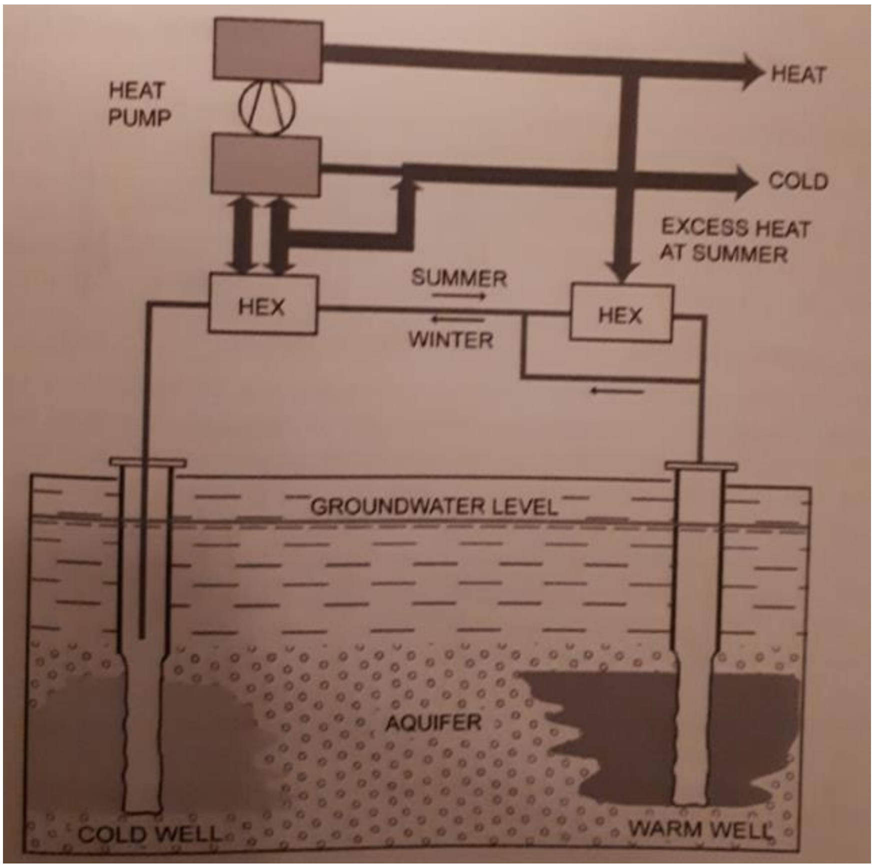

Figure 2.3: Illustration of an ATES system (Lee, 2010), (Andersson, 2007)

Numerous ATES facilities are in operation in Sweden, The Netherlands, Belgium, Germany and some other European countries (Lee, 2010). In Sweden there are over 50 ATES plants and they are used for commercial buildings from small scale applications to large scale district heating and cooling applications (Lee, 2010).

Experiences show that a significant number of ATES plants have had operational failures. The main reason behind these problems are chemical changes in the groundwater caused by temperature and pressure variations caused by the ATES system (Lee, 2010).

The use of ground- water for energy purposes will in most countries be restricted (Lee, 2010). To develop an ATES system, site investigations must be performed. Important parameters for an ATES installation are medium to high ground transmission rate around the boreholes, high ground porosity and a minimum of groundwater- flow through the reservoir (Lee, 2010). Site investigations usually consists of geological mapping, geophysical investigations, test drillings and pumping tests.

An example of an ATES- system in Norway

At Gardermoen one of the largest groundwater reservoirs in Norway is located (Eggen & Vangsnes). It is used for heating and cooling of Gardermoen Airport. During summer, water is pumped from cold wells and used for cooling and injected into the warm wells. In winter the flow is reversed and groundwater from the warm wells is used as heat source for the heat pump. The system consists of 9 cold wells and 9 warm wells, drilled down to 45 meters (Eggen & Vangsnes).

2.1.3 Cavern thermal energy storage

In Norway plenty of tunnels and caverns have been made the last 30- 40 years. Cost effective construction- methods have then been developed, and Norway probably produces the cheapest tunnels and caverns in the world (Eksperter i team, 2002).

Thermal stratification of heat storages refers to separation of the water in several layers because of density differences between cold and warm water. Since warm water is less dense it accumulates at the top of the storage, while the cold water is forced downwards (Park, Park, Sunwoo, 2014).

In caverns, stratification is useful because heat can then be extracted from different stratification layers and therefore at different temperature- levels. Loss of stratification can be due to heat loss to the surroundings, forced convection when charging or discharging thermal energy, heat conduction between thermally stratified layers, and natural convection due to conduction of heat into the wall. The aspect ratio (height to width ratio) of a tank or storage influence the stratification. The higher the aspect ratio, the better the stratification. This effect is significant up to an aspect ratio of 3 (Park, Park, Sunwoo, 2014).

High horizontal stresses in the earth will be unfavourable for wall stability in caverns with high aspect ratios. The stability of a cavern can be increased by reducing its size, and it is then possible to have a higher aspect ratio and still have a stable cavern. For a given storage volume two or more medium sized caverns could be built instead of one big to achieve a higher aspect ratio, but then the distance between them must be considered since it could affect the stability (Park, Park, Sunwoo, 2014). A drawback of building small caverns is that big caverns have a higher volume to surface ratio and are therefore more efficient (Eksperter i team, 2003).

For a CTES- system, low groundwater transport through the rock masses is preferable (Nielsen, 2003).

In the beginning when warm water is filled into the cavern there will be substantial heat losses, but after 1- 2 years of operation the rock around the storage will be heated substantially with decreasing temperatures away from the storage. Then the losses will stabilise to less than 10% during an operational cycle (season).

An example of a CTES- system

There are not so many examples of Cavern Thermal Energy Storage (CTES) systems in Europe, but there is a large one in Uppsala, Sweden (The Lyckebo Project). It is a district heating system with solar collectors, with an underground cavern storage of 100 000m^3. The system supplies 550 families with domestic hot water from a solar collector installation (Nielsen, 2003). The water at the bottom of the storage is 40ºC and the water on the top is 90ºC. The storage uses telescopic pipes to extract and inject water at different temperature levels. In that way turbulence can be reduced, so warm and cold water is not mixed and the stratification is conserved (Eksperter i team, 2002). Figure 6 below shows the cavern, which is formed like a donut. Its relatively high compared to its width (high aspect ratio), and the heat losses in the radial direction are reduced because of this shape (Eksperter i team, 2003).

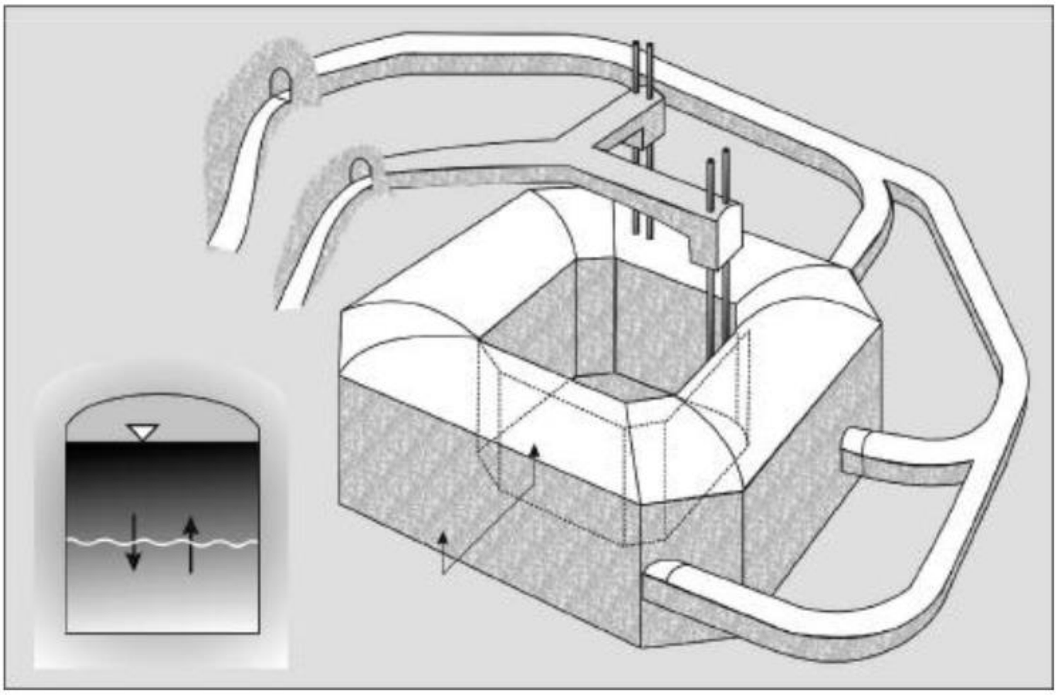

Figure 2.4: Cavern thermal energy storage at Lyckebo in Sweden (Nielsen, 2003).

2.2 Latent heat storage in phase change materials (PCMs)

Latent heat storage (LTS) in phase change materials (PCMs), offers higher energy densities than sensible heat storage. PCMs absorb or release heat when they change phase (liquid to solid) or (solid to liquid), without changing the temperature (J.Xu, R.Z. Wang, Y.Li, 2013).

PCM candidates for storage purposes are:

- $CaCl_2.6H_2O$
- $MgCl_2.6H_2O$
- $Na_2SO_4.10H_2O$
- $Na_2S_2O_3.5H_2O$

The heat of fusion of $CaCl_2.6H_2O$ is (190 kJ/kg) and its melting temperature is 29°C. For paraffin wax the heat of fusion is (173.6 kJ/kg) and its melting temperature is 48- 60°C (J.Xu, R.Z. Wang, Y.Li, 2013).

The changes in thermophysical properties of PCMs should be observed and repeated after a number of thermal cycles (number of melt- freeze cycles) to see if the PCMs degrade over time. A PCM is thermally stable if the changes in melting point and latent heat of fusion are negligible after repeated operative thermal cycles (Rathod, Banerjee, 2013). For solar thermal systems there will be a new thermal cycle every day, for storing heat absorbed by the collectors at daytime for use at night. For Kvitebjørn where seasonal storage is the case, there will only be one thermal cycle every year, so if the store will operate for ex. 100 years, 100 thermal cycles would be sufficient.

Phase change materials are classified into organic and non- organic PCMs. The organics are classified into paraffins and non- paraffins (Figure 7).

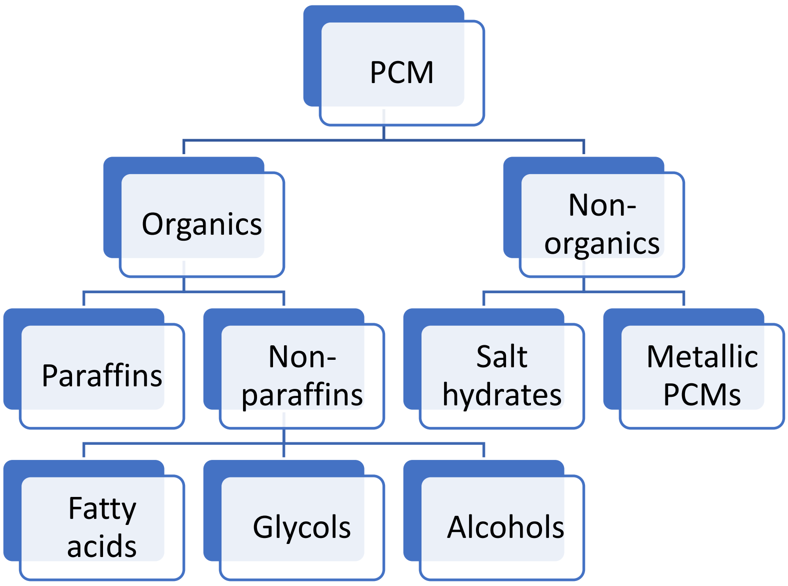

Figure 2.5: Classification of different PCM storage technologies

2.2.1 Organic paraffins

Paraffins are widely used because of high heat of fusion and varied phase change temperatures. Normal paraffins are of the type C_nH_{2n+2} with n ranging from 12- 38 and have almost similar properties. The higher the value of n, the higher latent heat of fusion and the higher the melting temperature. Paraffin wax is the most commonly used commercial organic PCM- storage material (Rathod, Banerjee,2013).

2.2.2 Organic non- paraffins

The organic PCMs that are non- paraffins are fatty acids, esters, alcohols, glycols, etc.

Fatty acids

Fatty acids are the most promising among the non- paraffins. They have high heat of fusion and can be produced from vegetable- and animal oils. Most common fatty acids that can be used for thermal energy storage are stearic acid, palmitic acid, lauric acid and myristic acid. Stearic acid has a melting temperature of 65°C and a latent heat of fusion of 210 (kJ/kg) and Palmitic acid has a melting point of 61.2°C. These have relatively high melting temperatures and might be usable for Kvitebjørn in combination with a heat pump.

Urea

Another non- paraffin is Urea with a melting temperature of 133°C. This might be high enough for Kvitebjørn- Varme without the use of heat pump. Experimental results showed degradation after only 50 thermal cycles, and this was not considered good enough for latent heat storage (Rathod, Banerjee, 2013), but for seasonal storage it might be sufficient.

Other organic non- paraffins

Erythritol is an alcohol with a melting point of 118°C and showed degradation after 1000 cycles. Acetanilide is another organic non- paraffin with a melting point of 113°C and showed degradation after 500 cycles (Rathod, Banerjee, 2013).

2.2.3 Non- organic PCMs

Among the non- organic PCMs we have salt- hydrates and metallic PCMs.

Salt hydrates

Salt- hydrates are attractive for solar heat applications because they have low costs and are readily available (Rathod, Banerjee, 2013). They also have high thermal conductivity. Disadvantages are that they tend to settle at the bottom and reduce the active volume, and corrosion of the metal container. Magnesium chloride hexahydrate $MgCl_2 \cdot 6H_2O$ has a melting temperature of 110.5°C and a latent heat of fusion of 155 (kJ/kg).

Metallic

Metallic PCMs have not yet been seriously considered for PCM- storage- technologies because of weight, but their advantages are low volume and high thermal conductivity. Al-34%Mg-6%Zn has melting temperature of 454°C and latent heat of fusion of 314 (kJ/kg) (Rathod, Banerjee, 2013).

2.2.4 Overview of different PCM storage materials

The table below gives an overview of the different PCM candidates mentioned above and their characteristics.

Storage Material	**Group**	**Melting temperature**	**Heat of fusion**
Paraffin wax	Paraffins	48-60°C	173,6 (kJ/kg)
Stearic acid	Fatty acids	65°C	210(kJ/kg)
Palmitic acid	Fatty acid	61,2°C	196.1(kJ/kg)
Urea	Amide (Organic- non paraffin)	133°C	250(kJ/kg)
Erythritol	Alcohol	118°C	339(kJ/kg)
Acetanilide	A non- organic PCM	113°C	169.4(kJ/kg)
$MgCl_2 \cdot 6H_2O$	Salt hydrate	110,5°C	155(kJ/kg)
$CaCl_2 \cdot 6H_2O$	Salt hydrate	29°C	190(kJ/kg)
Al-34%Mg-6%Zn	Metallic	454°C	314(kJ/kg)

Table 2.1: PCM materials with their melting temperatures and their heat of fusion.

2.2.5 An example of latent heat storage in a phase change material

An experimental evaluation of seasonal latent heat storage in PCM materials was performed in Turkey for heating a 180m^3 greenhouse (Figure 8). The system consisted of five main parts (flat plate solar air collectors, a latent heat storage unit, an experimental greenhouse and a data acquisition system). A steel tank filled with 6000 kg paraffin wax was used as the latent heat storage (J.Xu, R.Z. Wang, Y.Li, 2013).

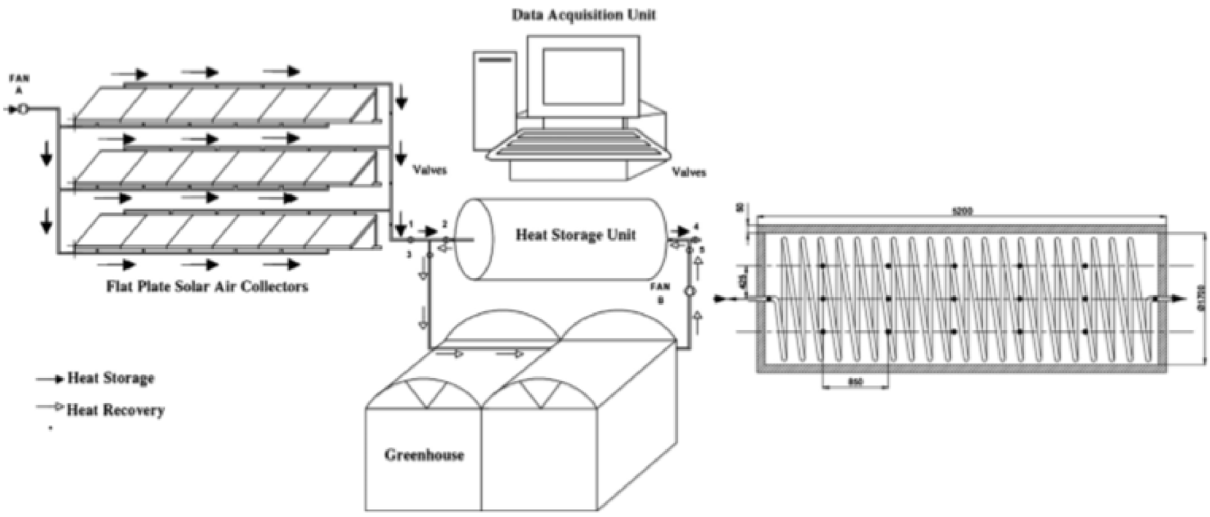

Figure 2.6: Energy storage with paraffin wax in a greenhouse (J.Xu, R.Z. Wang, Y.Li, 2013)

2.3 Chemical storage

In a thermochemical storage, heat is stored in chemical or physical bonds of special materials (Mette, Kerskes, Druck,2012). The charging/discharging process of the store can be described by the equation:

$$A + B \Leftrightarrow AB + \Delta\ \mathrm{H_R} \qquad (2.2)$$

Here A and B reacts to a product AB (Mette et al. 2012).

In the reverse reaction the compound AB can be split into the compounds A and B by adding heat (Mette et al. 2014).

An example of this type of reaction is the dehydration of salt hydrates, f.ex magnesium sulphate- heptahydrate into magnesium sulphate (Mette et al. 2014).

$$MgSO_4 + 7H_2O \Leftrightarrow MgSO_4 * 7H_2O + \Delta H_R \qquad (2.3)$$

Chemical storage has the advantages of high energy storage and low heat losses. It is the storage technology with the highest density for storing energy (J.Xu, R.Z. Wang, Y.Li, 2013). Chemical storage is expected to have enormous potential for storage applications, both for long and short term.

Chemical storage can be divided into thermochemical reaction and chemical sorption storage. The principle of chemical reaction is based on the reversible reaction between two substances, A and B. The sorption process includes both adsorption and absorption. In the adsorption process, gas bonds to the surface without creating a new material. In the absorption process a new material is formed (J.Xu, R.Z. Wang, Y.Li, 2013).

The table below shows some potential materials for chemical storage and their energy storage density.

Material and reaction			**Energy density (kWh/m^3)**	**Remarks**
AB	**A**	**B**		
Sorption				
$MgSO_4*7H_2O$	$MgSO_4$	H_2O	663	Hydrate slowly Low power density
$CaCl_2*2H_2O$	$CaCl_2*1H_2O$	H_2O	167	
$CaSO_4*2H_2O$	$CaSO_4$	H_2O	389	
Chemical reaction				
$Ca(OH)_2$	CaO	H_2O	872	
$Mg(OH)_2$	MgO	H_2O	889	
$ZnCO_3$	ZnO	CO_2	694	
$FeCO_3$	FeO	CO_2	722	

Table 2.2: Potential materials for chemical storage (from (J.Xu, R.Z. Wang, Y.Li, 2013)).

2.3.1 A chemical storage research project

A four- year research project about the technical feasibility of thermo- chemical heat storage for solar thermal applications and the achievable advantages compared to conventional technologies have been investigated. The investigations vas done in cooperation of the Institute of Thermodynamics and Thermal engineering (ITW) of the university of Stuttgart, and the Institute of Technical Thermodynamics (ITT) of the German Aerospace Center (DLR). During this project a thermochemical reactor was developed as described below (Mette et al. 2014).

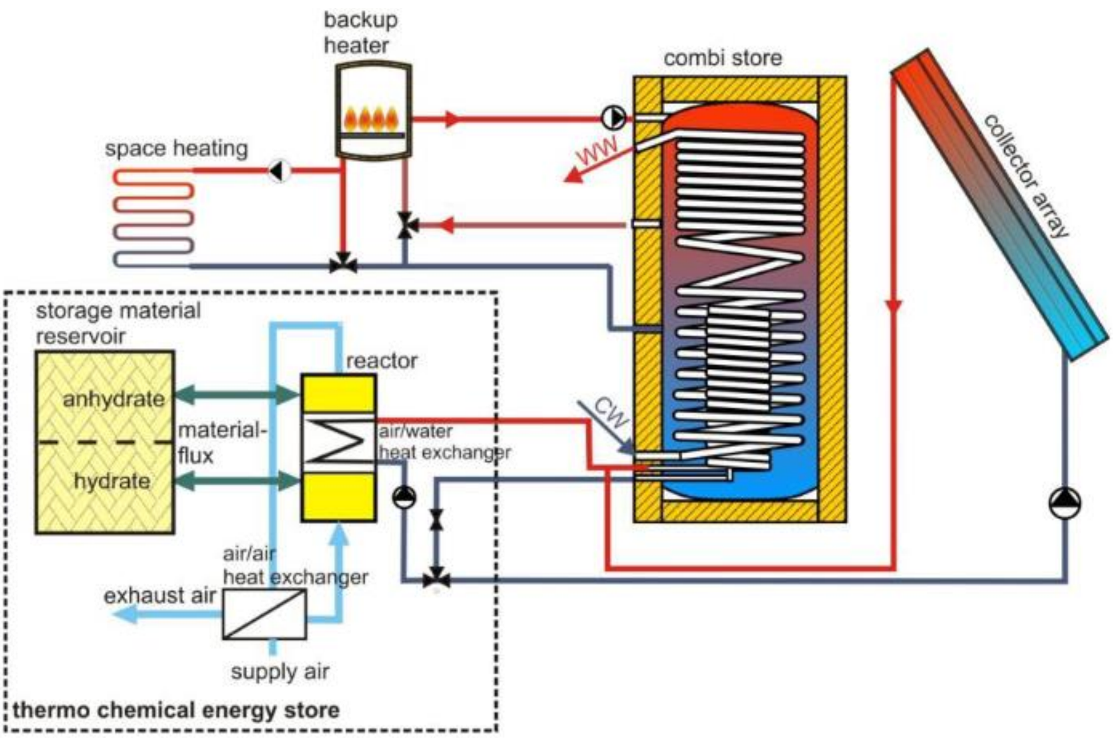

Figure 2.7: Schematic of reactor with collector array and energy storage (Kerskes, Mette, Bertsch, Asenbeck, & Druck, 2014)

The system consists of an external reactor where the chemical reaction takes place, a storage container for hydrated and dehydrated material and a material transport system (Figure 2.7).

The collector array serves as a heat source which heats the combi store or supply the heat needed for dehydrating the storage material (Mette et al. 2014)

During the summer- months when there is more solar radiation available than required to cover the heat demand, dehydration is taking place: $AB + \Delta$ H_R→A + B (Salt- hydrates dehydrates to salt + hydrates) (Mette et al.2014). The heat from the collectors heats up an air stream through an air/water heat exchanger and the hot air is blown through the reactor. Water vapour released during the dehydration is removed by the air stream and the air is conducted to the environment (Mette et al. 2014).

In winter when there is not enough solar radiation to cover the heat demand, hydration takes place: A + B→ $AB + \Delta$ H_R (salt + hydrates, hydrates to hydrated salt). Now wet air is sucked in from the environment and conducted through the reactor. At the same time dehydrated material is conducted through the reactor and get hydrated by the water vapour present in the wet air. The released heat is transported by the air stream to the air/water heat exchanger and applied to the combined storage tank (Mette et al. 2014).

The schematic shows a material flux during the reaction in the reactor. During dehydration, the reactor is supplied with hydrated material and after the reaction the dehydrated material is transported back to the storage. During hydration the reactor is supplied with dehydrated material and hydrated material is transported back to the storage (Mette et al. 2014)

2.4 Evaluating the different storage technologies

2.4.1 Comparison

Storage of energy as sensible- heat is a well known technology and there are many examples of practical use of this technology. When it comes to latent heat stored as PCM or chemical the experience is less. But today there is emphasis and research on these technologies and it is expected an increase in the future as these technologies becomes more mature

If we look into papers from the stock conference arranged by the International Energy Agency (IEA) where the latest development within research and development is presented, we see that in the latest years around 30 % of the papers are related to latent heat while in the first conferences no papers looked into this area

Sensible energy storage

The table below summarizes the different technologies for storage of sensible energy with their advantages and disadvantages.

Sensible Energy storage		
Technology	**Advantages**	**Disadvantages**
BTES	Well known technology Not so dependent on site conditions as ATES Less risk of operational failures than ATES	Higher construction costs than ATES Long time needed to reach typical performance
ATES	Well known technology Low construction costs Higher heat transfer capacity than BTES	Risk of operational failures Needs suitable site conditions.
CTES	Well known technology High transfer capacity	High costs
Water tank	Well known technology High transfer capacity	Most suitable for storage of smaller quantities of energy (Buffer tanks)

Table 2.3: Advantages and disadvantages for different sensible heat storage technologies.

Because of the experiences of operating failures with ATES systems, BTES systems seems like a safer alternative. The requirements for a suitable location for the ATES system are also higher, and there is a need for more thorough site- investigations. Advantages of an ATES system is shorter payback time (2- 5) years if the conditions are favourable compared to 6-10 years for BTES (Lee,2010). Another advantage of ATES is a higher heat transfer capacity. CTES- systems are expensive compared to BTES and ATES systems, unless there are existing caverns or abandoned mines that can be used (Nodell, 2012).

Latent heat (PCMs and chemicals)

The tables below shows the most common group of materials for latent heat energy storage (PCMs and chemical), comparing their advantages and disadvantages.

	Group of PCM materials			
	Paraffins	**Fatty acids**	**Salt hydrates**	**Metallic**
Advantages	High heat of fusion Varied phase-change-temperatures No corrosion	High heat of fusion	Low costs Readily available High thermal conductivity Relatively high heat of fusion	High storage density High thermal conductivity Low volume
Disadvantages	Low thermal conductivity	Costly compared to paraffines Low thermal conductivity	Settle at the bottom and reduce active volume Corrosion of metal container	Not mature technology Weight

Table 2.4: Advantages and disadvantages for different groups of PCM storage materials (Xu, Wang, Lee)

	Chemical reaction	Chemical sorpcion
Advantages	High energy density Low energy losses	High energy density Low energy losses Energy can be stores at temperatures that corresponds to storage of solar- and waste burning energy
Disadvantages	Technology not mature Storage at high temperatures (300°C). Not relevant for storage of solar and waste burning energy	Technology not well developed

Table 2.5: Advantages and disadvantages for chemical reaction and chemical sorption materials (Xu, Wang, Lee)

2.4.2 Discussion and recommendation

Advantages of storage in PCMs and chemical storage are higher energy densities. But the sensible heat storage has been investigated deeply and proven suitable for large- scale district heating systems (Xu, Wang, Lee).

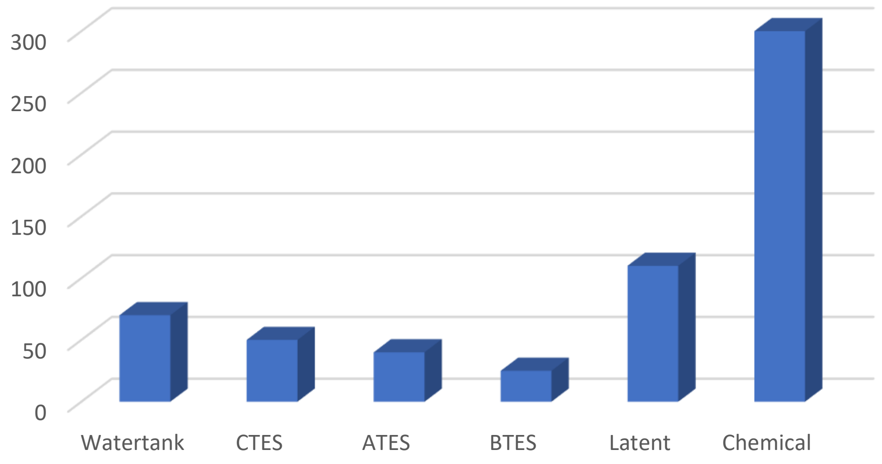

Figure 2.8: Energy storage capacity in kWh/m^3 for different groups of storage materials

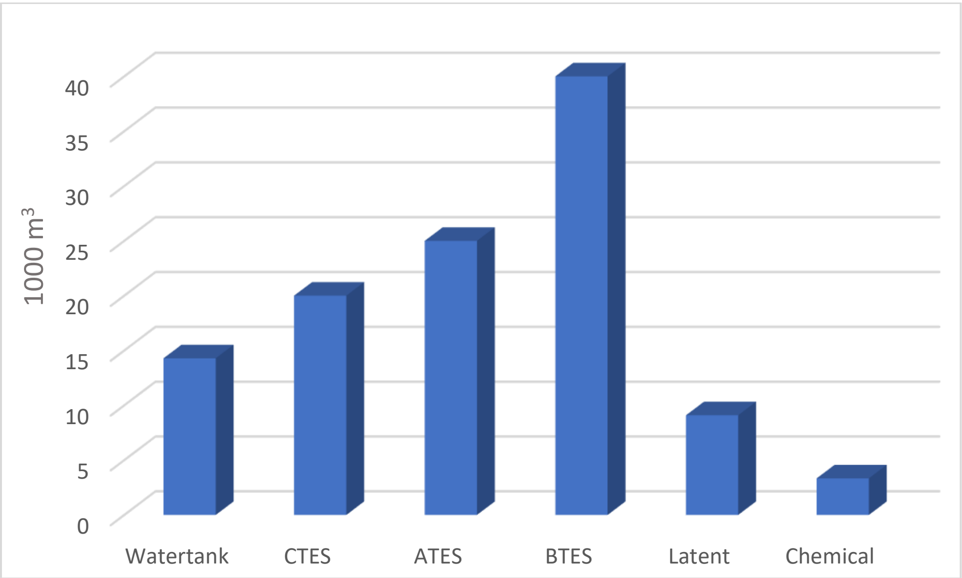

Figure 2.9: Necessary volume in 1000m^3 to store 1GWh for different groups of heat storage materials.

Comparing the different materials for seasonal energy storage as done in the previous chapter, it seems that BTES is the most feasible technology for storing Kvitebjørns thermal energy that today is lossed to air in the summer months.

2.5 BTES systems and district heating

2.5.1 District heating

District heating is a separate energy system which forms a part of the energy supply for towns and cities and involves heating of water. The hot water circulates between the heat production plant and the customers in underground pipes. The pipes can be laid together with other infrastructure like electricity cables and telecommunication lines, and the average heat losses are about ten percent (statkraft.com). Customers use the warm water to provide heating through underfloor heating or radiators, and to heat tap water.

A district heating system consists of a heat production plant, a district heating grid and an exchanger unit (at the customer). Heat is transferred from the district heating grid to the customers own heating system in the customer exchange unit.

Many energy sources can be used to generate district heating like waste, biofuel, heat pumps, landfill gas, natural gas, propane/butane gas, electricity and fuel oil. In a district heating system, several different energy sources can be used at the same time. When one source is unavailable for a period of time, another source can be used to heat the water. This results in a stable supply of heat. Expressions like base load and peak load are often used in combination with district heating. The base load consists of waste or biofuel and the peak load of oil and gas. The base load is the cheapest energy source, but because of variations in capacity requirements during the year a peak load is required (statkraft.com).

2.5.3 Heat pumps

A heat pump is a form of a heat engine. They use mechanical work to transport heat from a low temperature source to a high temperature sink. A widely used application for heat pumps is transporting heat between buildings and the external environment. (Rees, 2016). In a heat pump a refrigerant gas is evaporated and absorbs heat. Then the gas is compressed by external work. In the next step the gas is condensed while releasing heat and finally it passes through an expansion valve which reduces the pressure. Since the pressure now is reduced, the boiling point is lowered. The liquid then evaporates while absorbing heat and this thermodynamic cycle continues following these four steps [Figure 2.10].

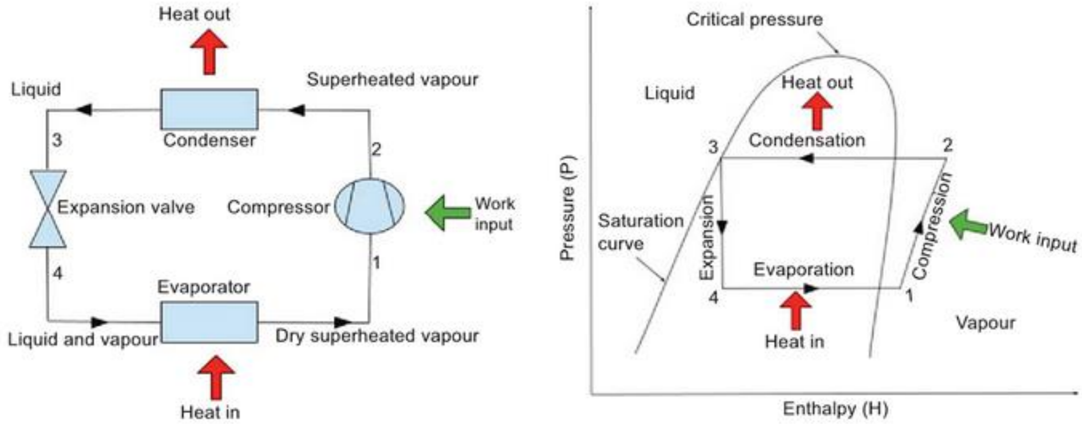

Figure 2.10: A conceptual model of a heat pump to the left and an idealized cycle represented on an enthalpy- pressure diagram to the right (Rees, 2016), (Naicker, 2016).

The efficiency of a heat pump is given by its coefficient of performance (COP). It is given by:

$$COP = \frac{Q_H}{W} \qquad (2.4) \qquad \text{(Rees, 2016)}$$

- Q_H= Quantity of heat delivered
- W= Work required

The maximum possible theoretical efficiency of a heat pump is:

$$COP_{max} = T_H/(T_H - T_C) \qquad (2.5) \qquad \text{(Rees, 2016)}$$

- T_C = temperature of the source
- T_H = temperature of the sink.

From the formula we see the efficiency (COP) of a heat pump is higher when the source and sink temperatures are close together. For heating a building an air source heat pump can be used, which uses heat from the ambient air to heat up the air inside the building. In contrast a ground source heat pump extracts heat from the ground. A ground source heat pump is more expensive to install, but has the advantage of higher efficiency. This is because the ground temperature is relatively stable throughout the year and the temperature difference between the ground and the inside air is therefore usually less than between the outside air and the inside air. The most common forms of ground heat exchangers (GHE) are vertical borehole devices or shallow horizontal loop. These are closed loop systems which uses a secondary heat exchange fluid such as an anti- freeze/water mixture (Rees, 2016).

2.5.4 Ground source heat pumps

In a ground source heat pump, the stored energy in the ground loop is the thermal source for one side of a refrigeration cycle (source). In the condenser (sink), heat is released to a hot water circuit. Figure 2.11 below shows the source is at 9°C and the sink at 40°C. For Kvitebjørn, the source is the BTES system and the sink is the district heating network. The medium temperature of the fluid in the ground loop which is the source can for example be 20°C and the temperature of the sink must be about 80°C. The temperature of the source will vary during a yearly cycle (Dwyer, 2010). From equation 2.4 we have that the efficiency of a heat pump is given by its coefficient of performance (heat delivered/power supplied). It can also be given by the seasonal performance factor (SPF).

$$\mathrm{SPF} = \mathrm{Heat\ energy\ delivered\ (kWh/season)/electrical\ energy\ supplied\ (kWh/season)}$$
(2.6)

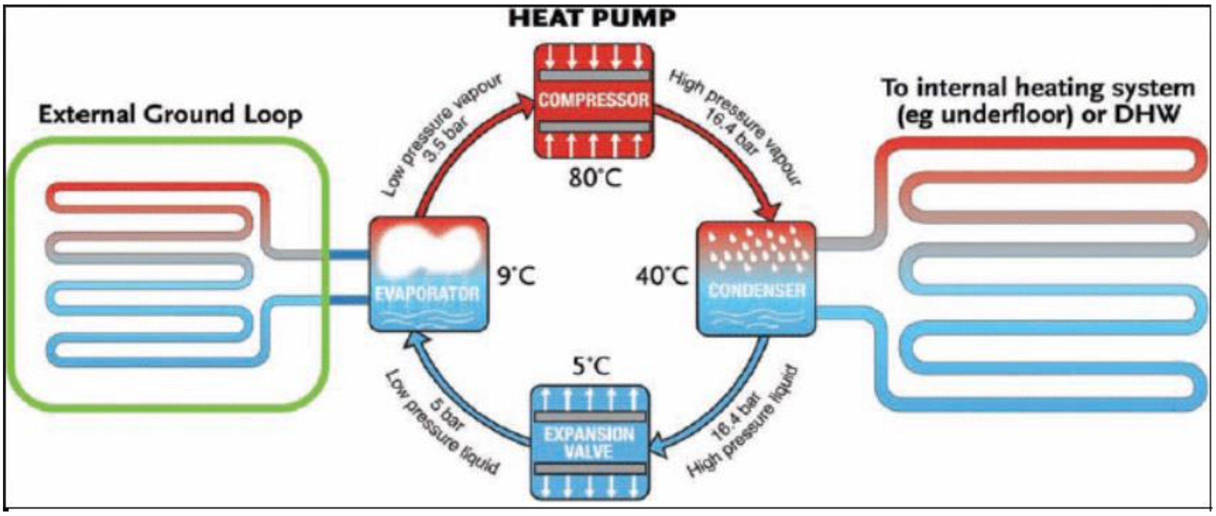

Figure 2.11: Heat exchange process in a ground source heat pump system (Dwyer, 2010)

2.5.5 Theory of BTES systems and software

Since a BTES system is the most feasible technology for energy storage for Kvitebjørn, I decided to look into the availability and functionality of appropriate software that could be used for simulating a BTES- storage systems.

