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Projecte Final de Grau

LARGE-SCALE UNDERGROUND THERMAL ENERGY STORAGE

-Using industrial waste heat to supply district heating-

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λ	Thermal Conductivity (W/K,m)
υ	Kinematic Viscosity (m^2/s)
A	Area (m^2)
c	Volumetric Heat Capacity(kWh/m^3,K)
D	Diameter (m)
E	Energy (J or MWh)
f	Friction factor
g	Gravity (m/s^2)
h	Pressure Loss
h_d	Minor loss
h_L	Major loss
k	Pipe rugosity (mm)
K	Local Pressure Loss Coefficient
L	Length (m)
q	Geothermal Heat Flux (W/m^2)
Q	Flow rate (m^3/s)
Re	Reynolds number
T	Temperature (ºC)
Tin	Inlet temperature
Tout	Outlet Temperature
Tmean	Mean temperature in the storage volume
V	Volume (m^3)
v	velocity (m/s)
z	Depth (m)

ATES	Aquifer Thermal Energy Storage
BHE	Borehole Heat Exchanger
BTES	Borehole Thermal Energy Storage
C_{as}	Annual Storage Cost
CTES	Cavern Thermal Energy Storage
DH	District Heating
dhw	District Hot Water
DN	Diameter Nominal
€	Euro
ES	Energy Storage
MSEK	Millions of Swedish Kronor
PE	Polyethylene
PF	Performance Factor
PN	Pressure Nominal
SEK	Swedish Krona
TES	Thermal Energy Storage
UTES	Underground Thermal Energy Storage

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1 Introduction

1.1 Abstract

The city of Luleå is growing and the municipality is looking to build a new urban area for about 5 000 people in an old air military area called Kronan. The concept is to build a green residential area, but no details have been decided yet.

Usually the space heating in the Swedish cities is supplied by a municipal district heating system. Luleå takes advantage of the gases generated in the local coke and steel plants. Using these gases as fuel in a co-generation plant, which is connected to Luleå's district heating system, means that the Luleå community has the cheapest district heating in Sweden (Luleå Kommun, 2014). The heat produced by these gases can easily supply the heat demand when the temperature is above -10^{o}C, but when it is colder than -10^{o}C additional energy is required and there are different plants to provide it. This extra energy comes from electricity and oil. In total, heat from the waste gases covers about 90 % of the district heating.

Moreover, the steel plant works the whole year while space heating demand depends on the weather. When there is no demand, the heat generated in the plant is mostly dumped into the Bothnian Bay, which means a significant waste of energy.

This project studies the possibility to store this waste heat in summer in order to supply space heating to the new residential area. This storage procedure is possible using a borehole thermal energy storage and the optimum parameters depend on the energy price.

The storage cost estimated is between 34 and 41 MSEK , with a payback of 7 to 9 years and it is able to supply 14 GWh/year during the winter months fulfilling the heat demand for the new neighborhood. The energy efficiency of the storage is above 75% from the fifth year of operation, which means barely 18GWh of waste heat will be used to supply the district heating.

1.2 Objective

The aim of this project was to investigate seasonal storage of waste heat in a borehole thermal energy storage (BTES) system to supply it to the new urban area in Kronan during the demand period. The main objective is to provide the total heating demand for Kronan, including the domestic hot water.

In order to estimate the heat demand for this new urban area of 1500 new dwellings (single-family houses, a mean annual heat demand of 12 MWh/dwelling is assumed, which means that 18,000 MWh is annually needed to heat the new buildings. The annual waste heat from the steel plant is 250-500 GWh, but a large share of this waste is of low temperature, i.e. below 20^{o}C (Skogsberg, 2014).

2 Background

2.1 Energy consumption

Nowadays one of the most urgent issues is the World energy consumption, better said overconsumption. The human civilization is consuming approximately 1.5 times more resources than Earth can sustain, (The Living Planet, 2012), leading to exhaustion of the resources. The fact is that the problem is accelerating since, as demonstrated for energy in Figure 1, the consumption is still increasing despite all previous global measures. The consumption of energy resources follows rather well the overall consumption of resources since energy is required to utilize other natural resources.

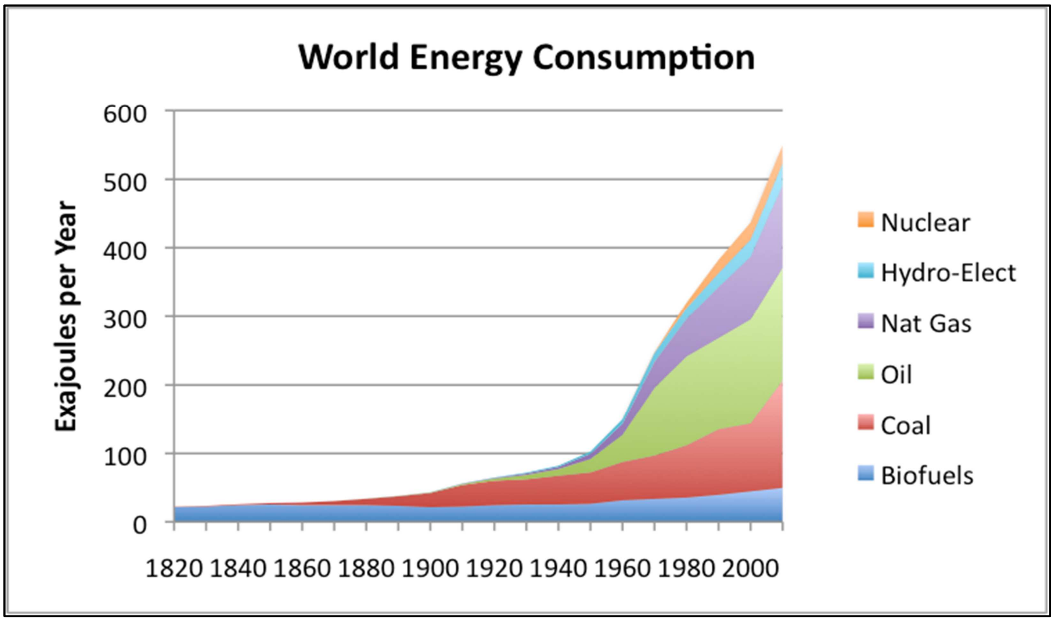

Figure 1. Global Energy consumption by Our Finite World 2012.

In order to slow down the exhaustion of energy resources, and thereby increased energy costs, the International Energy Agency (IEA) promotes renewable energies, more efficient use of energy, and energy storage technology.

The IEA's *Energy Conservation through Storage (ECES)* programme has held international global energy conferences since 1981. The first three conferences were held every second year (until 1985) and since 1988 the conferences have been held every third year. The most recent was Innostock´2012 (the 12th International Conference on Thermal Energy Storage) in Lleida, Spain. The next conference, Greenstock´2015, will be held in Beijing, 19-21 May 2015.

2.2 Energy cost

The decreasing oil (fossil energy) resource, which is currently the most important source of energy, means that the price of the energy is increasing (see Figure 2). This has resulted in greater interest in renewable energy resources. Apart from being environmentally benign, they have low operation costs.

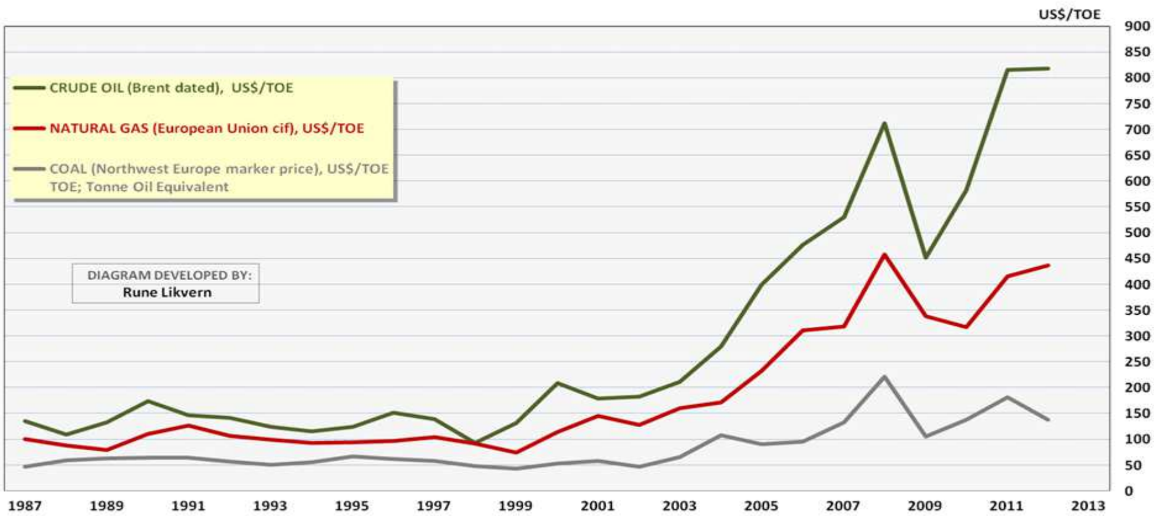

Figure 2. Nominal price developments for 3 fossil fuels in the European market. Price in US dollars per Ton Oil Equivalents.

At the same time these fossil fuel resources such as oil, natural gas and coal are increasingly less available.

2.3 Waste energy

Despite the increasing energy cost a substantial part of used energy is wasted, in all sectors of society. Even though a large portion of wasted energy could be saved by simple and inexpensive measures, much of the savings would require larger investments in the energy system.

Most of the wasted energy is heat because of for example poor insulation of buildings or bad or no systems to control and regulate the heating, cooling and ventilation demand, where simple means would make a big difference.

Recycling of heat and also using household waste as an energy resource is quite common in Europe. When it comes to recycling of household waste, Sweden is very successful as just four percent goes into landfills. The rest winds up either recycled or used as fuel in waste-to-energy power plants (Public Radio International, 2014). Burning the garbage in the incinerators generates 20 percent of Sweden’s district heating. Sweden has been so successful that it imports waste from neighboring countries.

One way to further increase recycling of heat is to store it for use at a later time; it could mean storage between day and night but also between the seasons. Here is where the field of Energy Storage becomes significant.

2.4 Energy Storage (ES)

The importance of energy storage has been increasing in past years and will continue growing; the main reason being that the many important renewable energy resources are intermitent, and generated when weather dictates, rather than when energy demand dictates (Hammerschlag & Schaber, 2007). The huge potential of energy sources substituting fossil fuels can only be exploited by energy storage systems, utilizing renewables such as solar thermal, photovoltaic and wind energy.

Dincer and Rosen (2011) summarized the significant benefits from use of ES systems as follows:

- Reduced energy costs.
- Reduced energy consumption.
- Improved indoor air quality.
- Increased flexibility operation.
- Reduced initial and maintenance costs.
- Reduced equipment size.
- More efficient and effective use of equipment.
- Conservation of fossil fuels.
- Reduced pollutant emissions.
- Peak shaving & peak shifting.

There are a number of promising areas of research in ES technology. Given the potential benefit of ES applications it is clear that a sustained development effort is necessary. Some current research and development areas in the field are as follows (Dinser & Rosen, 2011):

- Advanced ES and conversion systems with phase transformations, chemical and electrochemical reactions.
- Engineering integration of whole battery packs into vehicles.
- High-dielectric-constant polymers.
- High K composites for capacitors.

- Polymer electrode interfaces (low and high-frequency effects).
- Integrated polymer capacitors.

3 Thermal Energy Storage (TES)

Among the different energy storage methods, the one used in this project is Thermal Energy Storage (TES).

Thermal energy may be stored by altering the sensible heat of a substance, by changing the phase of a substance or through a combination of both. These technologies are useful for storing energy from systems that provide heat as a native output (e.g., solar thermal, geothermal), or for applications where the energy´s commodity value is heat (e.g., space heating, cooling, drying).

The TES systems are numerous and include designed containers, underground aquifers, soils, lakes, bricks and ingots. But always the energy is stored by cooling, heating, melting, solidifying, or vaporizing a material; and the thermal energy becomes available when the process is reversed.

The energy E required to heat a volume *V* of a substance with a volumetric heat capacity heat *c* from a Temperature T_1 to a temperature T_2 is defined by the equation (1) (Cengel, 2002):

$$E = V \cdot c \cdot (T_2 - T_1) \quad (1)$$

When the system consists in elevating or lowering a material temperature it is called **sensible heat storage**. Its functionality depends on the material thermal properties, mainly in specific heat. However when the system consists in a material transition from solid to liquid or liquid to vapor it is called **latent heat storage**. While sensible storage normally uses rocks, ground or water as storage media, the latent heat storage uses phase change materials (PCMs) and the specific heat of fusion or vaporization are main design parameters.

The selection of a TES system is subject to different factors such as period required, economic viability, energy volume, operation conditions and so on.

In some situations the TES have a dual functionality, not only keeping the energy for later use, but also being involved in other processes. One example is the following:

Plants and factories need cooling processes due to the fact that they are not perfectly efficient and they produce heat during the manufacturing or energy transformation. Because water is a perfect medium to dissipate heat and it is easily accessible many plants are located close to the sea or rivers. But instead of throwing back this warm water, as they normally do, it can be stored for other necessities, such as internal space heating or pre-heating in other processes. That would avoid thermal pollution and improve the plants overall efficiency.

The ES systems can be divided in two different groups depending on the storage period: **Short-term** and **seasonal storages.** In some climates there is a heat demand during winter and also a cooling demand during summer; with the seasonal storage it is possible to match the annual demand. The storage is charging heat from the warm summer and supplies it when it is required, while at the time the storage is charging cool from the cold winter to supplies it in summer. A short-term storage application on the other hand would be in single house solar systems with a tank, the objective of which is to store the energy from the night to supply it the following morning.

3.1.1 Barriers to TES

Although all the advantages of TES technology are not always taken into account when considering it as a real option, due to the following reasons mentioned by Dincer and Rosen (2011):

- Lack of proper information.
- Lack of commercial options.
- High initial cost.
- Infrastructure restrictions.

The high initial costs can be alleviated with funds as financing for TES investment is available from the European community. But the biggest disadvantage for large storage is the infrastructure constraints; depending on the location the media is not suitable for a TES system.

3.2 Underground Thermal Energy Storage (UTES)

The most common methods for large scale thermal energy storage (i.e. heat or cold storage) are sensible storage in aquifers (ATES) and in the bedrock through borehole heat exchangers (BTES). Another option is underground caverns (CTES), but this concept has so far rarely been applied commercially (Andersson O. , 2007).

The site specific conditions, geology and groundwater etc., are determining factors in deciding which UTES system could be implemented; each system needs different media and size, and for that reason not all locations are suitable. However, if one cannot find a suitable aquifer for ATES, it is almost always possible to use boreholes to create a BTES system. But, the underground conditions will always determine the system efficiency and this is therefore the most important factor.

To have a proper thermal performance, any UTES system needs a certain size. If not, the stored thermal energy will be lost in temperature quality due to thermal losses to the surroundings. The thermal losses will reduce the UTES performance and it is therefore important to carefully determine the ground conditions.

3.2.1 Application of UTES

Around the world there are contrastive types of climates and in each one are different potential applications for UTES. The following are some of these possible applications:

- Space heating in residential, commercial and industrial buildings.

- Air conditioning in residential, commercial and industrial buildings.
- Process cooling in manufacturing industries, telecom applications, IT facilities and electric generation with combustion technologies.
- Cooling for food preservation and quality maintenance.
- Cooling and heating for growing agricultural products in greenhouses.
- Cooling for fish farming in dams.

3.3 Rock Cavern Thermal Energy Storage (CTES)

In the Rock Cavern Thermal Energy Storage (CTES) the energy is stored as hot water in an underground cavern. Potential structures for CTES include abandoned mines, tunnels and rock caverns, and specially constructed caverns for thermal energy storage.

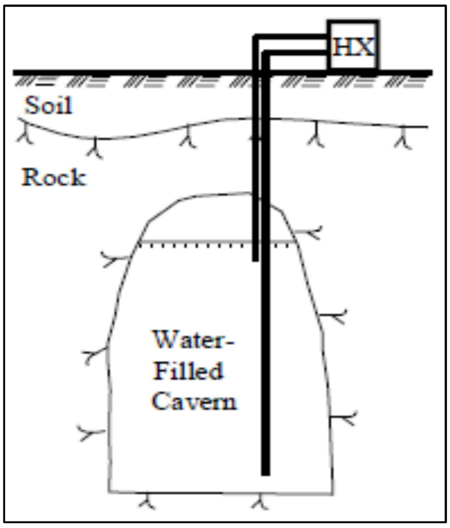

Figure 3. Rock Cavern Thermal Heat Energy Storage

As seen in **¡Error! No se encuentra el origen de la referencia.** the pipes for extraction and injection reach different depths, because during the injection the hot water is released in the upper part of the store while the colder water is extracted from the bottom, in this way the volume of water gets a stratified profile. There are also systems, e.g. the Lyckebo storage (Uppsala, Sweden) with has a "telescope" injection pipe, where the hot water is always injected at the same temperature as the temperature of injected heat.

Like the other underground energy storages during the first years of heat injections there is substantial energy loss to the surrounding rock. However, during the first few years of charging, the cavern develops a relatively stable thermal halo around itself with decreasing temperature away from the hot center (Sang Lee, 2013).

The advantage of CTES is the high injection and extraction powers which are mainly a function of pumping capacity and sizing of the heat exchangers, while the disadvantage is its high construction costs.

There are just a few examples of CTES in the world and the first two were built in Sweden in the early 1980s. One of them is the Avesta CTES which was built in 1981 for short-term energy storage of heat produced at an incineration plant with 15 000m^3 volume and the Lyckebo CTES with a storage volume of 115,000 m^3, which is connected to the Uppsala district heating net (Nordell B. , 2012). The CTES may also be used for storing snow as phase change material energy storage (PCMES).