A student Cichong Liu at Aalto university in Finland wrote a master's thesis called "Optimization of a new system combining district heating with underground thermal energy storage". He has written a MATLAB code which a Finnish Ph.d. student at Oulu university in Finland is modifying. He is modifying the code, since the original code only models a single borehole and he modifies it to model systems with many boreholes. Since the boreholes in a BTES- system are separated by several meters, they might not affect each other that much, but still it must be taken into account. In f. ex a square/rectangular configuration, the boreholes in the middle will be more affected by heat conduction from other boreholes than the outer boreholes. The code takes into consideration the heat conduction inside the borehole (interaction between the fluid in the U- tube and the grout material), and the heat conduction outside the borehole. These are two different models that needs to be coupled together (Liu, 2014).

There are different models to simulate the heat conduction outside the boreholes, but the code uses a model called the finite line-source model. In this model the ground is regarded as a homogenous medium with constant thermophysical properties (Lee, 2010). For the heat transfer inside the borehole the code uses a model called the quasi-three-dimensional model.

Heat transfer outside borehole (finite line-source model):

$$\Theta = \frac{q_l}{4k\pi}\int_0^H \left(\frac{erfc[\frac{\sqrt{r^2+(z-h)^2}}{2\sqrt{\alpha Ʈ}}]}{\sqrt{r^2+(z-h)^2}} - \frac{erfc\left[\frac{\sqrt{r^2+(z+h)^2}}{2\sqrt{\alpha Ʈ}}\right]}{\sqrt{r^2+(z+h)^2}} \right) dh \qquad (2.7) \qquad (Lee, 2010)$$

Here $\Theta = T - T_0$

- T_0 is the initial starting temperature
- Ʈ is the time
- H is the depth of the borehole
- q_l is the heating rate per length of the source
- α is the thermal diffusivity of the soil.
- r is borehole radius
- k is thermal conductivity of soil

The MATLAB code uses a simplified version of this model.

Heat transfer inside boreholes (two dimensional model)

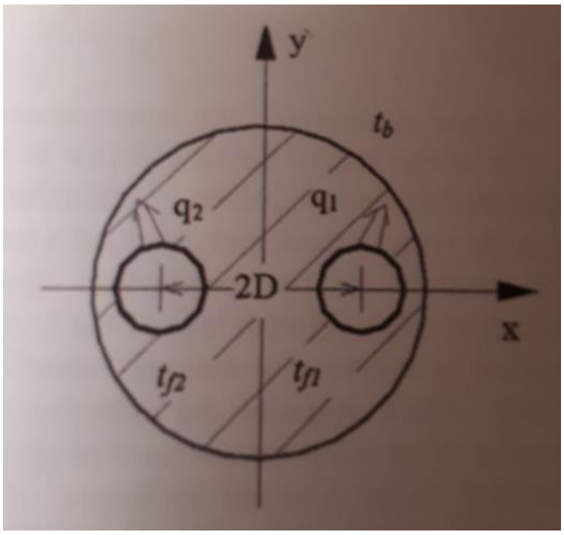

Figure 2.12: Cross section of vertical borehole heat exchanger (Lee, 2010)

$$T_{f1} - T_b = R_{11}q_1 + R_{12}q_2$$

$$T_{f2} - T_b = R_{12}q_1 + R_{22}q_2 \quad (2.8)$$

- T_b is the temperature of the borehole wall.
- T_{f1} and T_{f2} are the temperatures in each pipe.
- R_{11} and R_{22} are the thermal resistances between the fluid in each pipe and the borehole wall.
- q_1 and q_2 are the heat fluxes per unit length from the two pipes in the U- tube

The MATLAB code uses a model called the quasi- three- dimensional model which is based on the two dimensional model, but takes into consideration the fluid temperature variation along the borehole depth (Lee, 2010).

The code can calculate and plot the temperatures around the boreholes based on a heat load and can show the temperature in the ground as a function of time and heat extracted or added to the system.

Earth Energy Designer

There is a program called Earth Energy Designer (EED) to design BTES systems. EED can simulate systems up to 1200 boreholes and annual base- loads can vary between a few MWh to several TWh (Buldingphysics.com). Monthly and annual heating loads are the input data. The borehole pattern can be chosen from a database of 800 basic configurations.

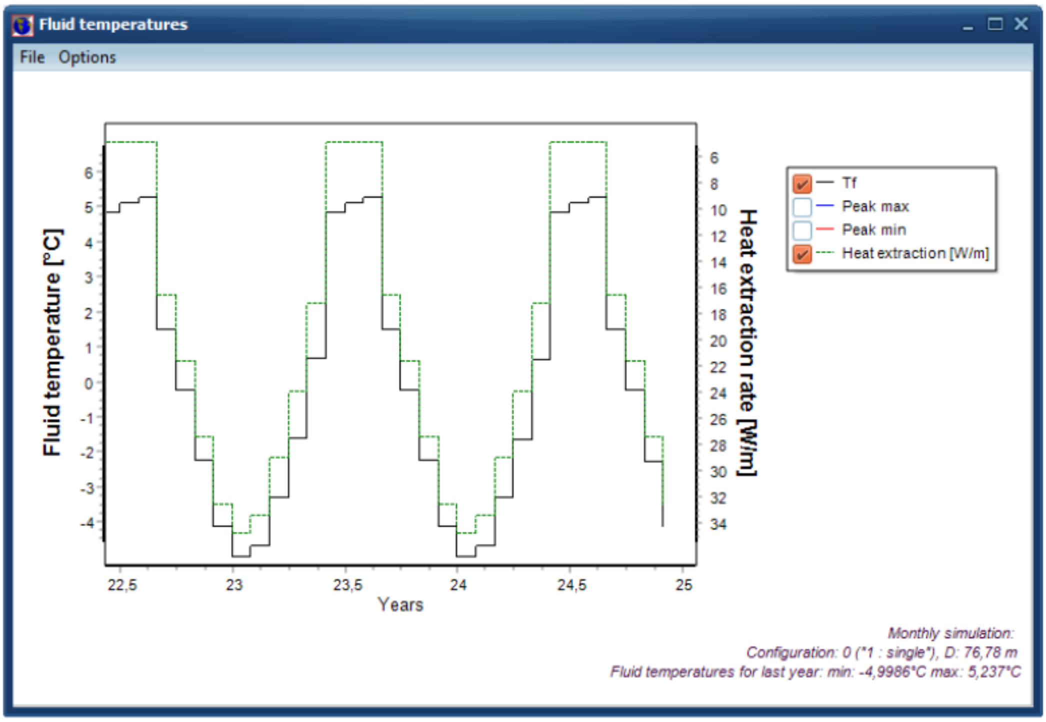

Figure 2.13: Example of a simulation with EED (buildingphysics.com) which shows the seasonal changes in fluid- temperature and heat extraction rate.

Based on the size of the system (number of boreholes, length, etc) and the monthly loads, the program calculates the mean fluid temperature.

2.5.6 Experience from BTES systems

KTH (University in Sweden)

A BTES system was constructed at Stockholm university, Sweden. The system consists of 130 boreholes, 230 meters deep. It is designed for 4 GWh of heat injection and 3 GWh of heat extraction. The bore field configuration is selected to ensure that fluid temperature varies between 2,5°C and 31°C during the lifetime of the system. By performing Thermal Response Tests in different boreholes, the average thermal conductivity was found to be 3,92 W/mK. The boreholes use double U- pipe heat exchangers that are water filled (not grouted). Some locations within the bore field have been selected to carry out measurements with a monitoring system consisting of temperature and energy flow meters. The temperature is measured along the depth of the boreholes. The measured data will be used for validation of current bore field design methods and for having a better understanding of the thermal interaction between neighbouring boreholes (Monzo, 2016). The temperature is measured using a temperature sensing instrument type (ORYX DTS) which uses optical fibers as linerar sensors. The instrument can measure temperatures with a spatial resolution of 1 meter. The optical fiber cables are installed in the boreholes outside the pipes.

BTES at UIOT (University of Ontario Institute of Technology)

A BTES system is installed on the campus of University of Ontario Institute of Technology in Oshawa, Canada. This BTES system is one of the largest in Canada and consists of 230 water filled boreholes, 200 meters deep. This BTES system is coupled with heat pumps and provides heating for the whole campus buildings. The total heating load of the campus buildings is about 6800 kW and the amount of energy pumped by the heat pumps is about 40 percent of the total heat demand of the buildings (Kizilkan, 2014). The rest of the demand is supplied by natural gas- boilers, shown in the Figure 2.14 below. There are four boilers with a capacity of 1030 kW and a total heat pump capacity of 2770 kW. Heat energy is absorbed from the borehole water by the evaporator and transferred to the refrigerant in the heat pump. The energy is transferred to the secondary fluid which carry heat to the buildings (Kizilkan, 2014).

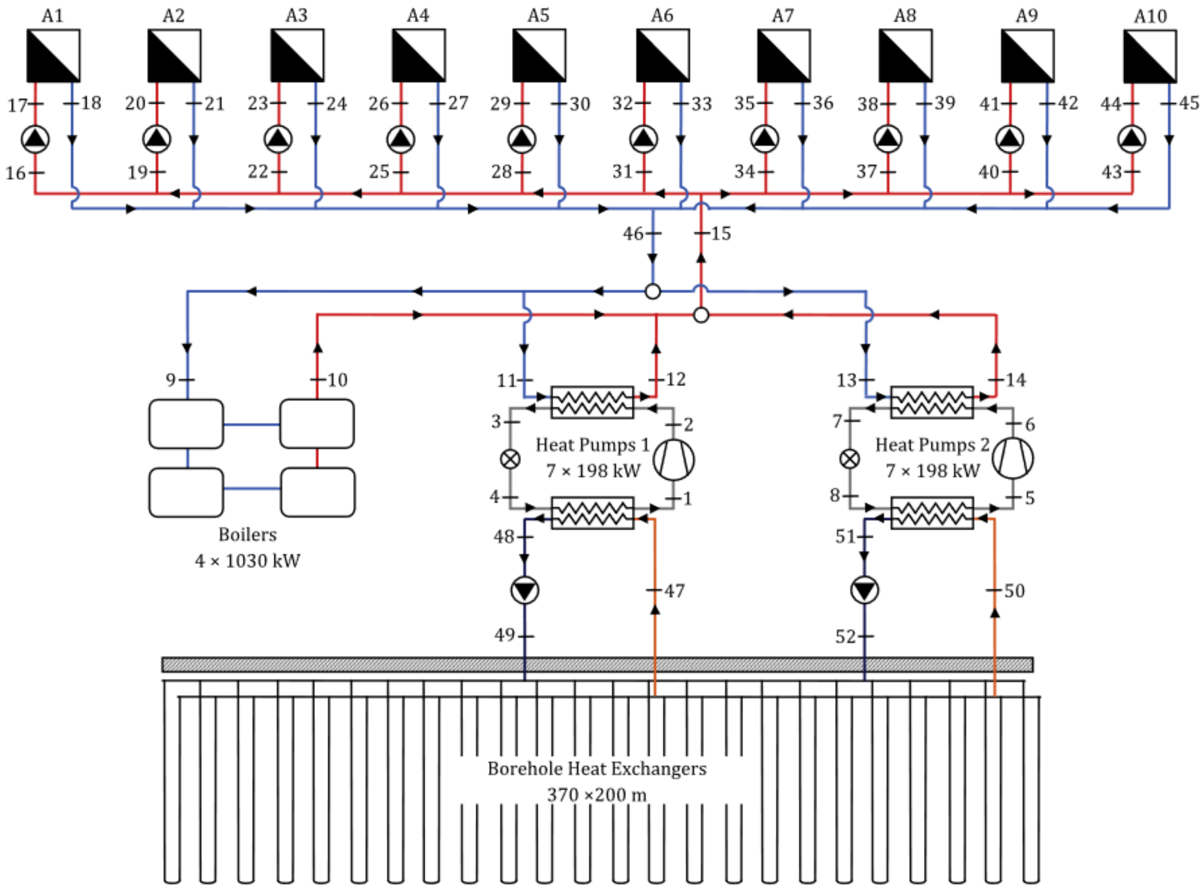

Figure 2.14: Schematic illustration of the heating system (Kizilkan, 2014)

Test drillings were done to determine groundwater and thermal characteristics. An almost impermeable limestone formation was found between 55m and 200 below the surface [Figure 2.15]. The homogenous and non- fractured rock was well suited for thermal energy storage because of practically no groundwater flow to transport away thermal energy (Paksoy, 2007).

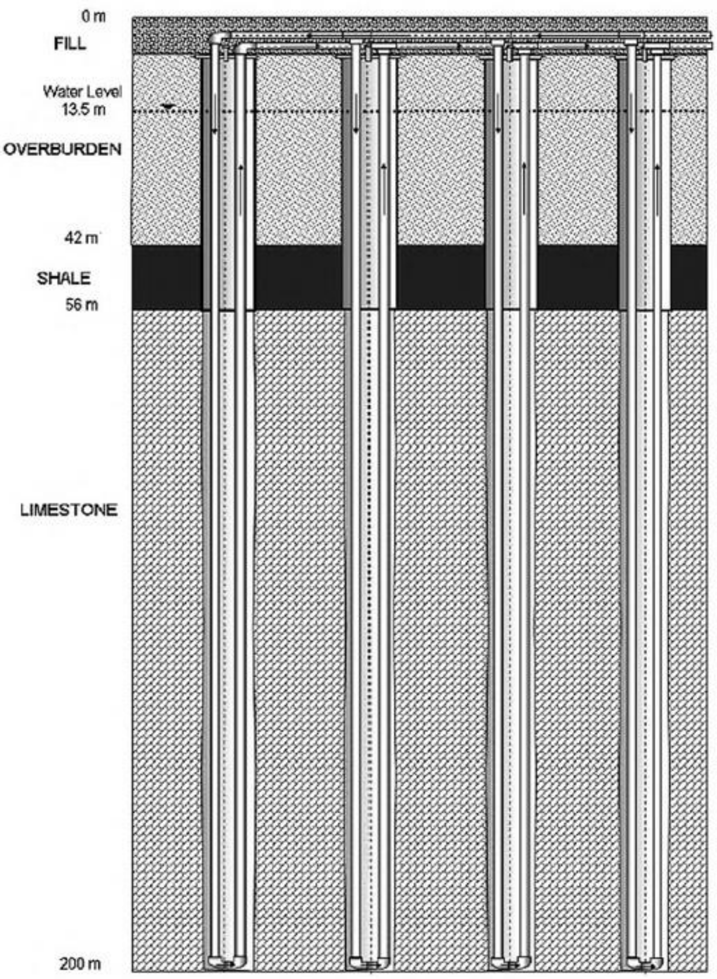

Figure 2.15: Illustration of the BTES system at UOIT (Paksoy, 2007)

3 Method

For simulating a BTES system for Kvitebjørn, I use the program Earth Energy Designer (EED). As mentioned in the theory chapter, EED can simulate systems up to 1200 boreholes and annual base- loads can vary between a few MWh to several TWh (Buldingphysics.com). Monthly and annual heating loads are the input data. The borehole pattern can be chosen from a database of 800 basic configurations.

Based on the size of the system (number of boreholes, length, etc) and the monthly loads, the program calculates the mean fluid temperature.

3.1 Storage spesifications

At Kvitebjørn Varme they do not have good estimations for the amount of excess heat from the heating sentral at Skattøra in the future. This is because it started up in November 2016, and the first year of operation there are more stops on the boilers than normally. They also have a fast expansion of more customers receiving district heating. The expansion of the district heating network will continue for many years and it is therefore hard to estimate excess heat and consumption from the customers exactly (Kvitebjørn Varme). Their estimation is that they will have an excess heat of 53 GWh yearly, but they do not know the monthly distribution. They believe that from these 53 GWh, they could manage to store 34 GWh. For storing that amount of energy at Strandkanten, it requires that they manage to inject 8- 10 MW when the excess power exceeds 8 MW. The excess power is limited because of the capacity of the pipes from the heating plants to Strandkanten.

Based on the meeting with my supervisor (Tobias) and my contact person from Kvitebjørn (Petter), Petter said it would be desirable to store 18 GWh of thermal energy in a BTES-system. The amount of thermal energy that is cooled off to air is higher than that, but at Kvitebjørn they had desided 18 GWh was sufficient. This is still a large amount of energy, so if this would be too expensive or require a too large area, 9 GWh could eventually be stored. This would still be helpful to cover peak demands in wintertime instead of burning oil.

A storage temperature for the BTES- system of 80°C was desirable. This would be high enough for exchanging heat with the district heating network. If this is not possible, heat pumps would be needed to reach the desired temperature of the circulating fluid in the BTES-system. The heating plant at Skattøra heats up water to 140°C which circulates in a closed loop. The energy is then transferred to the district heating network through a heat exchanger. The temperature of the water in the district heating network has an outgoing temperature of 100°C and a return- temperature of 70°C. The district heating network exchanges heat with several networks which deliver heat to different areas in Tromsø. These networks have a lower temperature than 80°C and the storage could exchange heat with one of these networks. When heat is extracted from the BTES system, heat could be transferred to one of these networks with relatively low temperatures, while it could receive heat from the district heating network when heat is injected into the storage. Another possibility is to reduce the temperature in the district heating network to 80°C during winter when heat is extracted from the BTES system. The fluid in the BTES system cannot exceed 80°C, since this is usually the boiling point of the type of fluid used in BTES systems. The fluid temperature will also change when heat is extracted or injected. To reach 80°C for extracting heat from the BTES system, heat pumps would be needed.

Later I got information from Kvitebjørn about where a BTES system could be placed as shown in Figure 3.1 below. It is the area between Framsenteret and Hålogaland teater at Strandkanten. When I went to see the area, I estimated it to be about 80 x 80 meters. When estimating, I kept a little distance to the buildings around and the road.

Figure 3.1: Storage area for BTES system for Kvitebjørn.

According to the geological map at ngu.no, the type of rock is granitic- gneiss in this area. Ground investigations done by Rambøll shows a surface layer of rockfill (4- 16m), above a layer of soils before we reach solid rock. The area is only 1- 2 meters above middle sea- water level.

3.2 Input parameters

3.2.1 Ground properties

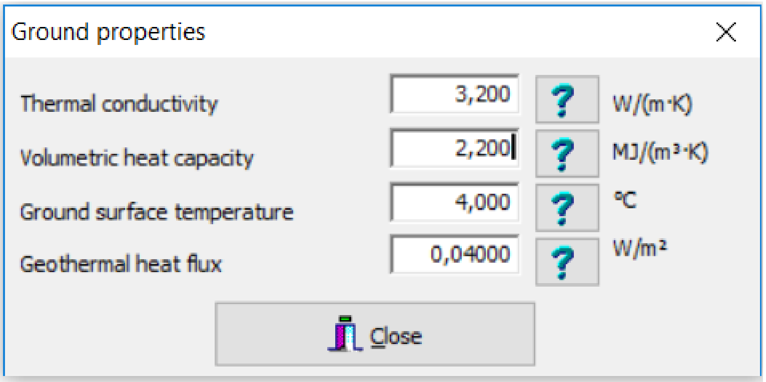

Figure 3.2: Input parameters (ground properties).

Clicking on the question marks on thermal conductivity gives a list of different types of rock or soil and their parameter- values. It shows their recommended value and their variation range. In the area shown above, the type of rock is granitic gneiss. The average **thermal conductivity** for Granite is 3,4W/(mK) and for Gneiss 2,9. I then choose a value of 3,2.

The average **volumetric heat capacity** for Gneiss is 2,1 and for Granite it is 2,4 so I choose it to be 2,2 MJ/(m^{3}K).

The question mark for **ground surface temperature** gives a list of the average ground surface temperature in different parts of the world. For Tromsø, Norway the value is given as 2,5°C, but since a BTES system will be under the sea- level I use the yearly average sea-temperature which for Tromsø is 4°C.

3.2.2 Borehole and heat exchanger

A geological report showing the results from ground investigations done by Rambøll at Framsenteret shows the depth of soils to be between 4- 16m above solid rock. Choose the depth of soil to be 10 meters in the calculations. I try to simulate with a borehole depth of 100m [Figure 3.3]. Soils has a much lower thermal conductivity than rock, so I ignore it in the simulations. Simulating with a borehole depth of 100m then means that the borehole in reality is 110m, taking the upper meters in soils into account. For input parameters related to the borehole, I use default values for the borehole diameter, U- tube (diameter, wall thickness,…) and flow rate. Use a borehole diameter of 110mm, borehole spacing of 70mm and use single U- pipe.

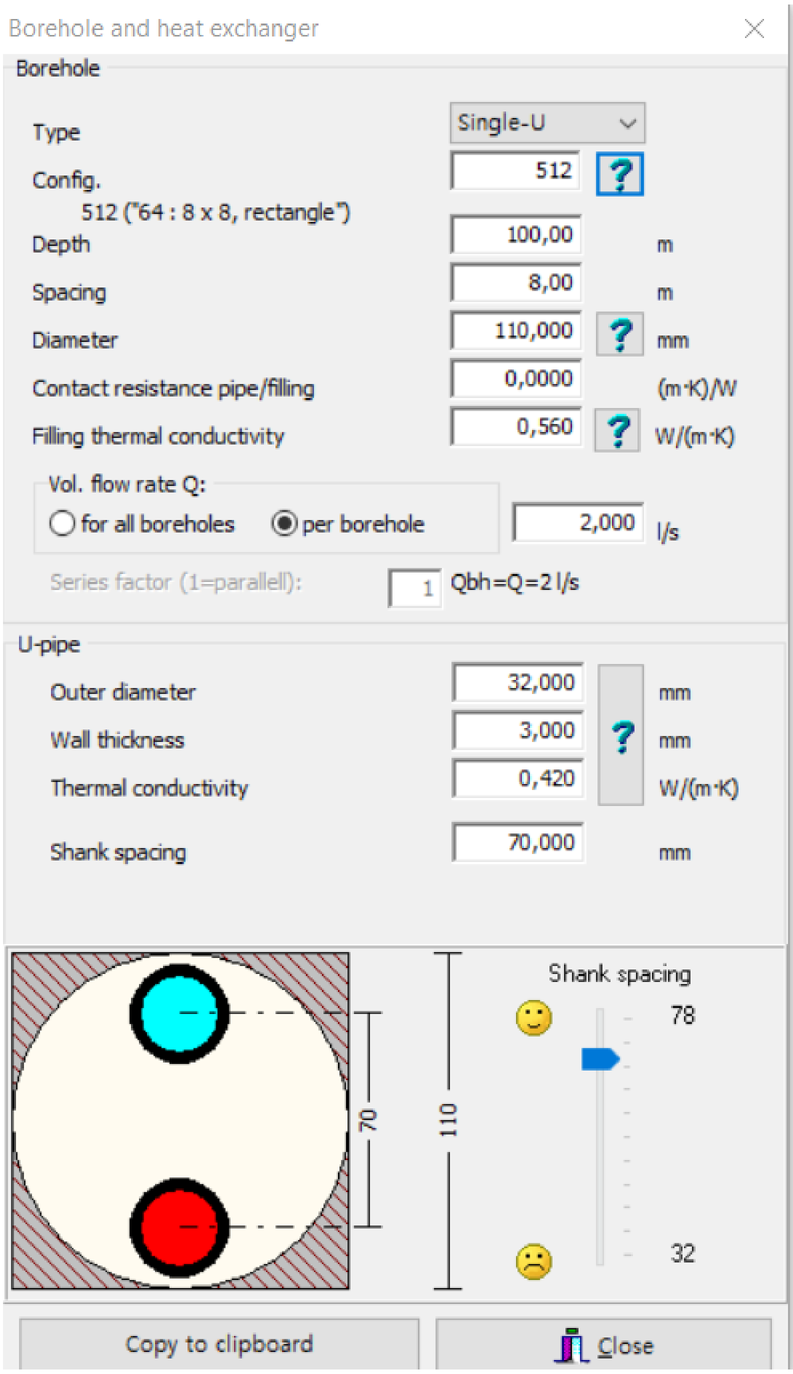

Figure 3.3: Input parameters (borehole and heat exchanger).

Use configuration number 560 which gives is a rectangular configuration of 8 x 8= 64 boreholes. The pattern is shown below together with its size (56m*56m)

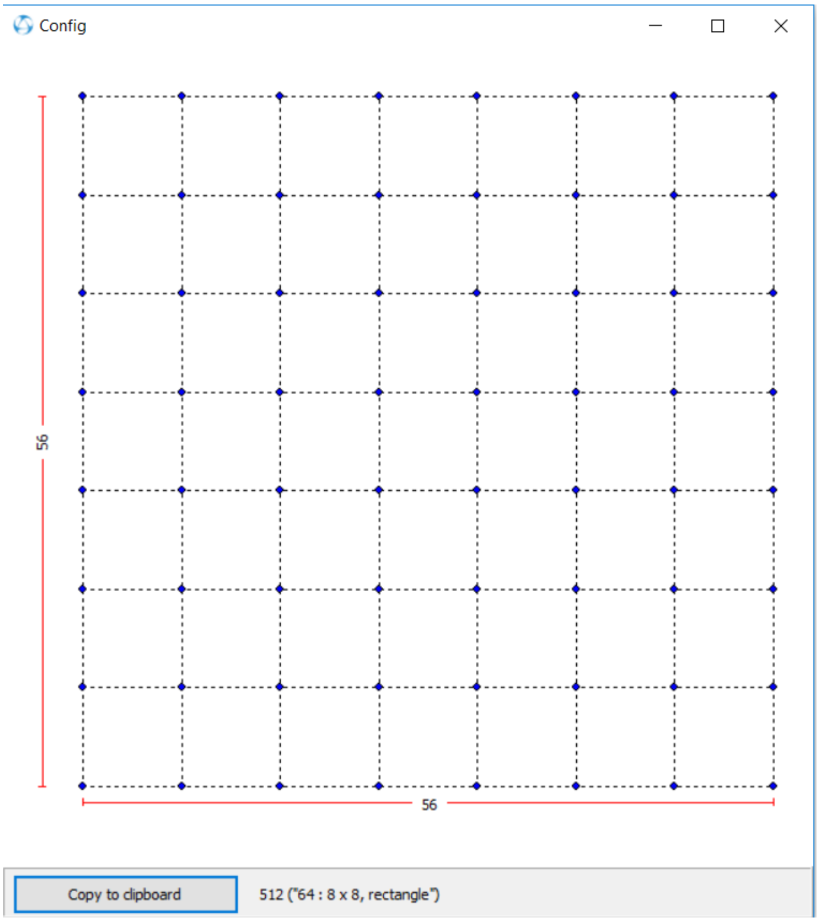

Figure 3.4: Borehole pattern (8 x 8 boreholes).

3.2.3 Base load

Doing simulations with EED, a base load has to be chosen. Here heat injected and extracted from the storage during a year is shown together with the monthly distribution of the loads for the BTES system.

Figure 3.5 below shows an annual cooling load of 1 GWh and an annual heating load of 1 GWh. The monthly distribution of these loads show that heat is injected 4 months a year and extracted 8 months a year. The warmest months of the year are chosen for heat injection, since the excess heat from the waste burning is highest during these months. The rest of the months are used for heat extraction.

For the base- load I choose four months (May to August) for the cooling load, with an equal factor of 0,25 for every month (4 x 0,25=1). The annual cooling load is the amount of heat transported to the ground (cooling of building), in this case it is the excess heat from the district heating network (waste burning).

The annual heating load is the amount of heat extracted from the ground. For simplicity and since I am mostly looking into how the mean fluid temperature vary with certain yearly heat loads with and without preheating the storage, I choose equal factors of 0,125 for the months (January to April) and (September to December) for the heating load. During these months heat is extracted from the storage. All the loads are direct, which means heat is transported without the use of heat pump.

When I write heat injection it means the cooling load and when I write heat extraction it means the heating load.

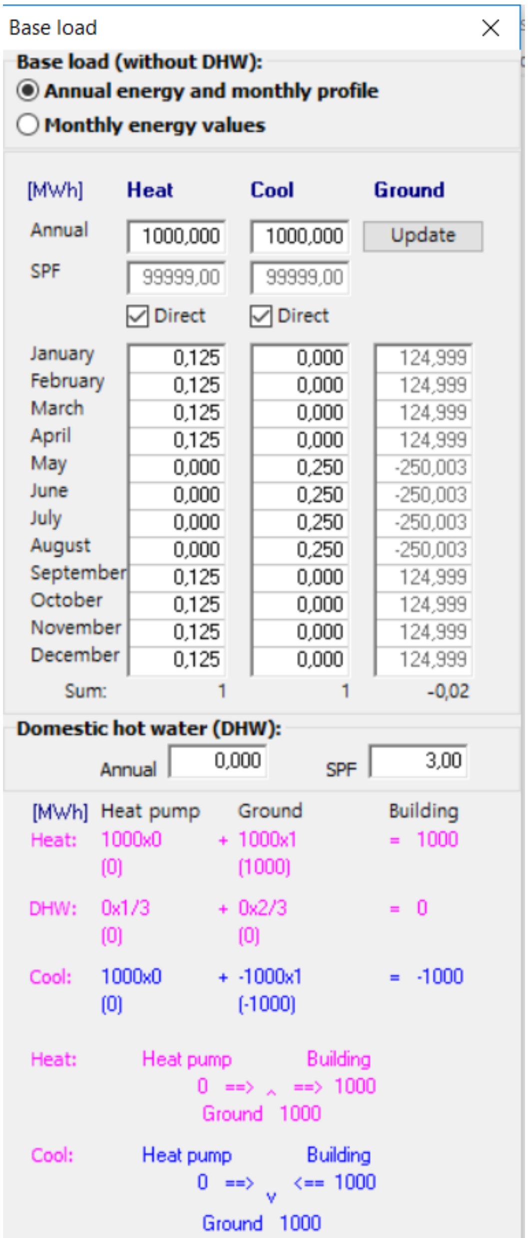

Figure 3.5: Input parameters (base load). Heating load= cooling load= 1 GWh. 4 months heat injection and 8 months heat extraction.

Another load profile I use in the simulations is with 6 months heat injection and 6 months heat extraction as shown below.

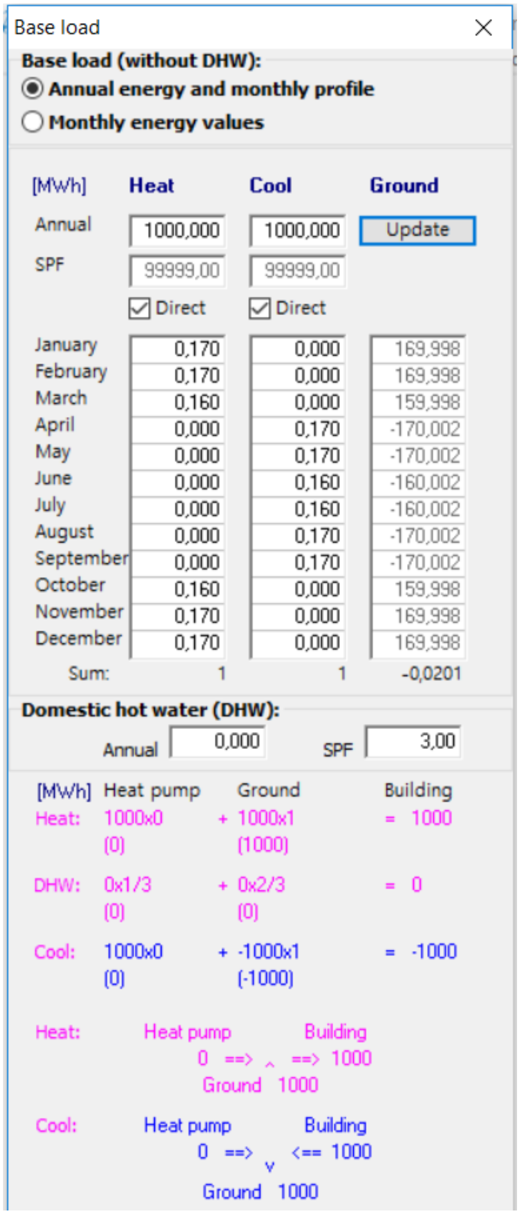

Figure 3.6: Input parameters (base load). Heating load= cooling load= 1 GWh. 6 months heat injection and 6 months heat extraction.

For reaching higher temperatures, the BTES system could be preheated. For preheating the heating load must be put to zero MWh.

3.3 Heat extraction

The information in the table below gives a simplified overview of the thermal conductivity and heat extraction rate for BTES- systems (RYBACK). The heat extraction rate increases with the thermal conductivity. Since there is a thick layer of soils, it would be preferable to drill deep so the largest part of the boreholes is in hard rock. Rock has higher thermal conductivity and heat extraction rate and it is less expensive to drill in rock. The heat extraction rate for hard rock is max. 70 W/m borehole. I choose to use an estimate of 60 W/m to be on the safe side.

Rock type	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Spesific extraction rate (W per m)**
Hard rock	3.0	Max. 70
Unconsolidated rock, saturated	2.0	45-50
Unconsolidated rock, dry	1.5	Max. 25

Table 3.1: From (RYBACK)

During the four summer months it would be possible to store per meter borehole:

60 (J/s)*(3600*24*30*4)s= 622 080 000 J ≈ <u>622 MJ/m</u>

This corresponds to in MWh/m:

$1W = 1\frac{J}{s}$

$1Wh = 1\frac{J}{s} * 3600s = 3600\ J$

1kWh= 3 600 000 J= 3,6MJ

622 MJ/m= 622/3,6= 173kWh/m= 0,173MWh/m (3.1)

A borehole of 110 meters (100m effective length) can uptake during four months:

100 * 0,173MWh= 17,3MWh (3.2)

During 6 months it can uptake:

17,3MWh x 1,5= 25,95 MWh (3.3)

During 8 months it can uptake:

17,3MWh x 2= 34,6 MWh (3.4)

3.4 Simulation steps

I divide the simulations in four parts.

Store 1 GWh (4 months heat injection and 8 months heat extraction)

First I choose input parameters for the simulations and decide which months of the year that is used for injecting heat into the storage and which months of the year heat is extracted. I choose four months for heat injection and eight months for heat extraction. I start with finding the required number of boreholes to store 1 GWh. T then find the appropriate configuration for storing that amount of energy. I use heat injected= heat extracted= 1 GWh and then I plot the mean fluid temperatures. This is done for borehole distances of 8, 6, 4 and 3 meters.

The different borehole distances will give different temperature variations, since shorter distances leads to less surface area which leads to lower storage volume and therefore higher temperature variations. For the different borehole distances, I also look into how fast the temperature increases if heat only is injected into the ground during a year, but not extracted (preheating). Here I first try to inject heat for 4 months a year, but I also try with 6 and 8 months. I try this because even though four months normally is used for heat injection and eight months for heat extraction, it might be excess heat for more than 4 months during years when heat is just injected into the storage. The amount of excess heat is relatively large (32 GWh). The largest part of it will probably be during the warmest summer months, but a part of it would probably be during autumn and spring too. Since the amount of excess waste heat is likely to be much larger than what the designed BTES system can store, preheating the storage for more than four months should be possible. Preheating will increase the ground temperature and the mean fluid temperature, but after preheating the fluid temperature variations will be the same when the BTES system is in use.

Sensitivity analysis

Then I do a sensitivity analysis by varying thermal conductivity and volumetric heat capacity and looking into if larger storages behaves in the same manner. I also do an analysis by varying borehole length.

Store 1 GWh (6 months heat injection and 6 months heat extraction)

Later I change the monthly distribution of the heating loads for storing 1 GWh. I try with injecting heat 6 months a year and extracting heat 6 months a year. To store 1 GWh with this monthly profile the amount of borehole meters can be less, since heat can be injected into the ground during 6 months instead of four months. Here I also look into how fast the temperature increases it heat only is injected into the ground, but not extracted. Here I try with 6 and 8 months of preheating.

Simulating larger storages

Finally I do some simulations for storages that can store 9 GWh, 18 GWh and a storage that can be placed inside an area of 80 x 80 meters which is the area available.

4 Results and discussion

4.1 Store 1 GWh (4 months heat injection and 8 months heat extraction)

As mentioned in chapter 3.1, Kvitebjørn Varme estimate the excess heat for storage to be about of 32 GWh. This is a large amount of energy that needs a large storage area, and there is no experience with BTES systems of this size. With reference to chapter 2.1.1 and 2.5.6, the energy storage capacity of existing BTES systems for seasonal storage varies from 0,5 GWh (DLSC) to 3 GWh (KTH)

I therefore start to simulate with storing 1GWh so I can compare with the results from the theory chapter and with existing projects. If a storage will be built, it will probably be built in steps to gain experience. A module of 1 GWh would be a reasonable size.

Here I simulate with injecting 1GWh during four months (May to August) and extracting 1 GWh during the other 8 months as shown in Figure 4.1 below and as explained in the theory chapter. I use the ground properties as described in Figure 3.2 in the theory chapter.