3.4 Aquifer Thermal Energy Storage (ATES)

The Aquifer Thermal Energy Storage (ATES) is a direct water heat exchanger system for large scale systems mainly for seasonal thermal energy storage both heating and cooling.

In the ATES systems thermal energy is stored in the ground water of an aquifer. The system consists of two or multiple wells used to extract water from the aquifer which is heated or cooled before it is re-injected. The wells are drilled separately in two groups in order to keep one part of the aquifer warm and the other part cold.

ATES are not as easy to construct as BTES, and need more maintenance and pre-investigations to get the authority approval, due to the protection of groundwater resources and environmental impact (Sang Lee, 2013).

However, the investment in ATES systems is not significantly higher than a conventional system and since the operational cost is much less due to energy savings, the ATES system is normally quickly paid off. Depending on the type of system the payback will vary, as can be seen in

Table 1 where the values are obtained from Swedish applications with the performance factor (PF) and the energy savings in respect to the conventional systems, these latter consist of fossil fuels or electricity for heating or district cooling for air conditioning.

Table 1. Economics and potential energy savings by ATES (Andersson O. , 2007).

System application	PF	Energy saving (%)	Payback (years)
A. Direct heating and cooling	20–40	90–95	0–2
B. HP supported heating and cooling	5–7	80–87	1–3
C. HP supported heating only	3–4	60–75	4–8
D. Direct cooling only	20–60	90–97	0–2

One example of ATES is at Stockholm Arlanda Airport (Figure 4), the largest airport in Sweden. This installation started its operation in the summer of 2009.

In the winter this ATES is used for preheating of ventilation air and for snow melting off the ramps at the gates. This way the water of the aquifer is cooled down during the winter. In the summer this cold water is used for comfort cooling. The waste cold from heating is distributed back and stored at the cold side of the aquifer. The cold storage temperature varies from +3 to +5°C under normal conditions. Before this system was taken into operation heating was supplied by district heating.

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

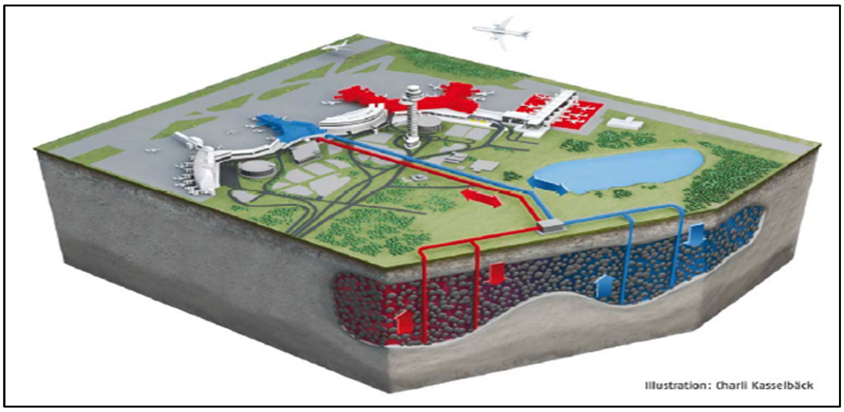

Figure 4. Arlanda airport ATES installation

3.5 Borehole Thermal Energy Storage (BTES)

The Borehole Thermal Energy Storage (BTES) consists of a network of vertical ground heat exchangers drilled on the ground or also called borehole heat exchangers (BHE), which are closely and uniformly spaced. Inside of the boreholes different duct types are used as heat exchangers to heat or cool the ground source, this ground is the volume where the heat is stored and it is composed of soils and rocks. A fluid pumped through the ducts, called heat carrier fluid, is the heat transmission medium for both extraction and injection. During the energy injection the heat is transferred from the heat carrier fluid to the borehole wall, in different ways depending on the system, and from the borehole wall conducted to the surrounding rock, while the energy extraction follows the opposite way when the store is at higher temperatures than the heat carrier fluid.

BTES systems are easier to construct and operate than ATES, need limited maintenance and have long durability. Moreover, BTES systems usually require only simple procedures for authority approvals. Another advantage with respect to ATES is that it is less dependent on site-specific conditions, therefore BTES provides an alternative for areas where groundwater conditions are insufficient. But while ATES needs just a few thermal wells, BTES needs a large quantity of boreholes for large-scale thermal energy storage, see Figure 5.

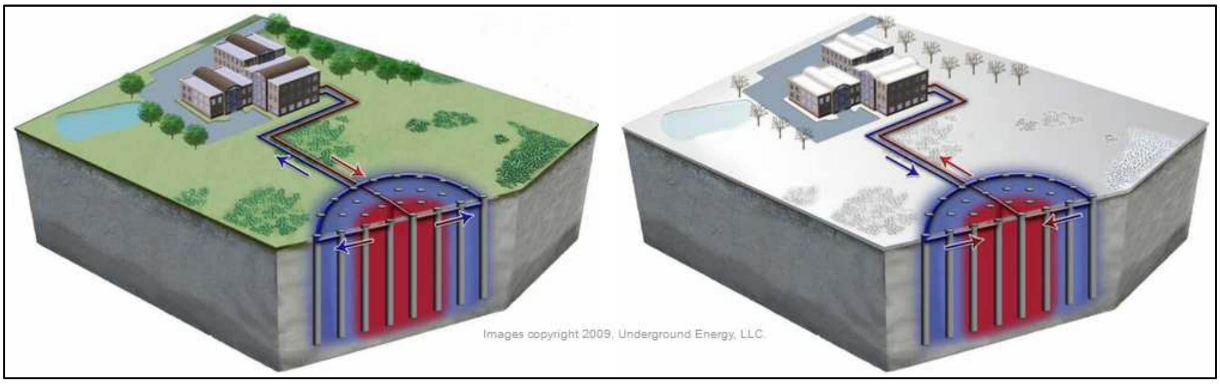

Figure 5. BTES operation. Cooling during summer (left) and heating during winter (right). (Underground Energy LLC, 2014)

As has been said there are different systems for the heat transfer to the storage volume, mainly closed and open system. The most common systems are the closed ones with U-pipes or double U-pipes, which have the heat carrier fluid circulating through the pipes and another fluid or a mix of fluids and solids as a borehole filling material.

Depending on the stored temperature the system is considered low temperature heat storage (T<40^{o}C) or high temperature heat storage (T>40^{o}C). Usually with the last case the heat is used directly for its purpose while in the first case a heat pump is used to reach higher temperatures and fulfill its objective, e. g. space heating.

There has been an increasing interest for high temperature heat storage in recent years with the idea to store waste heat and solar heat and recover stored heat without heat pumps. To achieve this aim, storage volumes are getting larger and the heat is distributed at lower temperatures such as floor heating or other lower temperature applications (Nordell B. , 2012).

3.5.1 Applications

BTES are the most commonly implemented UTES; it is feasible in a very small scale and also in large scale, due to BTES system is suitable to different dimensions and objectives.

Nordell (2000) summarized the different applications of the BTES system.

- Small-scale systems:
    - Single borehole for cooling.
    - Single borehole for heating with heat pump.
    - Single borehole for heating with heat pump and direct cooling.
- Large-scale systems:
    - System of boreholes for heat extraction with heat pump.

- System of boreholes for heat extraction with heat pump and recharging of extracted energy.

- Seasonal loading of thermal energy for later extraction.

- Seasonal loading of thermal energy for the purpose of cooling or heating the ground.

A couple of million BTES systems have been constructed around the world. The Geothermal Heat Pump Consortium (GHPC) estimates that 400.000 BTES systems will annually be built in the United States within a few years. Most of them are borehole systems of one or a few boreholes (Sang Lee, 2013). However, the number of large-scale BTES is also increasing. Table 2 shows the largest built BTES to be in Sweden.

Table 2. Large Swedish BTES (Hellström G. , 2013).

Project	Location	Boreholes	Bore depth (m)	Total (m)
Karlstad University	Karlstad	204	240	48240
Brf. Ljuskärrsberget	Stockholm Saltsjöbaden	156	230	35880
Kemicentrum (IKDC)	Lund	153	230	35190
Lustgården	Stockholm	144	230	33120
Vällingby Centrum	Stockholm	133	200	26600
Brf. Igelbodaplatån	Stockholm Saltsjöbaden	120	200	24000
Kv. Bergen	Stockholm Husby	98	215	21070
ITT Xylem	Emmaboda	140	150	21000
Kv. Galgvreten	Enköping	86	220	18920
Copperhill Mountain Lodge	Åre	92	200	18400
Centrala Gribbylund	Täby	87	210	18270
Thulehem	Lund	86	200	17200
IKEA	Uppsala	100	168	16800
NIBE	Markaryd	110	150	16500
Centralsjukhuset	Karlstad	80	200	16000
Backavallen	Katrineholm	91	172	15652
IKEA	Karlstad	100	120	12000
Musikhögskolan	Örebro	60	200	12000
Sjukhuset	Kristinehamn	55	210	11550
Vattenfalls Huvudkontor	Solna	53	200	10600
IKEA	Helsingborg	67	150	10050
Stenungsbaden Yatch Club	Stenungsund	50	200	10000
Näsby Parks Slott	Stockholm	48	180	8640
Projekt Lulevärme	Luleå	120	65	7800

4 BTES. System description

In order to design a BTES there are several factors that have direct influence. Some of these parameters may be chosen to find the optimum effectiveness, but others are constraints related with the storage location that is impossible to vary, for that reason it is very important to analyze and test the area to find the best place to locate the storage.

4.1 Ground thermal properties

The thermal properties of the ground are of primary importance for the storage design. The capacity to inject, extract and store is determined mainly by the thermal conductivity and the volumetric heat capacity.

4.1.1 Thermal conductivity

Thermal conductivity is a measure of the ability of a material to conduct heat. The deeper the soil layer is, the better the thermal conductivity will be for the storage because it will reduce the losses from the top of the storage due to the ambient temperature, it works as an insulation layer.

Regarding the bedrock, although a higher thermal conductivity worsens the energy efficiency because it increases the losses to the surroundings, it is better for the storage because it improves the heat transfer from the heat carrier fluid to the storage volume, enhancing the storage capacity to inject and extract, which means less surface is needed for the heat exchange.

4.1.2 Volumetric heat capacity

Volumetric heat capacity is a measure of the ability of a given volume of a substance to store internal energy while undergoing a given temperature change. With a bedrock material with higher volumetric heat capacity less volume will be needed to store the same amount of energy.

In contrast, volumetric heat capacity in the soil layer is not important as it does not significantly affect the results.

4.1.3 Geothermal Gradient

The vertical temperature gradient or Geothermal Gradient is the rate of increasing temperature with respect to increasing depth from a given reference point (equation (2)). The underground temperatures are increasing with depth according to the temperature gradient.

$$q = \lambda \cdot \frac{dT}{dz} \qquad (2)$$

Where: q is the geothermal heat flux (W/m^2)

λ is the thermal conductivity (W/K,m).

$\frac{dT}{dz}$ is the temperature gradient (K/m).

In Sweden the geothermal gradient is generally about 0,01 K/m, but there are locations with gradients of 0,02-0,03 K/m in mountainous areas with geologically young rocks (Nordell B. , 1994).

Figure 6 shows a typical ground temperature profile. Seasonal temperature variations do not reach below 15 meters from the ground surface (Ericsson, 1985).

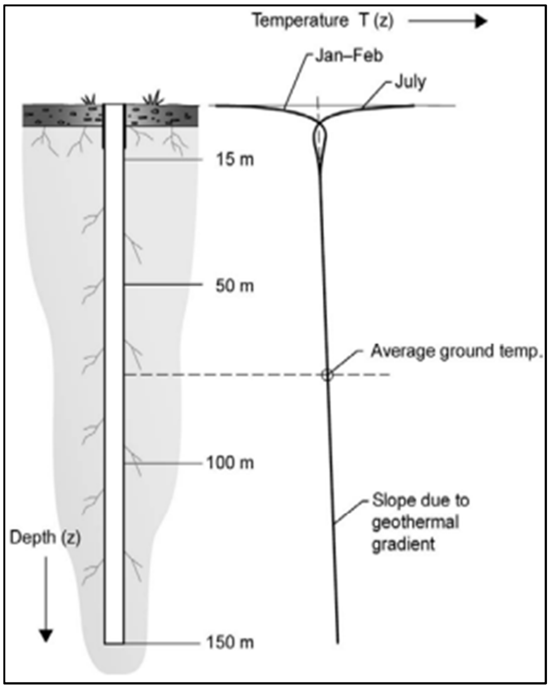

Figure 6. Temperature profile in the ground.

4.2 Heat carrier fluid

The heat carrier fluid is the fluid pumped through the pipes. Water is unique among materials in having an abnormally high specific heat of 4,186 J/Kg K, and furthermore has a reasonable density. Water is also cheap and safe.

Liquids other than water may need to be chosen if the delivery temperature must be higher than 100^{o}C, or if the system temperatures can fall below 0^{o}C (Hammerschlag & Schaber, 2007). When the temperature could be close to or below zero degrees it is necessary to mix water with a percentage of other liquid with a lower freezing point, such as methanol (-97.6°C) or ethanol (-114°C).

4.3 Filling material

The boreholes require some kind of backfilling material to fill the space between the pipe or pipes and the borehole wall. In order to provide good thermal contact between the pipe and the surrounding soil, the borehole is filled with a high thermal conductivity grouting material.

Moreover, it is possible to mix a liquid with different solids to produce a grouting material with higher thermal conductivity, see Table 3. A good example is the Drake Landing BTES in Alberta

(Canada) where a high solids grout composed of 9% Blast Furnace Cement, 9% Portland cement, 32% fine silica sand and 50% water is used as a filling material (Drake Landing Solar Comunity, 2014).

The mixtures must be pumpable to fill the boreholes during the installation. But in Sweden and Norway it is common to leave the boreholes ungrouted, i.e., the boreholes are filled with groundwater (Sang Lee, 2013).

Table 3. Thermal conductivity of borehole filling materials.

Material	Thermal conductivity (W/m,K)
Water	0,56-0,6
Ice	2,2-2,3
Concrete	0,92-2,02
Sand (moist)	0,58-1,75
Sand (dry)	0,27-0,75
Silt (moist)	1-2,30
Silt (dry)	0,38-1
Clay (moist)	0,9-2,22
Clay (dry)	0,4-0,9
Bentonite 10 %, in water	0,65-0,77
Bentonite 20%, in water	0,64-0,66
Bentonite 40 %, in water	0,53-0,82
Air	0,03

4.4 Borehole thermal resistance

The thermal process between the heat carrier fluid and the borehole wall is defined by the borehole thermal resistance. This borehole thermal resistance depends mainly on the arrangement of the flow channels in boreholes (see section 4.5) and defines the quality of the circulation heat transfer. The lower the borehole thermal resistance is, the greater the heat transfers, i.e. better energy injection and extraction.

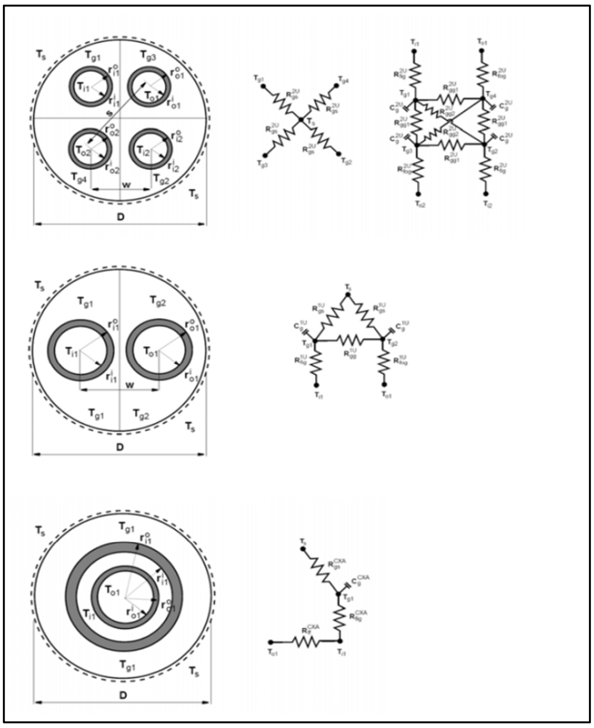

Figure 7. Borehole thermal resistance for different circulation systems.

The value of the borehole thermal resistance is influenced by the thermal properties of the different materials which take part in the heat transfer from the heat carrier fluid to the borehole wall. The number of influencing factors depends of the circulation system (see Figure 7 and Figure 10), but basically the following are relevant:

- Heat carrier fluid.
- Closed pipe material.
- Borehole filling material.
- Bedrock material.

4.5 Open and closed system

As mentioned above in section 3.5, there are different circulation installations, but only two basic types. In an open system the heat carrier fluid is directly in contact with the borehole wall, whereas in a closed system the heat carrier fluid is circulated in a closed pipe system through the boreholes.

4.5.1 Open systems

This system consists in a circular concentrically placed pipe through which the water is injected or extracted. It has one or multiple holes at the bottom to let the water flow through it and circulate in the annular part in direct contact with the borehole wall, another pipe takes up or injects the water from or in the annular volume. The flow direction is reversed depending on the mode of operation, charging or discharging the storage. One example of open system is the Emmaboda (Sweden) storage which has been working since 2010. Figure 8 shows the BHE used in each of the 140 boreholes of the storage.