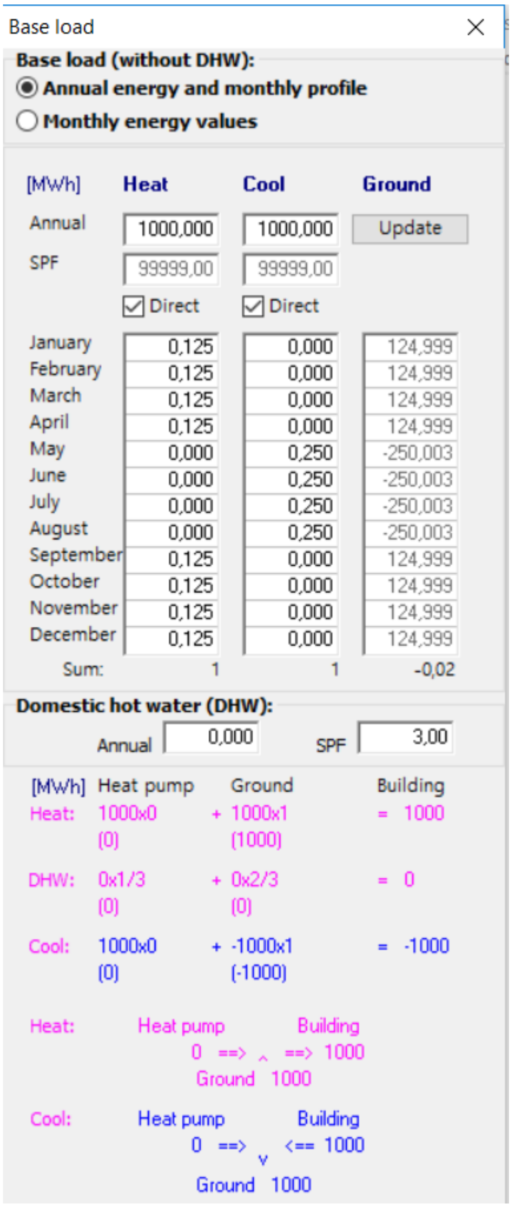

Figure 4.1: Input parameters (base load). Heating load= cooling load= 1 GWh. 4 months heat injection and 8 months heat extraction.

From eq. (3.2) we have that a borehole of 100m can uptake 17,3 MWh during four months.

Amount of boreholes needed to store 1GWh:

1000MWh/17,3MWh= ca. 60 boreholes

Use a quadratic borehole- pattern in EED of 8 x 8= 64 boreholes

This gives 6400 (64*100) borehole- metres for 1GWh

8m borehole distance. Storage area 64m x 64m

Select 8m borehole distance and borehole length of 100m as shown in Figure 4.2 below. Use the quadratic borehole pattern of 8 x 8 boreholes which covers an area of 64 x 64 meters when the distance between the boreholes is 8m.

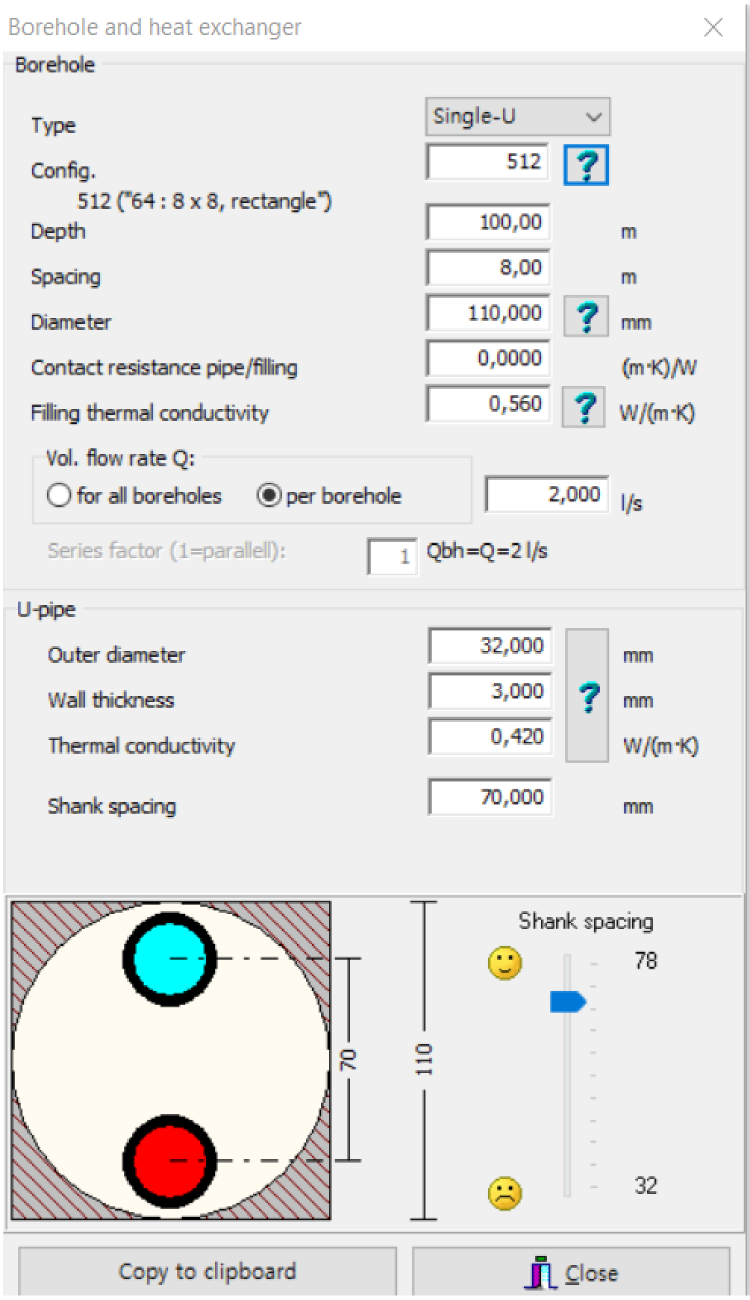

Figure 4.2: Input parameters (borehole and heat exchanger).

The first graph below shows the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

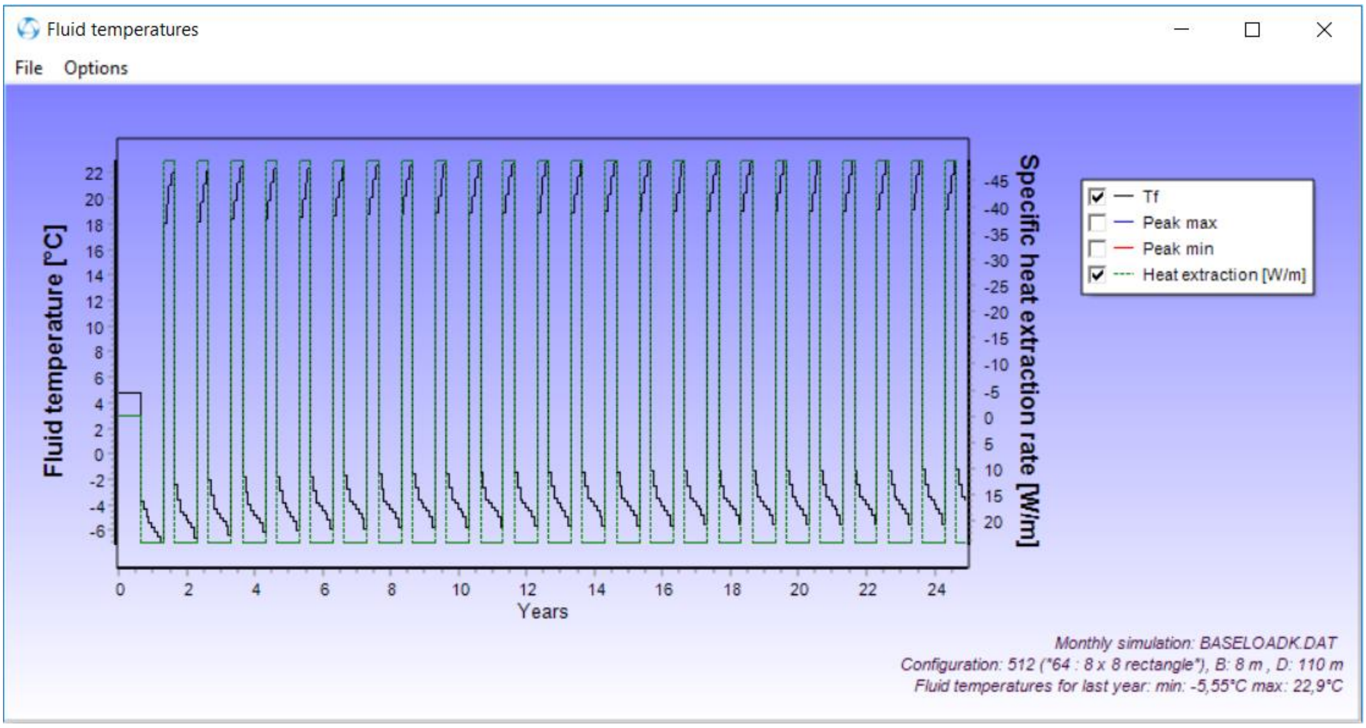

Figure 4.3: Temperature variations. Heating load= cooling load= 1 GWh. 8m borehole distance. 4 months heat injection and 8 months heat extraction

Gives temperature variations of about 28 degrees with temperatures varying between -6°C and 22°C.

Try now to just inject heat to the ground without extracting heat to see how fast the fluid-temperature increases. Cooling load= 1GWh and heating load= 0 GWh.

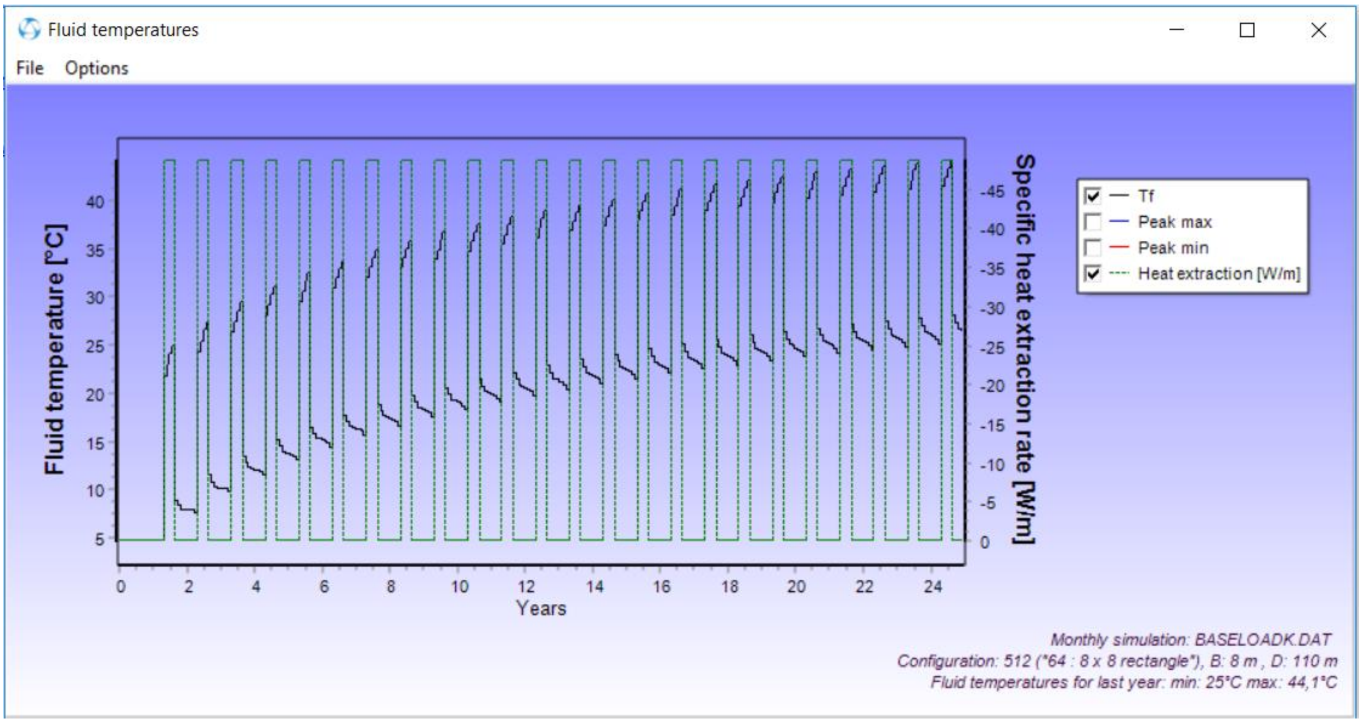

Figure 4.4: Cooling load= 1 GWh and heating load= 0 GWh. 8m borehole distance. Preheating 4 months yearly.

See that after about 3 years we reach a peak temperature of about 28°C. If the ground is heated for 3 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 28°C and 28- 28= 0°C. This is more desirable, since the temperatures are higher, but it is still relatively low temperatures.

After preheating for five years we reach a temperature of 31°C. If the ground is heated for 5 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 31°C and 31 - 28 = 3°C.

After preheating for seven years we reach a temperature of 34°C. If the ground is heated for 7 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 34°C and 34- 28= 6°C.

The results are summarized in the table below

	Storing 1 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**

No preheating	28 (-6- 22)	8
Preheating for 3 years	28 (0- 28)	14
Preheating for 5 years	28 (3- 31)	17
Preheating for 7 years	28 (6- 34)	20

Table 4.1: Fluid temperature variation and medium temperature with and without preheating. 8m borehole distance. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

6m borehole distance. Storage area 42m x 42m

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

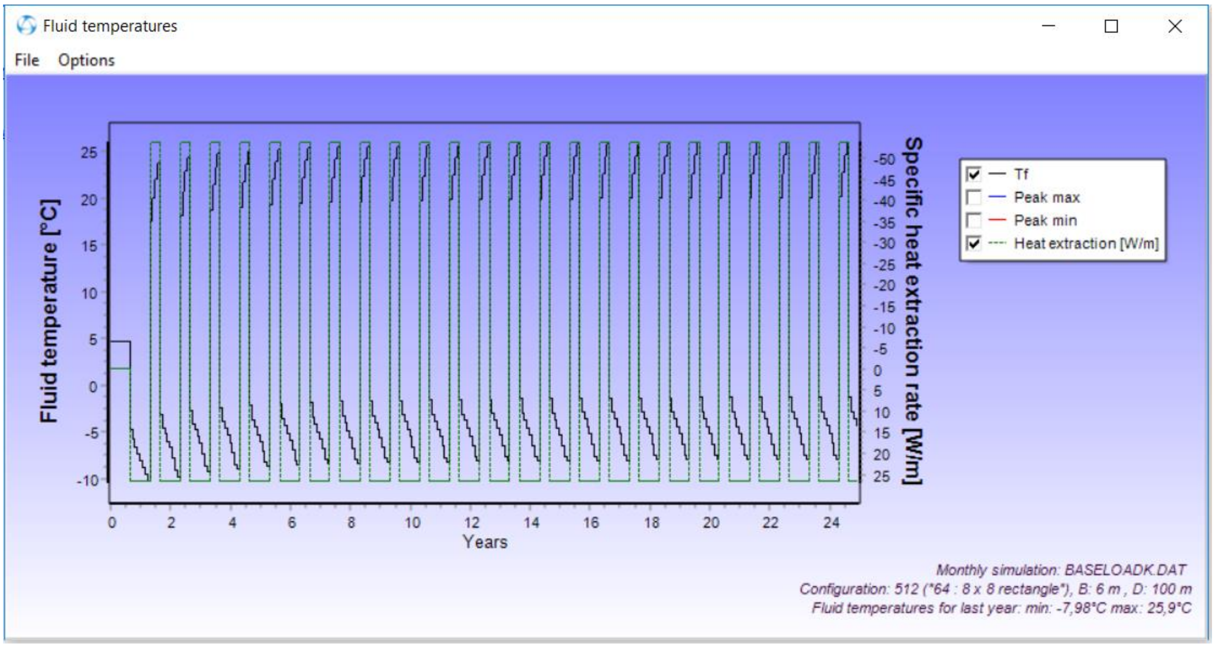

Figure 4.5: Temperature variations. Heating load= cooling load= 1 GWh. 6m borehole distance. 4 months heat injection and 8 months heat extraction

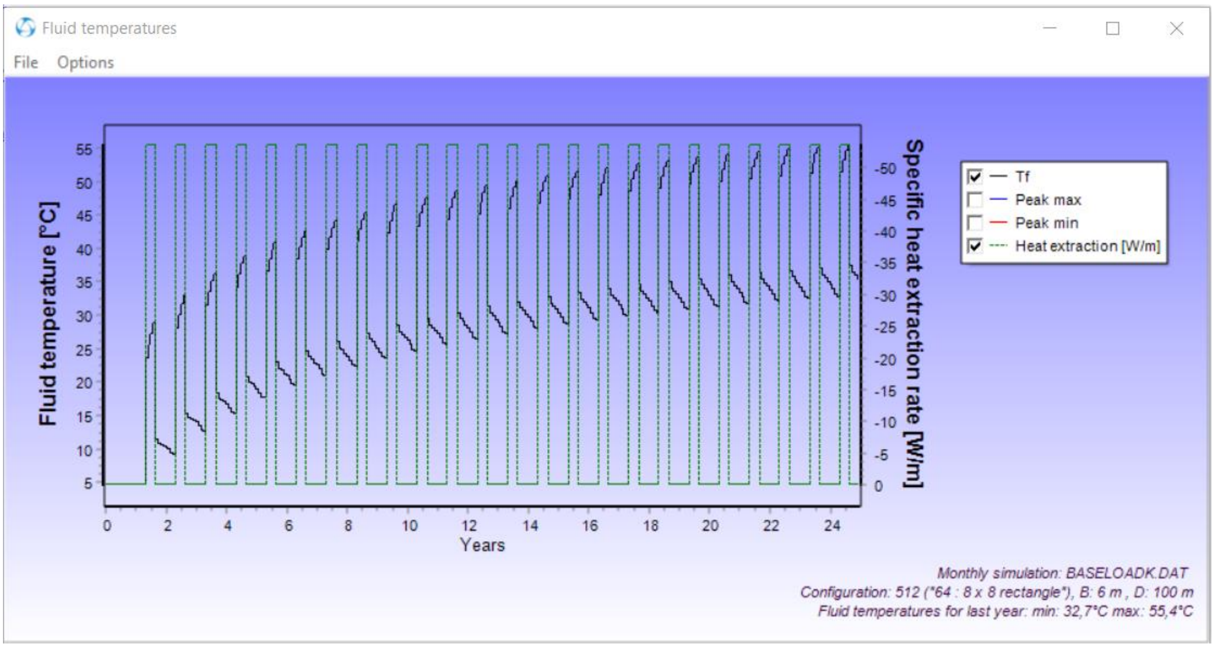

Figure 4.6: Cooling load= 1 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	34 (-10- 24)	7
Preheating for 3 years	34 (0- 34)	17
Preheating for 5 years	34 (6- 40)	23
Preheating for 7 years	34 (10- 44)	27

Table 4.2: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

4m borehole distance. Storage area of 28m x 28m

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

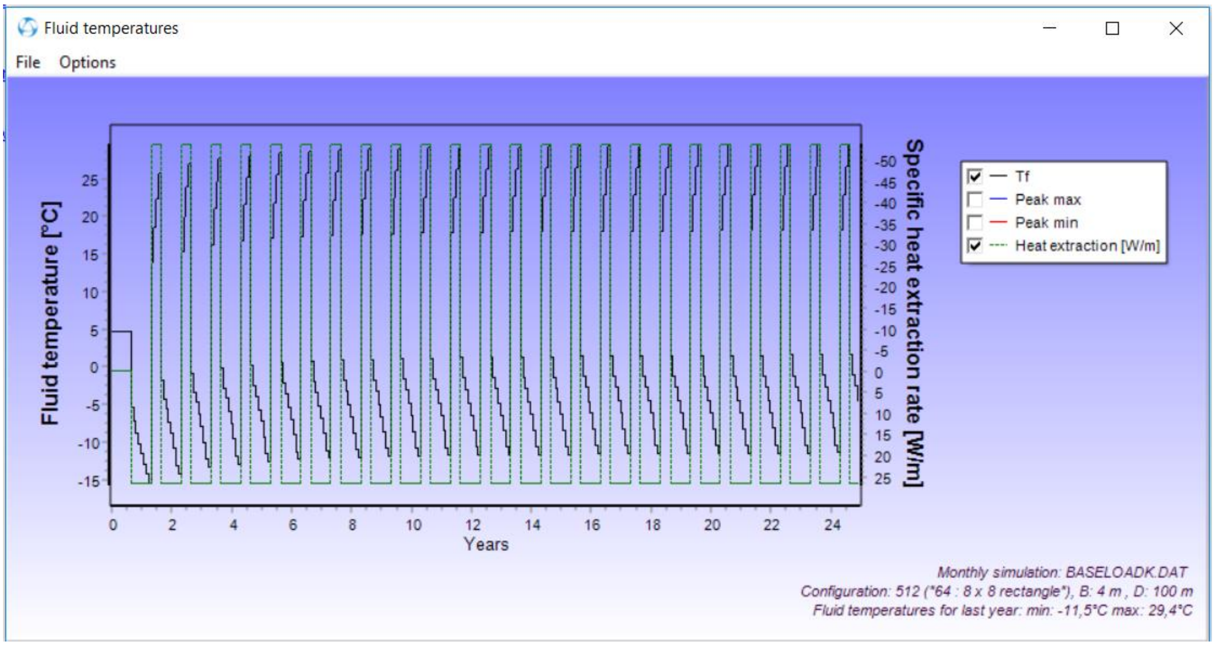

Figure 4.7: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

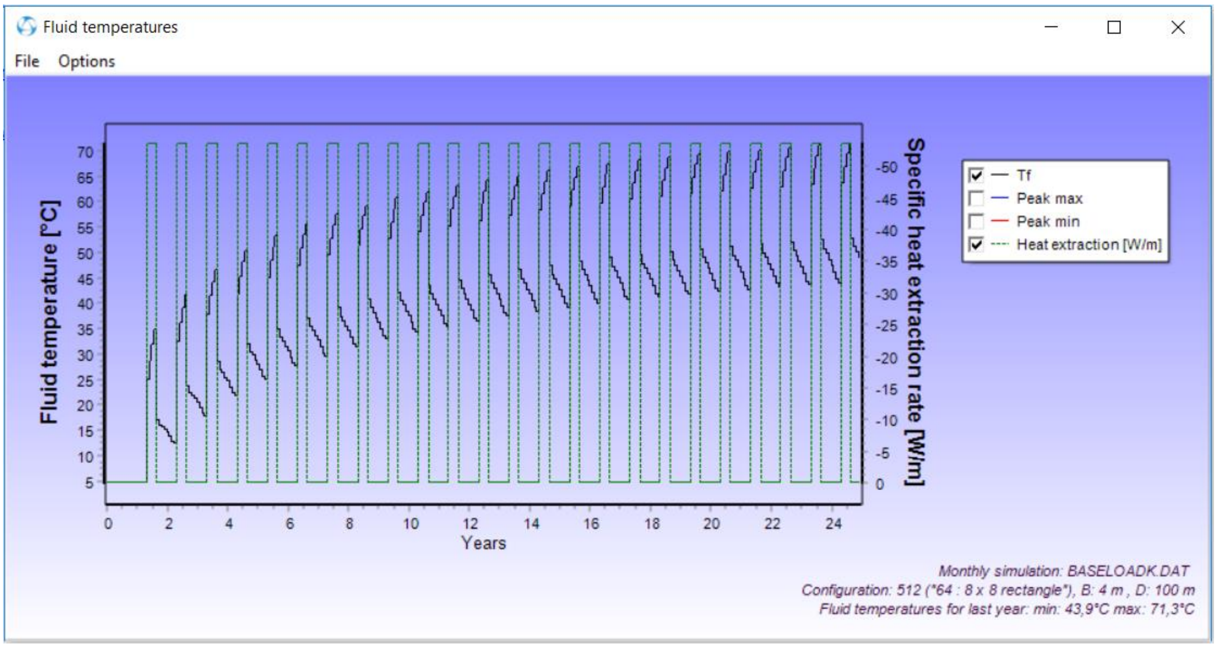

Figure 4.8: Cooling load= 1 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	41 (-15- 26)	5,5
Preheating for 3 years	41 (3- 44)	23,5
Preheating for 5 years	41 (10- 51)	30,5
Preheating for 7 years	41 (16- 57)	36,5

Table 4.3: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

3m borehole distance. Storage area of 21m x 21m

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 1 GWh and cooling load= 0 GWh (preheating).

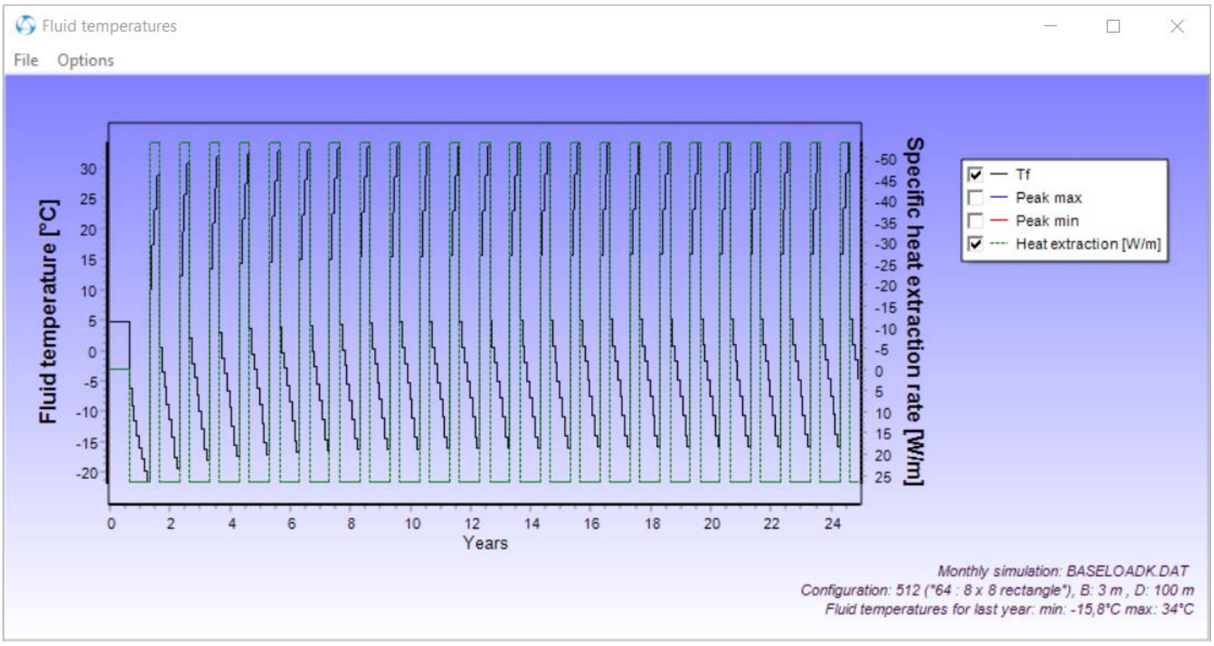

Figure 4.9: Temperature variations. Heating load= cooling load= 1 GWh. 3m borehole distance. 4 months heat injection and 8 months heat extraction.

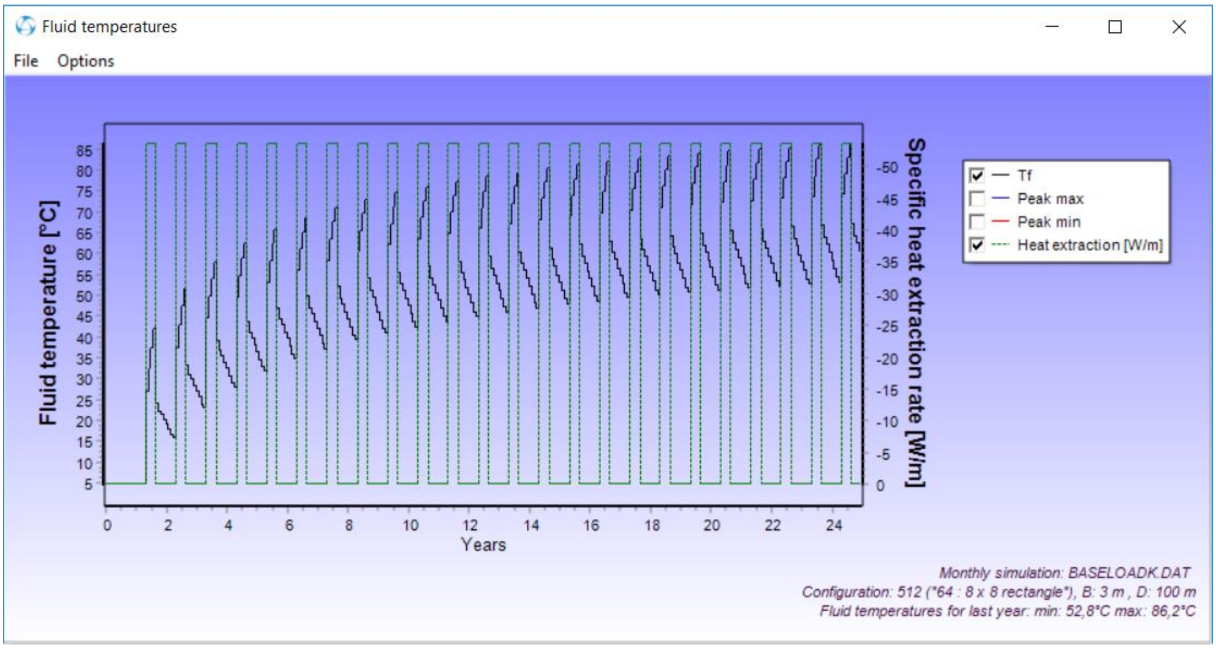

Figure 4.10: Cooling load= 1 GWh and heating load= 0 GWh. 3m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	50 (-20- 30)	5
Preheating for 3 years	50 (5- 55)	30
Preheating for 5 years	50 (14- 64)	39
Preheating for 7 years	50 (20- 70)	45

Table 4.4: Fluid temperature variation and medium temperature with and without preheating. 3m borehole distance. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

Summarizing

The results are summarized in the table below.

Borehole distance	Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW			
	None	3 years	5 years	7 years
8 (64 x 64 m)	8 28 (-6- 22)	14 28 (0- 28)	17 28 (3- 31)	20 28 (6- 34)
6 (48 x 48 m)	7 34 (-10- 24)	17 34 (0- 34)	23 34 (6- 40)	27 34 (10- 44)
4 (32 x 32 m)	5,5 41 (-15- 26)	23,5 41 (3- 44)	30,5 41 (10- 51)	36,5 41 (16- 57)
3 (24 x 24 m)	5 50 (-20- 30)	30 50 (5- 55)	39 50 (14- 64)	45 50 (20- 70)

Table 4.5: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

From the table above we can extract the following information:

- No preheating give negative fluid temperatures for all borehole distances. Temperatures below 0°C should be avoided even if freezing temperature for the liquid in U-tube is -14°C.
- Closer borehole- distance gives higher temperature variations.
- Medium temperature is relatively low, For 4m borehole distance it is 23,5°C after 3 years of preheating and 30,5°C after 5 years.

Closer spacing between the boreholes with the same number of boreholes gives less storage area, but higher mean fluid temperature variations with the same load since the storage volume is lower. Since total borehole- metres is the same, the storage could provide the same amount of power (0,36MW). An advantage is that high temperatures are reached in a shorter amount of time.

Preheating for 6 months

From eq. (3.3) we have that a borehole of 100m can uptake 25,95 MWh during months.

The storage can the uptake during 6 months:

25,95MWh x 64= 1658 MWh≈ 1,66 GWh

Try now to preheat the storage for 6 months. For the base- load, I choose 6 months (April to September) for the cooling load, with almost equal factors for each month (0,16 and 0,17). Use the load distribution from Figure 3.6 but with heating load= 0 GWh and cooling load= 1,66 GWh when preheating for 6 months. Can then combine the results from preheating with the results showing the temperature variations when the storage is used with 4 months heat injection and 8 months heat extraction.

Borehole distance 8m

The plot below shows the fluid temperatures when preheating 6 months a year. In the table below this result is combined with the plot in Figure 4.3 from the last subchapter, showing the mean fluid temperatures with 4 months heat injection and 8 months heat extraction.

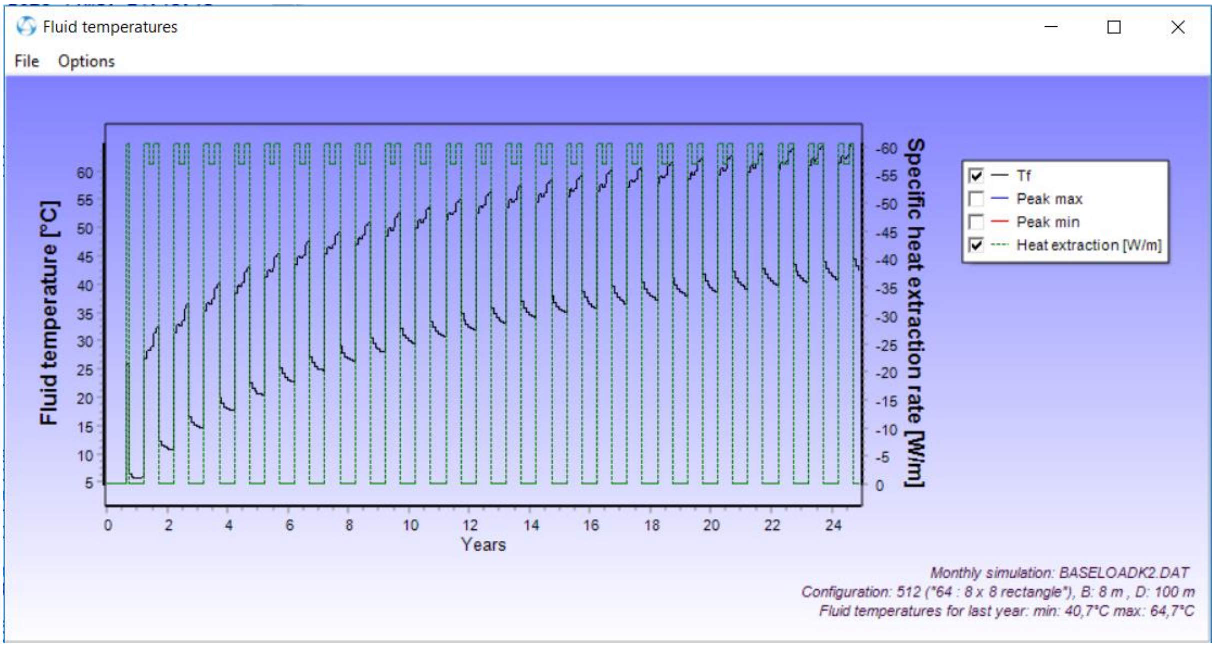

Figure 4.11: Cooling load= 1,66 GWh and heating load= 0 GWh. 8m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	28 (-6- 22)	8
Preheating for 3 years	28 (9- 37)	23
Preheating for 5 years	28 (16- 44)	30
Preheating for 7 years	28 (21- 49)	35

Table 4.6: Fluid temperature variation and medium temperature with and without preheating. 8m borehole distance. Preheating 6 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 6m.