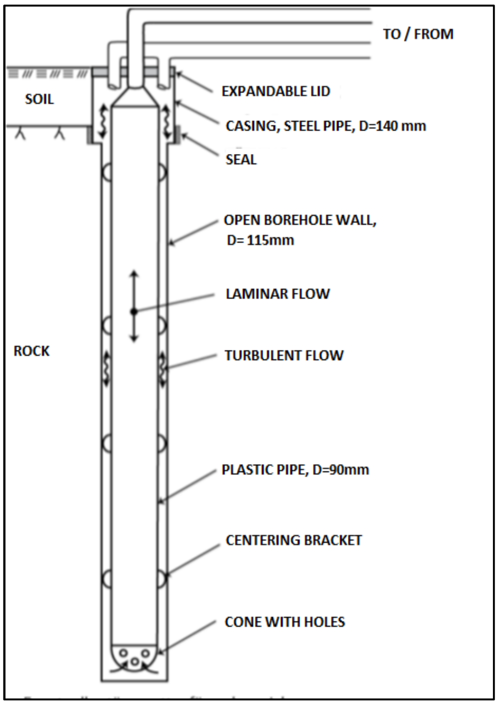

Figure 8. BHE used in Emmaboda storage in an open circulation system.

The main advantage of this circulation system is the low value of borehole thermal resistance, that it is approximately 0,03 W/mK depending on the pipe and rock materials, which means a good heat transfer between the fluid and the rock.

The disadvantage is the water circulating through the pipe is also in direct contact with the borehole wall, that fact produces water chemistry problems and potential problems with clogging and corrosion. Particles or dissolved materials from the rock and also corrosion of the steel pipes are the risks in an open system, because it changes the water properties increasing the content of oxygen and CO_2 and lowering the pH value, which increases the risk of corrosion of steel pipes.

Figure 9 shows the revealed precipitation of dirt, cuttings and iron hydroxide when the heat exchanger was flushed after almost one year of operation in the open system of Emmaboda BTES.

Figure 9. Cleaning of the heat exchanger after one year of operation in Emmaboda BTES.

There is an "open" system which has been created to avoid these disadvantages, it uses a thin plastic lining protection in the borehole walls that increases the borehole thermal resistance just a little. But this system has so far only been utilized in tests and investigations, not in large-scale cases.

4.5.2 Closed systems

The closed system is the most common among BTES, consisting of one or multiple pipes placed into the boreholes, which are backfilled with water or grouting material. The heat carrier fluid is pumped through the pipes and the heat is transferred to the pipe wall and from this to the filling material and finally to the borehole wall.

The most usual closed systems are the single U-pipes and double U-pipes, but there are others such as the concentric or triple U-pipe, see Figure 10. These U-pipes are small channels located close to the wall. Due to the narrow diameter the flow is laminar at high velocities, but to improve the heat transfer the flow must be turbulent.

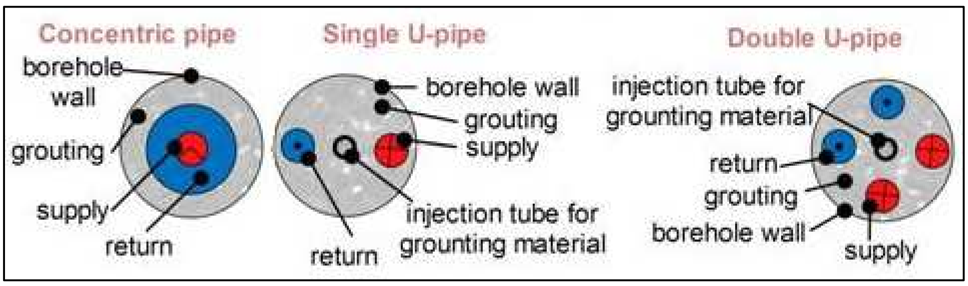

Figure 10. Different closed systems.

The advantage of this system is that the heat carrier fluid is never in direct contact with the rock, therefore it keeps its properties constant and does not damage the process during its operation.

The borehole thermal resistance for the double U-pipe and single U-pipe is approximately 0,08 W/mK and 0,11W/mK respectively, depending on the heat carrier, filling material, pipe and rock thermal properties.

4.6 Storage Shape

The most appropriate shape for a BTES would be spherical because the losses would be minimum avoiding corners. But this shape is not possible to implement and the closest is a cylindrical shape.

4.6.1 Borehole depth

Theoretically, the proper depth for the heat storage would be when the depth has the same value as the sides, in a square surface. Thereby, the losses are minimized. But usually the depth is larger than the sides to reduce the surface needed to store the same amount of energy, because of the surface price and the expense of drilling the soil layer, the price is twice the rock drilling cost (see section 7.4), for these economic reasons is common drill less boreholes but deeper.

Since the extra cost for digging deeper than 200 meters is just about 5% per meter (see section 7.4), it will be cheaper to dig the boreholes as deep as it is possible. That depends on the surface needed, but if the number of boreholes is less it means a reduction in the total cost.

Based on previous experiences despite the model prices we have, a further cost increase is expected when the digging and piping gets complicated because of the depth. For that reason boreholes deeper than 250 meters are rarely drilled.

Moreover, one detail that must be considered is that it is convenient to leave a distance between the borehole bottom and the U-pipes, due to falling sediments and thermal expansion. In a large-scale BTES located in Anneberg (Sweden), where this was not considered, the pipes were broken after an operation period and they had to be removed and fixed. A good example could be the storage in Emmaboda where the security distance between borehole bottom and pipe is 4 meters.

Effective depth

The distance between the groundwater levels to the borehole bottom is called effective depth or also called the active part of the borehole and it is the section in which heat transfer from the fluid to the rock takes part.

4.6.2 Borehole Spacing

The spacing is the distance between the borehole centers and it directly influences the storage design. When the boreholes are placed closer the storage has fewer losses and it is easy to increase the mean temperature during the heat injection, but it also decreases faster during the heat extraction.

The holes are drilled either in a quadratic or hexagonal pattern (see Figure 11). The hexagonal pattern is better regarding energy losses and heat transmission, but usually the large storages use the quadratic pattern, which involves drawing tracks on the surface that facilitate the work and the machinery transit and also makes it simpler to drill and install the piping between boreholes.

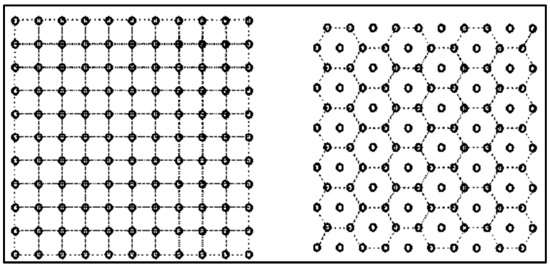

Figure 11. Borehole spacing patterns: quadratic (left) and hexagonal (right)

In a certain volume if the same spacing is used for both patterns the number of boreholes will be different due to the borehole cross sectional area, furthermore the equivalence between quadratic and hexagonal pattern can easily be known using the same cross sectional area, see equations (3) and (4). One example is shown in Table 4, where two different storage parameters are calculated with the same spacing to appreciate the difference in the number of boreholes drilled, as equations (3) and (4) prove the relation between the number of boreholes with the different drilling patterns: No Boreholes quadratic pattern is 0,866 times the No of boreholes in hexagonal pattern.

$$A_{quadratic} = spacing^2 \tag{3}$$

$$A_{hexagonal} = \frac{\sqrt{3} \cdot spacing^2}{2} \approx 0.866 \cdot spacing^2 \tag{4}$$

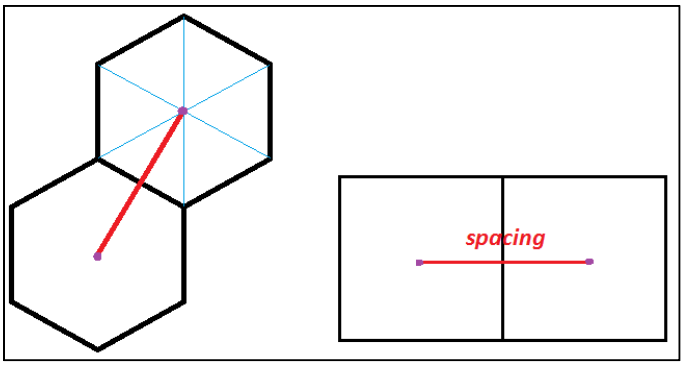

Figure 12. The borehole spacing depending on the pattern.

In the hexagonal pattern the spacing equals one half of the apothem, while in the quadratic it equals the side (see Figure 12).

Table 4. Comparison of number of boreholes drilled with hexagonal and quadratic pattern for two different storage parameters (volume and depth).

Drilling pattern	Volume (m^3)	Depth (m)	Total Surface (m^2)	Spacing (m)	Surface/ borehole (m^2)	Number of boreholes
Hexagonal	300 000	150	2 000	4,0	13,9	144
Quadratic	300 000	150	2 000	4,0	16,0	125
Hexagonal	800 000	200	4 000	4,5	17,5	228
Quadratic	800 000	200	4 000	4,5	20,3	198

Considering the commonly used quadratic pattern the usual spacing in large BTES is 4 meters. However it is possible to find storages with 2.5 to 6 spacing meters, this depends on the storage characteristics such as borehole depth and energy price. For example, when the energy cost is very expensive, for example if it is provided by solar collectors, then a shorter distance between boreholes is preferable to avoid further losses, whereas when the energy used is waste energy the spacing could be higher than 4 meters because the energy loss is not the most significant cost.

4.6.3 Storage volume

In order to calculate the storage volume there are a couple of details that must be considered. Firstly the depth used in the calculation is the effective one (see section 4.6.1). Secondly in the surface area half of the borehole spacing must be added for each side in square surface, if the surface is circular the borehole spacing must be added once to the BTES diameter.

Moreover the storage volume needed to storage a certain amount of energy can be estimated using equation (5):

$$V = \frac{E}{\Delta T \cdot c} \quad (5)$$

Where V: Storage volume (m^3)
E: Energy to store (kWh)
c: Volumetric heat capacity of bedrock (kWh/m^3,K)
T: Temperature difference of the volume (K)

However this equation does not consider the energy losses, which depend on storage shape and soil parameters.

4.7 Pipes

The BTES consists in a pipe network and there are multiple possibilities to arrange it. The borehole pipes can be connected in parallel, in serial or in a combination serial-parallel. The difference is noticed in the pump, because when the boreholes are connected in parallel the pump just has to provide the power to overcome the depth of one borehole, while if there are serial connections the pump has to provide the power to overcome the depth of the number of boreholes connected in serial.

Usually the borehole pipes are connected to two collectors, one for the injection and another for the extraction/return. These collectors are finally connected to two main manifolds.

In some cases the storage is divided in sections with the aim to get a stratified volume, in those cases where the injection load is not enough to heat up all the storage it is injected in the central section or sections. Also, when the extraction temperature needed is higher than the mean storage volume temperature it is only extracted from the center section or central sections. Figure 13 shows the 7 different sections of Emmaboda (Sweden) storage with 20 boreholes in each section.

Moreover, in the open systems it is necessary to install degas valves due to the increase of water temperature.

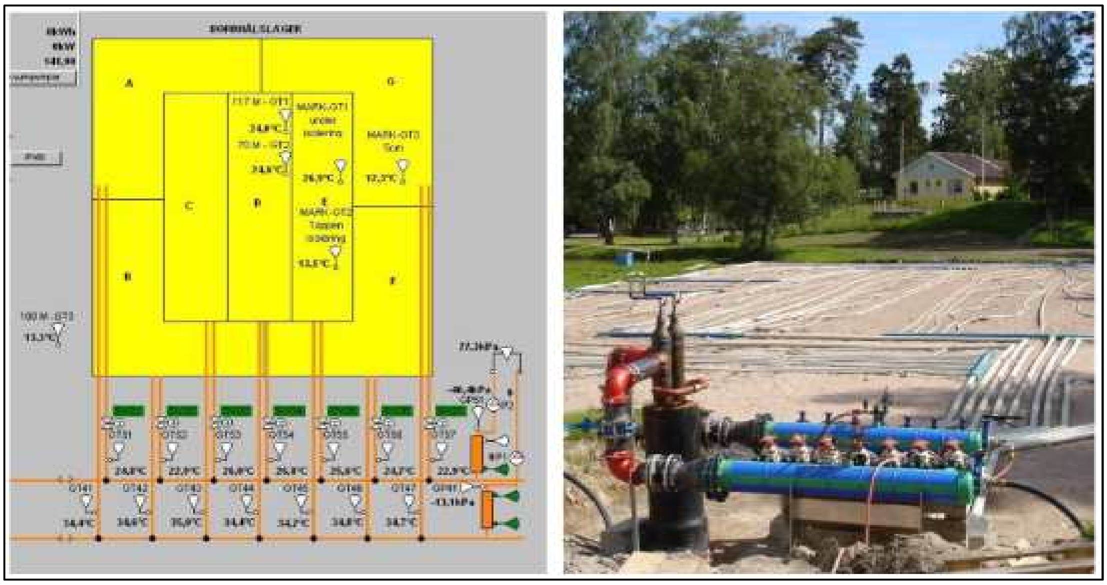

Figure 13. Storage divided in 7 sections, it has a manifold for each section that comes together in two main manifolds (Andersson & Leif, 2012).

4.8 Flow rates

Usually in the Swedish district heating system the supplied flow rate is kept constant while the ambient temperature is above 0 degrees and only the temperature varies due to the demand, but when the ambient temperature is below 0 degrees the flow rate is increased proportionally.

In the BTES normally two pumps with different power are installed in parallel to be able to pump different extraction flow rates depending on the demand.

However, in this case either extraction and injection flow rates are kept constant because what matters is to simulate the amounts of energy extracted per month.

There is only one factor to consider for the flow rate, it must be turbulent inside the borehole pipe because with a laminar flow the thermal resistance between the heat carrier fluid and the borehole walls is too high, which implies poor heat transfer.

4.9 Thermal Response Test (TRT)

One of the first and more important steps to design a BTES is the Thermal Response Test (TRT). The TRT is an in-situ measurement method used to evaluate the heat transfer parameters to be used in the BTES design. The thermal response is studied by measuring the change in circulating fluid temperature over time, which is dependent on the heat transport underground, the heat injection or extraction rate, fluid flow rate and influencing outside conditions (Gehlin, S., 2002).

The test equipment consists of two systems, one for heat injection and another for heat extraction. For the heat injection, an adjustable electrical heater supplies the injection energy. For heat extraction a fluid-to-air heat pump connected to a buffer supplies the circulation heat carrier with cooling power, the heat pump uses the outside air to release the heat (Gustafsson, 2010).

When a large-scale BTES is going to be built in a certain area a few boreholes in different points should be drilled to make the TRT test and decide where the best location is for the storage depending on the thermal properties results obtained by the tests.

Moreover with the first test boreholes it is possible to identify groundwater fractures and see the boreholes deviation with a deviation control device. This deviation will be almost the same for all the BTES if the storage is placed closer to that point due to the bedrock structures. For the optimal function of the BTES system it is of interest to have as straight holes as possible, but during the drilling process it is not possible to keep it straight.

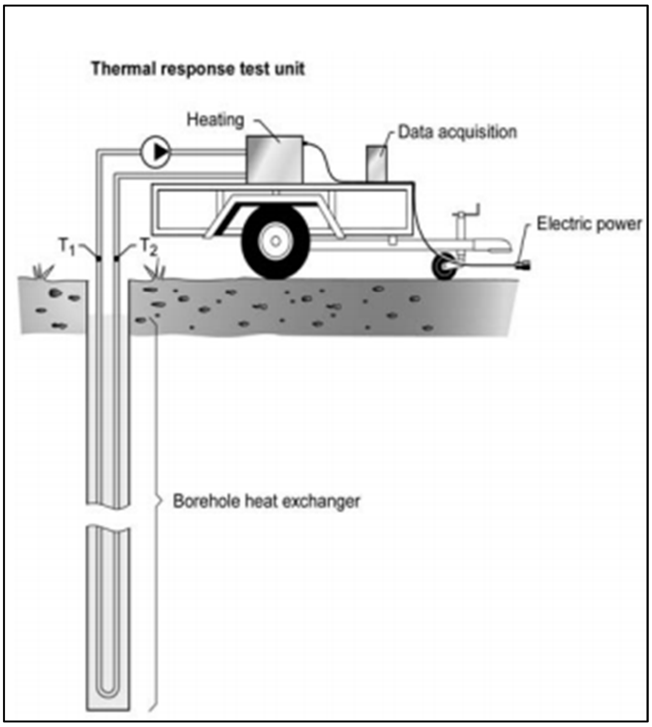

Figure 14. Thermal Response Test set-up.

4.10 Storage Lifetime

A BTES system has no expiration date, but depending on the storage function its operation could become less efficient. This happens when the storage is used for both heating and cooling, then if the operation is not balanced and the storage gets warm or cold and loses energetic power.

On the other hand, if the storage function is just heating it does not lose efficiency during the years, which means that the lifetime of the storage will not depend on technical factors, but rather economic factors. These economic factors are the following:

- Possibility of considerably increased maintenance costs.
- Reduction in price of another energy source i.e. cheaper alternative.
- New funds for another energy source.
- The storage location is needed for other services with greater economic potential.

5 Energy demand in Kronan

5.1 Kronan, Luleå.

Luleå is a city with 75000 inhabitants located in the north of Sweden, 70 km south of the Polar Arctic Circle, see map in Figure 15. Due to its location the winter is longer and it reaches temperatures below -30^{o}C, which indicates the importance of reliable heating systems.

Figure 15. Location of Luleå in the European map.

From 2003 to 2012 Luleå population increased by 2668 inhabitants and by 2022 an increase of 3150 or more is predicted (Larsson, 2013). Thus, the municipality is planning to expand the Kronan district with 1500 new houses, for about 5000 persons.

Kronan is an area in Luleå close to the city center and is a former military facility. This area belongs to the municipality and is currently under development.