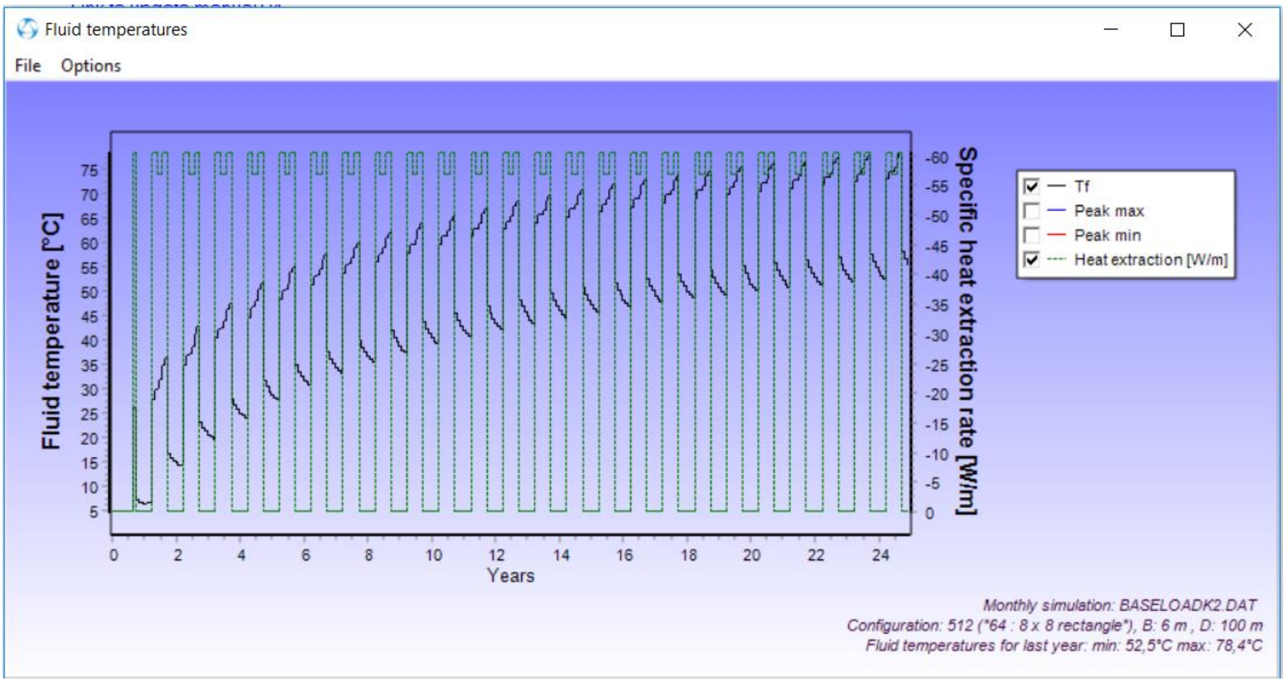

Figure 4.12: Cooling load= 1,66 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	34 (-10- 24)	7
Preheating for 3 years	34 (10- 44)	27
Preheating for 5 years	34 (18- 52)	35
Preheating for 7 years	34 (25- 59)	42

Table 4.7: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 6 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 4m

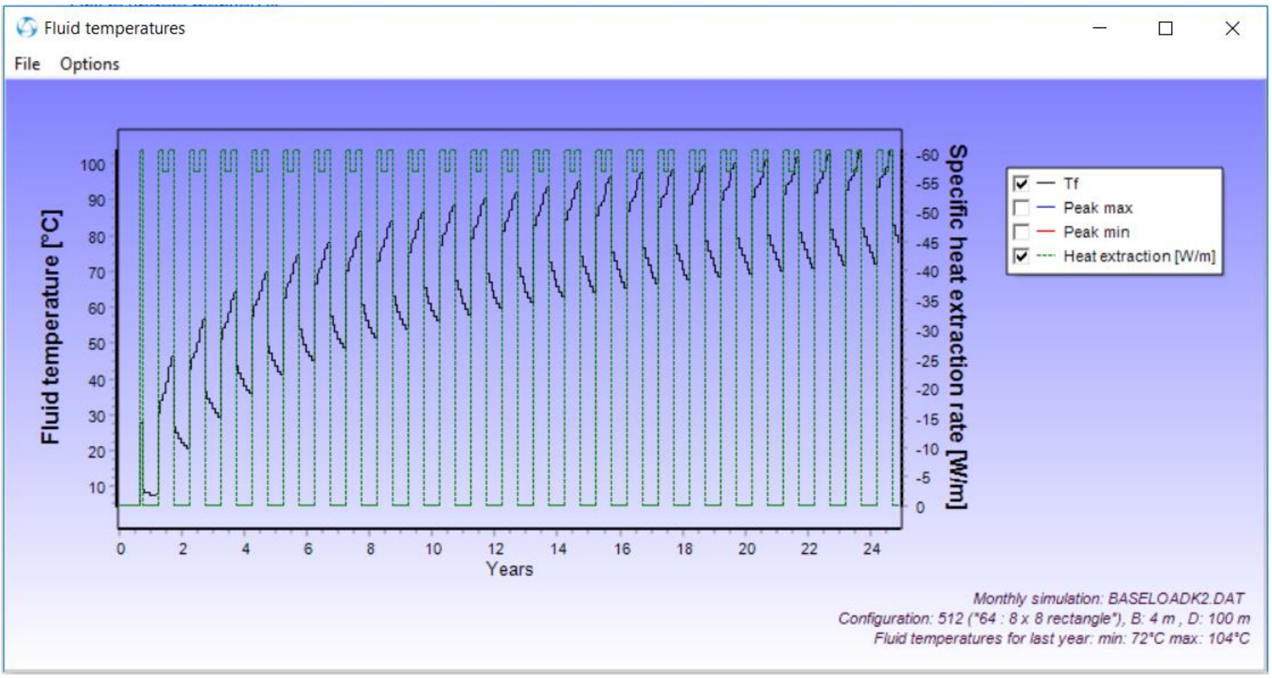

Figure 4.13: Cooling load= 1,66 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	41 (-15- 26)	5,5
Preheating for 3 years	41 (17- 58)	37,5
Preheating for 5 years	41 (70- 29)	49,5
Preheating for 7 years	41 (39- 80)	59,5

Table 4.8: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating 6 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 3m

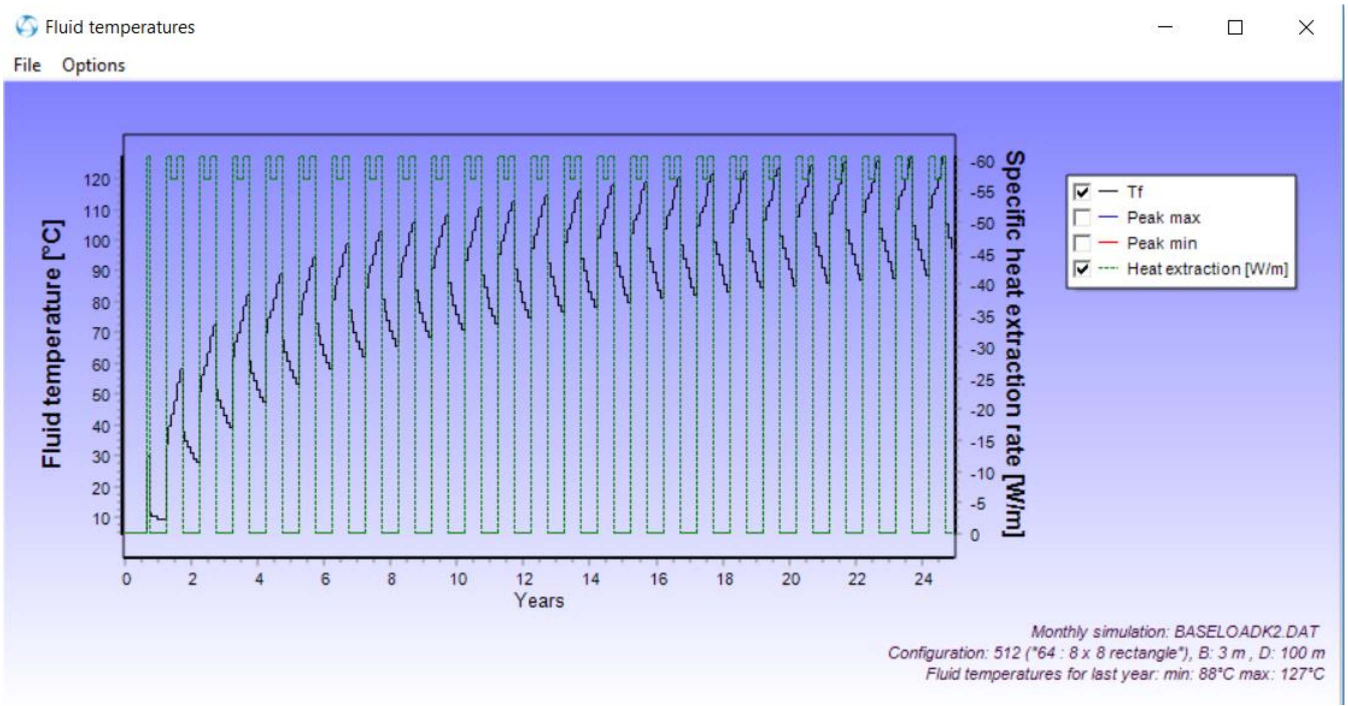

Figure 4.14: Cooling load= 1,66 GWh and heating load= 0 GWh. 3m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	41 (-15- 26)	5,5
Preheating for 3 years	41 (17- 58)	37,5
Preheating for 4 years	41 (39- 80)	59,5

Table 4.9: Fluid temperature variation and medium temperature with and without preheating. 3m borehole distance. Preheating 6 months yearly. 4 months heat injection and 8 months heat extraction.

Tables

Borehole distance	Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW			
	None	**3 years**	**5 years**	**7 years**
8 (64 x 64 m)	8 28 (-6- 22)	23 28 (9- 37)	30 28 (16- 44)	35 28 (49- 21)
6 (48 x 48 m)	7 34 (-10- 24)	27 34 (10- 44)	35 34 (18- 52)	42 34 (25- 59)
4 (32 x 32 m)	5,5 41 (-15- 26)	37,5 41 (17- 58)	49,5 41 (29- 70)	59,2 41 (39- 80)
3 (24 x 24 m)	5 50 (-20- 30)	50 50 (25- 75)	Temp exceed 80	Temp exceed 80

Table 4.10: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating. Preheating 6 months yearly. 4 months heat injection and 8 months heat extraction.

For 4m borehole distance, the table shows a medium temperature of 37,5°C and a peak temperature of 58°C after 5 years of preheating and 49,5°C medium temperature and 70 °C peak temperature after 5 years. Peak temperatures should not exceed 70°C as this temperature is close to the boiling point of the fluid and because the lifetime of the U-tube material is reduced with high temperatures.

Preheating for 8 months

From eq. (3.4) we have that a borehole of 100m can uptake 34,6 MWh during 8 months.

The storage can the uptake during 8 months:

34,6 MWh x 64= 1658 MWh≈ 2,21 GWh

Look now at preheating the storage for 8 months. In the figure below for the base- load, I choose 8 months (March to October) for the cooling load, with equal factors of 0,125 for each month. Use heating load= 0 GWh and cooling load= 2,21 GWh when preheating. Can then combine the results from preheating with the results showing the temperature variations when the storage is used with 4 months heat injection and 8 months heat extraction.

Borehole distance 8m

Figure 4.15 below shows the fluid temperatures when preheating 8 months a year. In the table below this result is combined with the plot in Figure 4.3, showing the mean fluid temperatures with 4 months heat injection and 8 months heat extraction.

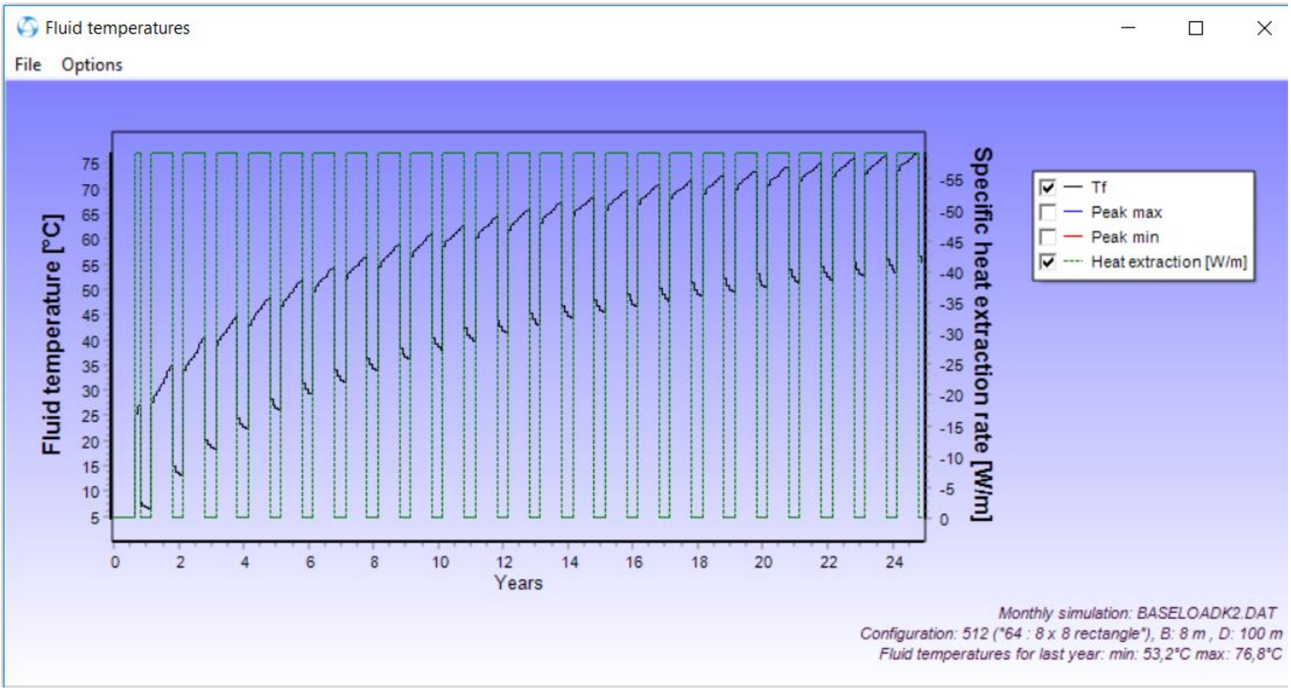

Figure 4.15: Cooling load= 2,21 GWh and heating load= 0 GWh. 8m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	28 (-6- 22)	8
Preheating for 3 years	28 (13- 41)	27
Preheating for 5 years	28 (21- 49)	35
Preheating for 7 years	28 (27- 55)	41

Table 4.11: Fluid temperature variation and medium temperature with and without preheating. 8m borehole distance. Preheating 8 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 6m

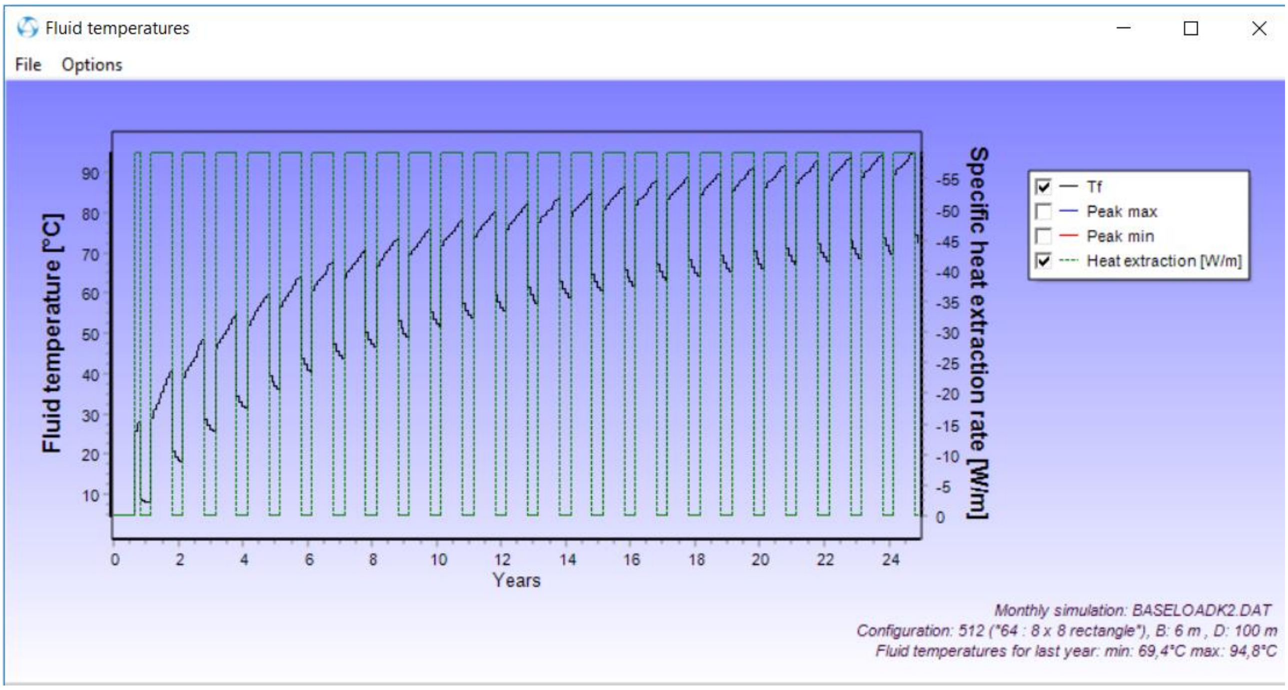

Figure 4.16: Cooling load= 2,21 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	34 (-10- 24)	7
Preheating for 3 years	34 (16- 50)	33
Preheating for 5 years	34 (26- 60)	43
Preheating for 7 years	34 (36- 70)	53

Table 4.12: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 8 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 4m

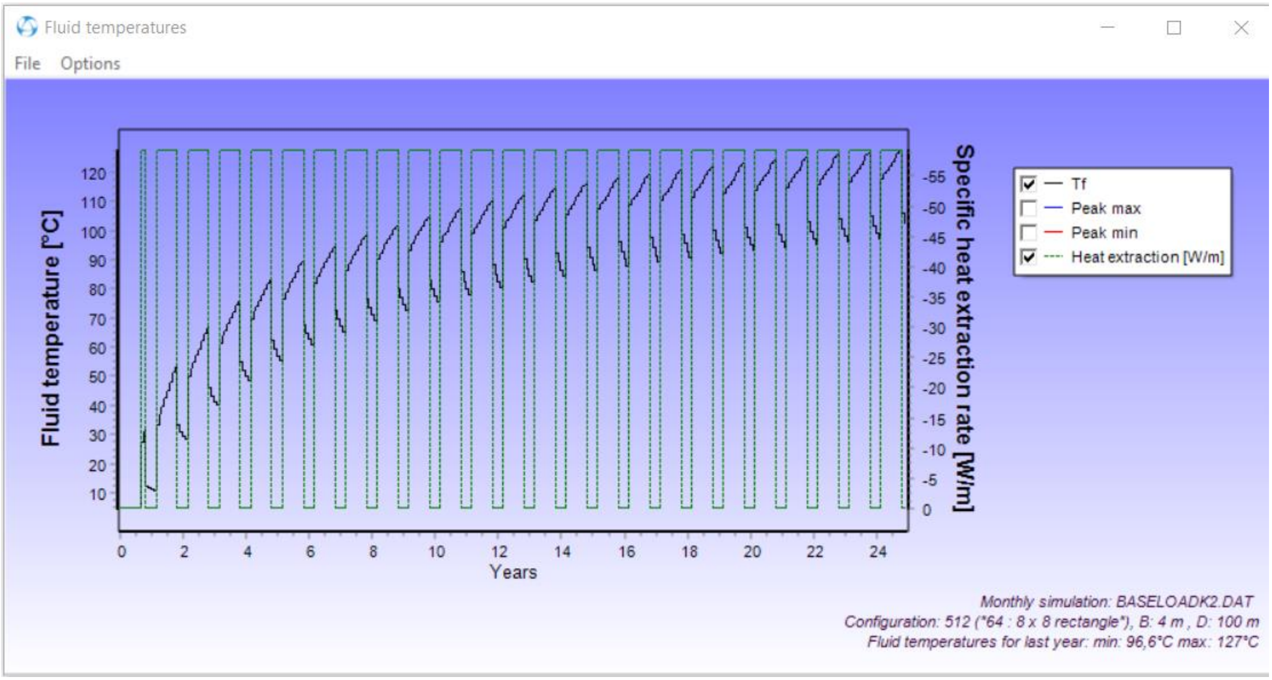

Figure 4.17: Cooling load= 2,21 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	41 (-15- 26)	5,5
Preheating for 3 years	41 (29- 70)	49,5
Preheating for 4,7 years	41 (39- 80)	59,5

Table 4.13: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating 8 months yearly. 4 months heat injection and 8 months heat extraction.

Borehole distance 3m

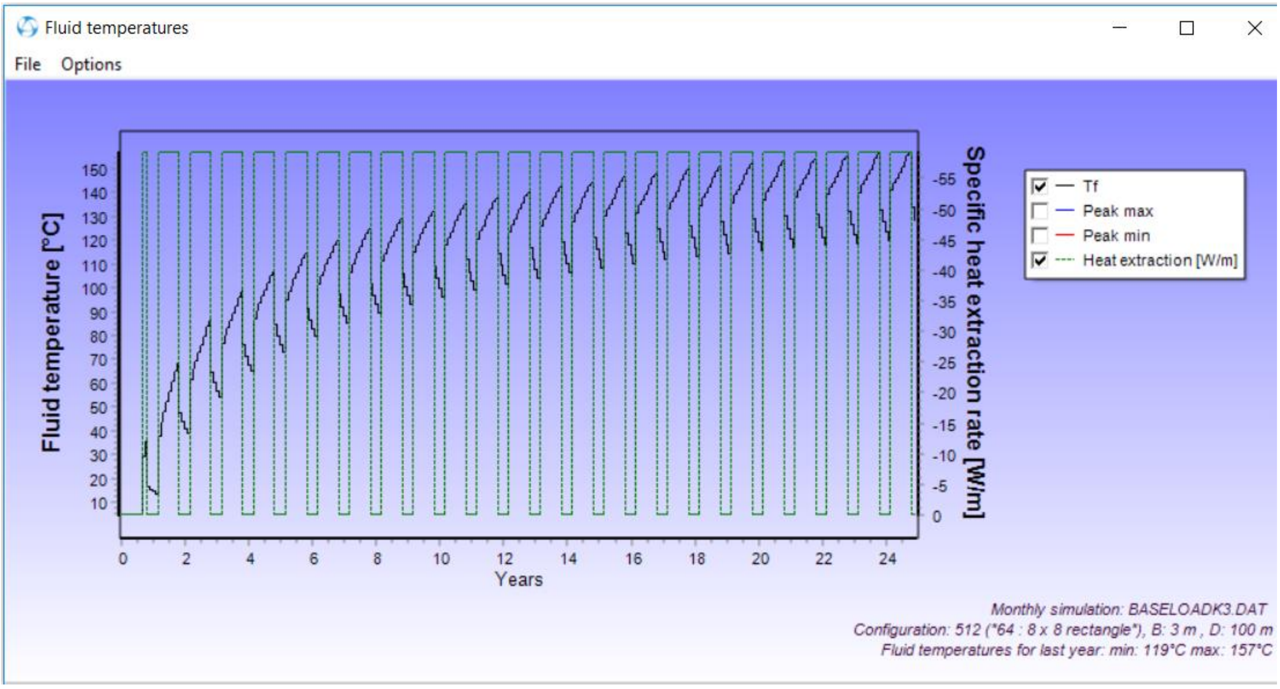

Figure 4.18: Cooling load= 2,21 GWh and heating load= 0 GWh. 3m borehole distance. Preheating 8 months yearly.

See we reach 80°C after about 2,7 years, so the ground should not be heated for a longer time.

The results are summarized in the table below

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	50 (-20- 30)	5
Preheating for 2,7 years	50 (30- 80)	55

Table 4.14: Fluid temperature variation and medium temperature with and without preheating. 3m borehole distance. Preheating 8 months yearly. 4 months heat injection and 8 months heat extraction.

Table

Borehole distance	**Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW**			
	None	**3 years**	**5 years**	**7 years**
8 (64 x 64 m)	8 28 (-6- 22)	27 28 (13- 41)	35 28 (21- 49)	41 28 (27- 55)
6 (48 x 48 m)	7 34 (-10- 24)	33 34 (16- 50)	43 34 (26- 60)	53 34 (36- 70)
4 (32 x 32 m)	5,5 41 (-15- 26)	49,5 41 (29- 70)	Temp exceed 80	Temp exceed 80
3 (24 x 24 m)	5 50 (-20- 30)	Temp exceed 80	Temp exceed 80	Temp exceed 80

Table 4.15: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating. Preheating 8 months yearly. 4 months heat injection and 8 months heat extraction.

- For 4m borehole distance a peak temperature of 70°C is reached after 3 years of preheating with a medium temperature of 49,5°C. If preheating for a longer period, the temperature exceed 80°C which is above the boiling point for the liquid.

- In this case we also reach a reasonable medium fluid temperature of 43°C and a peak temperature of 60°C for 6m borehole distance.

Summarizing and discussing

For optimal borehole length I choose four meters since with close spacing we get many borehole meters per unit area which leads to a high heat extraction per unit area. This is useful since the storage area is limited. Another advantage is that we reach higher temperatures when preheating because of many borehole- meters on the same volume. Three meters is probably too close because with deep drilling and close spacing there will be a risk for the boreholes interfering with each other.

4.2 Sensitivity analysis

Do a sensitivity analysis by varying some parameters. Use borehole distance of 4 meters. Use also heat injection 4 months a year and heat extraction 8 months a year, and preheating 4 months a year in the simulations below.

4.2.1 Varying thermal conductivity

Thermal conductivity: 3.2 +- 1 W/(mK).

Vary the thermal conductivity with +-1 since EED suggests it to vary by this amount around the mean value for Granite and Gneiss when selecting input parameters.

With thermal conductivity of 3,2 W/(mK)

With a thermal conductivity of 3,2 W/(mK) and a borehole distance of 4m we can use the results from chapter 1.1, where we find the temperature variations with heating load= cooling load=1 GWh and with preheating 4 months a year with cooling load= 1 GWh

With thermal conductivity of 2,2 W/(mK)

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating). Have now used a thermal conductivity of 2,2 W/(mK) as an input parameter.

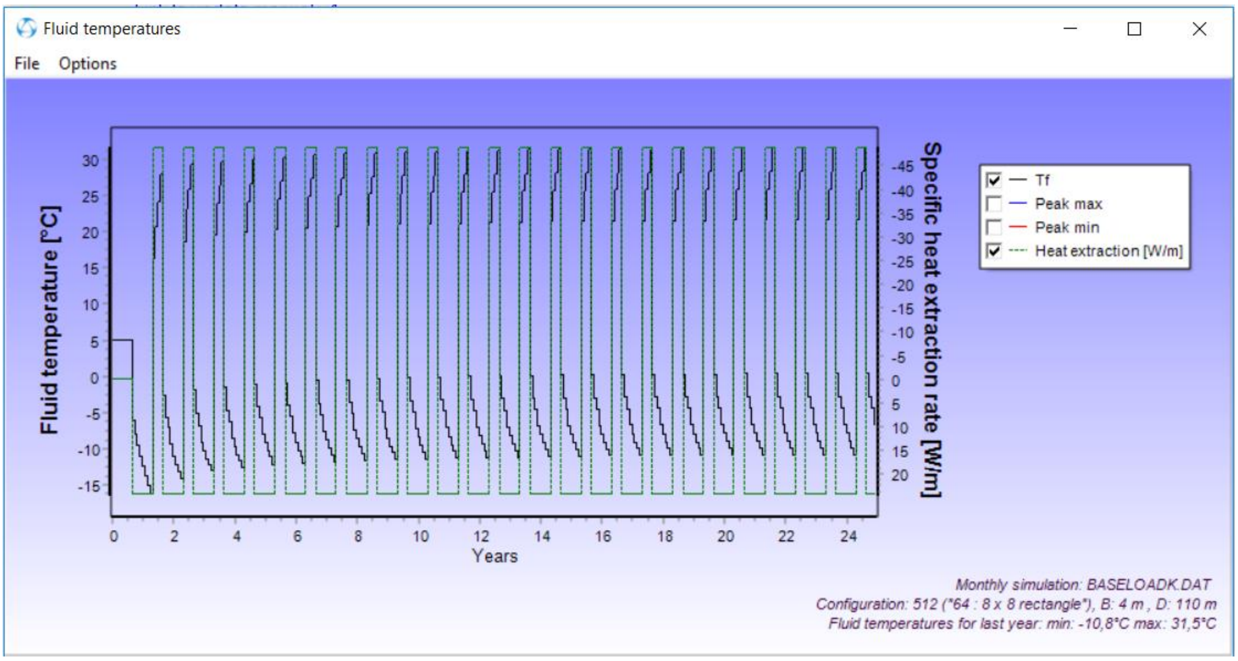

Figure 4.19: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Thermal conductivity 2,2 W/(mK) .

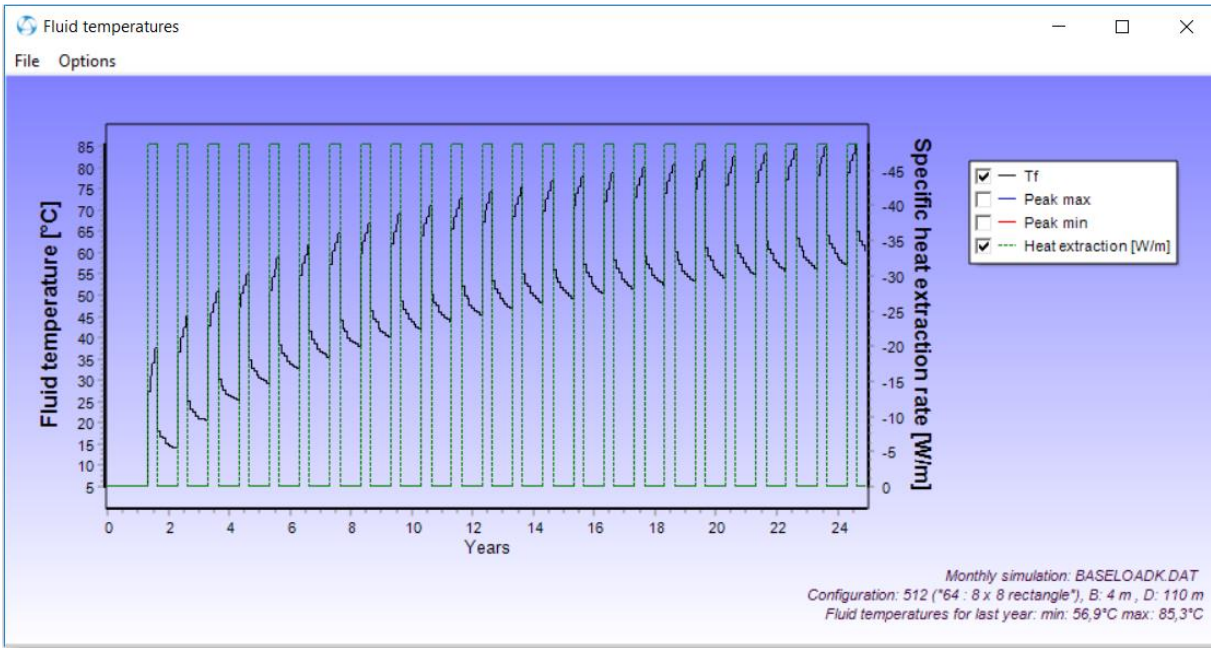

Figure 4.20: Cooling load= 1 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly. Thermal conductivity 2,2 W/(mK).

With thermal conductivity of 4,2 W/(mK) :

Do the same simulations, but now with a thermal conductivity of 4,2 W/(mK).

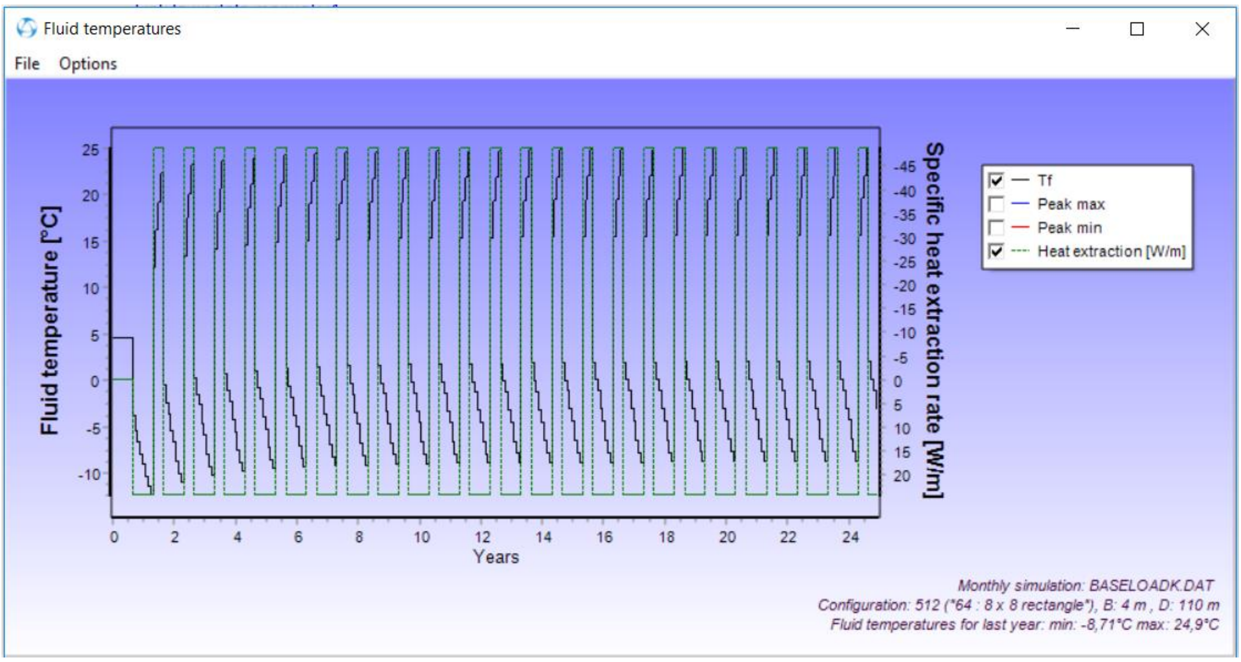

Figure 21: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Thermal conductivity of 4,2 W/(mK) .

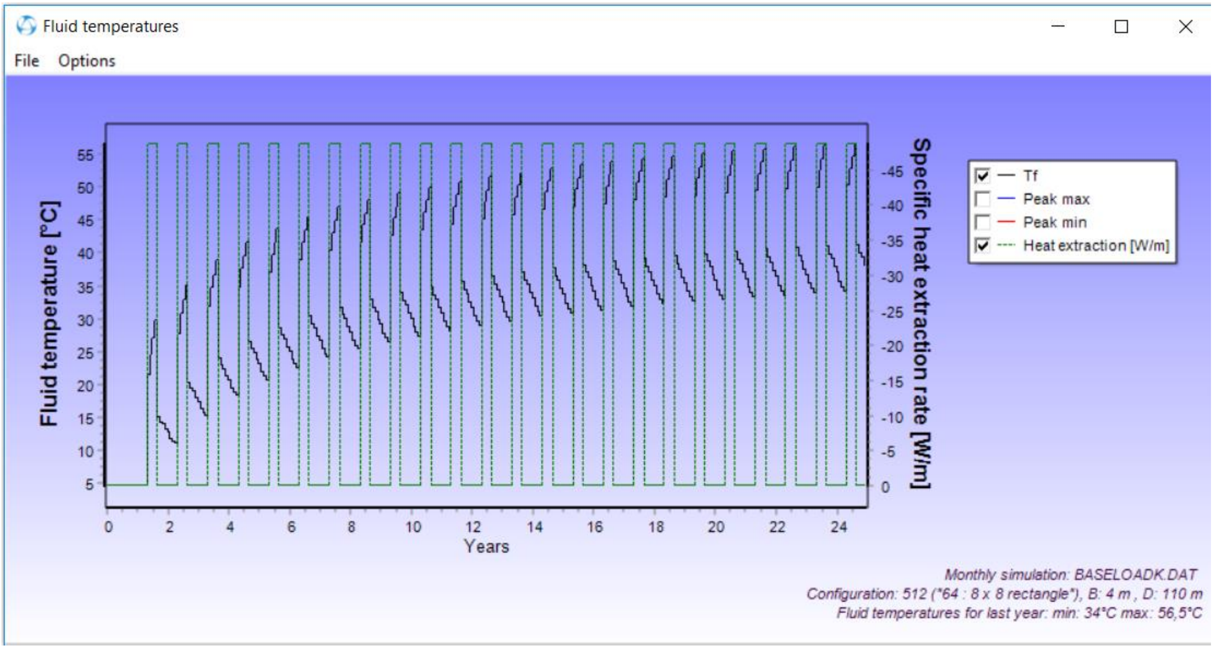

Figure 4.22: Cooling load= 1 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly. Thermal conductivity 4,2 W/(mK) .

Thermal conductivity (W/(mK))	Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW			
	None	3 years	5 years	7 years
3,2 (Default)	5,5 41 (-15- 26)	23,5 41 (3- 44)	30,5 41 (10- 51)	36,5 41 (16- 57)
2,2	6,5 43 (-15- 28)	24,5 43 (3- 46)	34,5 43 (13- 56)	42,5 43 (21- 64)
4,2	5,5 35 (-12- 23)	18,5 35 (1- 36)	24,5 35 (7- 42)	28,5 35 (11-46)

Table 4.16: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating for different values of thermal conductivity. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

Decreasing the thermal conductivity leads to a little higher temperature variations, while increasing it leads to lower temperature variations. The reason might be that when heat is injected, the fluid temperature increases. With a high thermal conductivity, the energy is transported away more rapidly from the borehole and the fluid temperature reaches a lower peak temperature. When heat is extracted from the fluid, the fluid temperature will decrease and heat stored in the rock will flow towards the borehole. This heat flow is more rapid with a higher thermal conductivity and therefore the minimum fluid temperature will be that low.

When the storage is preheated, a lower thermal conductivity leads to a faster increase in temperature, while a higher thermal conductivity leads to a slower increase. The reason might be that when preheating, heat is transferred to the fluid in the pipes. A higher thermal conductivity would probably transport away this energy to the surrounding rock faster.

For thermal conductivity between 2,2 W/(mK) and 4,2 W/mK), the mean fluid temperature has a variation of 5 degrees after 3 years of preheating and 10 degrees after 5 years.

4.2.2 Varying volumetric heat capacity

2,2 +- 0,3 MJ/(m^3K)

Vary the volumetric heat capacity with +-0,3 since EED suggests it to vary by this amount around the mean value for Granite and Gneiss when selecting input parameters.

With volumetric heat capacity of 2,2 MJ/(m^3K):

With a thermal conductivity of 2,2 and a borehole distance of 4m we can use the results from chapter 1.1, where we find the temperature variations with heating load= cooling load=1 GWh [Figure 4.7] and with preheating 4 months a year with cooling load= 1 GWh and a heating load of 0 GWh [Figure 4.8].

With volumetric heat capacity of 1,9 MJ/(m^3K):

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

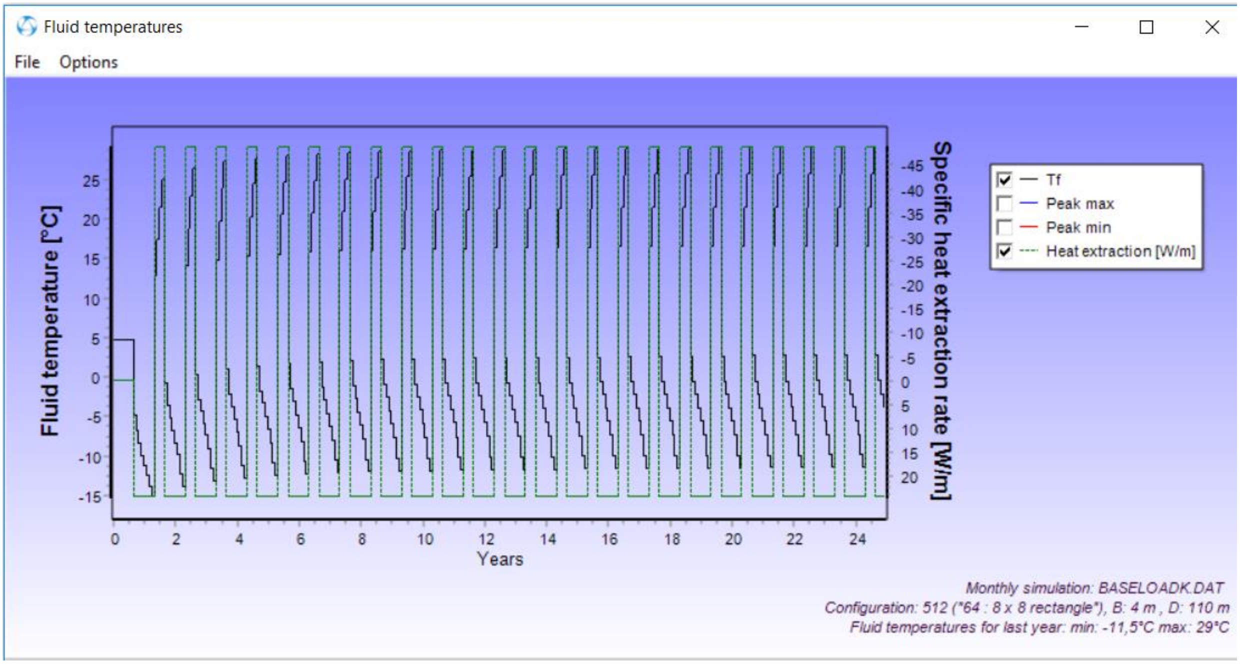

Figure 4.23: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Volumetric heat capacity of 1,9.

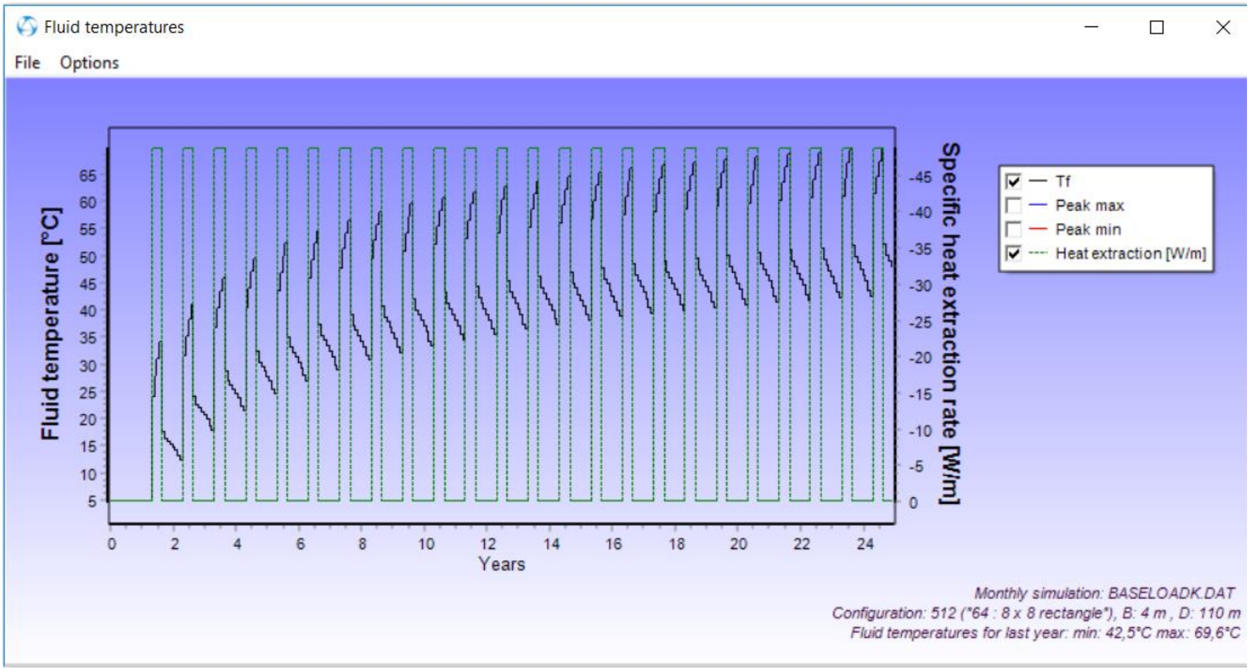

Figure 4.24: Cooling load= 1 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly. Volumetric heat capacity of 1,9 MJ/(m^3K).

With volumetric heat capacity of 2,5 MJ/(m^{3}K):

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

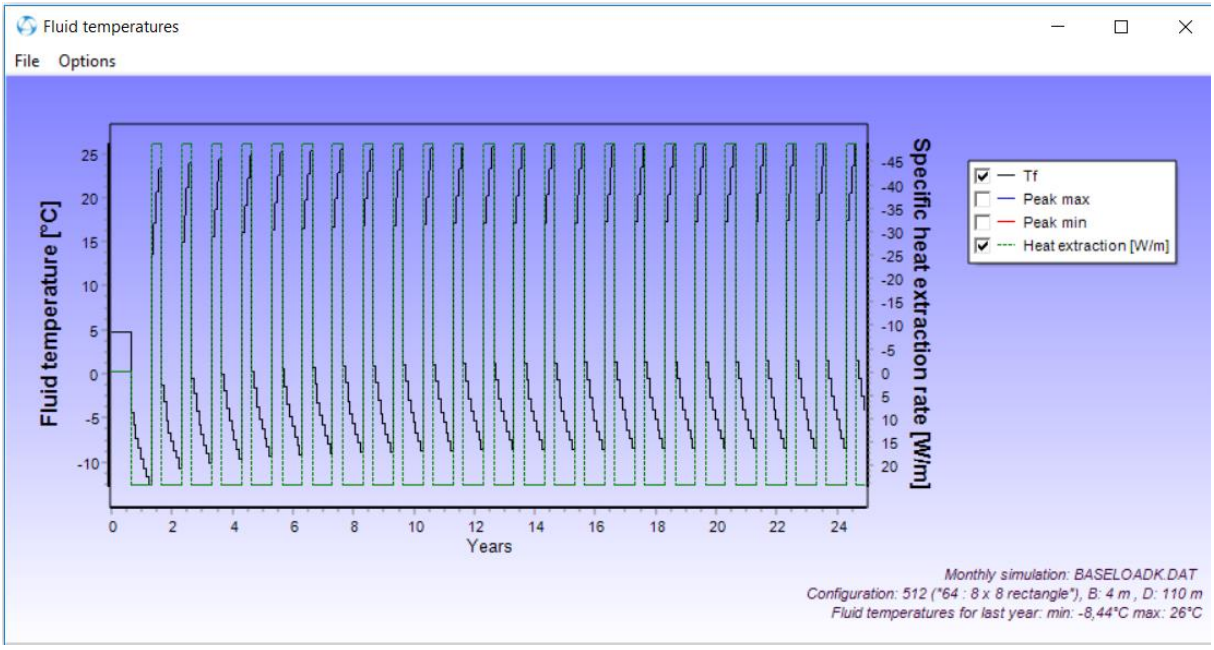

Figure 4.25: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Volumetric heat capacity of 2,5 MJ/(m^{3}K).

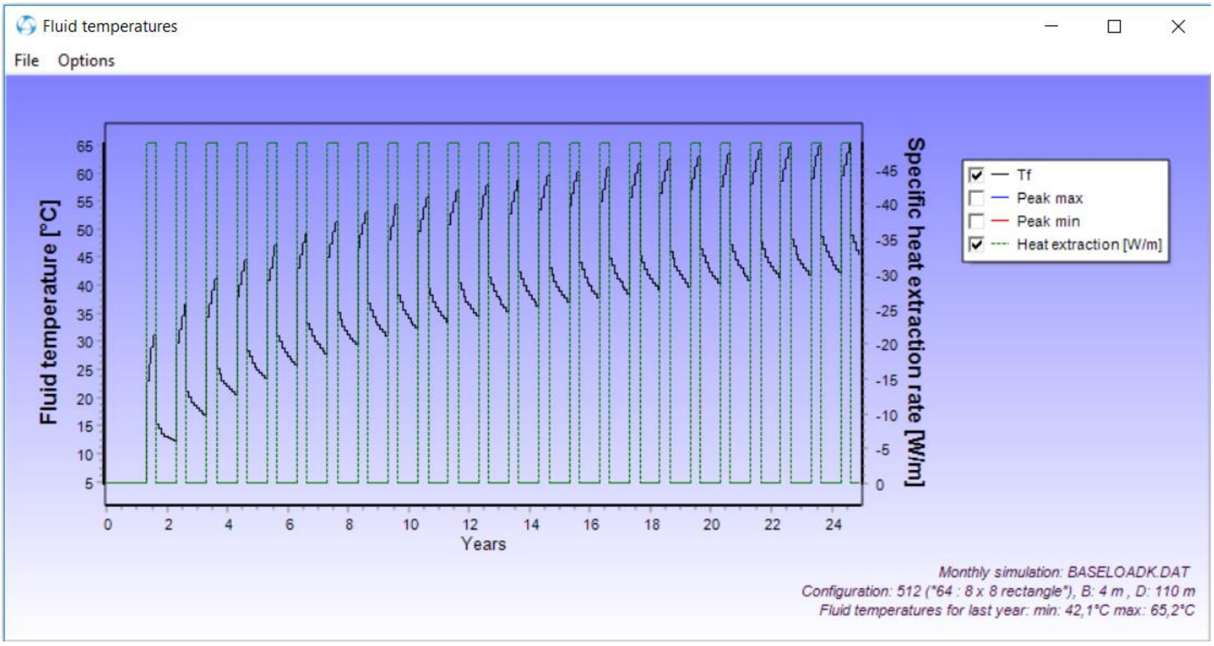

Figure 4.26: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Volumetric heat capacity of 2,5 MJ/(m^3K).

Volumetric heat capacity	**Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW**			
	None	**3 years**	**5 years**	**7 years**
2,2 (Default)	5,5 41 (-15- 26)	23,5 41 (3- 44)	30,5 41 (10- 51)	36,5 41 (16- 57)
1,9	5 40 (-15-25)	22 40 (2- 42)	30 40 (10- 50)	35 40 (15- 55)
2,5	5,5 35 (-12- 23)	19,5 35 (2- 37)	27,5 35 (10- 45)	32,5 35 (15- 50)

Table 4.17: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating for different values of the volumetric heat capacity. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

A volumetric heat capacity of 1,9 gives temperature variations of 1 degree less than with a volumetric heat capacity of 2,2. With a volumetric heat capacity of 2,5 the temperature variations are 6 degrees lower.

With a volumetric heat capacity of 1,9 the temperature increases a little slower when preheating than with a volumetric heat capacity of 2,2. With a volumetric heat capacity of 2,5 the preheating is slower.

It is logical that a higher volumetric heat capacity gives lower temperature variations since with a higher volumetric heat capacity more energy is needed to increase the temperature. It was strange that a lower volumetric heat capacity didn't show higher temperature variations but showed almost the same.

It was strange that both a lower and a higher volumetric heat capacity leads to a slower increase in temperature when the storage is preheated. A higher heat capacity gives a slower increase in temperature and a lower heat capacity gives a slightly slower increase, so this result was maybe not so convincing. It is logical that the time needed to preheat is longer with a high volumetric heat capacity, but with a low heat capacity the heating should be faster since a certain amount of energy should increase the temperature more.

4.2.3 Varying borehole length

Borehole length 150m

Increase the borehole length and the heating load= cooling load proportionally. If the borehole length is increased with 50 percent, the storage volume will increase with 50 percent and the total borehole meters too.

The first graph show the mean fluid temperature when heating load= cooling load= 1,5 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1,5 GWh (preheating).

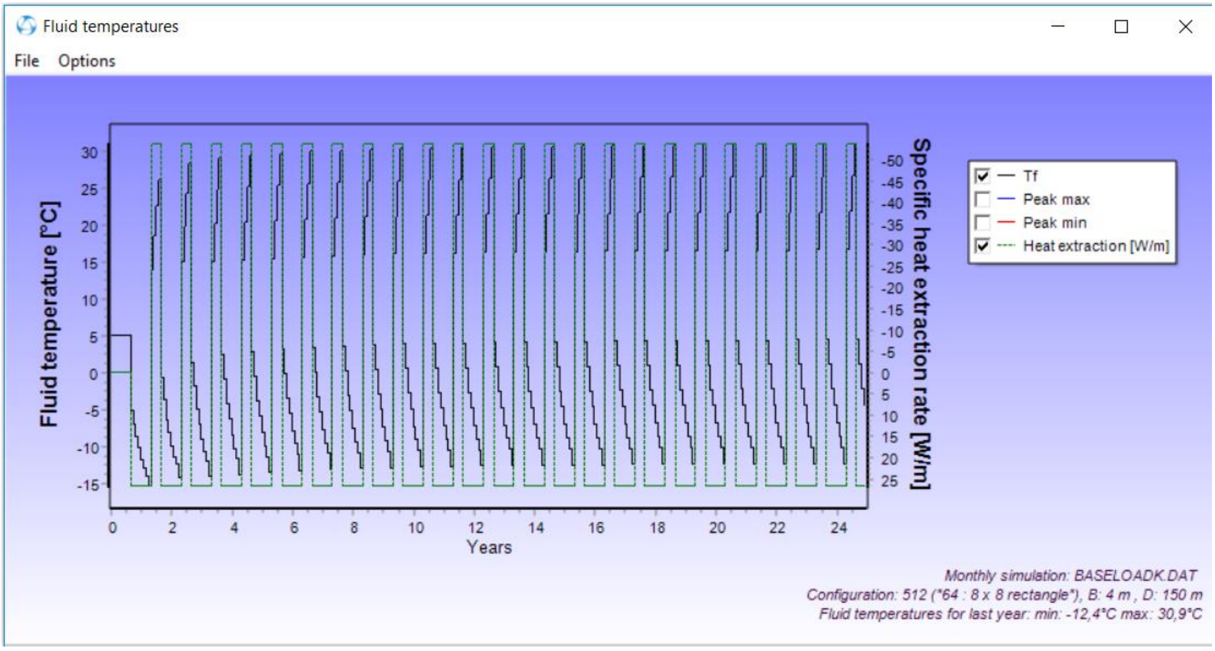

Figure 4.27: Temperature variations. Heating load= cooling load= 1,5 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Borehole length of 150m.

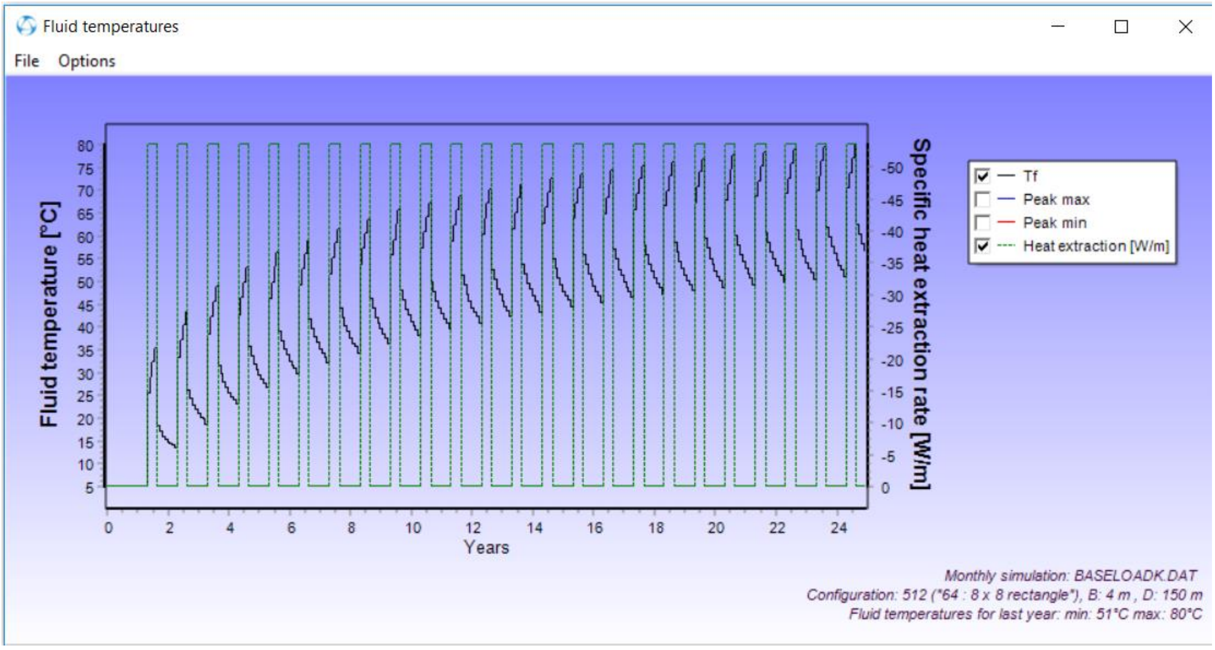

Figure 4.28: Cooling load= 1,5 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly. Borehole length of 150m.

Borehole length 70m

Decrease the borehole length and the heating load= cooling load proportionally.

The first graph show the mean fluid temperature when heating load= cooling load= 0,7 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 0,7 GWh (preheating).

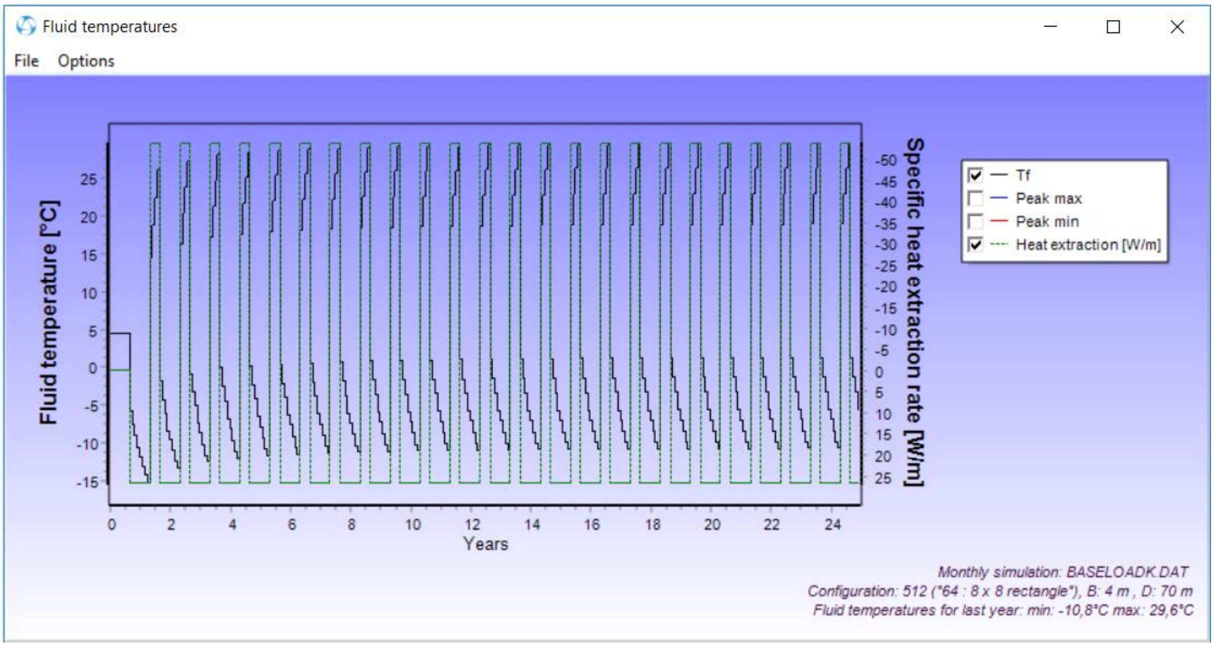

Figure 4.29: Temperature variations. Heating load= cooling load= 0,7 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Borehole length of 70m.

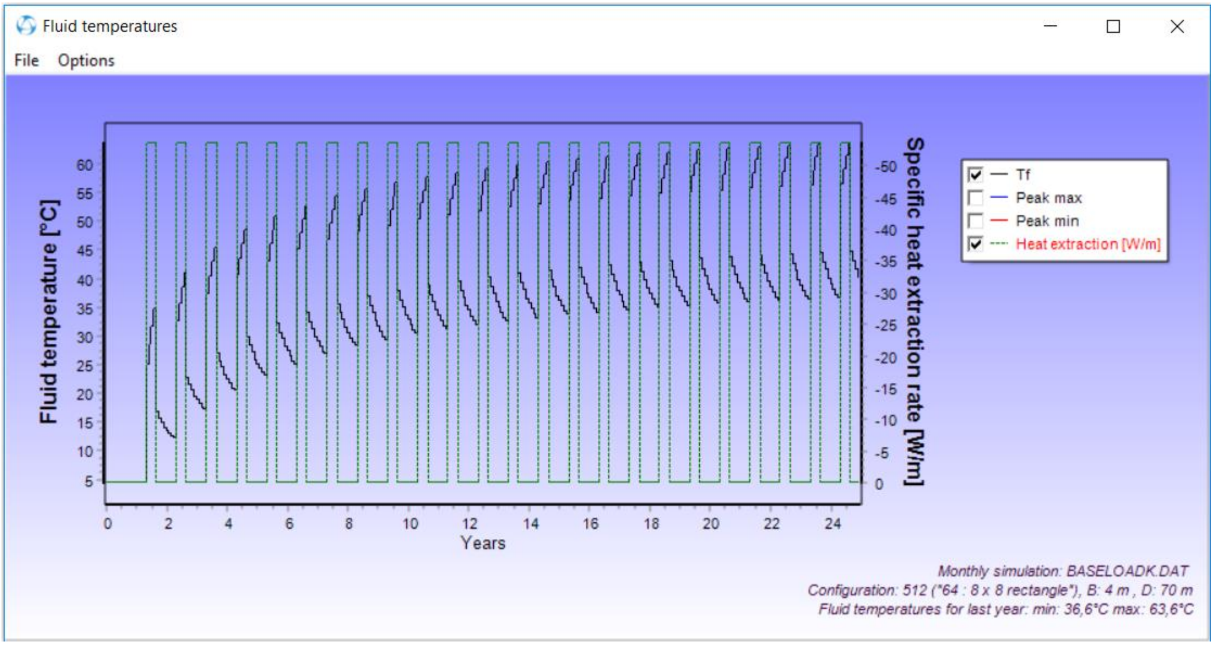

Figure 4.30: Cooling load= 9 GWh and heating load= 0 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction. Borehole length of 70m.

Borehole length	**Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW**			
	None	**3 years**	**5 years**	**7 years**
100m	5,5 41 (-15- 26)	23,5 41 (3- 44)	30,5 41 (10- 51)	36,5 41 (16- 57)
150m	5,5 41 (-15- 26)	24,5 41 (4- 45)	34,5 41 (14- 55)	39,5 41 (19- 60)
70m	5,5 41 (-15- 26)	22,5 41 (2- 43)	29,5 41(9- 50)	33,5 41 (13- 54)

Table 4.18: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating for different borehole lengths. Preheating 4 months yearly. 4 months heat injection and 8 months heat extraction.

When increasing the borehole length, the heating load and the cooling load with 50 percent, the temperature variations remains the same. When preheating the temperature increases a bit faster with longer boreholes. After preheating 7 years, the medium temperature is 3 degrees higher. When decreasing the borehole length, the temperature variations still remains the same, but the temperature increases a bit slower when the storage is preheated.

The reasons why we reach higher temperatures can be that with longer boreholes the volume to surface ratio will be higher. This will reduce heat losses.

4.2.4 Increase heat load and size and compare with the 1 GWh configuration

Use a configuration of 24 x 24 boreholes which is 9 times as many boreholes as the configuration with 8 x 8 boreholes (8 x 3= 24, 3 x 3= 9). Use a heating load and a cooling load which is 9 times as high. Use 4m borehole distance.

The first graph below show the mean fluid temperature when heating load= cooling load= 9 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 9 GWh (preheating).

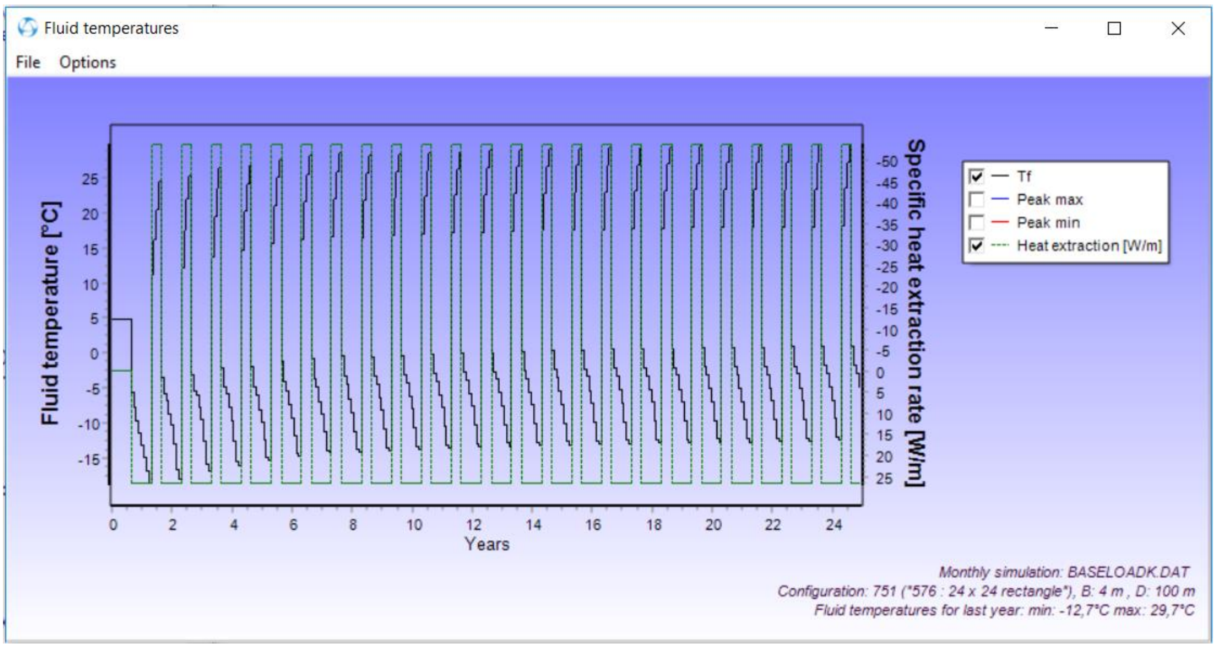

Figure 4.31: Temperature variations. Heating load= cooling load= 9 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

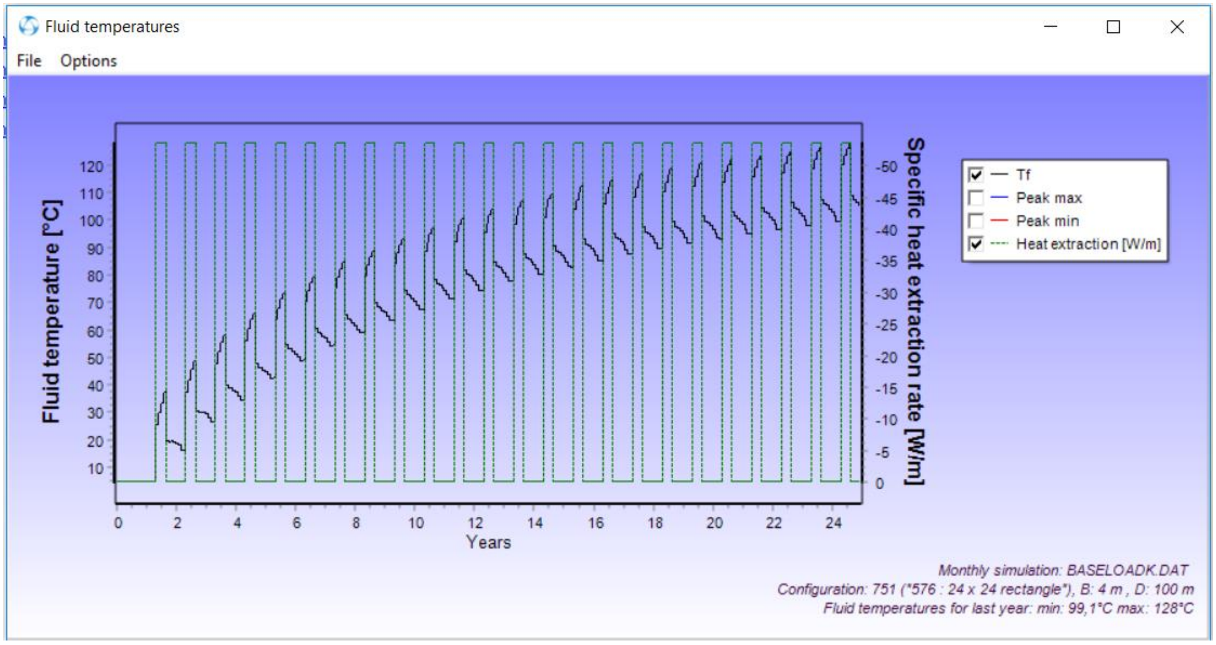

Figure 4.32: Temperature variations. Heating load= cooling load= 9 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

Volumetric heat capacity	Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW			
	None	3 years	5 years	7 years
1 GWh	5,5 41 (-15- 26)	23,5 41 (3- 44)	30,5 41 (10- 51)	36,5 41 (16- 57)
9 GWh	3,5 43 (-18-25)	28,5 43 (7- 50)	46,5 43 (25- 68)	60,5 43 (39- 82)

Table 4.19: Medium temperature (above) and temperature variations (below) for different storage sizes without preheating and for 3,5 and 7 years of preheating. (4 months preheating). 4 months heat injection and 8 months heat extraction.

Can see form the table that a larger storage leads to a little higher temperature variations. When preheating, the temperatures increases much faster with the large storage. The reason can be because of lower losses because of higher volume to surface ratio with a larger storage.

4.3 Store 1 GWh (6 months heat injection and 6 months heat extraction).

Change now the heating/cooling load profile. Instead of injecting heat four months a year and extracting heat 8 months a year, I look at injecting heat 6 months a year and extracting heat 6 months a year.

From eq. (3.3) we have that a borehole of 100m can uptake 25,95 MWh during 6 months.

Amount of boreholes needed to store 1GWh:

1000MWh/25,95MWh= ca. 39 boreholes

Use a quadratic borehole- pattern: 7 x 7= 49 boreholes

This gives 4900 (49 x 100) borehole- metres for 1GWh

With a heat extraction rate of 60W/m the storage could provide a total heat extraction of:

60W/m x (49 x 100) m= 294 000 W ≈ 0,29MW

In Figure 4.33 below for the base- load, I choose six months (April to September) for the cooling load (heat injection), with almost equal factors for each month (0,16 and 0,17). The rest of the months heat is extracted with equal factors for every month.

Borehole distance 8m. Storage area of 48 x 48m

With a borehole distance of 8m we get a storage area of 48m*48m

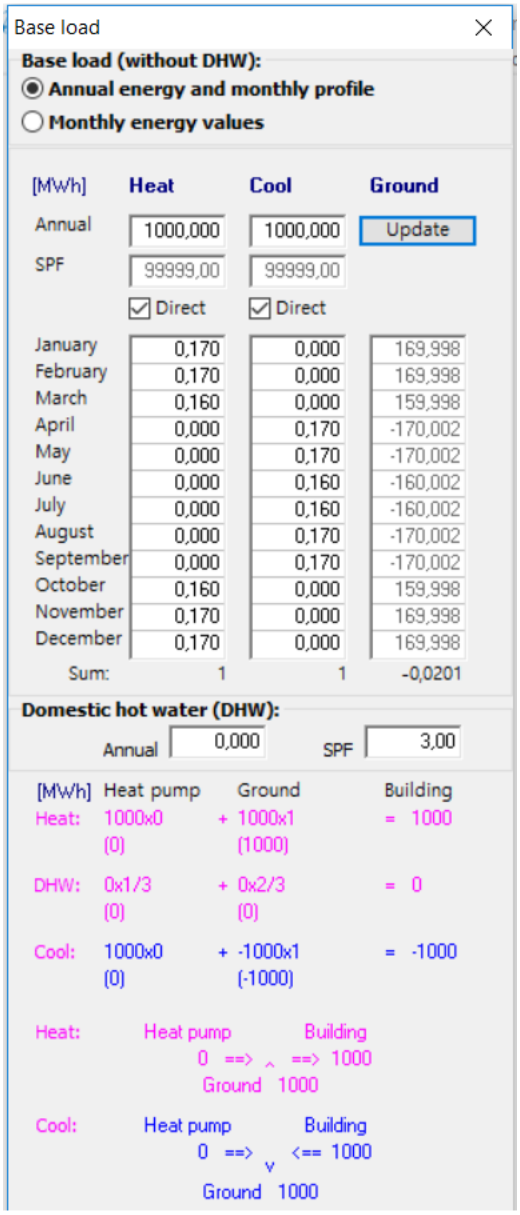

Figure 4.33: Input parameters (base load). Heating load= cooling load= 1 GWh. 6 months heat injection and 6 months heat extraction.

Plot mean fluid temperatures with these input parameters

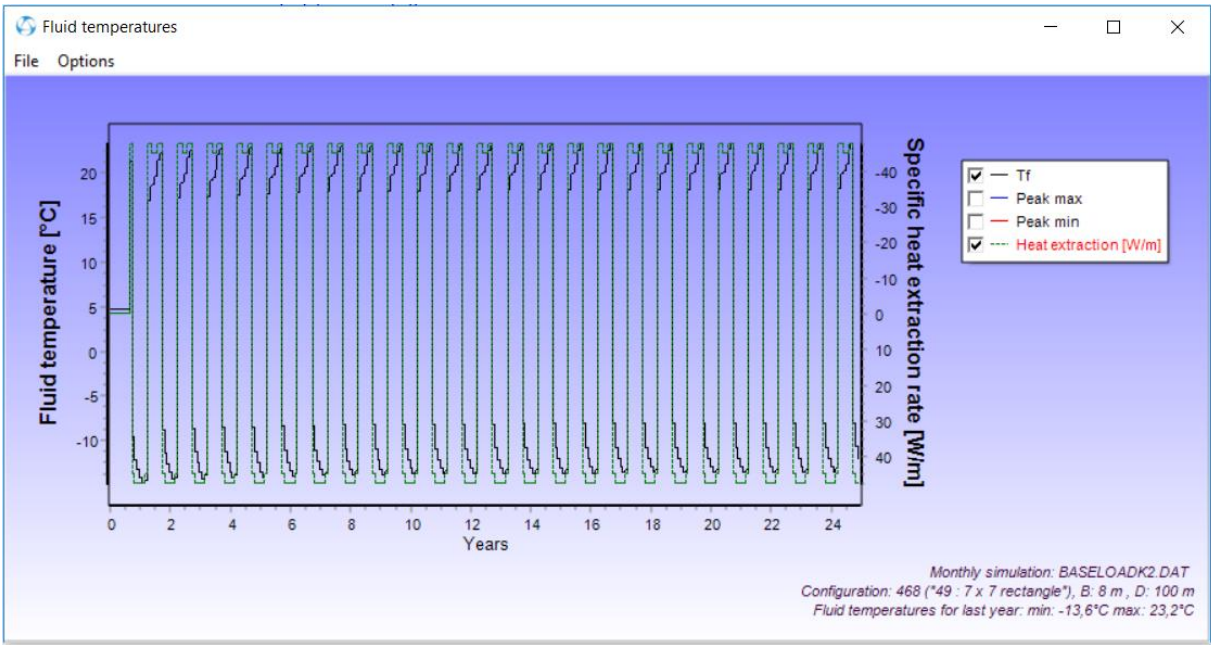

Figure 4.34: Temperature variations. Heating load= cooling load= 1 GWh. 8m borehole distance. 6 months heat injection and 6 months heat extraction

Gives temperature variations of about 38°C with temperatures varying between -15 and 23°C.

Try now to just inject heat to the ground without extracting heat to see how fast the fluid-temperature increases. Cooling load= 1GWh and heating load= 0 GWh.

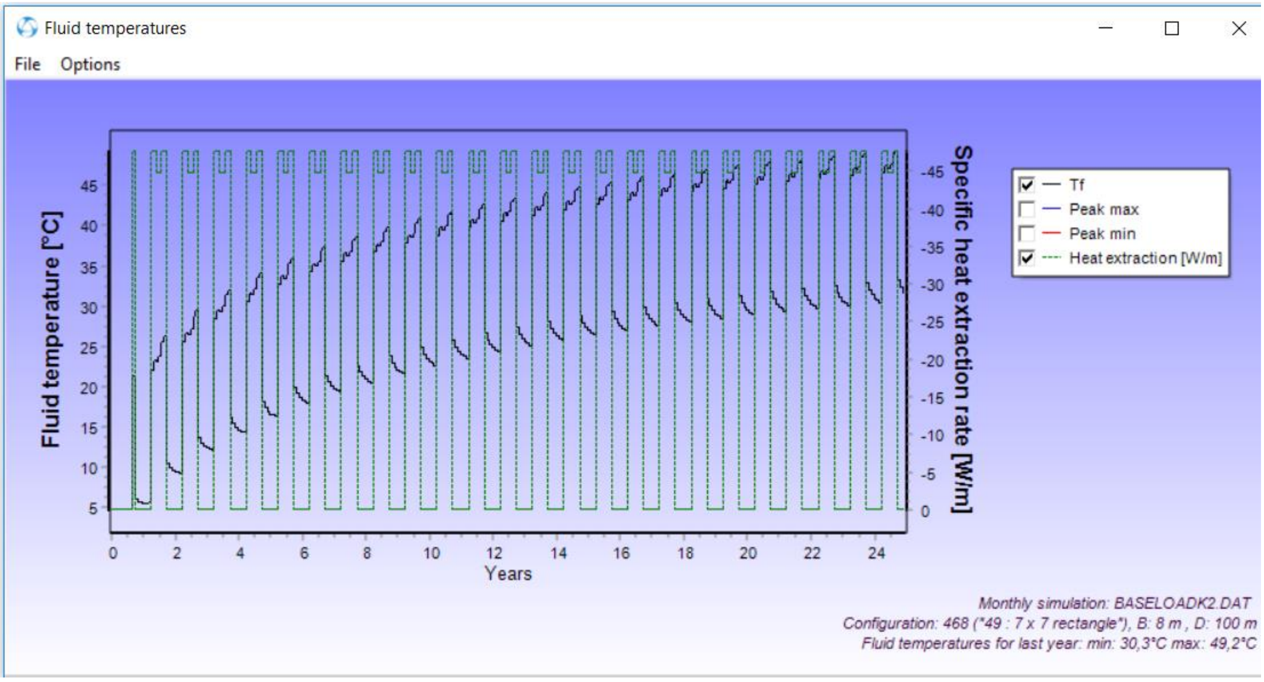

Figure 4.35 Cooling load= 1 GWh and heating load= 0 GWh. 8m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	38 (-15- 23)	4
Preheating for 3 years	38 (-8- 30)	11
Preheating for 5 years	38 (-3- 35)	16
Preheating for 7 years	38 (1- 39)	20

Table 4.20: Fluid temperature variation and medium temperature with and without preheating. 8m borehole distance. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction.