Commonly the space heating in the Swedish cities is supplied by a municipal district heating system. Luleå takes advantage of the waste gases generated in the local coke and steel plants (SSAB). Using this gas as fuel in a co-generation plant, which is connected to Luleå's district heating system, means that the Luleå municipality has the cheapest district heating in Sweden (Luleå Kommun, 2014).

5.2 Heating demand

In order to design the storage the most important parameter is the amount of stored energy or rather the recovered energy, as seen previously in equation (1). This amount of energy is the annual heat demand for those 1500 new houses.

The calculation of the annual heating demand is made on the basis of hours and is not included in this project report but it is available for the library as an Excel file called “Kronan, heat demand.xls”. Nevertheless an example for one day is included in Appendix A.

In Table 5 the calculations have been summarized, showing the space heating (E. heating) and the district hot water demand (E. dhw) for an average single family house.

Table 5. Space heating and district hot water demand for a single house in Luleå.

Month	T. air [°C]	E. heating [kWh/month]	E. dhw [kWh/month]	E. total [kWh/month]
January	-9,4	1 612	306	1 918
February	-13,1	1 659	276	1 935
March	-1,1	1 103	306	1 409
April	2,9	540	296	836
May	7,4	214	306	520
June	13,8	17	296	313
July	15,6	3	306	308
August	14,1	48	306	354
September	7,8	251	296	547
October	4,2	537	306	843
November	-4,5	1 271	296	1 567
December	-1,8	1 145	306	1 451
Total	**3,0**	**8 400**	**3 600**	**12 000**

For the space heating demand the value is simply multiplied by the number of houses, 1500, but for the district hot water (dhw) another factor is taken into account. This factor is the use of a heat pump to heat up the dhw, because the regulations require that the dhw temperature must be above 60°C (for a while) to avoid legionella, before it is supplied to the consumer. For that reason part of this 3600 KWh/year is electricity and the storage does not have to supply this total energy, just the difference.

The energy required to heat up the dhw is thus partly provided by the storage, while the rest is by driving energy from the heat pump. This is given by equations (6) and (7), in which the heat pump coefficient of performance (COP) is assumed to be 4.

$$E_{HEAT,dhw} = E_{dhw} \cdot \left(1 - \frac{1}{COP}\right) \qquad (6)$$

$$E_{ELECTRICITY,dhw} = E_{dhw} \cdot \frac{1}{COP} \tag{7}$$

The total heat demand shown in Figure 16 represents the average energy consumption. The figure also shows how it is related to the mean air temperature. The only month that does not follow the common temperature function is December, because the year when the data was obtained the temperature of December was higher than November, which is not usual.

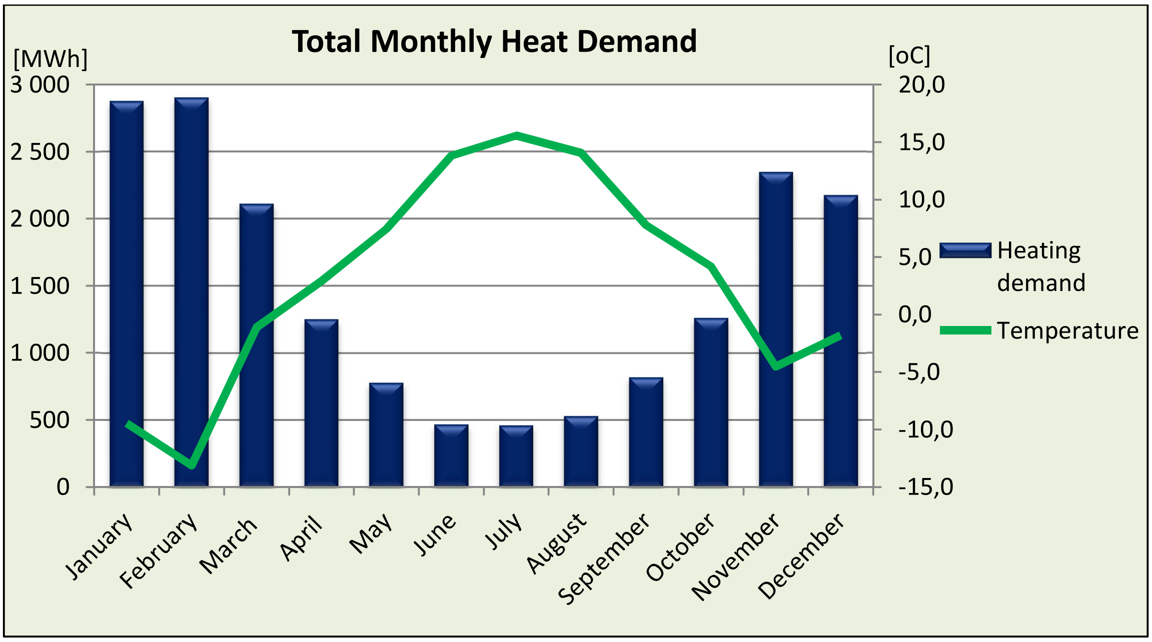

Figure 16. Total monthly heat demand and monthly mean air temperature.

Moreover, we know that all these new dwellings will not be available during the first year as the area will be developed over a few years. This will cause a slope in heating demand over the years with lower initial values that favor the storage process. The reason is that during the first years there is more loss to the surrounding rock and less energy available for extraction. After the first five years of operation the energy losses will be almost stable for each year, but clearly lower than the first years, and the system will be able to supply more energy for the district heating.

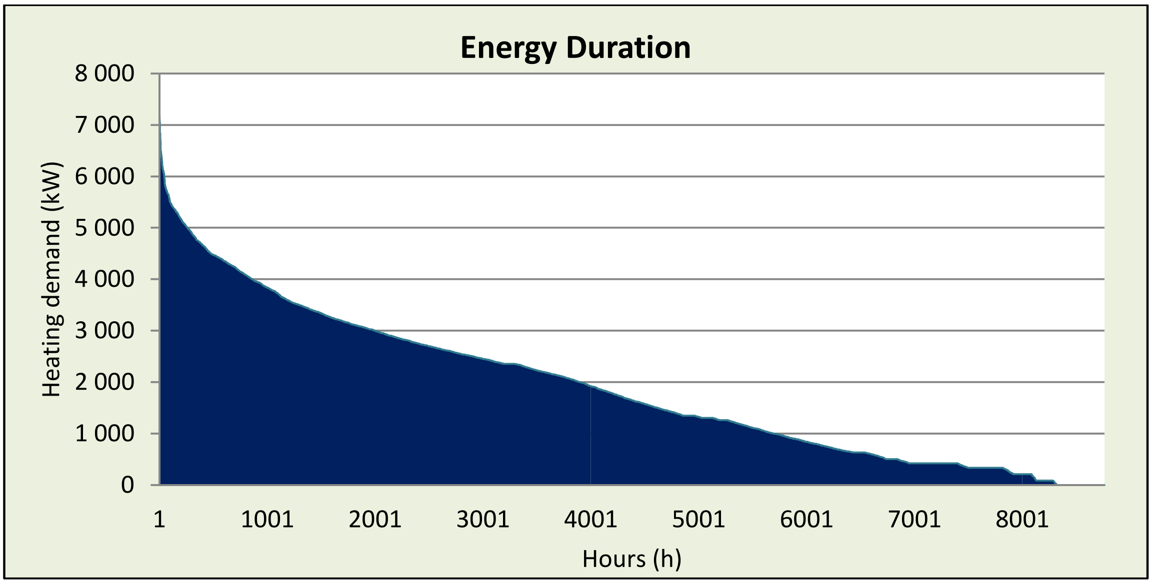

Figure 17. Duration curve for the annual heating demand of the 1500 houses.

A good method to analyze the heating demand is by an Energy duration graph as in Figure 17, which shows how many hours are necessary to supply a certain amount of power. The required energy is the area under this curve. It can be seen, logically, there is a peak of energy; the heating demand above the 5000 kW only represents 265 hours in a year, 3.0% annual. If the BTES system is designed to cover this peak, then the volume needed will be much larger and less exploitable. For this reason it is not designed to fulfill this peak and in this short period it is preferable to use another energy source to meet the demand.

5.2.1 Assumptions concerning heating demand

- The heating demand during the warm months (May to September) is assumed to be supplied directly from the district heating network, i.e. the heat that charges the storage during those months is used directly without passing through the storage. Then the energy that BTES has to supply is summarized in Table 6.

Table 6. Monthly values for heat demand to BTES entered in the program DST.

Month	Total Monthly Heat Demand [MWh]
January	2 762
February	2 799
March	1 999
April	1 143
May	0
June	0
July	0
August	0
September	0
October	1 150

November	2 239
December	2 062
TOTAL	***14 153***

- With the purpose of simulating the storage operation monthly values are used. Obtained results are also given on a monthly basis, despite the fact that some simulations have been done on hourly data. The main reason is that hourly data include short term peaks (as seen in Figure 17) that requires a much larger storage volume. While the same amount of energy is considered by monthly data it is understood that occurring peaks are met with other methods, such as a short-term storage tank or an auxiliary heat source.

The flow temperature varies during the year because in winter more heat sources are added to reach the 80-95 ^{o}C. The temperature values assumed for each month during the injection period are shown in

Table 7.

Table 7. Injection temperature in storage charging period.

Month	Temperature (^{o}C)
May	75
June	70
July	70
August	75
September	80

5.3 Energy system in Luleå

In order to understand how the energy would be provided to charge the storage each year to make it able to supply the heating demand, the energy system for the district heating in Luleå is described below.

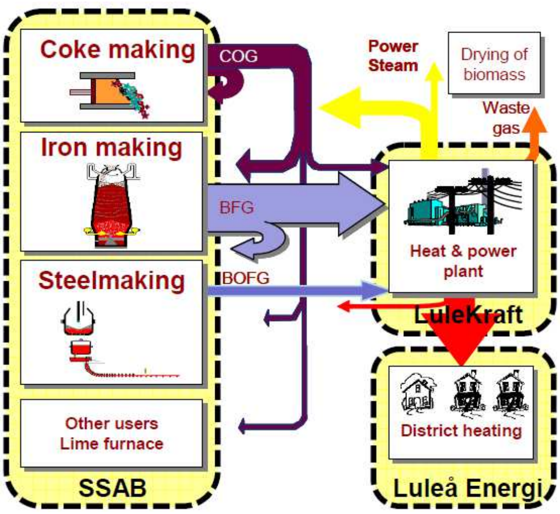

Figure 19a. Overview of energy system in Luleå.

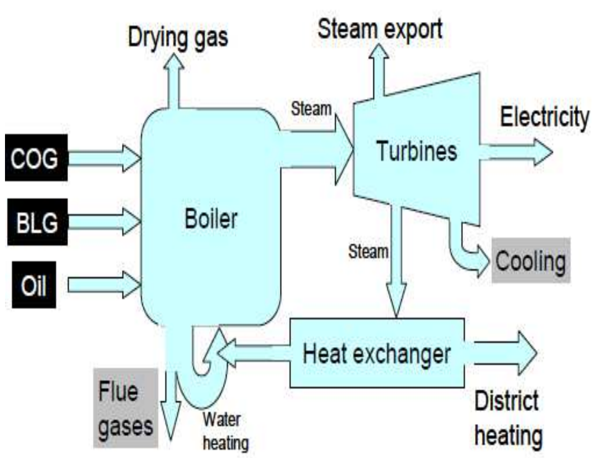

Figure 19b. Energy flows in the Luleå energy system.

The Luleå energy system consists in three major parts: the SSAB steel plant, the LuleåKraft CHP (Combined Heat and Power) plant and the district heating system (Luleå Energy), see Figure 19a.

The process gases generated at the steel plant such as coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG) are partially used in the plant, and the rest is sent to the CHP plant. There the energy gases are mixed and the result is called BLG ("blandgas" in Swedish i.e. mixed gas), which is combusted together with supplement oil in a boiler producing steam that reaches 520ºC and is then send to a turbine. The turbine generates about 80 MW and it is divided in four phases, the steam goes out at 300, 95, 80 and 30 ºC (Elfgren, Grip, Wang, & Karlsson, 2010), see Figure 19b.

- The 300°C steam is process steam used in the SSAB steel plant.
- The 95°C and 80°C steam are used for district heating by two-step heat exchanger.
- The steam remaining (30°C) is condensed using water from the nearby bay.

All the temperatures are approximate but represent winter conditions.

5.4 District Heating Price

Since the heat injected into this BTES proceeds from the District Heating (DH) network, the DH price influences both costs and incomes. The BTES incomes are the value of the extracted heat in the winter, when the DH price is higher due to the law of supply and demand. The heat injection cost is lower and depends on the deal with the energy company.

Moreover, the DH price varies over the years. Figure 20 shows the prices of the last ten years and the predicted price evolution for the next fifteen, which are used below in the economic calculations.

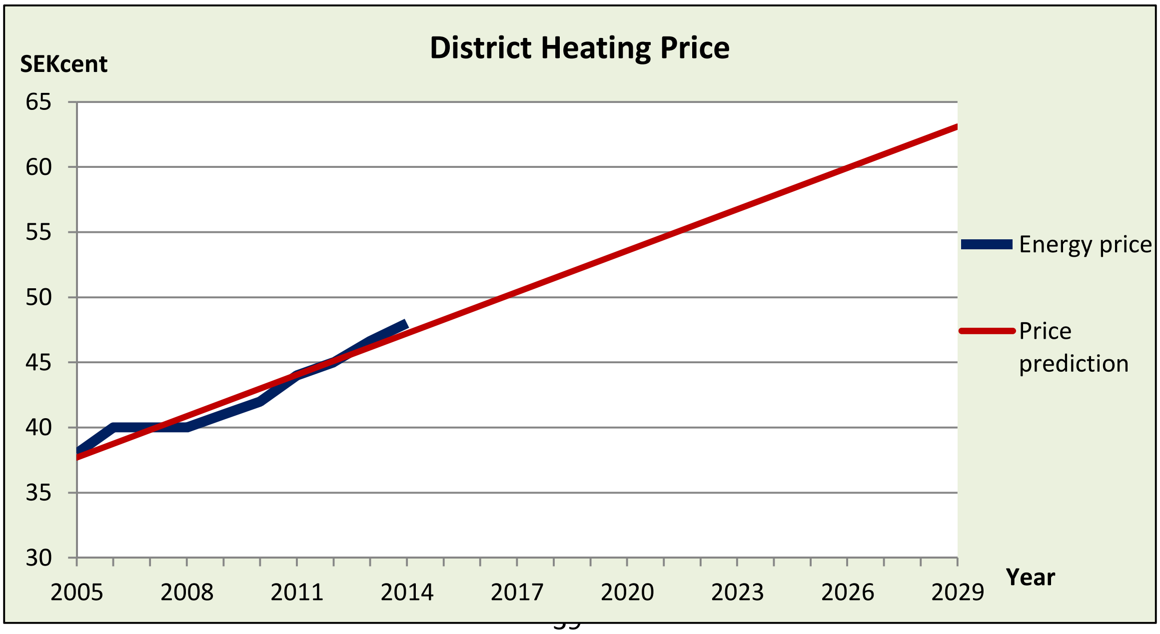

Figure 20. District heating price and prediction.

5.5 Heat source

An important issue that must be considered is the steel plant reliability. There is the possibility that the steel plant shuts down due to a drop in the steel price or does not produce enough waste energy to charge the BTES. For that reason other heat sources should be taken into account.

Depending on the source the energy price may vary a lot and the storage parameters must be changed to find the economically optimum option.

5.5.1 Solar energy

One renewable alternative is to use solar energy although it is an expensive alternative. The cost of the BTES system will increase at least 5 times if the cost of solar collectors is included. These solar collectors could be installed directly to the roofs when the new dwellings are built.

In that way the neighborhood would be sustainable. Despite the idea that foreigners might have of Luleå, there is enough solar energy to carry out the project with this renewable heat source, which would give the project more repercussion.

However, the storage design is affected by the energy cost and expensive solar heat means that it would be necessary to design the system In order to reduce the energy losses. There are different ways to achieve it, by for example:

- Reducing the spacing between boreholes.
- Reducing the surface in contact with the surroundings by decreasing the depth.
- Improving the insulation, either kind of material or thickness.

5.5.2 Other heat sources

The other alternative is to find another large heat source or multiple sources able to supply the energy needed. One possibility is the Facebook Data Center located in Luleå.

Luleå has the first Facebook data center in Europe and nowadays (2014) another Facebook building is under construction in the same area. This building uses the chilly Nordic air to cool tens of thousands of servers that store photos, videos, comments etc. Part of the excess heat produced is used to keep their offices warm but a large amount of heat is wasted. Although no official numbers are disclosed, the amount of energy would be enough to charge the BTES.

The BTES could replace the current cooling process by cooling down the data servers and storing this energy underground for the heating demand.

6 The Model

6.1 Duct Ground Heat Storage Model (DST)

The Duct Ground Heat Storage Model (DST) is a simulation model created by Dr. Göran Hellström for ground heat exchanger systems. The DST calculates the conductive heat transfer in the ground. The thermal process analyses are divided in three parts: global problem, local problem and steady-flux (Hellström G. , Duct Ground Heat Storage Model. Manual for computer code, 1989).

The global problem manages the large-scale heat flows in the store and the surrounding ground, whereas the local problem handles the heat transfer between the heat carrier fluid and the store. Both are solved with the use of the explicit finite difference method (FDM), whereas the steady-flux part is given by an analytical solution. The total temperature point is a superposition of these three parts.

The heat transfer from the fluid to the ground in the immediate vicinity of the duct (borehole) is calculated with heat transfer resistance. A steady-state heat balance for the heat carrier fluid gives the temperature variation along the flow path (Pahud & Hellström, 1996).