Borehole distance 6m. Storage area of 36 x 36m

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

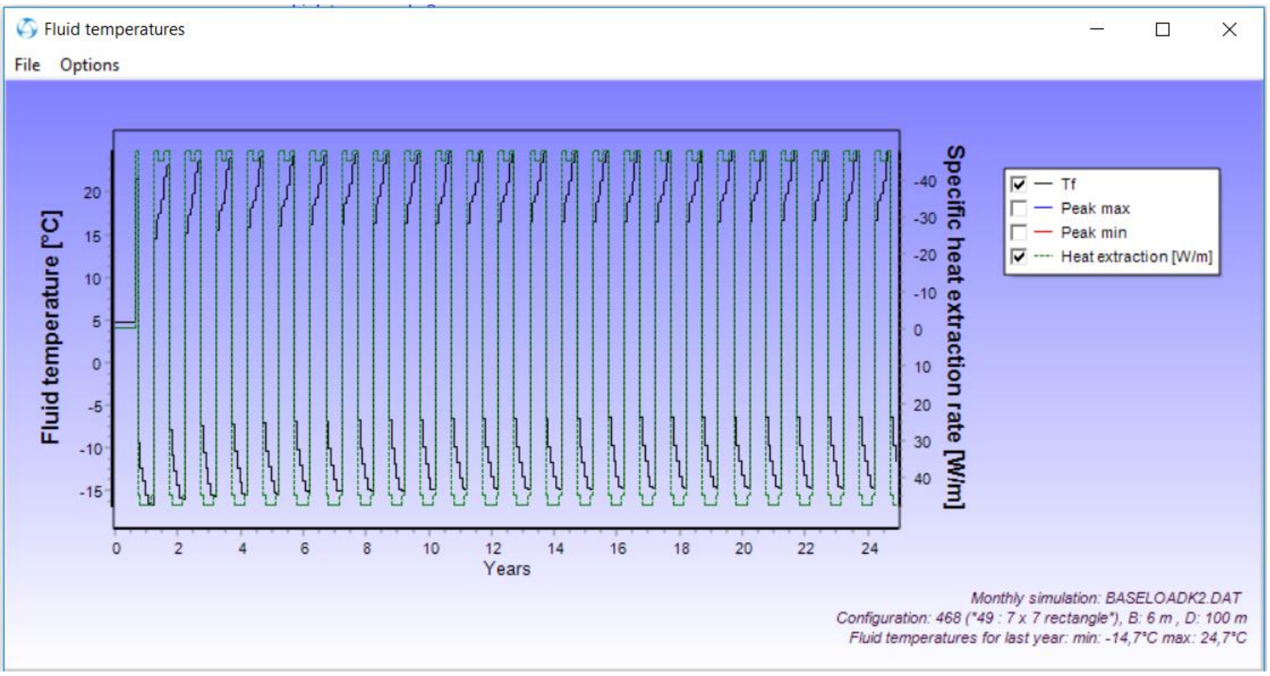

Figure 4.36: Temperature variations. Heating load= cooling load= 1 GWh. 6m borehole distance. 6 months heat injection and 6 months heat extraction.

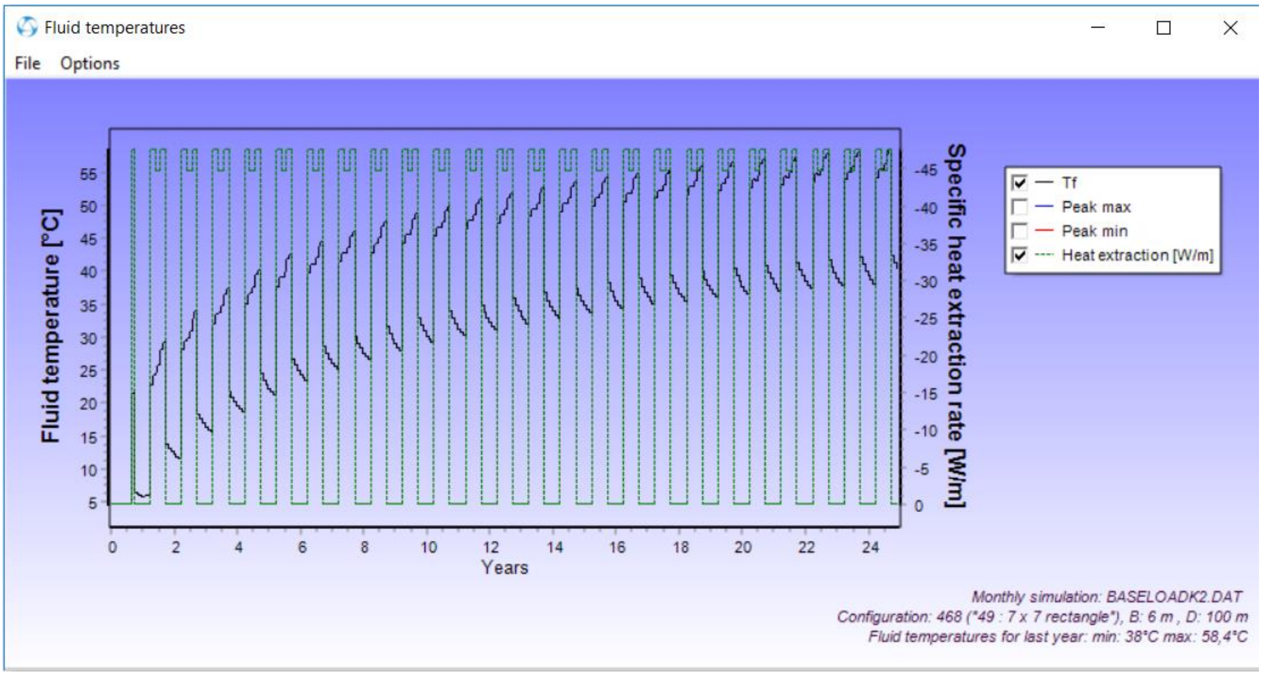

Figure 4.37: Cooling load= 1 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (-4- 35)	15,5
Preheating for 5 years	39 (2- 41)	21,5
Preheating for 7 years	39 (6- 45)	25,5

Table 4.21: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction.

Borehole distance 4m. Storage area of 24m x 24m

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

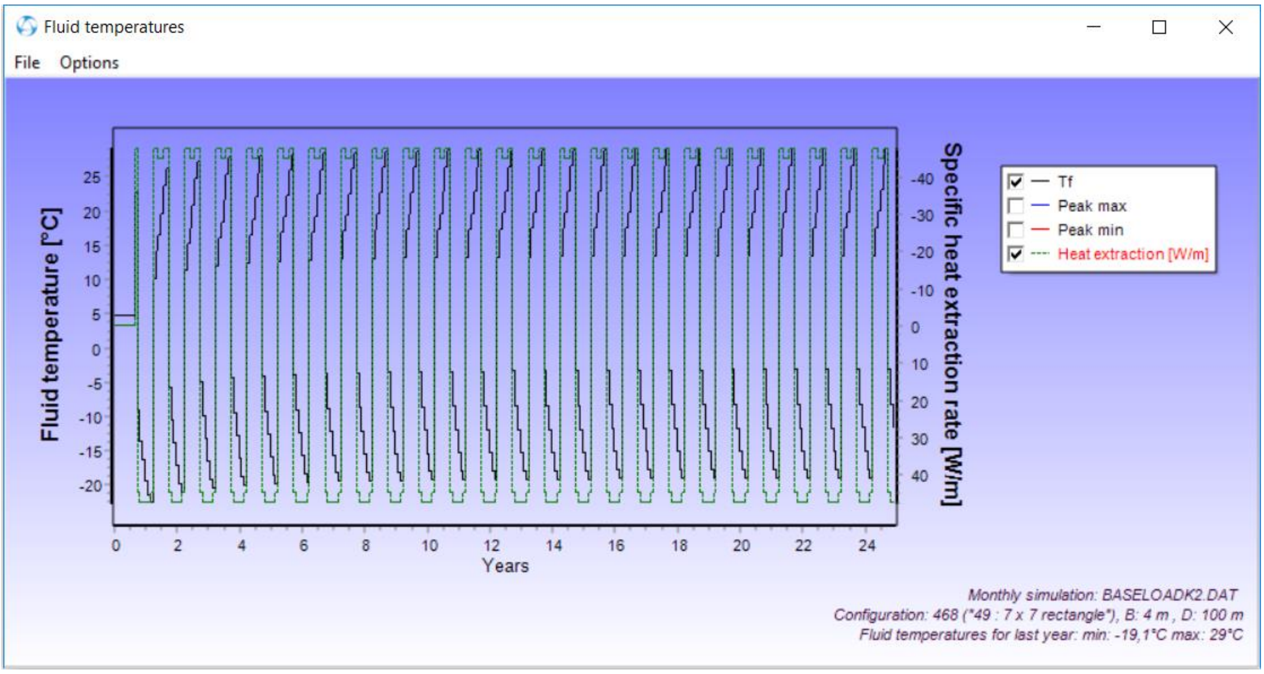

Figure 4.38: Temperature variations. Heating load= cooling load= 1 GWh. 4m borehole distance. 6 months heat injection and 6 months heat extraction.

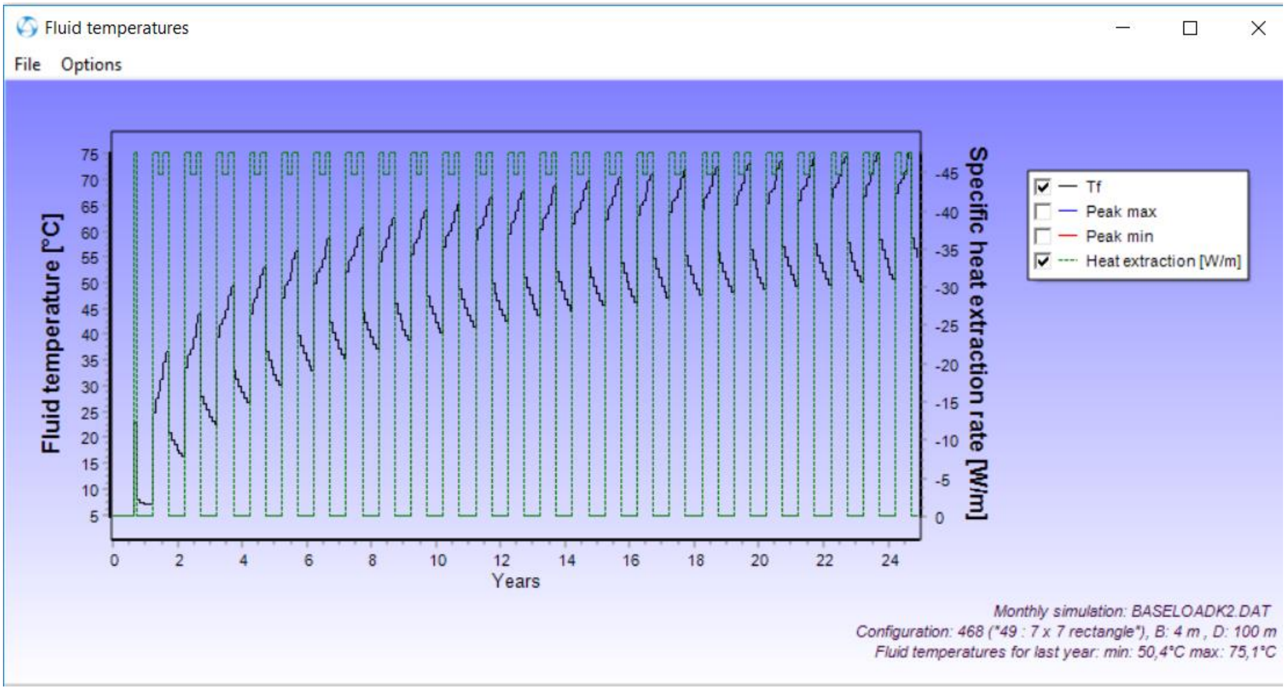

Figure 4.39: Cooling load= 1 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	48 (-22- 26)	2
Preheating for 3 years	48 (-3- 45)	21
Preheating for 5 years	48 (7- 55)	31
Preheating for 7 years	48 (12- 60)	36

Table 4.22: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction.

Borehole distance 3m. Storage area of 18m x 18m.

The first graph show the mean fluid temperature when heating load= cooling load= 1 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 1 GWh (preheating).

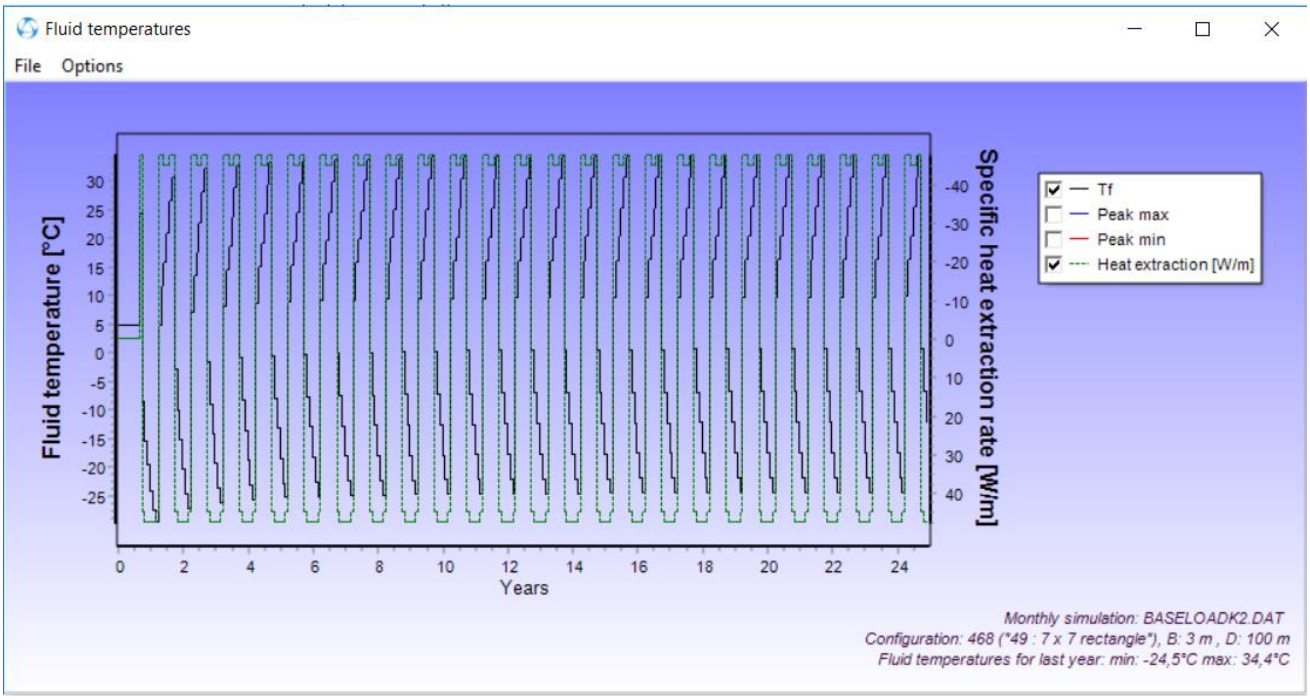

Figure 4.40: Temperature variations. Heating load= cooling load= 1 GWh. 3m borehole distance. 6 months heat injection and 6 months heat extraction.

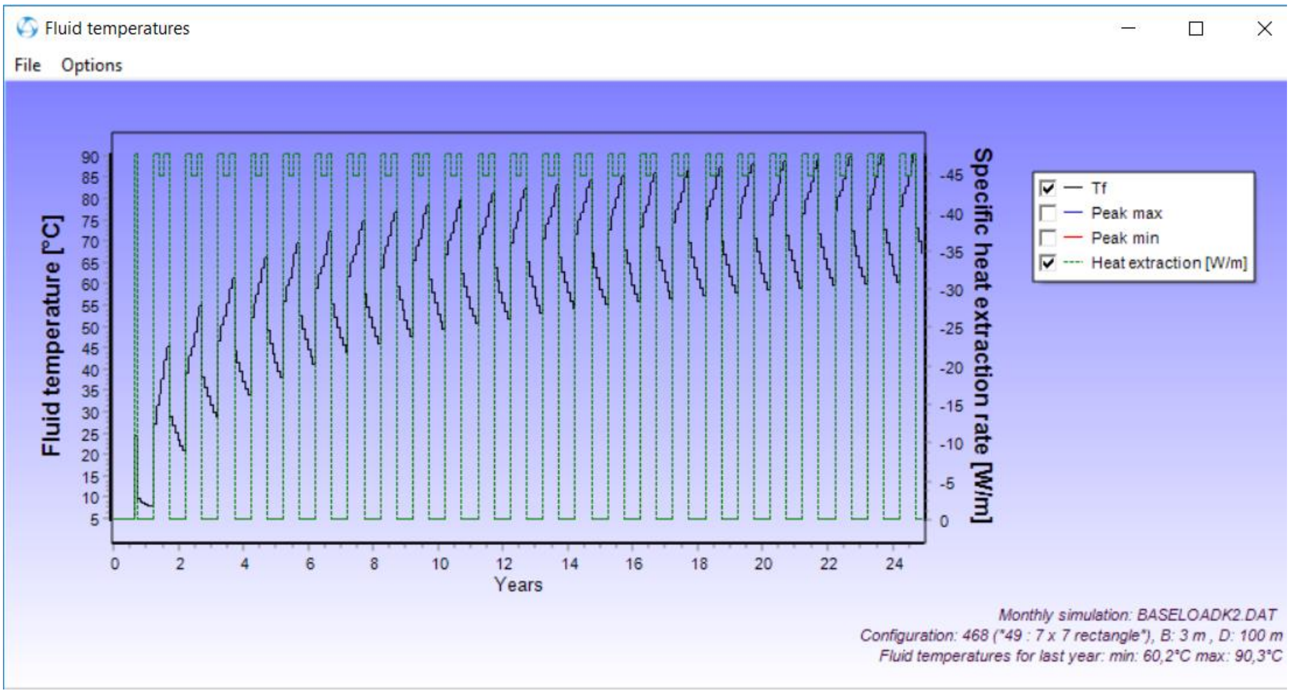

Figure 4.41: Cooling load= 1 GWh and heating load= 0 GWh. 3m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	60 (-29- 31)	2
Preheating for 3 years	60 (-4- 56)	26
Preheating for 5 years	60 (7- 67)	38
Preheating for 7 years	60 (14- 74)	44

Table 4.23: Fluid temperature variation and medium temperature with and without preheating. 3m borehole distance. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction.

Borehole distance	**Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW**			
	None	**3 years**	**5 years**	**7 years**
8 (48 x 48 m)	4	11	16	20

	38 (-15- 23)	38 (-8- 30)	38 (-3- 35)	38 (1- 39)
6 (36 x 36 m)	3,5 39 (-16- 23)	15,5 39 (-4- 35)	21,5 39 (2- 41)	25,5 39 (6- 45)
4 (24 x 24 m)	2 48 (-22- 26)	21 48 (-3- 45)	31 48 (7- 55)	36 48 (12- 60)
3 (18 x 18 m)	2 60 (-29- 31)	26 60 (-4- 56)	38 60 (7- 67)	44 60 (14- 74)

Table 4.24: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction.

Preheating for 8 months

From eq. (3.4) we have that a borehole of 100m can uptake 34,6 MWh during 8 months.

The storage receives in total:

34,6 MWh x (7 x 7)= 1,7 GWh

Try now to preheat the storage for 8 months. In the figure below for the base- load, I choose six months (March to October) for the cooling load, with equal factors of 0,125 for each month. Use heating load= 0 GWh and cooling load= 1,7 GWh when preheating. Can then combine the results from preheating with the results showing the temperature variations when the storage is used with 6 months heat injection and 6 months heat extraction.

8m borehole distance

Figure 4.42 below shows the fluid temperatures when preheating 8 months a year. In Table 4.25 below this result is combined with the plot in Figure 4.34 from the last subchapter, showing the mean fluid temperatures with 6 months heat injection and 6 months heat extraction.

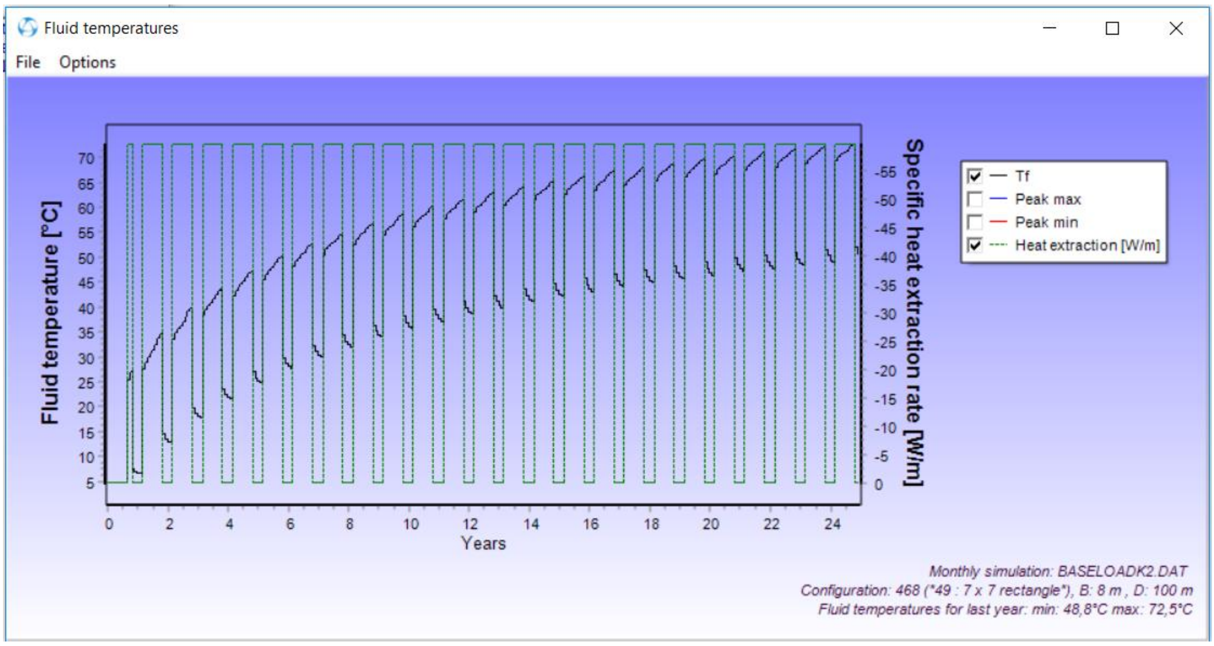

Figure 4.42: Cooling load= 1,7 GWh and heating load= 0 GWh. 8m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	38 (-15- 23)	4
Preheating for 3 years	38 (2- 40)	21
Preheating for 5 years	38 (9- 47)	28
Preheating for 7 years	38 (16- 54)	35

Table 4.25: Fluid temperature variation and medium temperature with and without preheating. 8m borehole distance. Preheating 8 months yearly. 6 months heat injection and 6 months heat extraction.

6m borehole distance

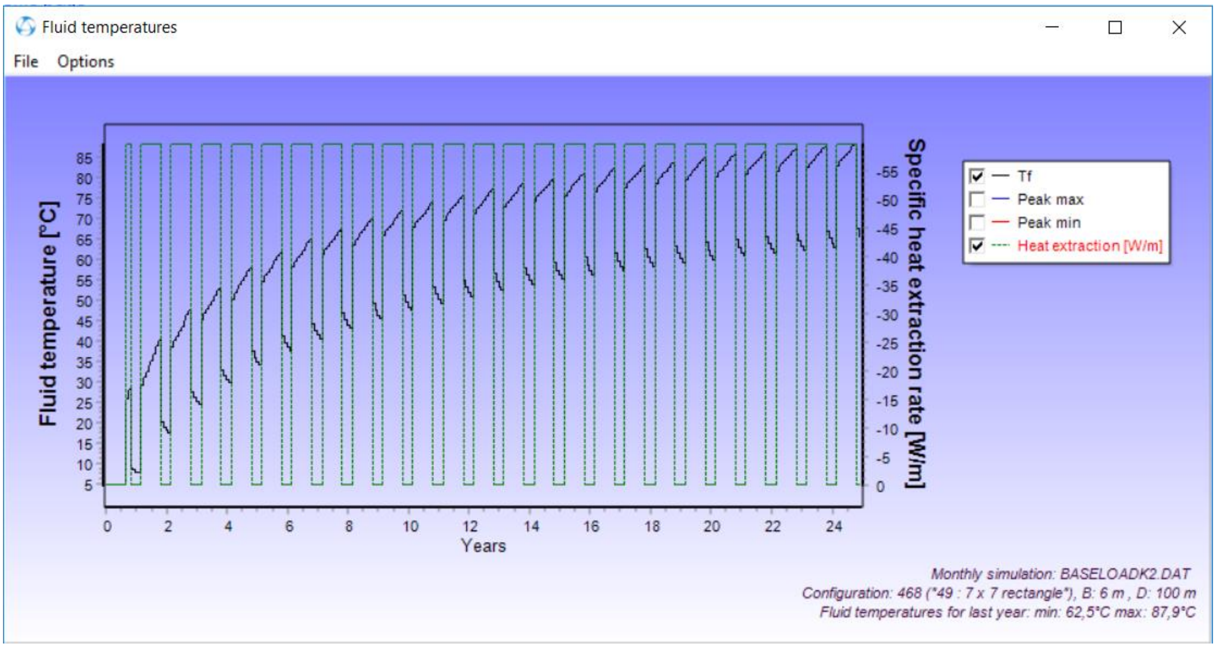

Figure 4.43: Cooling load= 1,7 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (10- 49)	29,5
Preheating for 5 years	39 (20- 59)	39,5
Preheating for 7 years	39 (27- 66)	46,5

Table 4.26: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 8 months yearly. 6 months heat injection and 6 months heat extraction.

4m borehole distance

Try now to just inject heat to the ground without extracting heat to see how fast the fluid-temperature increases. Cooling load= 1,7 GWh and heating load= 0 GWh.

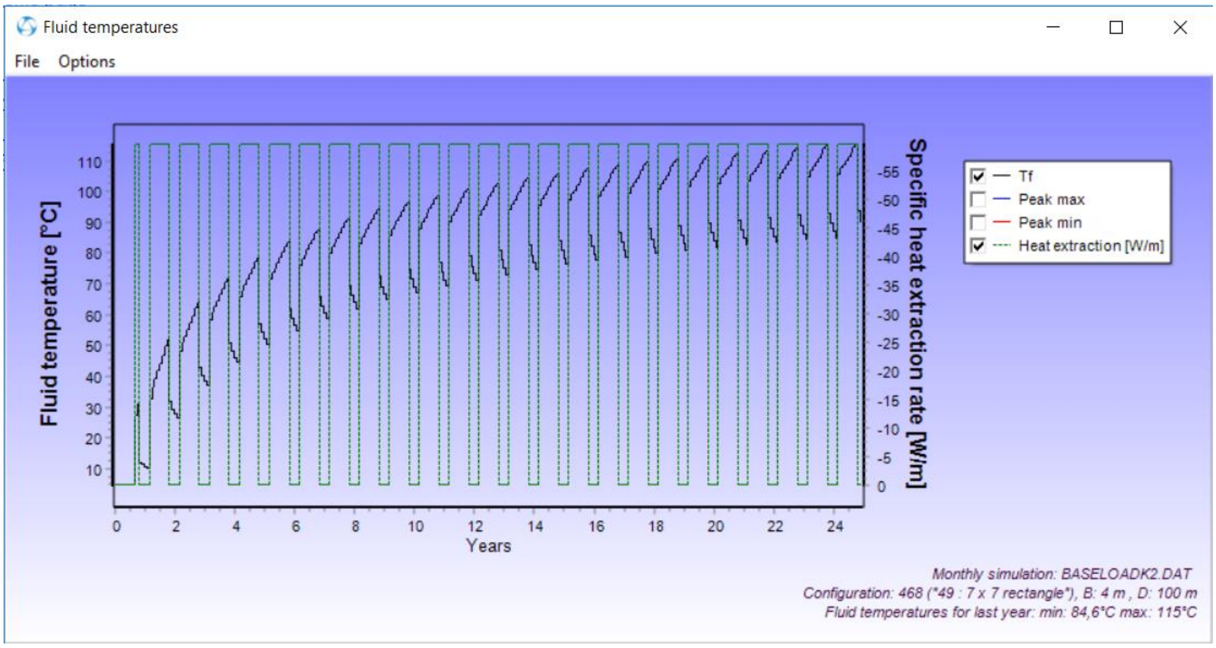

Figure 4.44: Cooling load= 1,7 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

The results are summarized in the table below.

	Storing 1 GWh and preheating eight months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	48 (17- 65)	41
Preheating for 5 years	48 (32- 80)	56

Table 4.27: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating 8 months yearly. 6 months heat injection and 6 months heat extraction.

Borehole distance	**Medium temperature and temperature variation with and without preheating. Heat extraction of 0,38 MW**			
	None	**3 years**	**5 years**	**7 years**
8 (48 x 48 m)	4 38 (-15- 23)	21 38 (2- 40)	28 38 (9- 47)	35 38 (16- 54)
6 (36 x 36 m)	3,5 39 (-16- 23)	29,5 39 (10- 49)	39,5 39 (20- 59)	46,5 39 (27- 66)

4 (24 x 24 m)	2 48 (-22- 26)	41 48 (17- 65)	56 48 (32- 80)	Exceed 80 deg.

Table 4.28: Medium temperature (above) and temperature variations (below) without preheating and for 3,5 and 7 years of preheating. Preheating 8 months yearly. 6 months heat injection and 6 months heat extraction.

4.4 Simulating larger storages

4.4.1 Store 9 GWh

Use the configuration with 24 x 24 boreholes but now with borehole distance of 4m to store 9 GWh. It occupies an area of 92 x 92 meters. This storage provide a power of 60 $\frac{W}{m}$ x 100 x (24 x 24)= <u>3,46 MW.</u>

The first graph below show the mean fluid temperature when heating load= cooling load= 9 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 9 GWh (preheating).

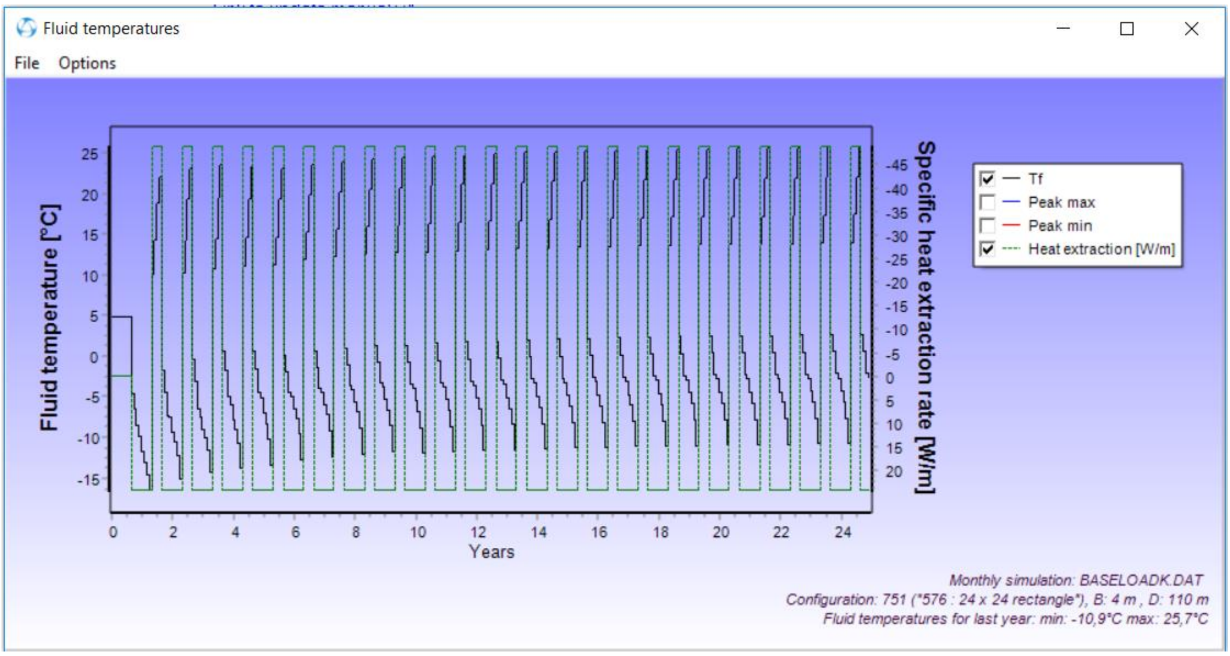

Figure 4.45: Temperature variations. Heating load= cooling load= 9 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

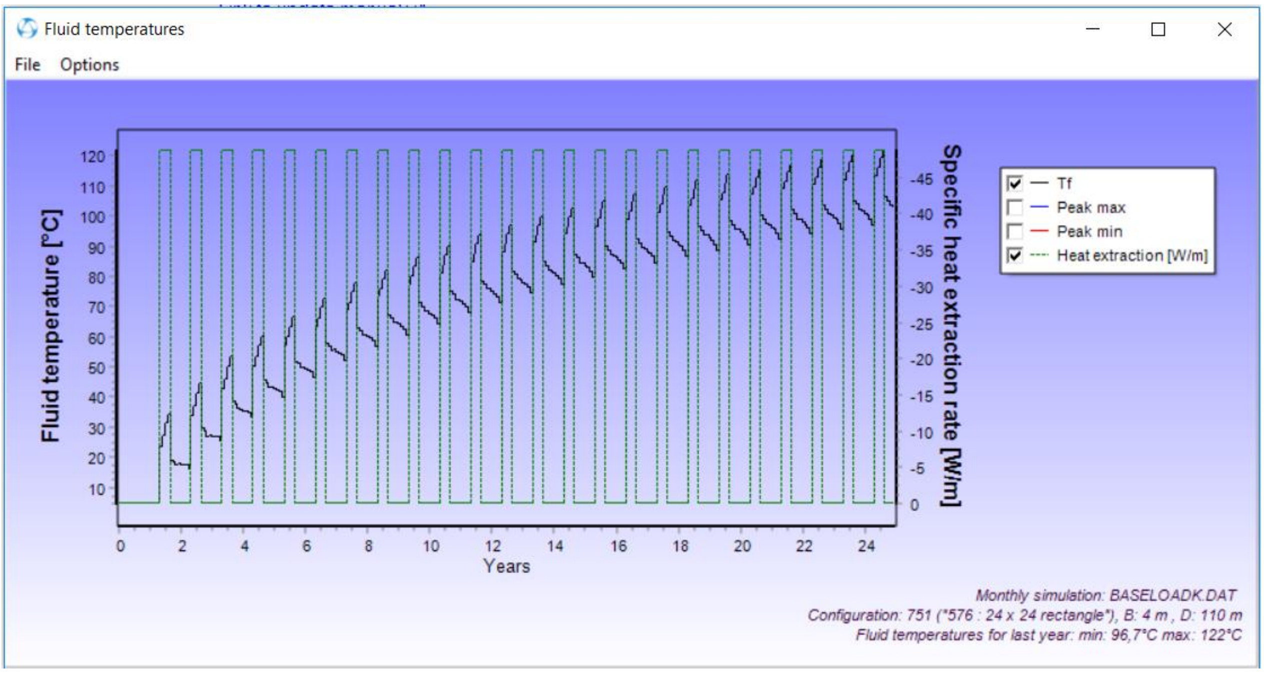

Figure 4.46: Cooling load= 9 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below.

	Storing 9 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (7- 46)	26,5
Preheating for 5 years	39 (23- 62)	42,5
Preheating for 7 years	39 (36- 75)	55,5

Table 4.29: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating four months a year. (4 months heat injection and 8 months heat extraction).

Preheating 6 months

This storage can uptake 9 GWh during 4 months. During 6 months it can uptake 9 GWh x 1,5= 13,5 GWh

Figure 4.47 below shows the mean fluid temperature when preheating 6 months a year. In Table 4.30 below this result is combined with the plot in Figure 4.45, showing the mean fluid temperatures with 4 months heat injection and 8 months heat extraction.