For computational accuracy and efficiency, the DST model is used in this project to analyze and design the optimum storage for the specific circumstances of this case.

6.1.1 DST assumptions

The DST program follows some assumptions and others are made for this model.

- DST considers the storage volume has the cylindrical shape with the axis of symmetry in the vertical direction. The numerical mesh is generated automatically; it is adjusted to the thermal properties in the ground, daily changes in loading conditions and duration of the simulated period (Hellström G. , 1989). See Figure 21.
- In the model the boreholes are uniformly placed within the storage volume in a hexagonal pattern, where the spacing between them is twice the apothem. See Figure 21.

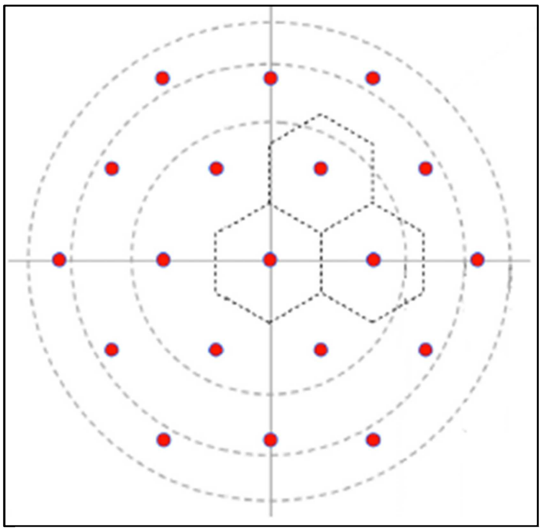

Figure 21. DST model cylindrical shape and hexagonal distribution.

- Also, the DST program assumes that all **the ducts in the store are coupled in parallel,** which is precisely what is necessary for the model. There are BTES with two or a few boreholes coupled in series, but these tend to be shallow systems. The reason for this is the pressure drop through the borehole pips. In the Kronan case the boreholes are rather deep so the pressure drop that the pump must overcome is twice the depth (the flow goes downwards and upwards). Otherwise, in serial connections, the pipe pressure drop is twice the borehole depth multiplied by the number of boreholes coupled in series.

- The bedrock in Sweden is typically crystalline, isotropic and very deep, for this reason in the project the storage location is assumed to be over the same bedrock type along the boreholes depth. In order to meet this assumption it is entered in the code that **there is just one bedrock layer**. Despite the fact that the software allows for different soil layers with separate properties.

- The model **does not consider the presence of fractures and groundwater**. Firstly, the software was designed in Sweden, where the rock generally has few fractures. This is confirmed by a great number of underground studies for thermal response tests conducted in recent years in Luleå (Thermal response test integrated to drilling).

  Another reason is the groundwater does not affect the results if there are no stream flows, because the connection between boreholes through the fractures avoids the pressure difference.

- The temperature extraction has to be higher than 35°C. During the extracting period the energy is supplied while the extraction temperature is enough to provide heat for floor heating systems, the temperature assumed is 35 degrees, although on the coldest days the temperature must be higher.

6.2 Model parameters

6.2.1 Rock properties

The bedrock of Sweden consists of crystalline rocks. As shown in Figure 22 in Kronan area the predominant bedrock types are granite and diorite, but no detailed geological map exists.

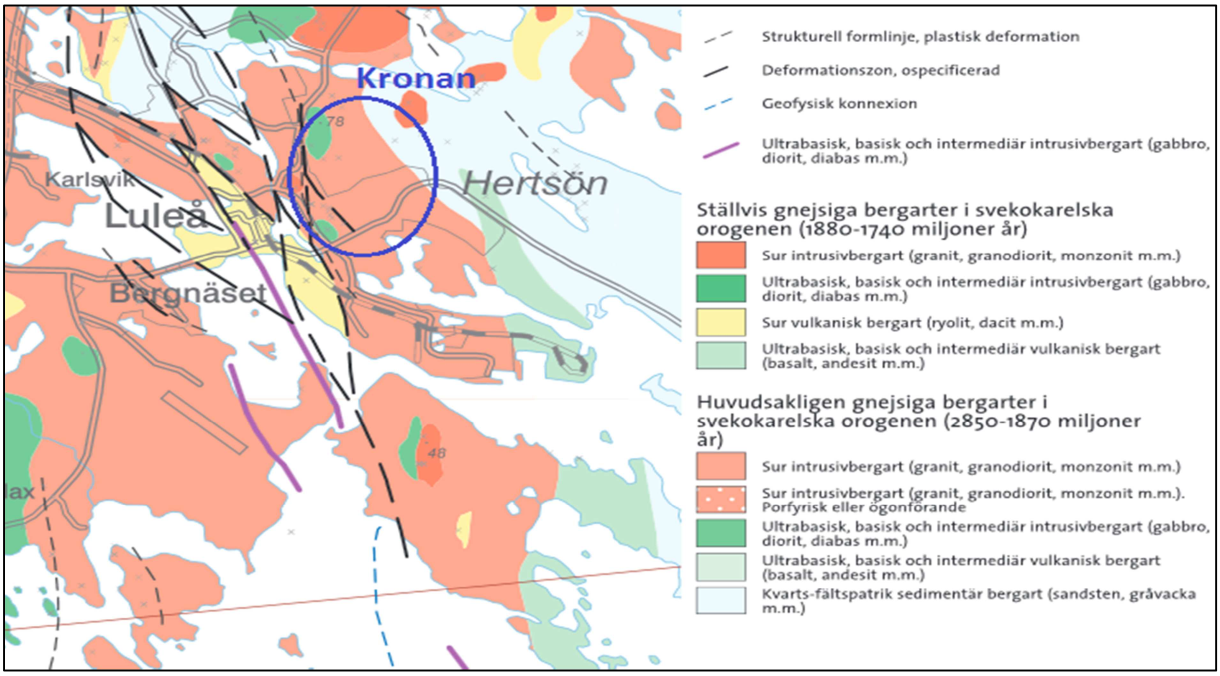

Figure 22. Lithological map from Geological Survey of Sweden (SGU).

Moreover, a study from 4000 samples of different rock types completed in Sweden proves that the majority of crystalline rocks in the country is granite-granodiorite and different types of gneiss. The major part of these groups has a mean conductivity of 3,5 W/m,K, but the mean value of all samples is 3,45 W/m,K (Sundberg, 1988).

For this reason the values used in the model are the properties of granite:

- Thermal conductivity : 3,45 W/m,K
- Volumetric heat capacity: 2,16E+6 J/m^3,K

6.2.2 Soil properties

Since the place where Kronan is located is close to a bay the values used for the thermal properties of the soil are from very moist soil (The Engineering ToolBox, 2014):

- Thermal conductivity : 1,4 W/m,K
- Volumetric heat capacity: 2,5E+6 J/m^3,K

6.2.3 Soil layer

The area available for the storage is located in a valley, which was below sea level a few centuries ago. The sediments and particles dragged by the currents ended in the valley. For that reason an overburden of 10 meters is assumed in the simulations, a value higher than that found in the Luleå Storage, 2-6 meters (Nordell B. , 1994), placed in other point of the city.

6.2.4 Spacing and depth

The borehole spacing and borehole depth are varied to find the optimum storage. The BTES shape depends directly on these two parameters, which influence the surface and volume of the storage.

In that case the spacing is tested between the values of 3,75 and 5 meters. Usually in a large-scale BTES the borehole spacing is 4 meters, but as it is mentioned in section 4.6.2 it mainly depends on the energy price. Regarding the borehole depth four different distances are tested 175, 200, 225 and 250 meters.

6.2.5 Thermal Resistance

Considering an open system and double U-pipes (see Figure 23) for the BHE the thermal resistance value used in the simulations is 0,08 W/mK. The conditions considered to obtain this value are the following:

- *Filling material: Water.*
- *Heat carrier fluid: Water.*
- *Pipes: plastic PE100 PN10 DN32mm.*
- *Borehole diameter: 115mm.*
- *Bedrock material: Granite.*

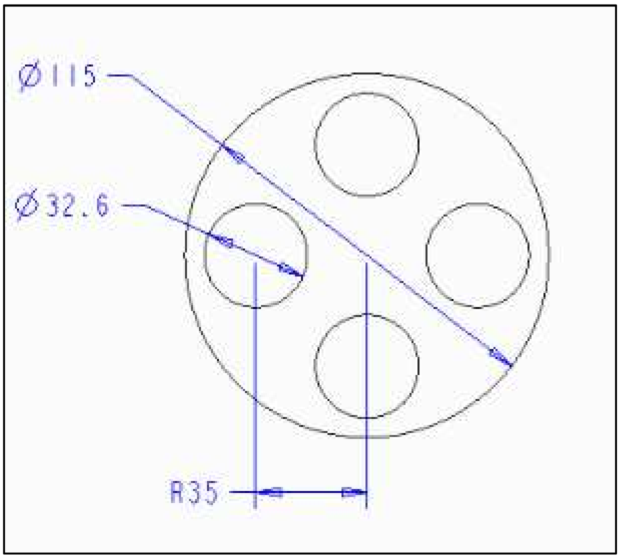

Figure 23. Borehole top view.

6.2.6 Geothermal Gradient

As mentioned in rock properties (section 6.2.1) the thermal conductivity used for the model is 3,45 W/m,K and the geothermal heat flux in Luleå is 0,045 W/m^2. In Table 8 the geothermal heat flux for different areas in Sweden is shown.

Table 8. Geothermal heat flux in different locations in Sweden (Hellström & Sanner, Earth Energy Designer 2.0, 2000)

Location	Geothermal Heat Flux (W/m2)
Stockholm	0,055
Göteborg	0,06
Malmö	0,07
Jönköping	0,05
Falun	0,05
Sundsvall	0,04
Östersund	0,04
Umeå	0,04
Luleå	0,045
Kiruna	0,05

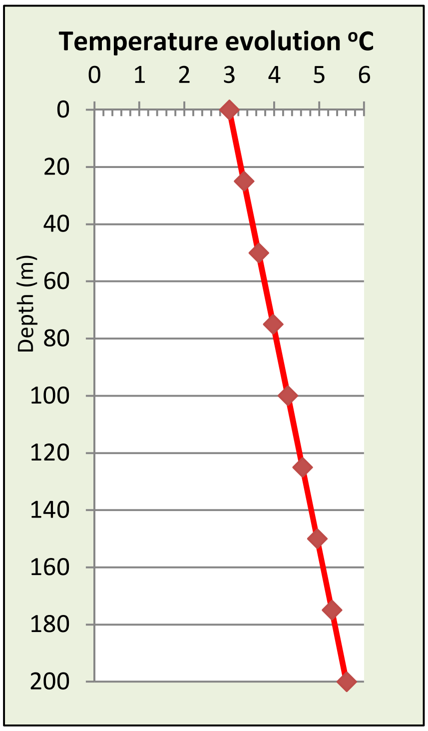

Figure 24. Ground temperature profile in Luleå.

Then, by using equation (2) the geothermal gradient is obtained:

$$\frac{dT}{dz} = \frac{0{,}045\ W/m^2}{3{,}45\ W/m \cdot K} = 0{,}013\ K/m$$

In Figure 24 you can see the temperature change as a function of the depth, in that case the mean temperature of the ground surface is 3^{o}C, which is the starting point in the simulations.

6.2.7 Heat carrier fluid

The heat carrier fluid used in the model is water because it has the best thermal properties and a low price. Since the present storage is for high temperatures it is not necessary to be afraid of freezing, and water will not be mixed with other substances.

The properties used for the model are from water at 50^{o}C (Hellström & Sanner, Earth Energy Designer 2.0, 2000):

- Volumetric heat capacity: 4.181 J/m^3,K
- Thermal conductivity: 0.637 W/m,K

The properties for a water temperature of 45°C are selected due to the mean temperature over the year for all the simulated models, where the temperatures are about 38°C the minimum and 66 °C the maximum.

6.2.8 Insulation

The program allows three different options for thermal insulation of the storage. The first one is without any insulation, the second one is for insulating the upper surface and a fraction of the side, and the third one is for insulating the upper surface and extending horizontally outside the top.

In all the cases the third option is used, the one used in the large-scale BTES, and the protruding extension covers just 4 meters.

The insulation layer has a thickness of 0.4 meters and it is made of foam glass (λ=0.13W/m,K), it was chosen after different simulations and economic comparisons, see section 8.4.

6.2.9 Flow rate during heat injection

It is known that the flow coming from the steel plant would be at least at 70 degrees (see section 5.2.1), but it is necessary to set the flow rate to calculate the amount of energy injected.

With the objective of finding the proper injection flow rates some simulations were made together with the pressure losses calculation. Figure 25 summarizes the results obtained graphically; the procedure and calculations are included in Appendix F.

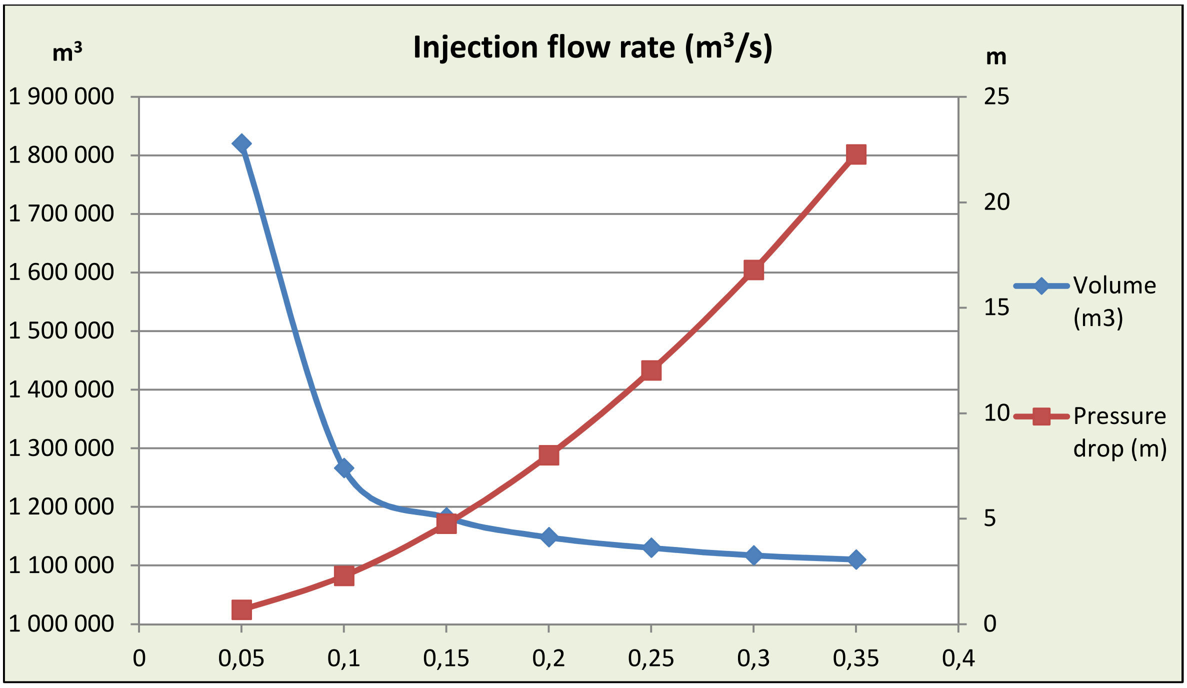

Figure 25. Pressure drop and volume as a function of the injection flow rate.

The flow rate chosen is 0.2 m^3/s, because it means a substantial reduction in the required volume and the pressure drop is not too high, while a higher flow rate barely would reduce the required volume. The calculation starts at 0.05 m^3/s because below this quantity the flow in borehole pipes would be laminar.

In order to decide the injection flow rate different models have been calculated, the graph represents the results obtained with storage model number 12. The storage model parameters, the flow rate for the different pipes and the pressure losses calculation are also included in Appendix F.

6.2.10 Flow rate during heat extraction

The extraction flow is managed by a district heating control system and it follows more or less the heat demand. But for the simulations it is necessary to enter a constant value, whose only requirement is to meet the demand.

The restriction for the minimum extraction flow is exactly the same as for injection, the flow has to be turbulent. But in this case, using a lower flow rate less volume is required to store the same amount of energy. That is due to the fact that the lower the flow rate is the colder it returns to the BTES, and it has more time to warm up when it is circulating through the boreholes. This implies that the difference between the minimum and the maximum temperatures will be higher, which means greater heat transfer.

In this way, with different flow rates to inject and remove heat, it would be better to have two different pumps in parallel, which is usually used in large-scale heat storages because it makes it possible to manage three different powers depending on the specific need. The price of the pumps with motor and all accessories included will be approximately 180 000 SEK (KSB, 2014).

6.2.11 Temperatures

In the simulation it is necessary to set the ambient temperature and the ground surface temperature starting point. For the last parameter 3^{o}C is used, because the simulation period starts in May and the average temperature in April is very close to 3^{o}C.

The software simulates a sinusoidal ambient temperature function, where the user enters the mean value, the amplitude and the period. In Luleå the annual average temperature is 3^{o}C, and it reaches -30^{o}C in winter and +26^{o}C in summer, but the maximum and minimum monthly average temperatures are +15,6^{o}C and -13,1^{o}C. With the aim of simulating similar conditions the mean value selected is 3^{o}C, the amplitude 15 and the cycle of the function is one year.

In Figure 26 the simulated sinusoidal temperature function can be seen, which compared with the real temperatures is 2 degrees higher during the summer months, but quite precise for the winter months.

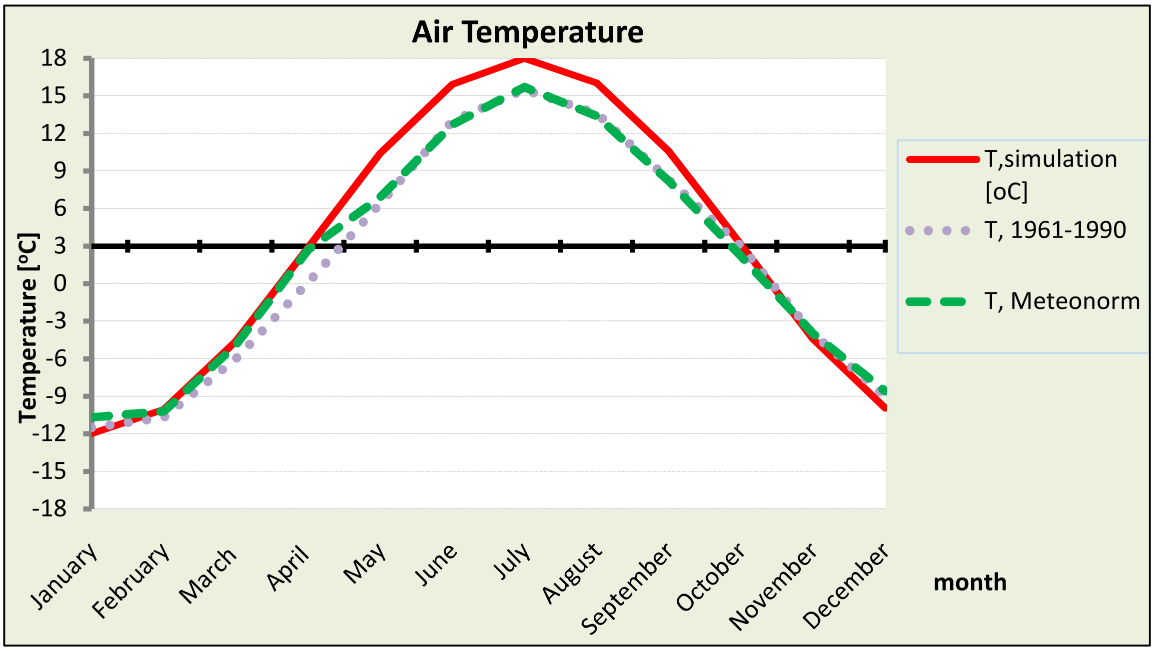

Figure 26. . Comparison between simulation temperature and real temperatures, values in monthly average.

7 Costs

The decisive factor that sets one project ahead of others is the economic one. The annuity factor method (see sections 7.1 and 7.2) is used to decide which of the different BTES models is optimal.

The calculation includes the different costs divided in groups, some of these groups are greatly dependent on the storage parameters such as depth, volume and spacing, while others are common for all the models. Moreover, some costs are estimated as a percentage of the construction costs.

In Table 9 there is a costs summary and equations (8) and (9) show the procedure to calculate it.

Table 9. Total investment costs summary

Total investment costs	▪ *Construction Costs*	*Drilling* *Piping* *Land Movements* *Insulation* *Indoor material*
	▪ *Design and administration*	
	▪ *Transient heat losses*	

$$C_{cons} = C_{drill} + C_{pipe} + C_{land} + C_{insu} + C_{indoor} \quad (8)$$

$$C_{Tot\ Inv} = C_{cons} + C_{design} + HL_{transient} \quad (9)$$

The injection energy cost is not included (except the losses) because it is directly subtracted from the incomes of the energy extraction.

Exchange rate

The economic calculations have been made in Swedish Krona, currently (2014) 1 SEK equals 0,11 Euro.

7.1 Annuity method

The annuity method is used in order to decide the optimal BTES model. This method is a reliable means of comparing the economic viability of various investment options. The annuity factor (*AF*) is calculated over the mortgage time (*n* years) at the given capital interest rate (*i*), see equation (10).

$$AF = \frac{i}{1 - \frac{1}{(1+i)^n}} \quad (10)$$

It is assumed an interest rate of 5% and a mortgage time of ten years, which means the total investment cost of the storage, considering the interest rate, will be paid off in 10 years.

With the annuity factor the Annual Storage Cost is calculated, which is used to choose the optimum storage.

7.2 Annual Storage Cost

The Annual Storage Cost represents the amount of money, considering the interest rate, to pay equitably each year until the total investment cost is paid off, in this case in 10 years.

The Annual Storage Cost includes the corresponding part of the total investment cost (C_{TI}) and the operation (O_A), maintenance (M_A) and steady-state heat losses (HL_{AS}) costs of the year, see equation (11).

$$C_{AS} = AF \cdot C_{Tot\ Inv} + O_A + M_A + HL_{AS} \qquad (11)$$

7.3 Heat Loss cost

The energy or heat loss is a significant factor depending on the energy price. Although it has to be considered, it is as mentioned above not a constant value over the years. The heat loss is higher at the beginning when the surroundings are warming up and after a few years becomes an almost constant value.

Thereby a criterion to differentiate the costs in transient heat losses and steady-state heat losses is assumed. The heat loss in the tenth year is considered as the steady-state and all the losses higher than this value during the previous years are considered transient losses. In this way, the costs for the transient heat losses are included as an investment cost, while the steady-state losses are included in the annual costs.

In Figure 27 the heat loss profile of one of the storage models can be seen (concretely, storage model 12, see section 8.3). The red line shows the heat losses for each year, while the blue columns show how the heat losses are considered from an economic point of view.

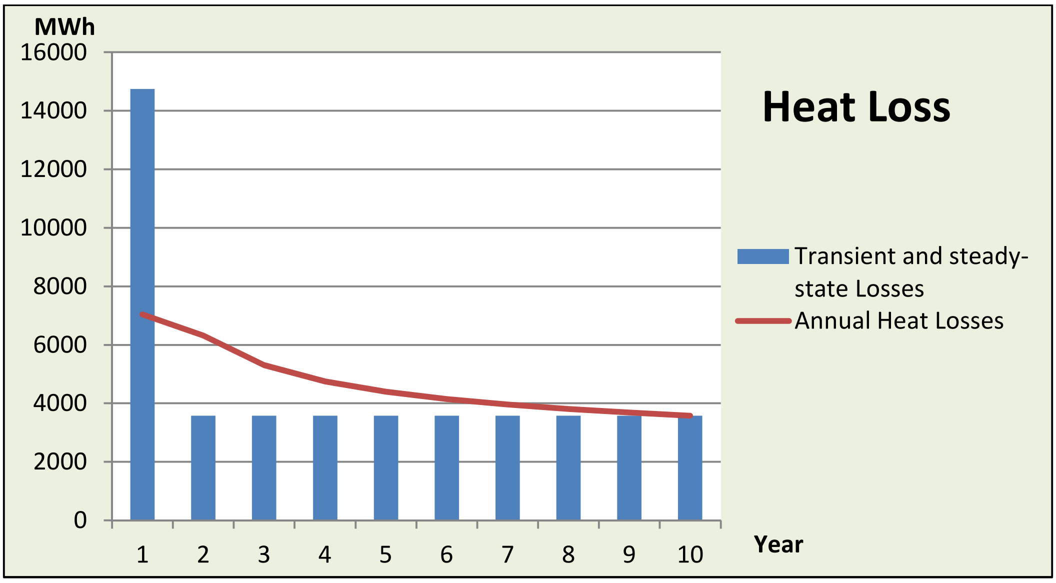

Figure 27. Transient and steady-state heat losses.

7.4 Drilling cost

The single most important cost in BTES construction is the cost of drilling. For that reason the drilling costs are detailed below in function of the storage model parameters.

Table 10 shows the costs from a drilling company in Norrfjärden, a northern Swedish city located close to Luleå. The prices include the borehole U-pipes and the backfilling. As the project concerns large-scale BTES, the third column with prices for more than 26 boreholes will be used.

Table 10. Drilling costs, including the borehole double U-pipes.

No of bore holes		1 - 10	11 - 25	26 -n
Establishment within 50 km from Norrfjärden	SEK	3 500	1 500	0
Distance to establishment in addition to 50 km	SEK/10km	200	200	200
Distance between drill holes up to 15 meters	SEK/borehole	0	0	0
Distance between boreholes over 15 meters	SEK/borehole	1 500	1 500	1 000
Container/borehole	SEK/borehole	3 200	2 800	2 500
Demolition of untouched land surface (soil drilling)	SEK/m	440	440	440
Rock drilling 0-200 m (fr untouched land surface)	SEK/m	230	225	220
Rock drilling 200-300 m	SEK/m	235	230	230
Waiting time caused by the customer	SEK/h	1 950	1 950	1 950

Since the distance between Luleå and Norrfjärden is 48 km and the distance between boreholes is lower than 15 meters there would not be costs for material transfer. Moreover it is assumed there will be no waste time caused by the costumer due to good planning.

The price to drill the soil layer is at least twice the price of drilling the rock and it highlights the importance of choosing a place with a thinner soil layer. On one hand it is more expensive due to the different header used to drill in the soil with a rotational movement while in the bedrock a fracturing system is used; on the other hand the soil drilling includes the casing, which is a pipe that covers around the borehole to avoid particles or land falls on it. For instance, in a large-scale BTES with 200 boreholes each meter of soil layer reduced represents 44000 SEK of savings respect drill in rock.

It is also remarkable, that the price of drilling deeper than 200 meters is just 5% higher, which means for the same storage volume deeper boreholes are more advantageous than increasing the number of boreholes.

7.5 Piping cost

The largest cost in a BTES after drilling is the piping. It includes the cost of the entire network; the connecting pipes between boreholes, the collector pipes for injection and extraction and the culvert which connects with the energy operation center. The prices obtained from the drilling company include the borehole U-pipes, the price for the borehole U-pipe can be seen in Table 11, together with the other pipe prices.

In order to calculate the piping cost for the different models the pipes lengths have been assumed based on the number of boreholes, the spacing between them and a distance of 50 meters from the storage to the heat exchanger. This latter distance is used as a culvert length and it is a fixed cost for all the storage models.

The pipes diameter has been chosen depending on the flow rates (see section 6.2.9) and pressure losses (see Appendix F).

Table 11. Pipe prices.

Pipe DN(mm)	***Price (SEK/m)***	***Use***
32,6	*46* *(up to 1000 m per roll)*	*Borehole U-pipe*
73,6	*235* *(up to 1000 m per roll)*	*Connection between boreholes*
96,8	*112* *(6 m pipes, welding cost of 500 SEK/weld)*	*Manifold or collector*
315,0	*377* *(6 m pipes, welding cost of 1000 SEK/weld)*	*Culvert*

7.6 Land movements and insulation

It has to be emphasized that there is no cost for the land acquirement because it already belongs to the municipality of Luleå, though the cost to prepare the land to build the storage has to be accounted.

7.6.1 Land movements

The storage surface is an optimization parameter; the costs for land movements and excavation depend on it (Table 12). Therefore increasing the boreholes depth signifies less boreholes and surface needed, i.e. lower costs of land movements and insulation.

Table 12. Land movements and insulation installation costs.

Operation	Price
Excavate and remove earth/soil	70 SEK/m^3
Land leveling	80 SEK/m^2
Install insulation	67 SEK/m^3

The prices are given by Bilfrakt Bothnia AB, company located in Luleå.

Moreover the excavation cost also depends on the insulation. The excavated depth will be characterized by the insulation thickness designed.

7.6.2 Thermal Insulation

In order to reduce the heat losses the BTES system is covered by some thermal insulation. Usually this insulation layer covers the entire storage surface and sometimes exceeds a few meters more. The thickness of this layer and the kind of insulation material are the parameters which reveal the thermal conductivity or the thermal resistance between the top of the storage and the ground surface.

Logically by increasing the thickness of the layer or choosing an insulation material with lower thermal conductivity the energy losses through the top of the storage will decrease.

Table 13. Different insulation materials with the respective price and thermal conductivity.

MATERIAL	Thermal Conductivity (W/m,K)	Price (kr/m3)
Soil	1,400	0
Foam glass	0,130	534
Recycled Foamed Glass	0,085	1 561
Polyfoam C 4 LJ 1250	0,036	1 725

The prices are provided by the companies Knaufinsulation, Ty-Mawr Lime Ltd.

Since the bedrock has a thermal conductivity of 3,45W/m,K, the soil also acts as an insulator. But by looking at Table 13 it can be seen that the foam glass thermal conductivity is ten times lower than the soil one, i.e. ten meters of soil equals one meter of foam glass.

In addition it must be taken into account that a BTES system has losses throughout the whole contour but only the top surface is insulated due to the difficulty and the high costs of excavating and insulating the BTES peripherally.

7.7 Indoor Costs

The indoor costs include all of the operation control system, measurement devices, the heat exchangers, valves, frequency converters, pumps and accessories.

Just the cost for the two pumps with the power required to overcome the pressure losses and provide the flow rate is approximately 200 000 SEK (KSB, 2014).

It is estimated to cost 1 million SEK for all the elements.

7.8 Design and Administration

The Design and Administration costs include the tests, calculations and drawings of the BTES, normally made by a consultancy office, and the legal procedures to carry out the project.

This cost of design and administration is estimated as a percentage of the construction cost, approximately 10% of the construction cost.

7.9 Operation and Maintenance

During the BTES operation there are constant costs for the maintenance and work processes. These costs include the electricity for the pumps and other control electronic devices, control employees and maintenance for the proper operation.

These costs are estimated as a percentage of the construction cost, 1% for operational costs and 1% for maintenance.

8 Results

In order to find the optimum features for the chosen model, different parameters and conditions were set in multiple simulations with the program DST. Basically the boreholes spacing and depth are the key of the storage shape, because varying these two parameters the number of boreholes, storage surface and volume change as well.

The different BTES models used with the purpose to find the optimal solution for the Kronan heat storage are shown in Table 14:

Table 14. Basic features of the BTES models studied.

	Storage 1	Storage 2	Storage 3	Storage 4	Storage 5	Storage 6
Volume (m3)	1 366 000	1 372 000	1 379 000	1 386 000	1 246 000	1 251 000
Spacing (m)	5,00	5,00	5,00	5,00	4,75	4,75
Borehole depth (m)	175	200	225	250	175	200
Surface/borehole (m2)	25,00	25,00	25,00	25,00	22,56	22,56
Number of boreholes	312	274	245	222	316	277
Total surface (m2)	7806	6860	6129	5544	7120	6255

	Storage 7	Storage 8	Storage 9	Storage 10	Storage 11	Storage 12
Volume (m3)	1 258 000	1 265 000	1 143 000	1 148 000	1 154 000	1 160 000
Spacing (m)	4,75	4,75	4,50	4,50	4,50	4,50
Borehole depth (m)	225	250	175	200	225	250
Surface/borehole (m2)	22,56	22,56	20,25	20,25	20,25	20,25
Number of boreholes	248	224	323	283	253	229
Total surface (m2)	5591	5060	6531	5740	5129	4640

	Storage 13	Storage 14	Storage 15	Storage 16	Storage 17	Storage 18
Volume (m3)	1 048 000	1 052 000	1 058 000	1 063 000	963 000	967 000
Spacing (m)	4,25	4,25	4,25	4,25	4,00	4,00
Borehole depth (m)	175	200	225	250	175	200
Surface/bh(m2)	18,06	18,06	18,06	18,06	16,00	16,00
Num. of boreholes	332	291	260	235	344	302
Total surface (m2)	5989	5260	4702	4252	5503	4835

	Storage 19	Storage 20	Storage 21	Storage 22	Storage 23	Storage 24
Volume (m3)	972 000	977 000	883 000	887 000	892 000	896 000
Spacing (m)	4,00	4,00	3,75	3,75	3,75	3,75
Borehole depth (m)	225	250	175	200	225	250
Surface/bh(m2)	16,00	16,00	14,06	14,06	14,06	14,06
Num. of boreholes	270	244	359	315	282	255
Total surface (m2)	4320	3908	5046	4435	3964	3584

8.1 Procedure and storage operation.

The procedure to compare the different models with the same criteria using DST is rather simple: firstly the main characteristics are established and then the volume is increased until the BTES extraction is able to fulfill the heating demand in the tenth year of operation. All the models have a similar energetic profile (see Figure 28), the extraction since the third year is almost the maximum needed for the whole neighborhood and then it increases slowly until it reaches the total demand.

The objective is to fulfill the total demand in the tenth year of operation because of the fact that all the houses will not be occupied the first year, which means the heating demand will increase gradually over the years until the neighborhood is totally filled. Although it should be highlighted that all the simulated models are able to supply at least 95% of the total demand after the three first years and after that the increase is slow until reaching the maximum in the tenth year.

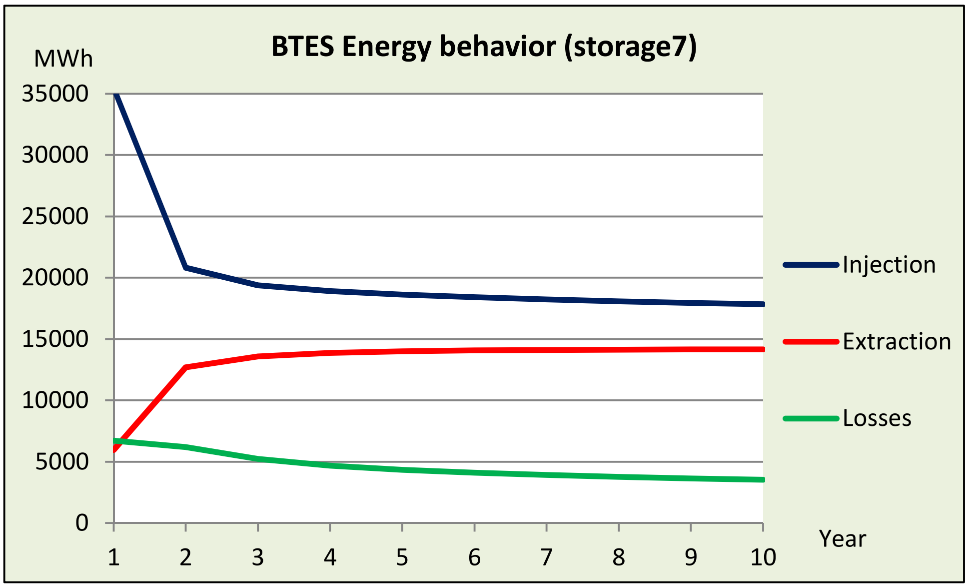

Figure 28. Energy injection, extraction and losses evolution during 10 years in storage model 7.