Plot below with heating load= 0 GWh and cooling load= 13,5 GWh

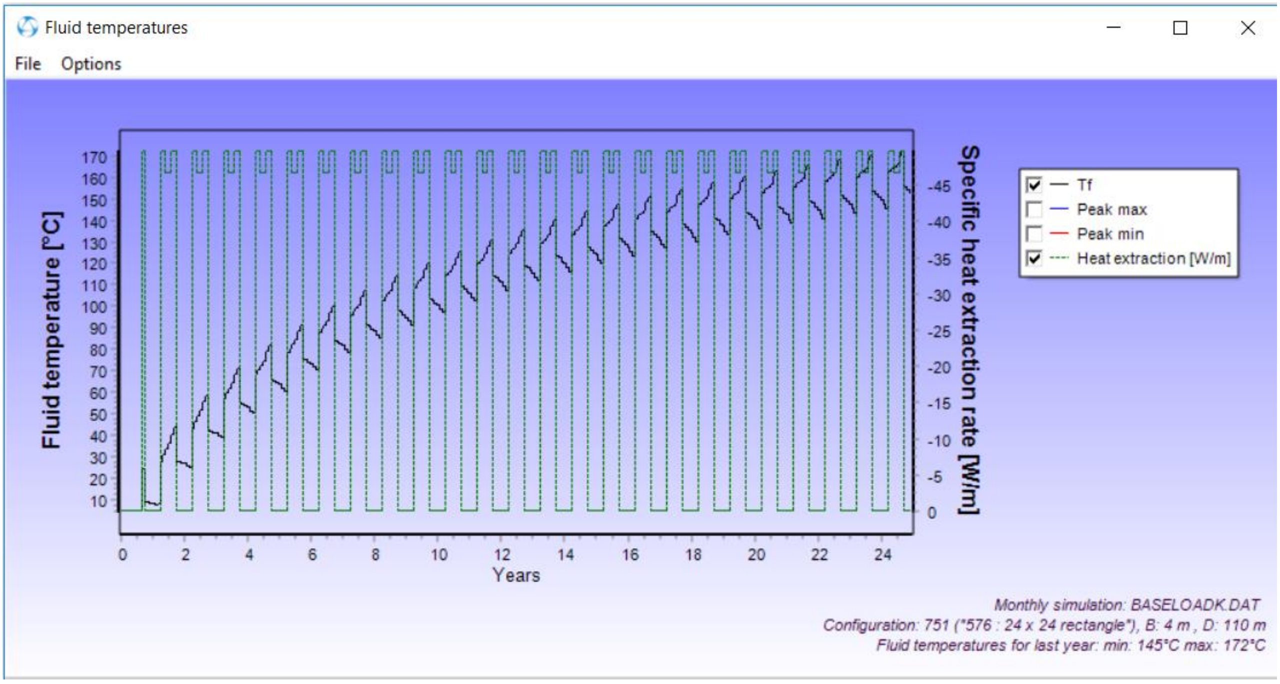

Figure 4.47: Cooling load= 13,5 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 9 GWh and preheating six months a year	
	Temperature variation	Medium temperature

No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (7- 60)	33,5
Preheating for 4,7 years	39 (41- 80)	60,5

Table 4.30: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating six months a year. (4 + 8) months profile).

If preheating for eight months a year, 80°C will probably be reach after about 3 years.

4.4.2 Store 9 GWh (extracting heat 6 months a year and storing heat 6 months a year)

To store 1 GWh when heat is injected 6 months a year and heat is extracted 6 months a year we used the configuration with 7 x 7= 49 boreholes. Now we are storing 9 times as much so I use the configuration with 21 x 21= 441 boreholes. Use the same monthly load profile as on the 1 GWh case [Figure 4.36], but now with heating load= cooling load= 9 GWh. Use 4 meter borehole distance as decided earlier. This covers an area of 80 x 80 meters which is exactly the size of the area where a BTES system for Kvitebjørn will be placed.

The storage can provide a power of 60 $\frac{W}{m}$ x 100 x (21 x 21)= 2,65 MW

The first graph below show the mean fluid temperature when heating load= cooling load= 9 GWh and the second graph shows the mean fluid temperature when heating load= 0 GWh and cooling load= 9 GWh (preheating).

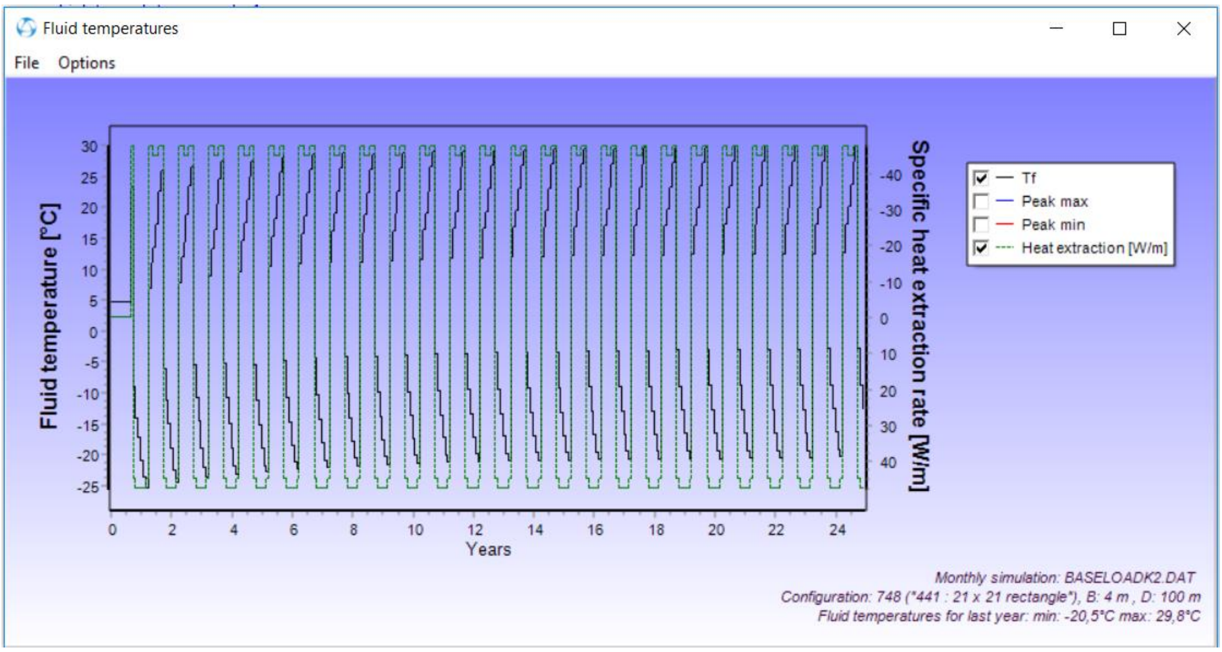

Figure 4.48: Temperature variations. Heating load= cooling load= 9 GWh. 4m borehole distance. 6 months heat injection and 6 months heat extraction.

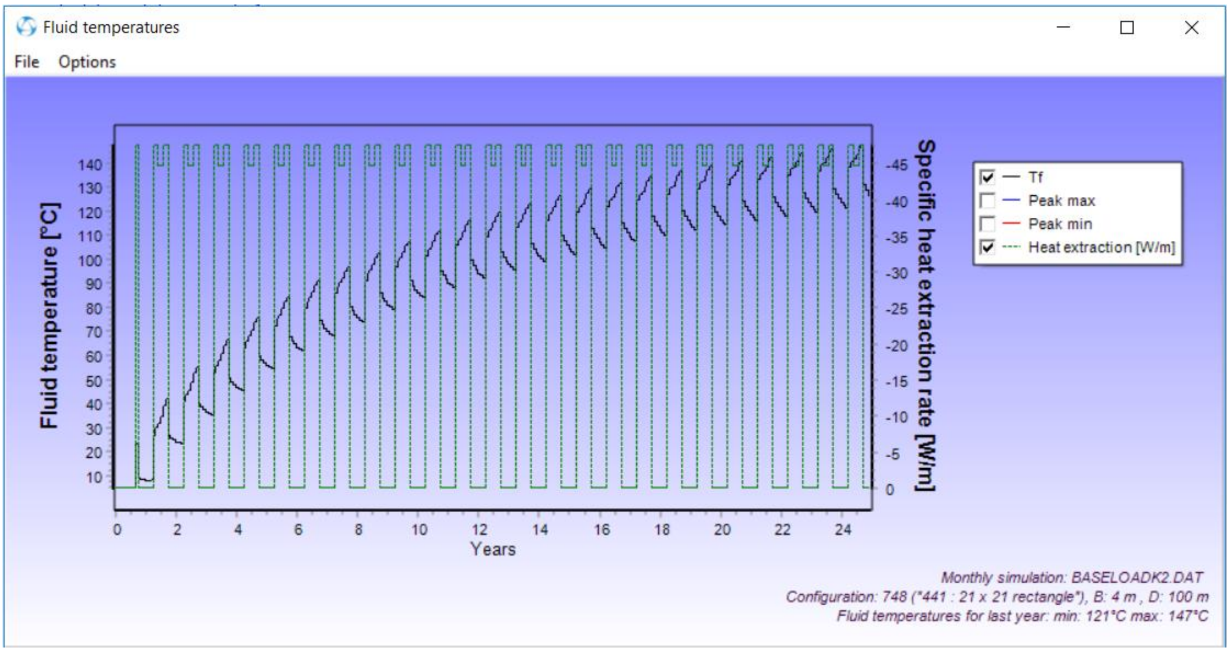

Figure 4.49: Cooling load= 9 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 9 GWh (heating load for 6 months)	
	Temperature variation	**Medium temperature**
No preheating	51 (-25- 26)	0,5
Preheating for 3 years	51 (7- 58)	32,5
Preheating for 5 years	51 (27- 78)	52,5
Preheating for 7 years	80°C exceeded	

Table 4.31: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating six months a year. (6 + 6) months profile).

Preheating 8 months

From chapter 4.3 we have that with the configuration with of 7 x 7 boreholes, storage can receive 1,7 GWh during 8 months. The configuration of 21 x 21 boreholes can then receive 9 x 1,7 GWh= 15,3 GWh.

The plot below [Figure 4.50] shows the fluid temperature when preheating 8 months a year. In the table below this result is combined with the plot from the last subchapter, showing the mean fluid temperatures with 6 months heat injection and 6 months heat extraction.

Plot below with heating load= 0 GWh and cooling load= 15,3 GWh

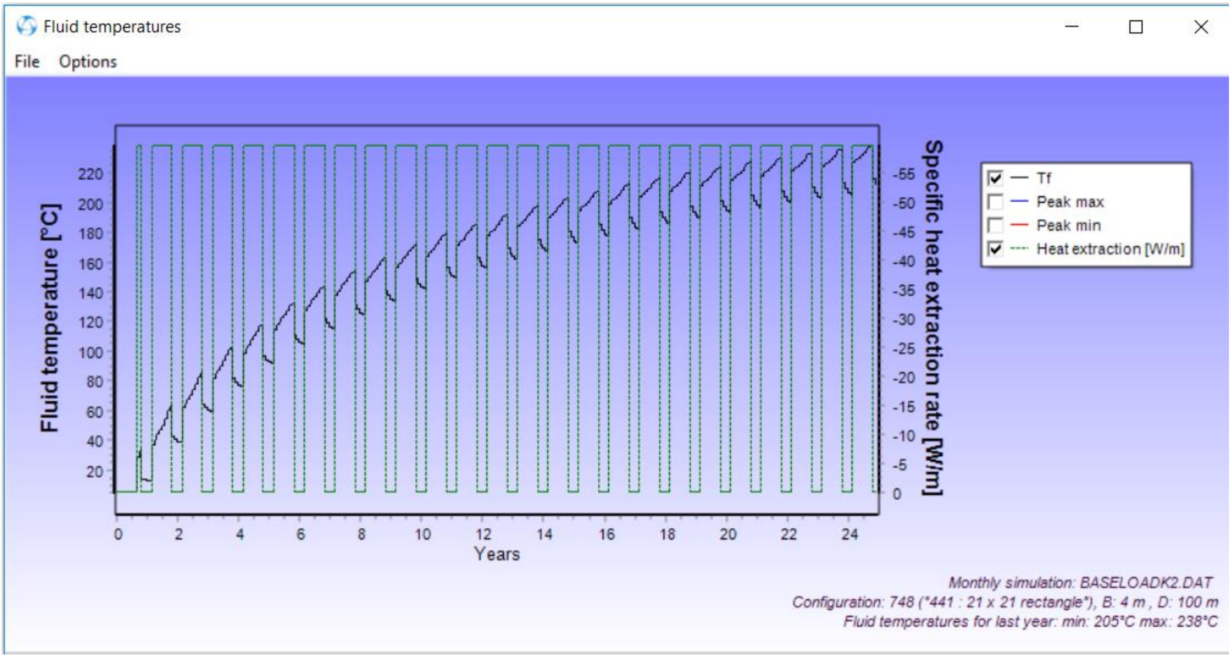

Figure 4.50: Cooling load= 15,3 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

We reach 80°C after about 2 and a half year. With this configuration we have temperature variations of 51 degrees. After preheating, the temperature will vary between 80°C and 80-51= 29°C which will give a medium temperature of 54,5°C.

4.4.3 Store 18 GWh

The number of boreholes in the configuration of 24 x 24 boreholes is 24 x 24=576 boreholes. The largest configuration in EED has 34 x 34=1156 boreholes. 576 x 2= 1152 so the configuration with 34 x 34 boreholes has a little more than twice as many boreholes than the configuration with 24 x 24 boreholes. It will therefore be suitable to store twice as much energy (2 x 9GWh= 18GWh) with this configuration. With a borehole spacing of 4m we get an area of 132 x 132 meters.

This storage provide a power of 60 $\frac{W}{m}$ x 100 x (34x34)= 6,94 MW

Figure 4.51 below show the mean fluid temperature when heating load= cooling load= 18 GWh and Figure 4.52 shows the mean fluid temperature when heating load= 0 GWh and cooling load= 18 GWh (preheating).

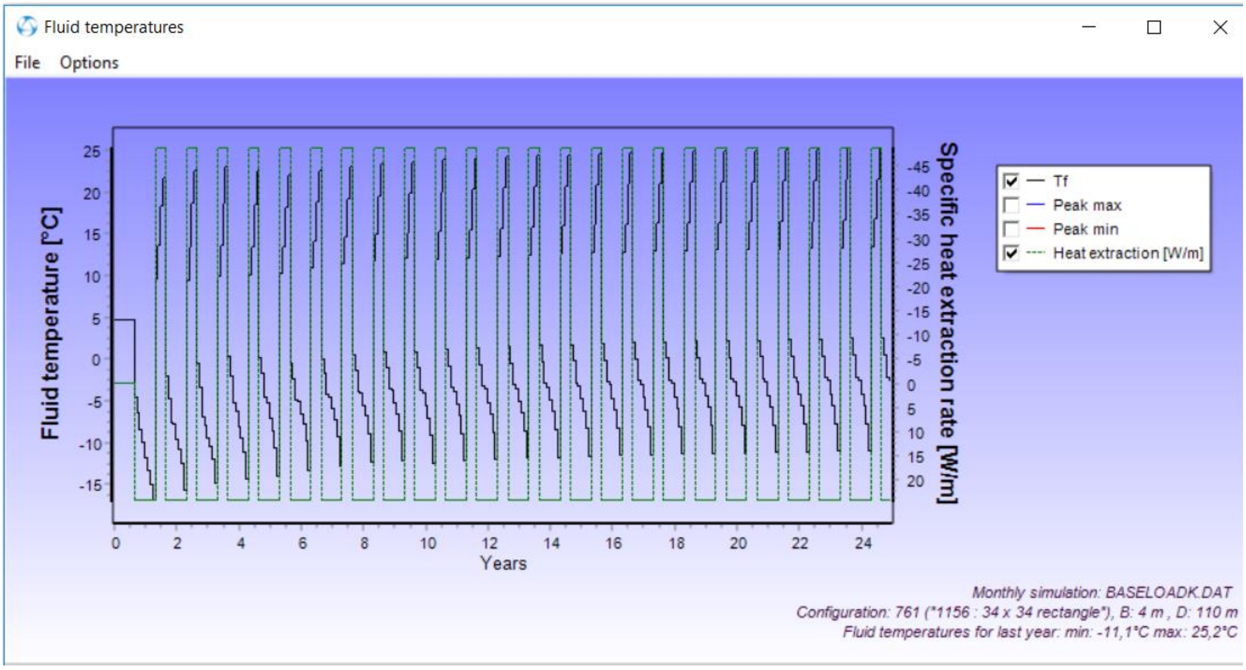

Figure 4.51: Temperature variations. Heating load= cooling load= 18 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

Plot below with cooling load= 18 GWh and heating load= 0 GWh.

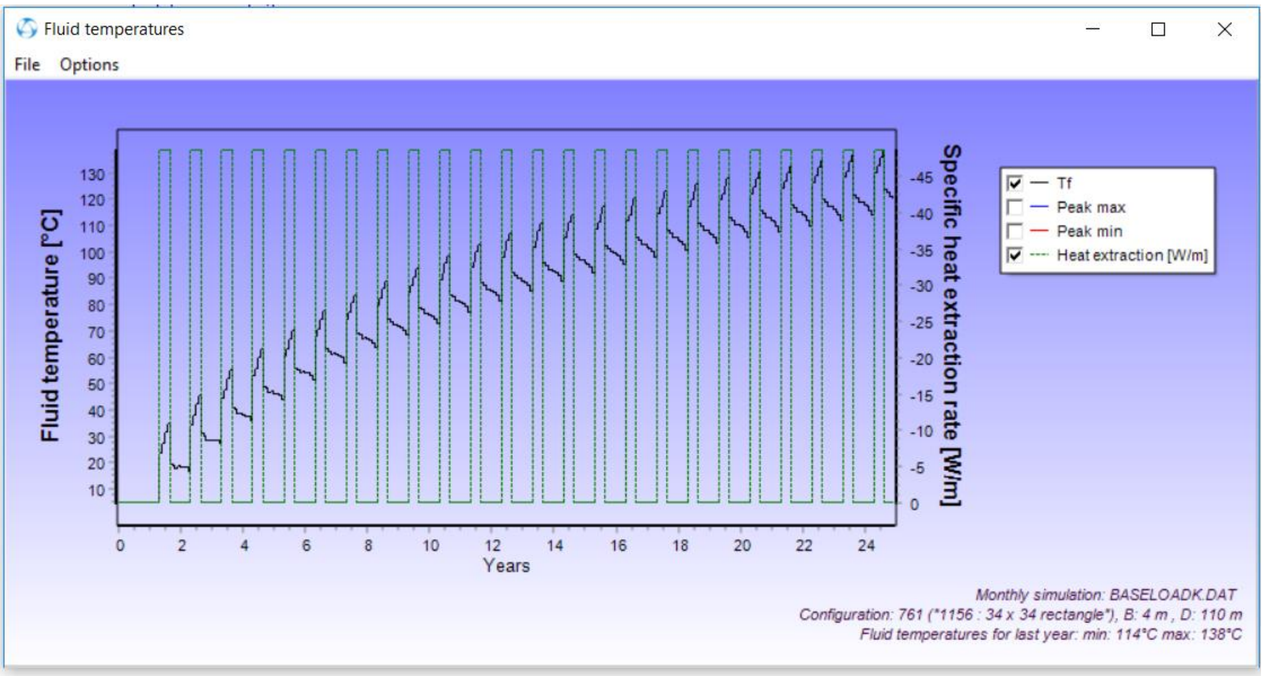

Figure 4.52: Cooling load= 18 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below.

	Storing 18 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (11- 50)	30,5
Preheating for 5 years	39 (26- 65)	45,5
Preheating for 7 years	39 (41- 80)	60,5

Table 4.32: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating four months a year. (4 + 8) months profile).

Preheating for 6 months

During 6 months the storage can receive:

18 GWh x 1,5= 27 GWh

Figure 4.53 below shows the fluid temperatures when preheating 6 months a year. In Table 4.33 below this result is combined with the plot in Figure 4.51 showing the mean fluid temperatures with 4 months heat injection and 8 months heat extraction.

Plot below with heating load= 0 GWh and cooling load= 27 GWh

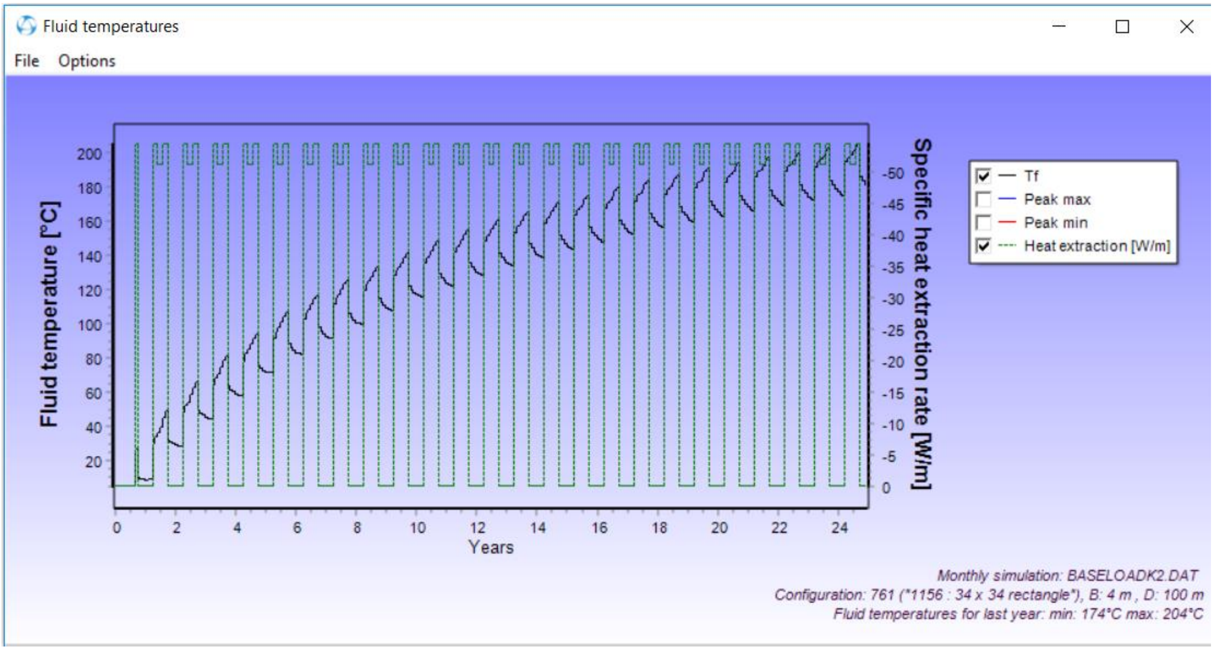

Figure 4.53: Cooling load= 27 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 18 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	39 (-16- 23)	3,5
Preheating for 3 years	39 (31- 70)	50,5
Preheating for 4 years	39 (41- 80)	60,5

Table 4.33: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating six months a year. (4 + 8) months profile).

Preheating for 8 months

During 8 months the storage can receive 18 GWh x 2= 36 GWh

Figure 4.54 below shows the mean fluid temperatures when preheating 8 months a year.

Plot below with heating load= 0 GWh and cooling load= 36 GWh.

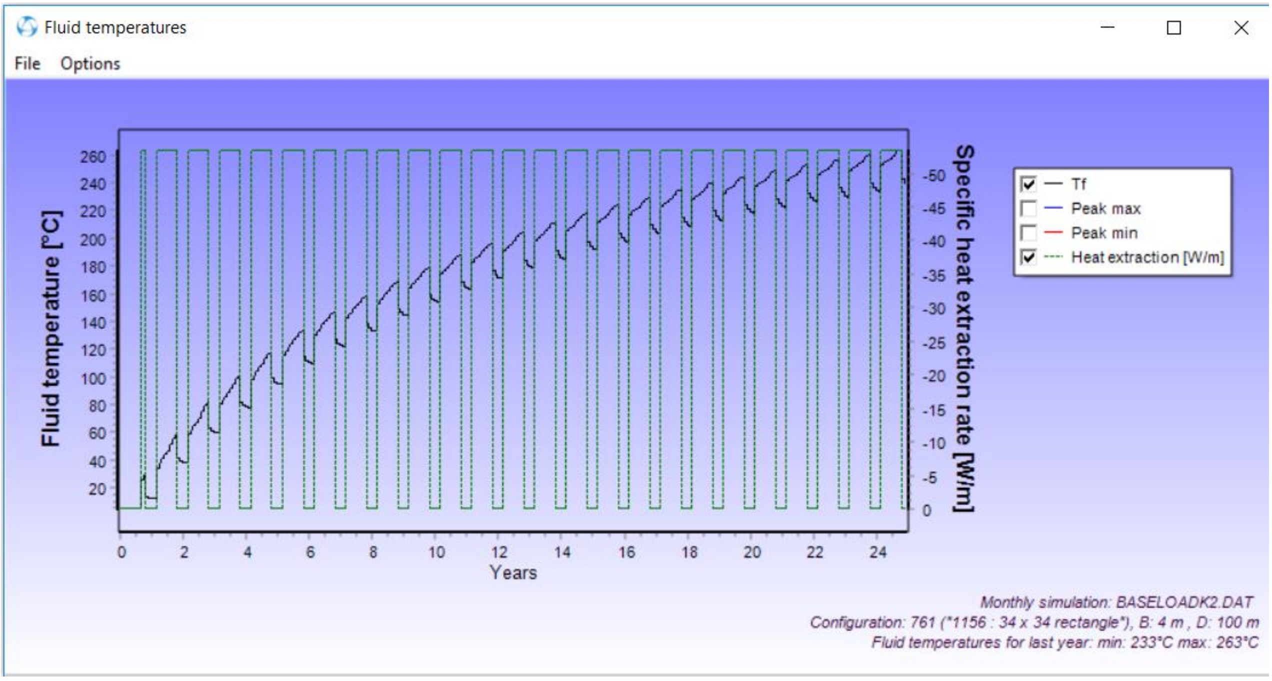

Figure 4.54: Cooling load= 36 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

See that after about 3 years we reach a peak temperature of about 80°C. Table 4.33 shows that the temperature variations are 39°C when the storage is used so if the ground is heated for 3 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 80°C and 80- 39= 41°C. This will give a mean fluid temperature of 60,5°C.

4.4.4. Store 18 GWh (extracting heat six months a year and storing heat six months a year)

The number of boreholes in the configuration with 21 x 21 boreholes is 441. Storing twice the amount of energy we need about twice as many boreholes which is 882 boreholes. Use the configuration of 30 x 30= 900 boreholes which with a borehole distance of 4 meters covers an area of 116m x 116m

The storage can provide a power of: $60\,\frac{W}{m}$ x 100 x (30 x 30)= 5,4 MW

Figure 4.55 shows the mean fluid temperature when heating load= cooling load= 18 GWh and Figure 4.56 shows the mean fluid temperature when heating load= 0 GWh and cooling load= 18 GWh (preheating).

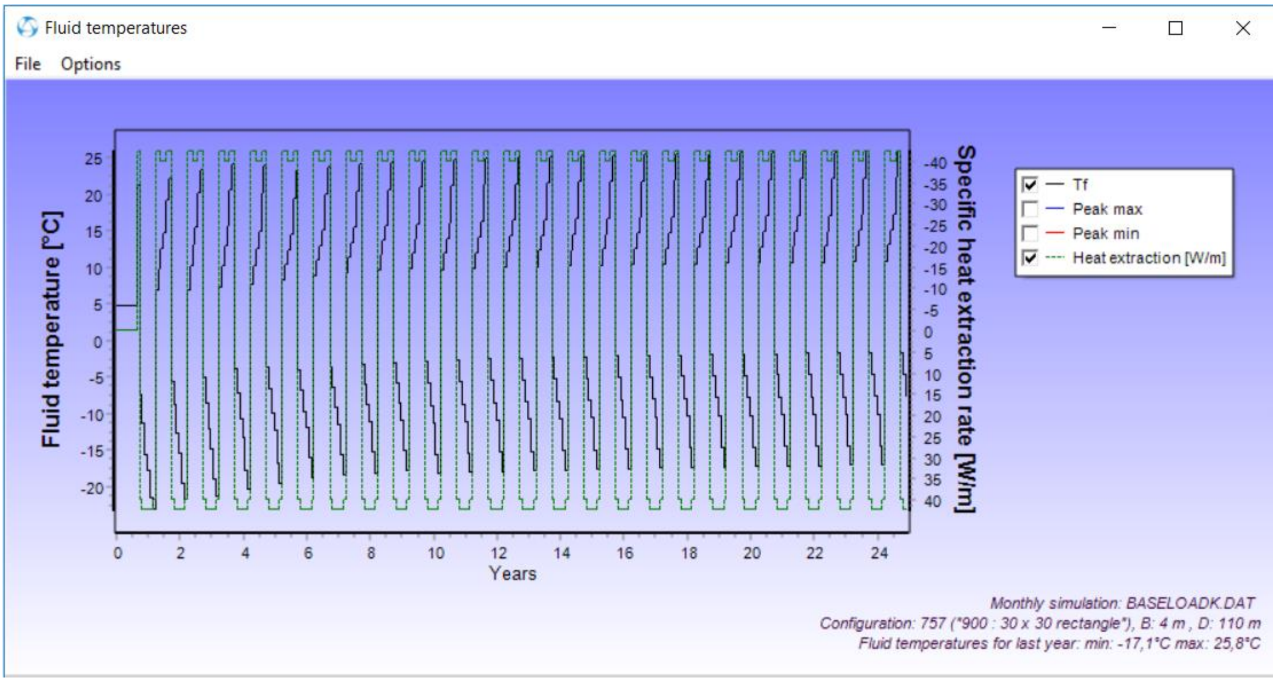

Figure 4.55: Temperature variations. Heating load= cooling load= 18 GWh. 4m borehole distance. 6 months heat injection and 6 months heat extraction.

Try now with heating load 0 GWh and cooling load= 18 GWh

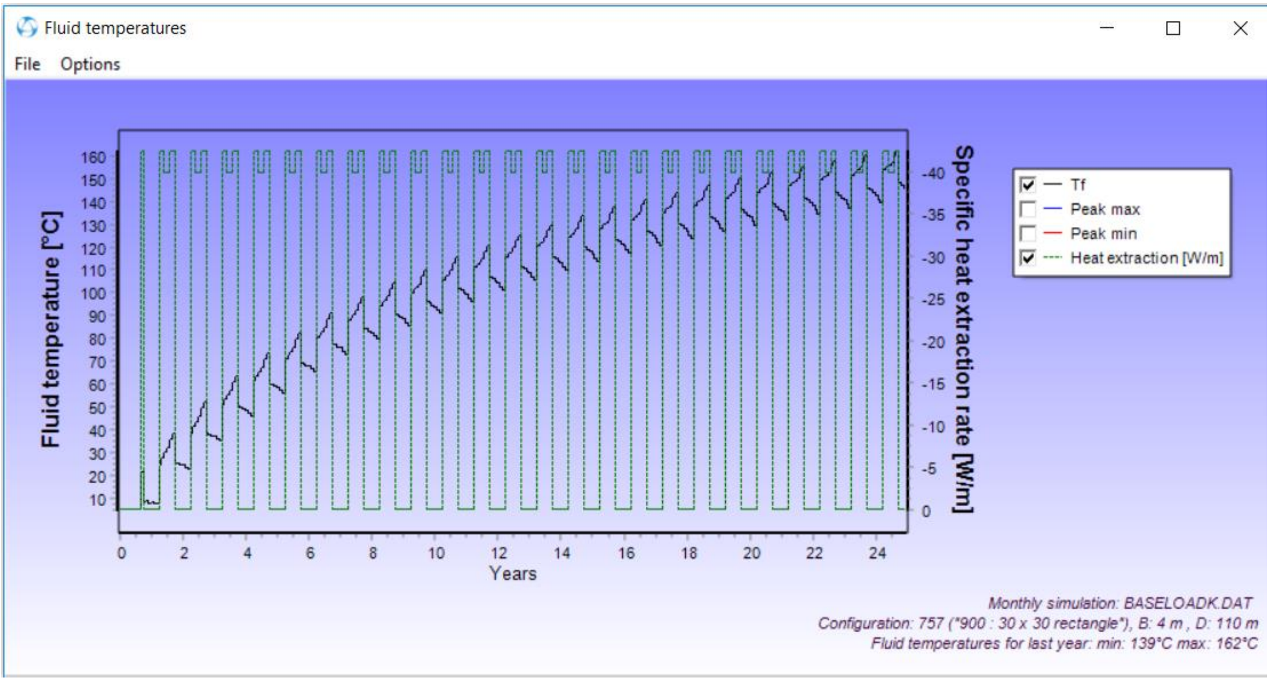

Figure 4.56: Cooling load= 18 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

The results are summarized in the table below.

	Storing 18 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	46 (-23- 23)	0
Preheating for 3 years	46 (9- 55)	32
Preheating for 5 years	46 (29- 75)	52
Preheating 7 years	Exceed 80 degrees	

Table 4.34: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating six months a year. (6 + 6) months profile).

Preheating 8 months a year

From eq. (3.4) we have that a 100m long borehole can uptake 34,6 MWh during 8 months. 900 boreholes can then uptake:

34,6 MWh x 900= 31 140 MWh = ca. 31 GWh

Figure 4.57 below shows the mean fluid temperatures when preheating 8 months a year. In the table below this result is combined with the plot from the last subchapter, showing the mean fluid temperatures with 6 months heat injection and 6 months heat extraction.

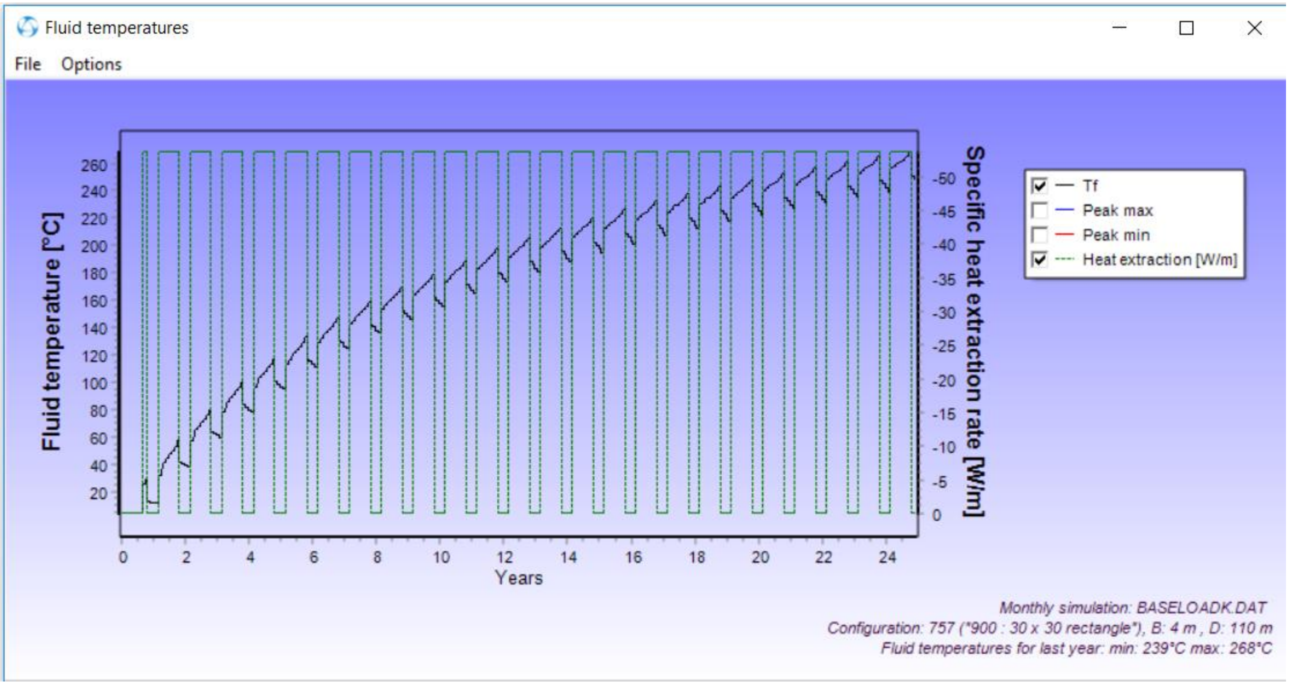

Figure 4.57: Cooling load= 31 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

After about 2,8 years we reach a peak temperature of 80°C. Figure 4.34 shows the temperature variations are 46°C when the storage is used. If the ground is heated for 2,8 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 80°C and 80- 46= 34°C. Average temperature will then be 57°C.

4.4.5 Storage for Kvitebjørn

The area where a BTES system could be placed is 80 x 80 meters. Using 4m borehole distance, the configuration with 21 x 21 boreholes is covers exactly an area of 80 x 80 meters.

The amount of boreholes is 21 x 21= 441

We have that one borehole of 100 meters can store 17,3 MWh in four months eq. (3.2)

The amount of energy that can be stored is 17,3 MWh x 441= 7629 MWh= 7,63 GWh

The storage can provide a power of 60 $\frac{W}{m}$ * 100 * 441= <u>2,65 MW</u>

Figure 4.58 below shows the mean fluid temperature when heating load= cooling load= 7,63 GWh and Figure 4.59 shows the mean fluid temperature when heating load= 0 GWh and cooling load= 7,63 GWh (preheating).

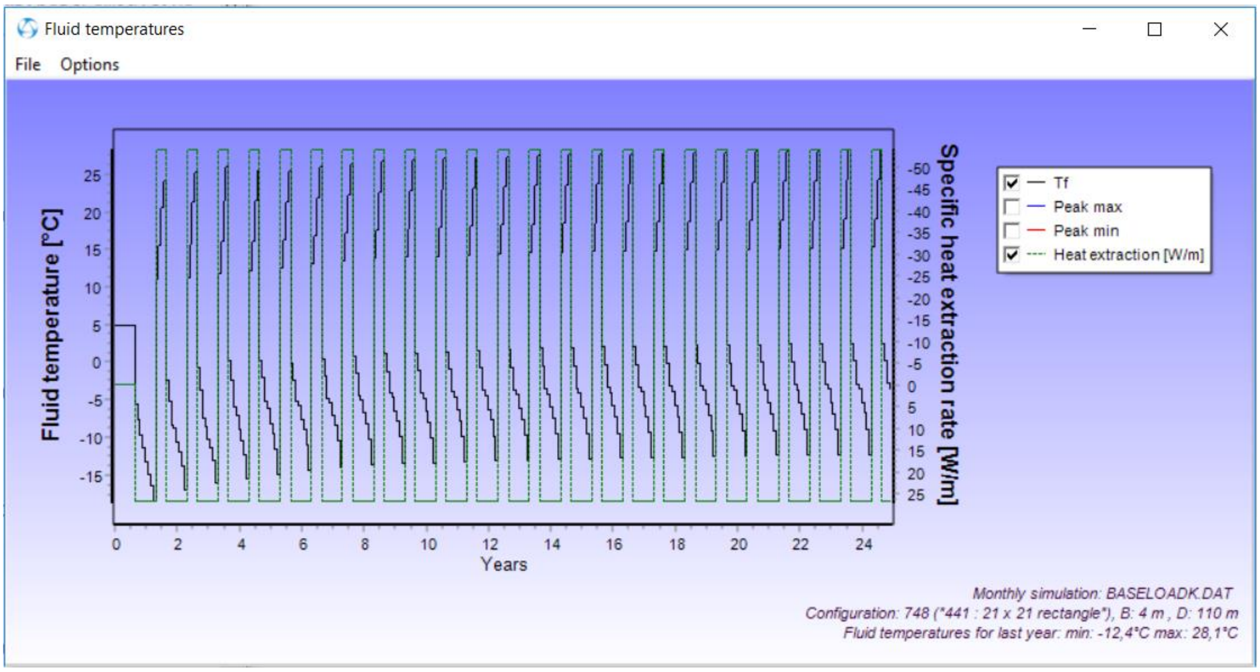

Figure 4.58: Temperature variations. Heating load= cooling load= 7,63 GWh. 4m borehole distance. 4 months heat injection and 8 months heat extraction.