As seen in Figure 28 this is the behavior of a BTES, despite the flow rate and the temperature for the injection being constant the energy injection is very high at the beginning and then decreases slowly, that is because the bedrock temperature in the storage volume and surroundings is colder in the first years and increases easily. Simultaneously the energy losses decrease over the years, because at startup the surrounding has to heat up, then when the temperature difference between the storage volume and the surroundings decreases the losses are reduced proportionally.

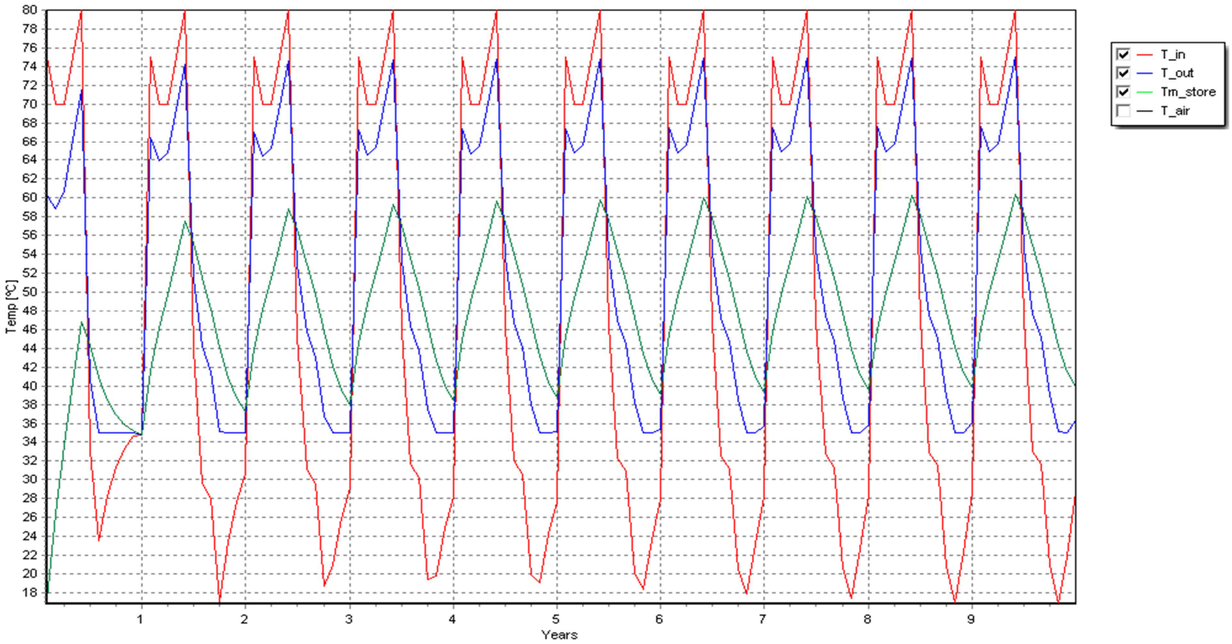

Figure 29. Evolution of injection, extraction and mean storage temperatures during 10 years in storage model 7.

Regarding the temperature behaviour, in Figure 29 can be seen how after three years of operation the storage mean temperature (green line) reaches almost the same values, with a maximum of 60ºC at the end of summer and a minimum of 38ºC at the end of winter. Meanwhile the temperature injection, represented by a red line, has the values given by the user during the summer months (

Table 7). Then in the cold months, during extraction, the red line represents the value of the return temperature coming back from the simulated district heating.

Finally, the blue line symbolizes the extraction temperature which in cold months (when it is decreasing) represents the supplied temperature to the district heating. In this case the minimum was established to not extract energy when it is below 35 degrees. For that reason in the first years flat portions can be seen at the end of summer.

8.2 Spacing and depth

As mentioned earlier the two parameters that characterize the storage shape are the spacing between boreholes and the borehole depth. Keeping the other parameters constant and varying those two reveals how it affects the storage.

Table 15 shows how the borehole spacing influences the storage shape and its behaviour. Increasing the separation between boreholes means that more volume is needed to store the same amount of energy, but due to the larger volume fewer boreholes are needed. Also, increasing volume means a bigger surface is in contact with the surroundings, which means larger heat losses. Steady-state heat losses are shown in Table 15.

The last column of the table represents the difference between the maximum and minimum storage mean temperature during one year, the values are given from the tenth year when the storage is highly stable. As equation (1) indicates to store the same amount of energy, when the storage volume decreases the temperature difference must increase and that is shown in the table as well. Therefore when a BTES system needs to supply higher temperatures it is easier with a smaller storage, i.e. decreasing the borehole spacing.

Table 15. Results as a function of the borehole spacing.

Borehole Spacing (m)	Average Volume (m^3)	Average N^o boreholes	Average Losses (MWh/annual)	Average Temp. Difference (^oC)
5	1 375 750	263	3 603	19,1
4,75	1 255 000	266	3 490	20,7
4,5	1 151 250	272	3 401	22,4
4,25	1 055 250	280	3 321	24,3
4	969 750	290	3 253	26,3
3,75	889 500	303	3 184	28,5

Table 16 shows how the borehole depth influences the results. As seen in the first column the depth is not significant for the storage volume, with boreholes 75 meters deeper the storage barely increases 2%, which indicates a bigger surface is needed when the depth is lowered. At the same time when a larger surface is required the number of boreholes increases, e.g. if the borehole depth is increased from 175m to 200m the number of boreholes required can be reduced by 40, but the savings are also reduced with increased depth.

Regarding the steady-state heat losses, the deeper the storage the less it follows the ideal shape, the cubic one. This explains why the heat storage loss is higher the deeper it is.

Meanwhile the temperature difference does not change in function of depth, as said before it depends on the storage volume following equation (1), since the volume does not change at all the temperature difference behaves constantly.

Table 16. Results in function of the borehole depth.

Borehole depth (m)	Average Volume (m^3)	Average N^o boreholes	Average Losses (MWh/annual)	Average Temp. Difference (^oC)
175	1 108 167	331	3 205	23,6
200	1 112 833	291	3 308	23,6
225	1 118 833	260	3 430	23,5
250	1 124 500	235	3 558	23,5

8.3 Storage design as a function of cost

The parameters of the optimum storage depend on the injection energy price, as mentioned above the higher the injection energy price, the lower the energy losses have to be in order for it to be more profitable.

8.3.1 Low energy cost

The energy provided to charge the storage during the summer is waste heat coming from the steel plant (see section 5.3). This waste heat is currently dumped into the bay, which means there is no profit gained. For that reason there is the possibility to charge the storage with a very cheap energy. The cost to provide the energy would be just for the electricity consumption of pumps, plus a few benefits for the company.

In that situation a cost of 0,03 SEK/kWh is assumed and in Figure 30 the Annual Storage Cost is represented for different storage models.

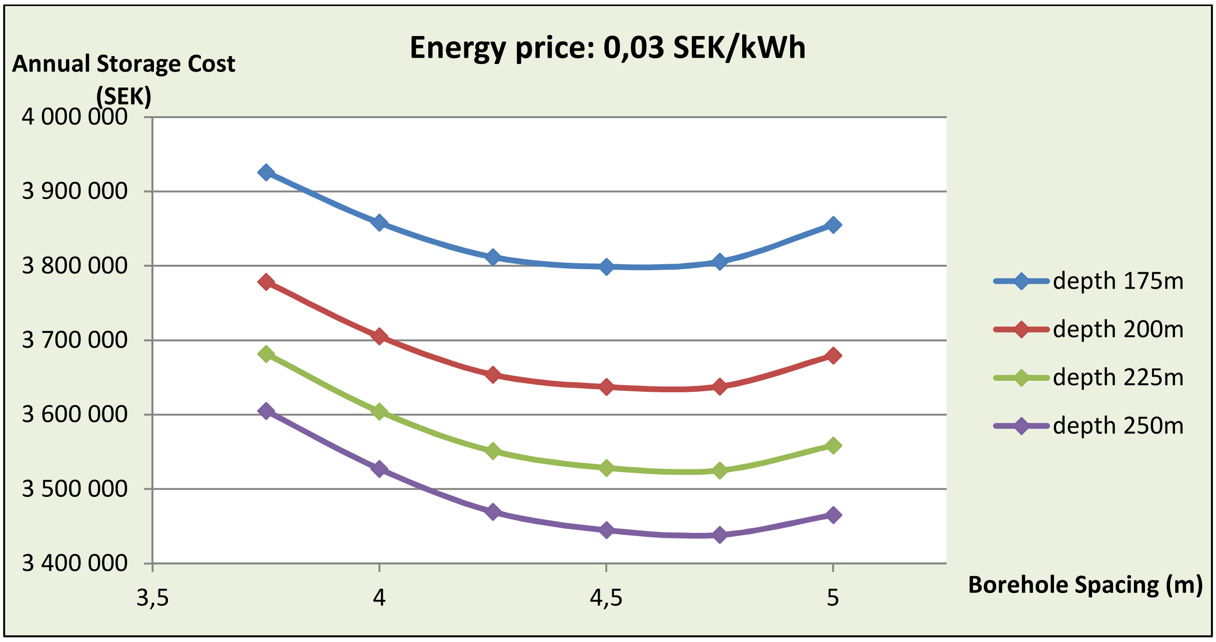

Figure 30. Annual Storage Cost for the different models with low energy price.

The graph shows that deeper boreholes mean cheaper storages. Furthermore, the costs are higher when the borehole spacing is less due to more boreholes being needed, although if it is too wide it gets expensive as well, because more surface and insulation is needed and there are more heat losses.

So here, the optimum storage is number 8, and it should be noted that the spacing of 4,75 meters is wider than what is usually used in large-scale BTES systems. In Table 17 the most outstanding results are shown, including economical.

All the results of storage model 8 obtained with DST are shown in Appendix C.

Table 17. Results of storage model 8.

Year	Injection (MWh)	Extraction (MWh)	Losses (MWh)	Efficiency	C_{as} (SEK)	Cost kWh (SEK/kWh)	Income (SEK)
1	35616	5872	6978	16,5%	3 438 375	0,586	2 706 992
2	20990	12641	6440	60,2%	3 438 375	0,272	5 966 552
3	19548	13554	5439	69,3%	3 438 375	0,254	6 546 582
4	19077	13859	4871	72,6%	3 438 375	0,248	6 846 346
5	18785	13997	4508	74,5%	3 438 375	0,246	7 068 485
6	18559	14069	4254	75,8%	3 438 375	0,244	7 259 604
7	18372	14112	4060	76,8%	3 438 375	0,244	7 437 024
8	18215	14137	3905	77,6%	3 438 375	0,243	7 605 706
9	18082	14150	3779	78,3%	3 438 375	0,243	7 768 350
10	17965	14154	3672	78,8%	3 438 375	0,243	7 926 240
TOTAL	**205 209**	**130 545**	**47 906**	**63,6%**	**34 383 749**	**0,263**	**67 131 881**

As commented above in section 8.1 the energy injection at the beginning warms up the storage and the surroundings and for that reason the heat losses are pretty high, but over the years the heat loss decreases and the efficiency increases. As mentioned in section 4.10, the storage life cycle has no specific limitation and the total efficiency shown in the last row will continue improving over the years.

The kWh Cost represents the price of the energy extraction considering the Annual Storage Cost. Since the storage cost, slightly higher than 34 MSEK, is paid off in ten years, afterwards the cost of kWh will decrease to 0,07SEK because the costs for each year will be only for operation, maintenance and heat loss (approximately 1MSEK/year). Hence the benefits (incomes - annual cost) will increase to 7 MEK/year.

The last column represents the incomes earned by selling the energy extracted from the storage, in the price of this energy the injection costs are subtracted and the energy price evolution is also considered. Thus, to calculate the profits subtract the Annual Storage Cost from the income.

The payback of the BTES takes 6,72 years, which is very good considering the long term benefits.

8.3.2 Medium Energy cost

Another possibility is if the energy company wants to benefit from selling this waste heat, which would be the most expected situation. In order to simulate this circumstances an energy injection cost of 0,15 SEK/kWh is assumed.

As seen in Figure 31, the cost curves get closer when the price is increased. On one hand the overall result is similar to the first, but approximately 600 000 SEK/year more expensive. On the other hand the optimal storage is not the same, because in that case the model number 12 with shorter borehole spacing, 4,5 meters, would be best. This proves when the energy price increases it becomes more important to reduce the heat loss and one way to do it is by reducing the borehole spacing.

It should be noted that the difference between the optimal borehole spacing and ±0,5 meters is less than 70000 SEK per year, which means barely 2%.

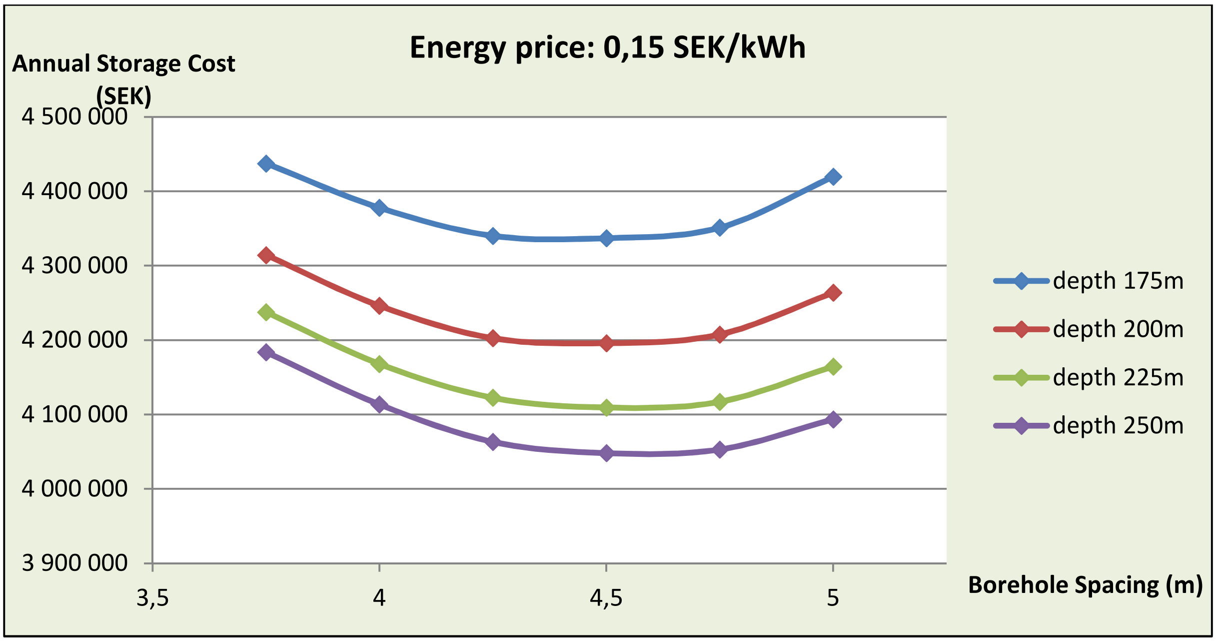

Figure 31.Annual Storage Cost for the different models with medium energy price.

All the results of storage model 12 obtained with DST are shown in Appendix D.

In the following table (Table 18) the most important results for the optimal storage (model 12) are shown.

Table 18. Results of storage model 12,

Year	Injection (MWh)	Extraction (MWh)	Losses (MWh)	Efficiency	C_{as} (SEK)	Cost kWh (SEK/kWh)	Incomes (SEK)
1	34950	6966	7031	0,20	4 048 019	0,581	2 375 406
2	20589	12771	6317	0,62	4 048 019	0,317	4 495 392
3	19327	13580	5306	0,70	4 048 019	0,298	4 929 540
4	18905	13870	4748	0,73	4 048 019	0,292	5 187 380
5	18637	14010	4396	0,75	4 048 019	0,289	5 393 850
6	18431	14080	4147	0,76	4 048 019	0,288	5 575 680

7	18256	14118	3959	0,77	4 048 019	0,287	5 746 026
8	18106	14139	3809	0,78	4 048 019	0,286	5 910 102
9	17975	14149	3686	0,79	4 048 019	0,286	6 069 921
10	17861	14154	3582	0,79	4 048 019	0,286	6 227 760
TOTAL	**203 037**	**131 837**	**46 981**	**0,65**	**40 480 194**	**0,307**	**51 911 057**

As in the first case the energy efficiency improves over the years but after ten years it becomes almost stable. There is 1 GWh less in total heat losses but the higher number of boreholes and the increased energy price make the storage cost 40,5 MSEK.

After the tenth year the Annual Storage Cost including operation, maintenance and heat loss is 1 MSEK which means a price for each kilowatt of 0,069 SEK. Thus the profits after the storage investment is paid off are 5,2MSEK per year.

The payback of this BTES takes 9,14 years, which is still good for this kind of project.

8.3.3 High energy cost

The last supposition is if the energy injection is provided by an expensive heat source, e.g. solar collectors. In this situation the energy price represents the costs of buying and installing the collectors and the pipe network. For this situation an injection energy cost of 0,35 SEK/kWh is assumed, which means a cost of 45 MSEK for the solar collectors.