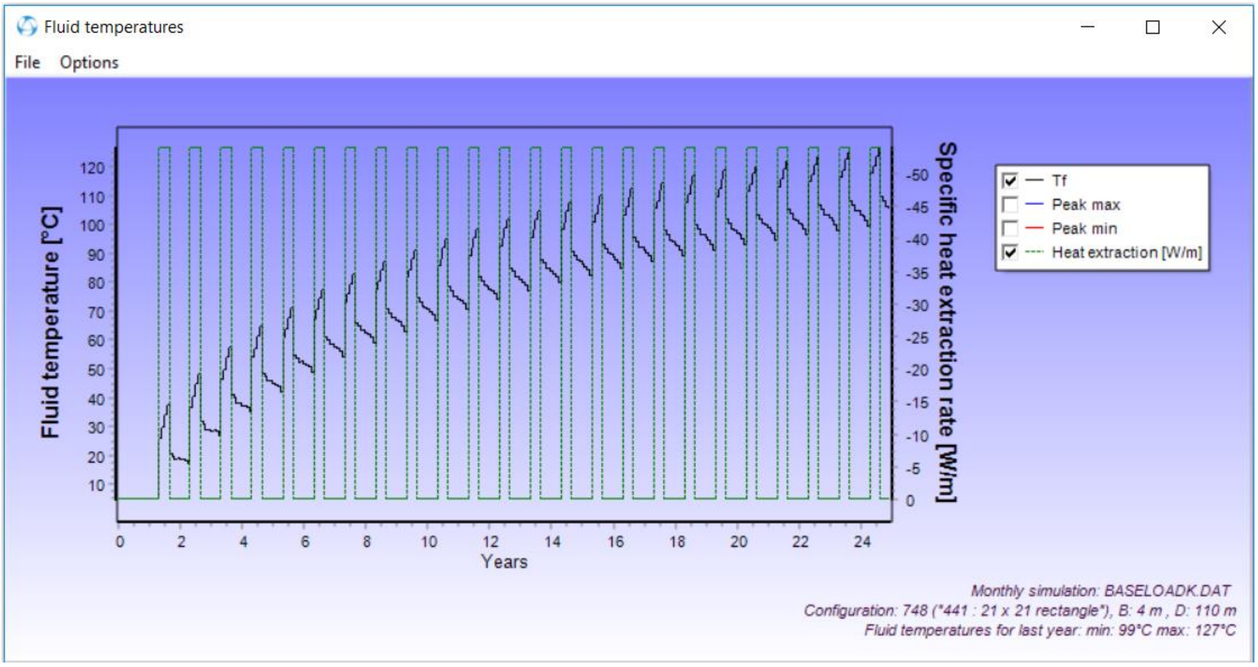

Figure 4.59: Cooling load= 7,63 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 4 months yearly.

The results are summarized in the table below.

	Storing 7,63 GWh and preheating four months a year	
	Temperature variation	**Medium temperature**
No preheating	42 (-17- 25)	4
Preheating for 3 years	42 (10- 52)	31
Preheating for 5 years	42 (26- 68)	47
Preheating for 7 years	42 (38- 80)	59

Table 4.35: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating four months a year. (4 + 8) months profile).

Preheating 6 months a year

A borehole of 100m can store 25,9 MWh during six months eq. (3.3). The amount of energy that can be stored is then:

25,9 MWh x 441= 11422 MWh= 11 GWh

Figure 4.60 below shows the mean fluid temperatures when preheating 6 months a year.

Plot below with heating load= 0 GWh and cooling load= 11 GWh

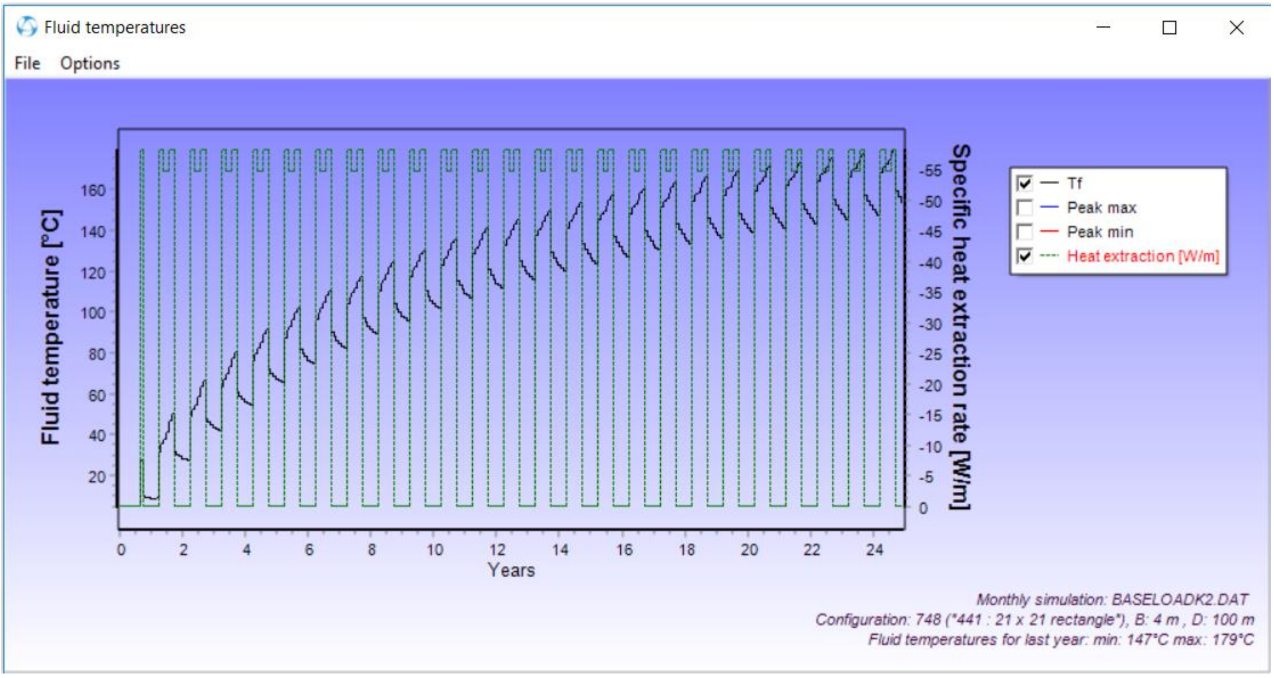

Figure 4.60: Cooling load= 11 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 6 months yearly.

See that after about 3 years we reach a peak temperature of about 70°C. Table 4.35 shows the fluid temperature variations are 42 degrees when the storage is used. If the ground is heated for 3 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 70°C and 70- 42= 28°C. Average fluid temperature is then 49°C.

After preheating for five years the boiling point of 80°C is exceeded.

Preheating 8 months a year

A borehole of 100m can store 35,6 MWh during 8 months eq. (3.4). The amount of energy that can be stored is then:

35,6 MWh x 441= 15 700 MWh= 15,7 GWh

Figure 4.61 below shows the fluid temperatures when preheating 8 months a year.

Plot below with heating load= 0 GWh and cooling load= 15,7 GWh

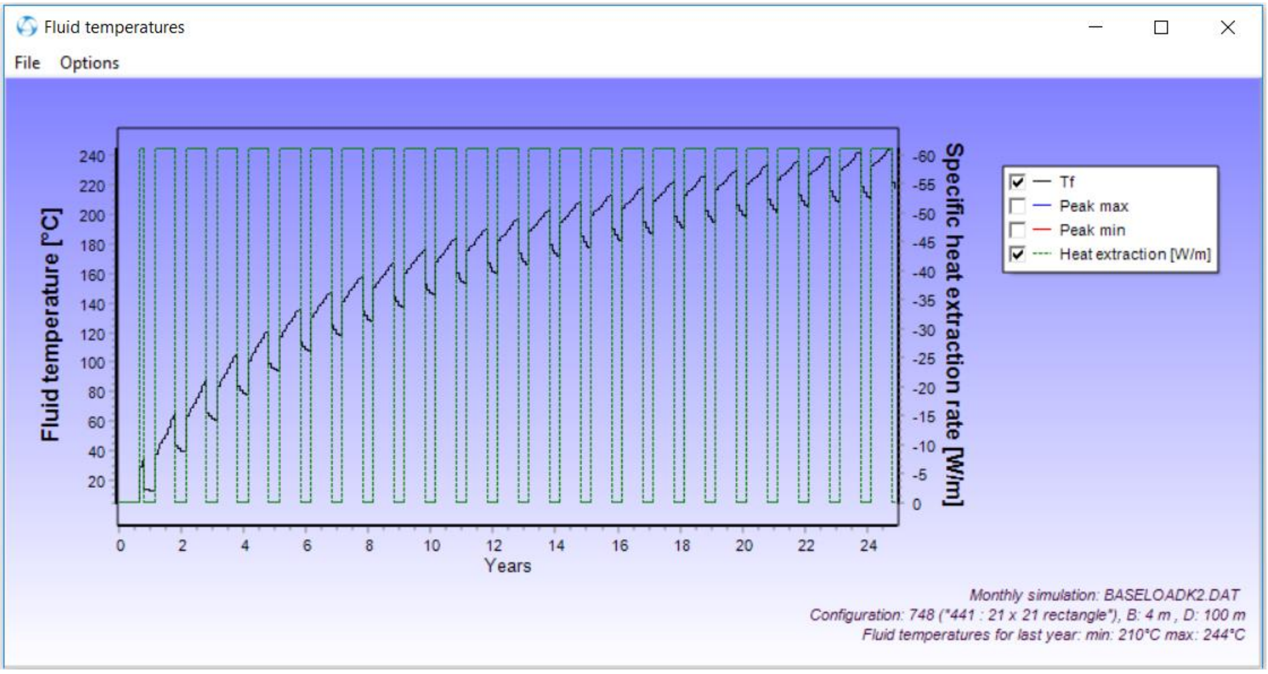

Figure 4.61: Cooling load= 15,7 GWh and heating load= 0 GWh. 4m borehole distance. Preheating 8 months yearly.

80°C is reached after about 2,8 years. Table 4.35 shows the temperature variations are 42 degrees when the storage is used. If the ground is heated for 3 years before heat is both extracted and injected during a yearly cycle, the temperature will vary between 80 degrees and 80- 42= 38°C. The medium temperature will be 59°C.

4.4.6. Storage for Kvitebjørn (extracting heat six months a year and storing heat six months year

Inside the limited area where the BTES system for Kvitebjørn can be placed is 80 x 80 meters and with a borehole spacing of 4 meters the configuration of 21 x 21 boreholes can be used. This is the same as for chapter 4.4.2 where 9 GWh is stored and heat is extracted six months a year and heat is stored six months a year. Within this area 9 GWh can be stored with these monthly profiles. Can use the table from 1.4.2.

	Storing 9 GWh (heating load for 6 months) Kvitebjørn	
	Temperature variation	**Medium temperature**
Preheating for 3 years	51 (7- 58)	32,5
Preheating for 5 years	51 (27- 78)	52,5
Preheating for 7 years	80°C exceeded	

Table 4.36: Fluid temperature variation and medium temperature with and without preheating. 4m borehole distance. Preheating six months a year. (6 + 6) months profile).

With preheating for eight months a year we reached a temperature of 80°C after 2,5 years with a mean fluid temperature of 54,5°C.

4.4.7. Storage for Kvitebjørn (extracting heat six months a year and storing heat six months year. 6m borehole distance, 150m borehole depth

Look now at changing the borehole depth to 150m. Use now a longer spacing of 6m because of longer borehole depth for not risking that the boreholes interact. Inside the area of 80 x 80 14 x 14 boreholes can be placed.

From eq. (3.3) we have that a borehole of 100m can uptake 25,95 MWh during 6 months. A 150m long borehole can then uptake 1,5 x 25,95 MWh= 38,9 MWh

The storage can then uptake: 38,9 MWh x (14 x 14)≈ 7,6 GWh

Figure 4.62 below shows the mean fluid temperature when heating load= cooling load= 7,6 GWh and Figure 4.63 shows the mean fluid temperature when heating load= 0 GWh and cooling load= 7,6 GWh (preheating).

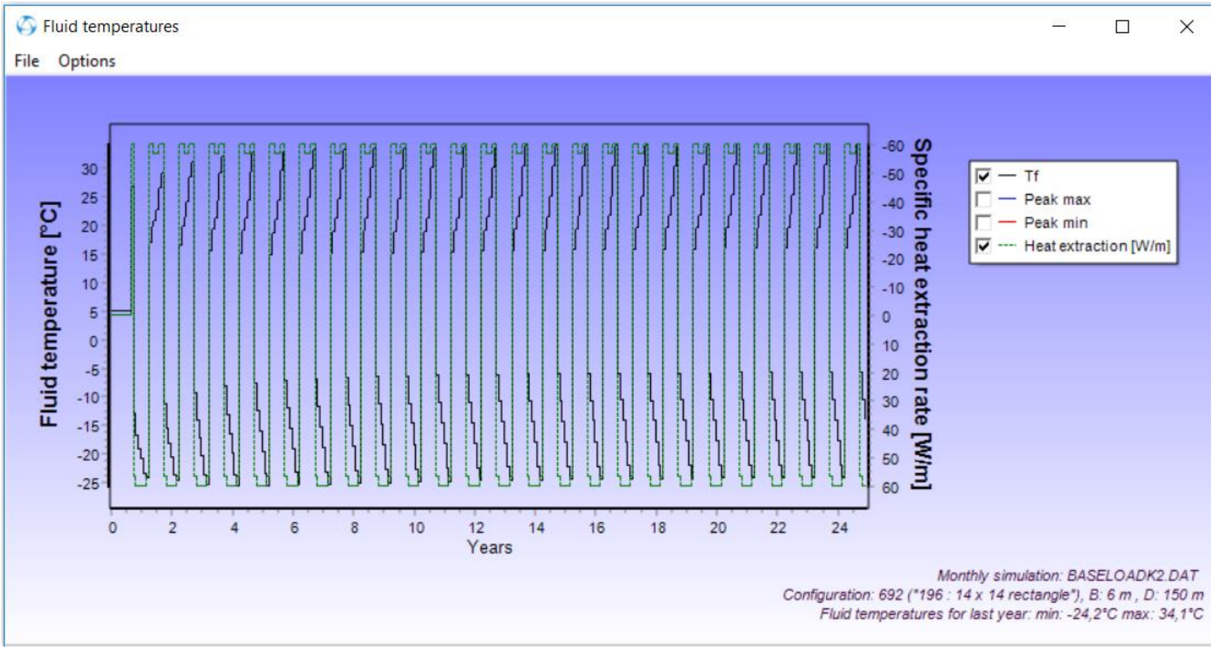

Figure 4.62: Temperature variations. Heating load= cooling load= 7,6 GWh. 6m borehole distance. 6 months heat injection and 6 months heat extraction. Preheating 6 months yearly. 150m borehole length.

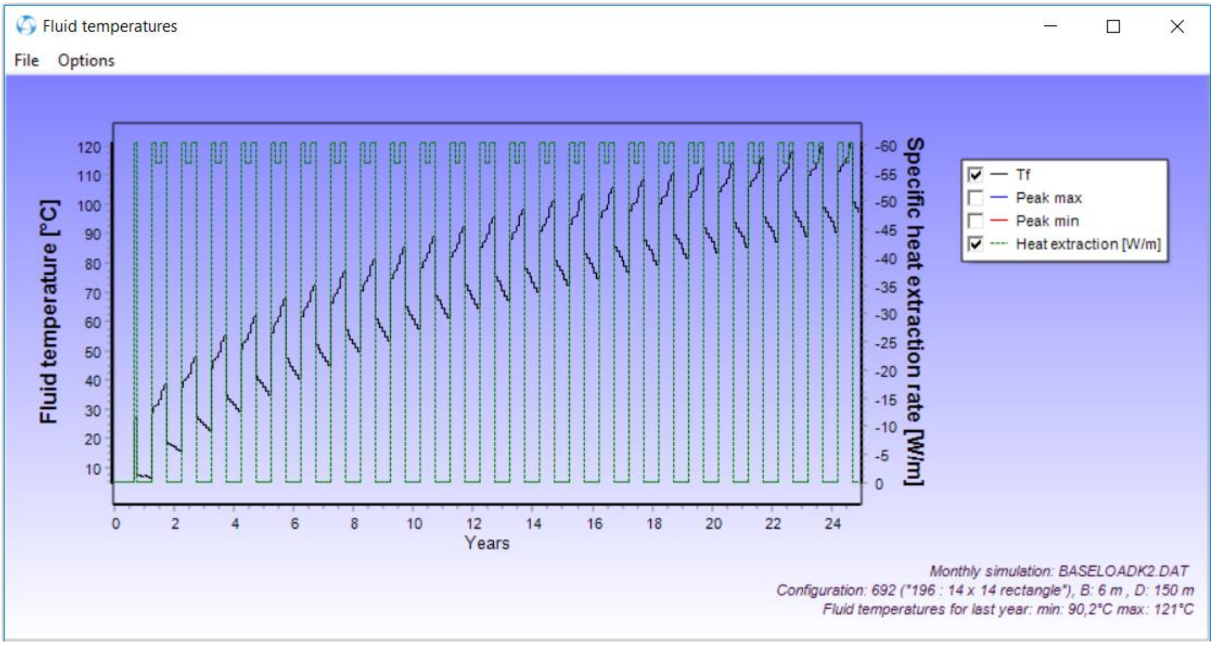

Figure 4.63: Cooling load= 7,6 GWh and heating load= 0 GWh. 6m borehole distance. Preheating 6 months yearly. 150m borehole length.

	Storing 7,6 GWh and preheating six months a year	
	Temperature variation	**Medium temperature**
No preheating	55 (-25- 30)	2,5
Preheating 3 years	55 (-5- 50)	22,5
Preheating for 5 years	55 (10- 65)	37,5
Preheating for 7 years	55 (20- 75)	47,5

Table 4.37: Fluid temperature variation and medium temperature with and without preheating. 6m borehole distance. Preheating 6 months yearly. 6 months heat injection and 6 months heat extraction. 150m boreholes. 14 x 14 boreholes.

See from Table 4.37 that the temperature variations are high (55 degrees). By preheating for 7 years, a temperature of 47,5°C is achieved. Assume that a mean fluid temperature of 40°C can be achieved after about 4 years with preheating 8 months a year. Figure 4.63 shows that the preheating curve is quite straight, at least for the first 8 years.

4.5 Economical analysis

When looking into the economy for the BTES system, I select a storage module of 1 GWh. For a larger storage, I suggest for simplicity that we scale up the information from 1 GWh.

Boreholes. Drilling and installation

The table below shows drilling costs for different drilling depths supplied by the drilling company Verås Brønnboring (verås.no). The prices are drilling costs in solid rock. In soil deposits, the drilling costs are approximately 3 times as high as in solid rock.

Depth	100m	140m	170m	200m
Price borehole	25 000	31 000	39 000	46 500
Price fluid	2400	3360	4080	4800
Total	27 400	34 360	43 080	51 300

Table 4.38: Borehole prices in NOK (verås.no)

From the table we see the price for a 100m deep borehole is about NOK 27 000 which means that the price per metre borehole is 27 000/100= 270 NOK/m.

Drilling the top 10 meters in soil deposits will cost:

NOK 270 x 3 x 10= ca. NOK 8000

Total costs per borehole: 27 000 + 8000= NOK 35 000

Drilling the configuration of 7 x 7= 49 boreholes (6 months heat injection and 6 months extraction) and 110 m borehole depth (100m in solid rock), the total drilling costs will be:

NOK 35 000 x 49= NOK 1,71 mill.

Heat pumps

Assume a mean fluid temperature of about 40°C. To meet the requirements from the district heating system, the water temperature should be raised to 70 – 80°C. This is a high temperature lift that can be done with heat pumps.

Heat extracted from storage= 0,29 MW

Assume COP= 3,5

With a COP of 3,5 the power from the storage is 3,5 higher than the power needed to run the heat pump. The power from the storage is the sum of the heat extracted from the ground and the power needed to run the heat pump. The power extracted is then 2,5 times higher than the power needed to run the heat pump. Assume 1 GWh is injected into the ground during 6 months. Because of heat losses we do not get 1 GWh from the ground, but assume that the sum of the energy from the ground together with the energy gained from the heat pump equals 1 GWh. The energy from the heat pump is 1/2,5= 0,4= 40% of the energy extracted from the ground. This means we are assuming 40% heat losses.

Power need from heat pump: 0,29 MW/2,5= 0,12 MW

Costs of heat pumps according to information from Kvitebjørn:

NOK 7200 per KW installed

Total costs of heat pumps: 120 x NOK 7200 = NOK 864.000

Total investment in NOK: 1,71 mill. + 0,86 mill = NOK 2,57 mill.

Yearly income

Assume that the stored energy can be sold for NOK 0,25 per kWh during winter. (Statoil.no). This assumption is very uncertain. In the latest years energy prices has dropped, but it is expected that energy prices will increase in the future.

Value of stored winter energy of 1 GWh: NOK 250.000

Energy consumption of heat pumps: 1 GWh/3,5= 0,286 GWh

Assume that energy cost for running the heat pumps also is 0,25 NOK:

Cost for running heat pump: NOK 250 000 x 0,286 GWh= NOK 71 500

Net yearly income: NOK 250.000 – NOK 71.500 = NOK 178.500

Profitability

For an investment cost of NOK 2,57 mill, and NOK 0,178 mill. yearly income we get a straight pay back time of 15 years (no interest).

If we assume a life time of the project of 30 years, a present value calculation indicates that a calculation interest of 5,5 % is obtainable.

Comments

- Heat pumps create additional output energy to the district heating system, contrary heat losses extract energy from the storage. As heat losses as well as the efficiency depend on temperature and other uncertain factors, I for simplicity assume that additional energy from heat pumps compensate for energy losses from the heat store.
- Yearly operation and maintenance costs are not considered.
- Costs related to using the area is not considered.
- As the project is innovative in character and reduce waste- energy losses we can expect support from governmental agencies like ENOVA and others.

4.6 Summarizing and discussing

4 months heat injection and 8 months heat extraction

Compare the different storage sizes below when the storage is preheated four months a year for three, five and seven years.

Storage size	**Max. Power**	**Med. Temp 3 ye.**	**Med. Temp 5 ye.**	**Med Temp. 7 ye.**
1 GWh	0,38 MW	22,5	30,5	36,5
9 GWh	3,46 MW	26,5	42,5	55,5
18 GWh	6,94 MW	30,5	45,5	60,5
For Kvitebjørn (7,63 GWh)	2,65 MW	31	47	59

Table 4.39: Fluid temperature variation and mean fluid temperature with and without preheating, and maximum power. 4m borehole distance. Preheating four months a year. 4 months heat injection and 8 months heat extraction.

The table below compare the different storage sizes when the storage is preheated six months a year for three, five and seven years.

Storage size	**Power**	**Med. Temp 3 ye.**	**Med. Temp 5 ye.**	**Med Temp. 7 ye.**
1 GWh	0,38 MW	37,5	49,5	59,5
9 GWh	3,46 MW	33,5	Exceed 80 deg.	Exceed 80 deg.
18 GWh	6,94 MW	50,5	Exceed 80 deg.	Exceed 80 deg.
For Kvitebjørn (7,63 GWh)	2,65 MW	48	Exceed 80 deg.	Exceed 80 deg.

Table 4.40: Fluid temperature variation and medium temperature with and without preheating, and maximum power. 4m borehole distance. Preheating six months a year. 4 months heat injection and 8 months heat extraction.

The table below compare the different storage sizes when the storage is preheated 8 months a year for three, five and seven years.

Storage size	**Power**	**Med. Temp 3 ye.**	**Med. Temp 5 ye.**	**Med Temp. 7 ye.**
1 GWh	0,38 MW	49,5	Exceed 80 deg.	Exceed 80 deg.
9 GWh	3,46 MW	80 exceeded?	…	…
18 GWh	6,94 MW	60,5	Exceed deg.	Exceed 80 deg.
For Kvitebjørn (7,63 GWh)	2,65 MW	Exceed 80 deg.	Exceed 80 deg	Exceed 80 deg.

Table 4.41: Fluid temperature variation and medium temperature with and without preheating, and maximum power. 4m borehole distance. Preheating eight months a year. 4 months heat injection and 8 months heat extraction.

6 months heat injection and 6 months heat extraction

The table below compare the different storage sizes when the storage is preheated six months a year for three, five and seven years.

Storage size	**Power**	**Med. Temp 3 ye.**	**Med. Temp 5 ye.**	**Med Temp. 7 ye.**
1 GWh	0,29 MW	21	31	36
9 GWh	2,65 MW	32,5	52,5	Exceed 80 deg.
18 GWh	5,4 MW	32	52	Exceed 80 deg.
For Kvitebjørn (9 GWh)	2,65 MW	32,5	52,5	Exceed 80 deg.

Table 4.42: Fluid temperature variation and medium temperature with and without preheating, and maximum power. 4m borehole distance. Preheating six months a year. 6 months heat injection and 6 months heat extraction.

The table below compare the different storage sizes when the storage is preheated eight months a year for three, five and seven years.

Storage size	**Power**	**Med. Temp 3 ye.**	**Med. Temp 5 ye.**	**Med Temp. 7 ye.**
1 GWh	0,29 MW	41	56	Exceed 80 deg.
9 GWh	2,65 MW	Exceed 80 deg.	…	…
18 GWh	5,4 MW	Exceed 80 deg.	Exceed 80 deg.	Exceed 80 deg.
For Kvitebjørn (9 GWh)	2,65 MW	Exceed 80 deg.	Exceed 80 deg	Exceed 80 deg.

Table 4.43: Fluid temperature variation and medium temperature with and without preheating, and maximum power. 4m borehole distance. Preheating eight months a year. 6 months heat injection and 6 months heat extraction.

Variations in rock- and fluid temperature

The amount of heat that can be stored in a BTES system is limited by the number of borehole-meters since the boreholes need to absorb heat from the circulating fluid when heat is injected into the storage. The higher the thermal conductivity of the storage material, the more energy can be stored. For storing a given amount of energy (1 GWh) with different borehole-spacing, larger spacing led to using a larger storage area. When 1 GWh was injected into the storage 4 months a year and 1 GWh was extracted 8 months a year, we got temperature variations of 28°C with 8m borehole distance and 41°C with 4m borehole distance. This means that storing the same amount of energy with longer distances between the boreholes leads to less variations in the fluid temperature. The reason is because of a larger storage volume.

With 4 meters borehole distance, the storage volume was: 28m x 28m x 100m= 78 400m^3. The heat capacity of water is 4,18 MJ/(m^{3}K). We have that 1kWh= 3,6 MJ and 1MJ= 0,28 kWh. The heat capacity of water can then be written as 1,17 kWh/(m^{3}K).

The energy density in the storage will be: 1 GWh/78 400 m^3= 12,76 kWh/m^3

The expected increase of the temperature in the storage is then: $\frac{12{,}76\ kWh/m^3)}{1{,}17 kWh/(m^3 K)}$= 11 degrees

So when the fluid temperature increases with 41 degrees, the temperature of the storage volume increases with 11 degrees in this case.

With 8m borehole distance, the storage volume was 64m x 64m x 100m= 409 600m^3. This give an energy density in the storage of: 1 GWh/ 409 600m^3= 2,44 kWh/m^3. The expected increase in ground- temperature is then: 2,44/1,17= 2,09 degrees.

Here the fluid temperature increases with 28 degrees and temperature in the storage volume by 2,09 degrees.

Can see from Table 4.3 in hapter 4.4 that when preheating with 1 GWh 4 months a year, the fluid temperature of the storage with 4m borehole distance increases with 23,5°C- 5,5°C = 18 degrees during the first three years which gives an average increase of 6 degrees per year. Between year 3 and 5 it increases with 30,5°C - 23,5°C = 7 degrees which gives an average increase of 3,5 degrees per year. This result might indicate that the increases in peak- and medium temperatures when the storage is preheated, represents the change in the average storage temperature. After about 5 years the increase is just half the amount as in the beginning, which might indicate 50 percent heat losses after 5 years. During five years the medium temperature has increased from 5,5°C to 30,5°C which is an increase of 25 degrees. In this case a medium increase in average storage temperature of 25 degrees leads to about 50 percent heat losses. If the heat losses is 50% with 4m borehole distance and an increase of 25 degrees, I estimate it to be about 25% for 25°C increase in temperature for the storage for Kvitebjørn since this storage volume is much larger.

With 8 meter borehole- distance it increases with 14°C - 8°C = 6 degrees during the first three years which gives an average increase of 2 degrees and between year 3 and 5 it increases with 17°C -14°C = 3 degrees which gives an average increase of 1 degree yearly.

Sensibility analysis

A higher thermal conductivity led to lower temperature variations in the fluid temperature. When the storage were preheated, the temperature increased slower with a high thermal conductivity. The reason is probably because of higher heat losses. When the storage is preheated, the total loss out of the storage volume would be higher since heat is transported out from the storage volume at a higher rate.

Also with a higher volumetric heat capacity, preheating were slower. This is probably because more energy is needed to raise the temperature in the storage volume. The increase in temperature is lower, but the amount of energy stored will be the same. It also led lo less temperature variations when heat was extracted and injected during a year.

Changing monthly distribution of loads

When I changed the distribution of heat loads to 6 months heat injection and 6 months heat extraction, the same amount of energy could be stored using a smaller surface area, since heat is now injected during a longer time- period. It led to higher temperature variations since the same amount of energy is stored in a smaller storage- volume. I expect the losses to be higher when a larger amount of energy is stored in the same storage- volume, but still I think it is better to inject heat for 6 months, so more energy can be extracted during the coldest part of the year. Taking heat losses into account, it might be better to inject heat for 7 months yearly and extract for 5 months yearly, so heat extracted is closer to heat injected.

The result show that when increasing the storage volume and the heat injected/extracted proportionally, preheating is more effective. This is probably due to lower heat losses. If the storage should be preheated for a long time, it might be might be best to build a large storage, but for gaining experience and for not taking too many risks it is maybe best to begin with building a small storage. More modules could then later be built beside this storage. With a borehole distance of 4m, these modules should be placed 4m apart from the other modules. I would expect the behaviour of this system to be much the same as a large storage of the same size but EED do not have the possibility to simulate this. At least I think we could expect lower heat losses because of a lower volume/surface ratio. When extending the storage, more heat- pump capacity must be added.

Increasing storage volume for Kvitebjørn

In the simulations, I focused on 4m borehole distance and 100m borehole- depth. I also did a simulation with 6m borehole distance and 150m borehole depth. This increases the storage volume with 50%, and we will have a larger storage- volume per unit area. A larger storage volume has lower heat losses because of higher volume to surface ratio. The preheating curve [Figure 4.63] indicates this since it is very straight, especially during the first 8 years.

With 4m borehole distance and an area of 80 x 80 meters, we can use a configuration of 21 x 21 boreholes. For 6m borehole distance we can place 14 x 14= 196 boreholes inside this area. With 150m borehole- depth we get 196 x 150m= 29 400 borehole- meters. With 4m borehole distance and 100m depth we had 44 100 borehole metres. Heat extraction depends on borehole metres, so with 6m borehole distance and 150 depth we get a lower heat extraction. Less heat can also be stored, since the heat stored depends on how much heat that can be extracted/injected during a season. The results from chapter 4.4.7 also showed this. The amount of energy that could be stored were 7,6 GWh instead of 9 GWh. Since the amount of heat stored is distributed over a larger volume, the average temperature variations over the storage- volume would be less. On the contrary the results show that the variations in the mean fluid temperature were higher [Figure 4.37]. This is because the temperature is not the same in the middle of the borehole than in the rock surrounding it. When injecting heat into the boreholes, the temperature will increase. The heat will flow slowly away from the boreholes, giving an exponential decrease in temperature between two boreholes. The larger the distance between the boreholes, the larger this temperature difference will be.

Heat losses

From the graphs showing the mean fluid temperatures when an equal amount of energy is extracted and injected during a yearly cycle, we see that temperature varies between the same minimum and maximum temperatures. Therefore there are no heat losses from the storage volume. When heat is injected, the temperature around the boreholes increases and part of that heat- energy moves away from the boreholes. A part of this energy might be lost. When heat is extracted, the opposite probably happen. When heat has been extracted for some time, the temperature around the boreholes will probably be lower than in the surrounding rock. Now heat will instead flow towards the borehole. We will now gain heat from the surrounding rock. The heat gained will probably equal the heat lost during a yearly cycle and therefore the graphs do not show a decrease in mean fluid temperature after many years.

If the storage is preheated before using the storage, the temperatures will vary around a temperature which is higher than the temperature outside the storage. If the same amount of energy is added to and extracted from the system after preheating, we would expect heat losses from the storage volume. This loss of heat will be from the surface of the storage volume. The medium fluid temperatures will then be lower and lower. Heat losses can be seen from the graphs showing how the fluid temperature varies when the storage is preheated a part of the year. Here we see that fluid temperature increases when heat is injected, but the part of the year when heat is not injected, the fluid temperature decreases. This is because heat flows from the boreholes to the surrounding rock. But this heat is not lost, it is just stored between the boreholes. In the next period when heat is injected, the fluid temperature reaches a higher peak temperature than the year before. After many years, we see that the fluid temperature increases less for each year. This is because the losses from the storage volume is higher when the medium temperature of the storage is higher.

Heat pumps

From eq. (2.5) we have that the maximum possible coefficient of performance of a heat pump is given by $COP_{MAX} = T_H/(T_H - T_C)$ where T_C is the temperature of the source and T_H is the temperature of the sink. The source will be the mean fluid temperature and the sink will be 80°C. Calculate for mean fluid temperatures of 20°C and 40°C.

For 20°C: COP_{MAX}= 353,15°K/(353,15°K - 293,15°K)= 5,88

For 40°C: COP_{MAX}= 353,15°K/(353,15°K - 313,15°K)= 8,83

Assuming the coefficient of performance to be half of maximum possible theoretical efficiency, it will be about 3 for an average fluid temperature of 20°C and about 4,4 for and average fluid temperature of 40°C. Before constructing a BTES system, different heat pumps and their COP values for different temperature lifts should be investigated. This would also influence how much a storage should be preheated.

Thermal response tests

For investigating the rock properties, especially the thermal conductivity, thermal response tests in the area should be made before a BTES system be built. In principle this test measures the rocks ability to absorb energy.

5 Conclusion and future work

5.1 The literature study

It seems that the most realistic alternative for storing large amounts of energy for a whole season is a BTES system. For an ATES system to be built, it would be hard to find suitable sites. CTES systems are expensive, especially if there are not already existing underground caverns available.

Chemical storage technologies and PCM storage technologies are probably not sufficiently developed for large scale seasonal energy storage.

For district heating applications a high temperature storage would be preferable, but heat pumps would probably be needed anyway because of the high temperatures. The problem with high temperatures are higher heat losses, so a compromise between temperature level and minimising losses should be made. A high temperature system will have higher energy density, and for storing the same amount of energy, the system will be smaller. For a low temperature system there will be lower losses, but more energy must be used by the use of heat pumps to extract heat from the ground.

5.2 Simulation with Earth Energy (Designer EED)

The amount of heat that can be store in a BTES system is determined by the number of borehole meters, since the amount of energy stored is determined by how much heat that can be injected during a season. If heat is injected for 6 months instead of 4 months during a year, a larger amount of heat can be stored with the same number of borehole meters.

Heat losses depends on the storage volume, where a large storage volume leads to less losses. A larger storage volume can be achieved with a larger surface area, or deeper boreholes. With the same heat loads and number of boreholes, closer spacing between boreholes leads to higher fluid- temperature variations.

Preheating the storage for some years before using it increases the mean fluid temperatures but it will also increase heat losses when the storage is used. How fast high temperatures are reached, depends on how many months the ground can be preheated yearly. Preheating is also more effective with large storages.

A higher volumetric heat capacity leads to less temperature variations and a longer preheating period to reach high temperatures. Higher thermal conductivity also leads to less temperature variations and lower men fluid temperatures when preheating.

For Kvitebjørn I would recommend the borehole configuration of 21 x 21 boreholes and 4m borehole distance and, 100m borehole depth in rock. With this system we reach a mean fluid temperature of 32,5°C after 3 years of preheating and a mean fluid temperature of 52,5°C after 5 years of preheating. A smaller storage should be built first (7 x 7) boreholes for investigating the behaviour of the system, and to investigate heat losses when the system is preheated. The system could then be extended and less heat losses could now be expected. If high medium fluid temperatures are required, I would recommend the configuration with 14 x 14 boreholes, 6m borehole distance and 150 meter borehole depth. This because of a larger storage volume which leads to lower heat losses. The disadvantage of this configuration is lower heat extraction because of fewer borehole metres. The choice between these two configurations would depend on investment costs and the COP of heat pumps for different temperature lifts. This would influence the importance of having high medium fluid temperatures. Before building a storage, more precise ground investigations should be done, especially including thermal response tests.

Future work should be to investigate prices and performance of heat pumps. The heat pumps need to perform high temperature lifts with a relatively high COP for the system to be economical.

Investigations can be done to find drilling companies with experience and technology to drill precise. Then it will be possible to drill deep with close spacing between boreholes, without risk for the boreholes interacting with each other.

Perform a feasibility study for a BTES system at Strandkanten, based on the simulations with EED in this thesis and look more closely into:

- Yearly loss distribution of the waste energy and total waste energy available.
- Design and technology.
- Investigate the costs of a BTES system as well as the possibilities of receiving economical support from governmental organizations like Enova.

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