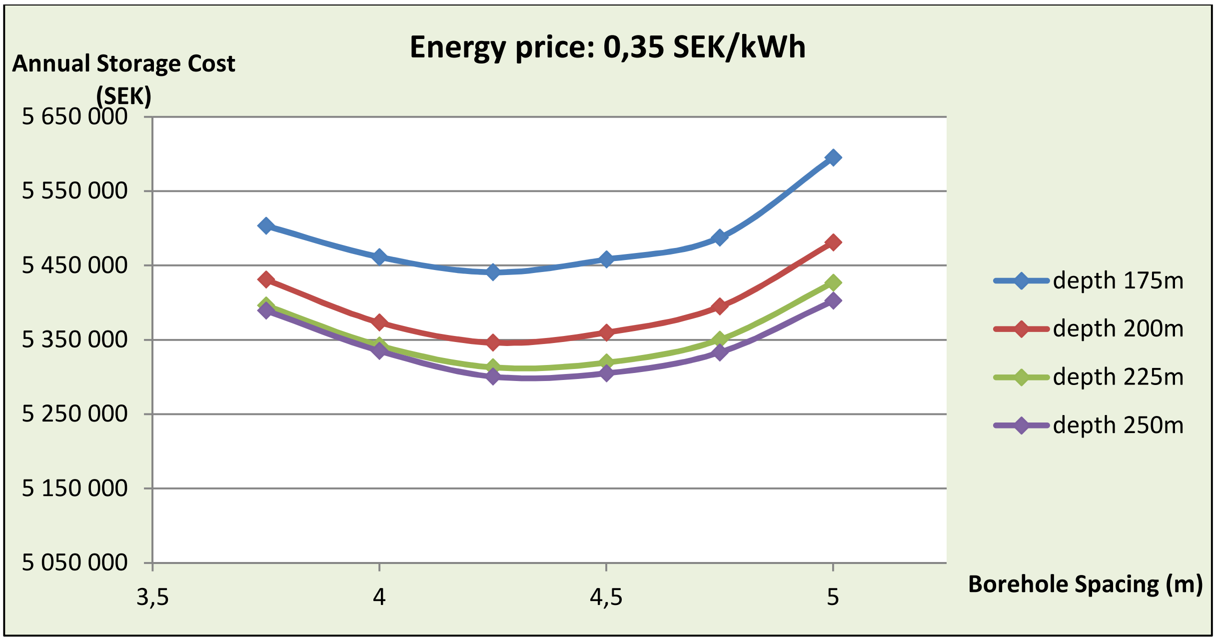

Figure 32. Annual Storage Cost for the different models with high energy price.

In this case the optimum storage is storage model 16 with a borehole spacing of 4,25 meters and the same depth as the other situations, 250 meters.

Table 19. Results of storage model 16.

Year	Injection (MWh)	Extraction (MWh)	Losses (MWh)	Efficiency	C_{as} SEK	Cost kWh (SEK/kWh)	Incomes (SEK)
1	34325	7940	7122	0,23	5 052 914	0,636	1 119 540
2	20220	12892	6196	0,64	5 052 914	0,392	1 959 584
3	19139	13607	5183	0,71	5 052 914	0,371	2 217 941
4	18756	13881	4639	0,74	5 052 914	0,364	2 415 294
5	18507	14018	4296	0,76	5 052 914	0,360	2 593 330
6	18314	14090	4054	0,77	5 052 914	0,359	2 761 640
7	18151	14124	3870	0,78	5 052 914	0,358	2 923 668
8	18006	14140	3724	0,79	5 052 914	0,357	3 082 520
9	17878	14149	3604	0,79	5 052 914	0,357	3 240 121
10	17767	14154	3503	0,80	5 052 914	0,357	3 396 960
11	17767	14154	3503	0,80	1 069 714	0,076	8 506 554
12	17767	14154	3503	0,80	1 069 714	0,076	8 662 248
13	17767	14154	3503	0,80	1 069 714	0,076	8 817 942
14	17767	14154	3503	0,80	1 069 714	0,076	8 973 636
TOTAL	**272 131**	**189 611**	**60 203**	**0,70**	**50 529 140**	**0,266**	**60 670 978**

As seen in Table 19 the cost of extracted heat is not profitable until the tenth year because the sum of the cost of extracted and injected heat is greater than the selling price in winter. Then, when the Total Storage Investment Cost is paid off the incomes are much higher, because from the tenth year the cost is just for the maintenance, operation and heat loss plus 100 000 SEK, a value assumed as a maintenance and operation cost for the solar collectors installation, in total 1,1MSEK/year.

In that case the payback is 13 years and then the benefits are approximately 8 MSEK per year after fourteen years. In addition the lifetime of the solar collectors should be considered because it is shorter than that of the storage, which means in approximately 30 years, depending on the type of collectors, they must be replaced by new ones which will involve another future investment.

Summarizing from the three different energy costs, while the injection energy price is not higher than 0,45 SEK/kWh the models with 250 meters of boreholes depth are the best option. If it reaches a very expensive price, as seen in Figure 33, then the optimum depth and spacing become shorter, but curiously the 175 m of borehole depth is still the worse choice. In this case a depth of 200 m and spacing of 4,25m are the optimal parameters.

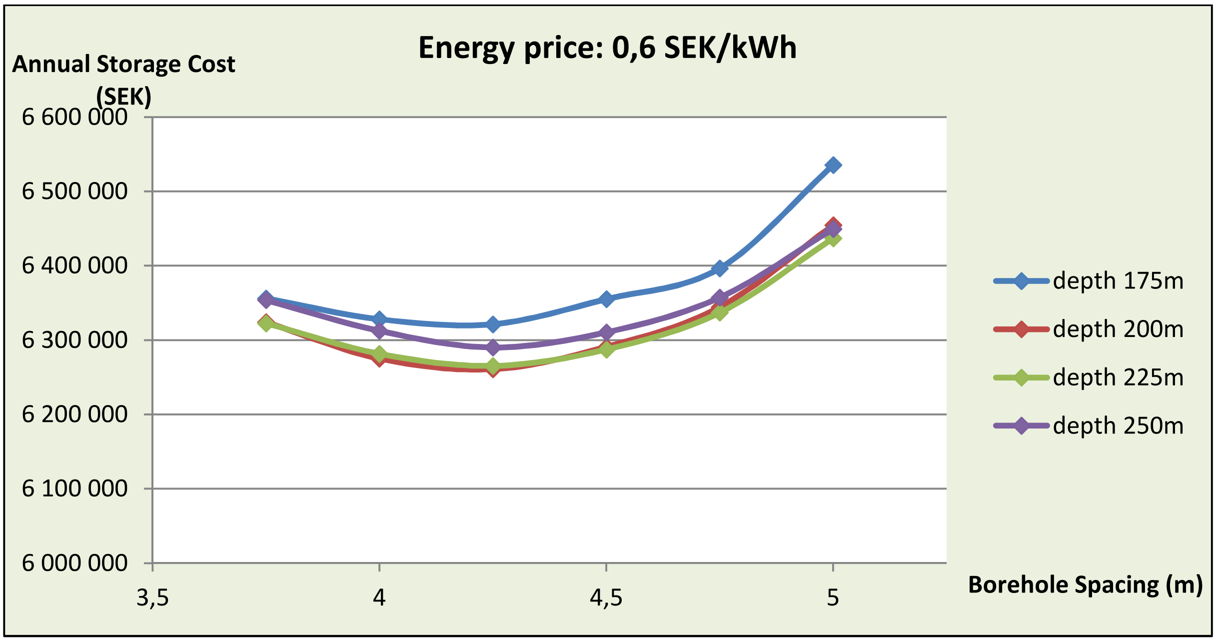

Figure 33. Annual Storage Cost for the different models with expensive price.

As seen in the figures 25 to 28 the higher the energy price the closer the lines of the different models annual cost, which reduces the importance of finding the optimal parameters.

In the previous four graphs there is the same difference between the maximum and the minimum value in the vertical axis to better see the cost curves evolution.

8.4 Thermal Insulation

As is mentioned above the heat losses have a greater influence with increasing energy price. The factor that can reduce the heat loss is the thermal insulation, but it should be investigated how profitable and helpful it is. In order to evaluate whether the insulation is profitable two different situations are tested.

These two cases are when the energy price is medium (0,15 SEK/kWh) and expensive (0,35 SEK/kWh). In both situations a borehole depth of 250 meters is used, because as seen before it is the best choice.

Figure 16 shows the cases studied for the different storage models. It should be remembered that a soil layer of 10 meters is above the bedrock and the following insulation layers would start at the ground surface level.

The option A is the one used in the simulations above. It is a cheap material with a conductivity ten times lower than the soil. The option B is without any specific insulation material, just leaving 1 meter of soil above the boreholes. Option C tests a very good insulation material which is quite expensive. The layers A and C have a thickness of 0,4 and 0,5 respectively, and are not too wide to avoid irrational costs with land movements and insulation, while option B (the soil) has a thicker layer which means more land movement costs but no insulation costs.

Table 20. Different insulations

	A	B	C
Material	Foam glass	No (soil)	Polyfoam C 4 LJ 1250
Thermal Conductivity (W/m,K)	0,13	1,4	0,036
Insulation Layer (m)	0,4	1	0,5
Price (SEK/m^3)	534	0	1725
Average Loss through the top (%)	4,3	17	2,4
Average Number of boreholes	235	241	234

As seen in the table the percentage of energy loss through the top is reduced considerably by using an insulation material, as A and C columns. Also, due to the reduction of heat loss less volume is needed to store the same amount of energy, which implies the number of boreholes decreases. Despite the conductivity of material C is almost four times lower, the number of boreholes barely changes.

Figure 34 shows the Annual Storage Costs if the price of the energy injection is 0,15 SEK/kWh, which is the price expected approximately for the waste heat. On one hand it is clear that using the expensive material (option C) is not worthwhile, it is surprisingly worse than let a soil layer of 1 meter without insulation material, option B, the difference between them is 385 000 SEK/year. On the other hand, the difference between using a cheaper insulation material and only the soil is not very important, an average of 76 800 SEK/year.

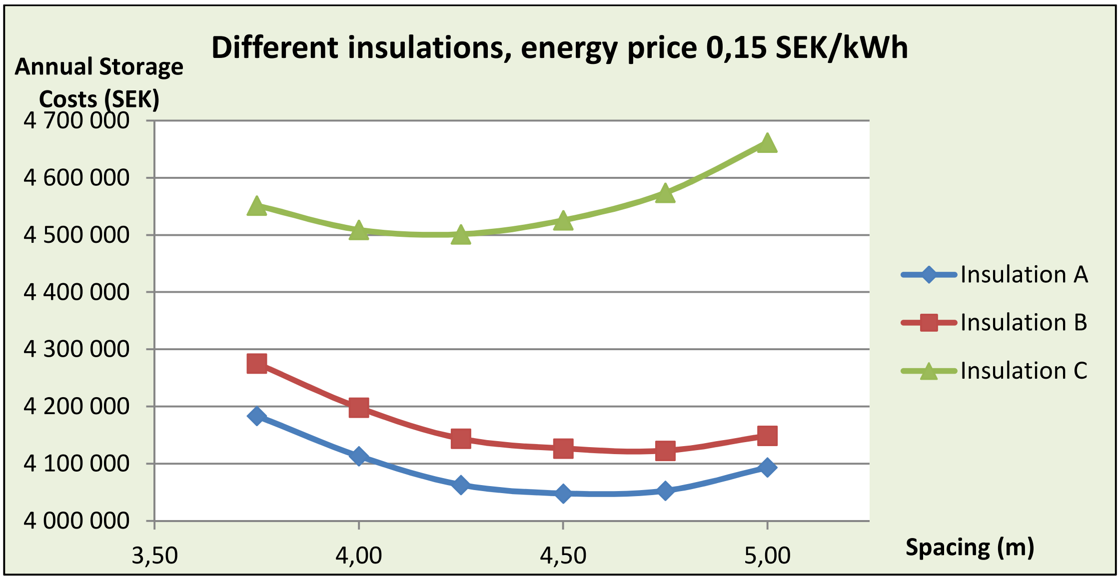

Figure 34. Annual Storage costs with different insulation layers. Data: Energy price 0,15 SEK/kWh; λ_A=0,13 W/m,K, λ_B= 1,4 W/m,K and λ_C=0,036W/m,K; thickness: zA=0,4m, zB=1m, zC=0,5m

In the following graph (Figure 35) a higher price, 0,35 SEK/kWh, is considered. The results show a greater separation between the curves A and B, which means the insulation is becoming more important, proved also by the closer distance to the curve C. Nevertheless the expensive insulation material is by far not profitable to use. The average money saved using option A respect B and C is 200 000 and 445 000 SEK/year.

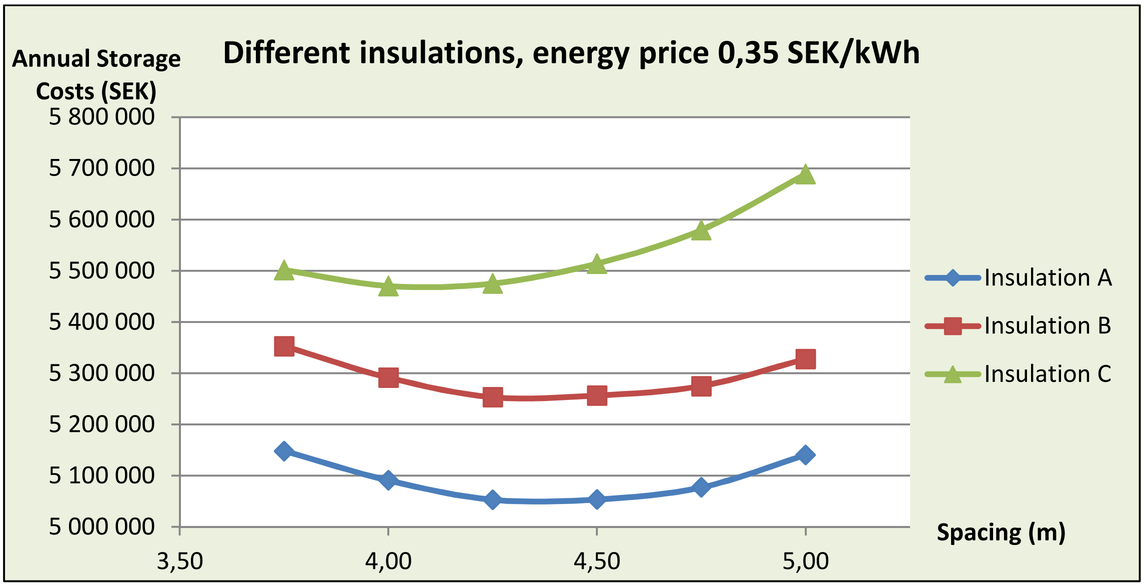

Figure 35. Annual Storage costs with different insulation layers. Data: Energy price 0,35 SEK/kWh; λ_A=0,13 W/m,K, λ_B= 1,4 W/m,K and λ_C=0,036W/m,K; thickness: zA=0,4m, zB=1m, zC=0,5m.

In the last two charts the expectations are confirmed: logically, the cheaper the injection energy the narrower the separation between curves A and B, because the cost of the heat loss becomes less significant. Moreover it is not worth using a very good insulation material even if the injection energy price is very high.

8.5 Sensitivity Analysis

With the purpose of analyzing how conditions different from those previously established would affect the optimal BTES model a sensitivity analysis is made. However only the most transcendental parameters are varied and tested, namely the bedrock thermal conductivity and volumetric heat capacity.

In the hypothetical and expected case where the injection energy price is around 0,15 SEK/kWh the optimal model for this situation is used as a reference, i.e. model 12 (see section 8.3.2).

8.5.1 Bedrock Thermal conductivity

Depending on the bedrock material the thermal properties are different. Table 21 shows how the model varies if the thermal conductivity value is 10% higher or lower than expected.

Table 21. Results with different bedrock thermal conductivity.

	+10%	**Storage 12**	**-10%**
Thermal conductivity (W/m,K)	3,80	3,45	3,11
Volume (m3)	1 120 000	1 160 000	1 209 000
Number of boreholes	221	229	239
Energy efficiency (%)	78,40	79,25	80,10
Annual Steady Heat Loss (MWh)	3 768	3 582	3 401
Annual Storage Cost	3 977 115	4 048 019	4 143 671

With a higher thermal conductivity value there is a higher heat transfer rate, which means it is easier to heat up a material. For this reason the volume needed is lower but at the same time causes greater heat loss. Conversely, with a lower value the losses are smaller and there is a better efficiency, but the fact that it needs a greater volume, i.e. more boreholes, causes its annual costs to be higher. It is important to remember the annual storage cost is the money that is to be paid each year for a decade, to pay off the storage.

8.5.2 Bedrock Volumetric Heat capacity

Also depending on the bedrock material the density and specific heat could be different, multiplying both material properties the volumetric heat capacity is obtained. Table 22 shows how the results are influenced if this thermal property is 10% higher or lower.

Table 22. Results with different bedrock volumetric heat capacity.

	+10%	**Storage 12**	**-10%**
Volumetric heat capacity (J/m^3,K)	1,94E+06	2,16E+06	2,38E+06
Volume (m^3)	1 127 000	1 160 000	1 201 000
Number of boreholes	223	229	237
Energy efficiency (%)	79,10	79,20	79,40
Annual Steady Heat Loss (MWh)	3 608	3 582	3 557
Annual Storage Cost	3 963 574	4 048 019	4 154 253

On one hand, as seen in table the volumetric heat capacity has less influence on the storage results, but it has a bigger impact in the annual costs because of the combination of the results variation.

On the other hand, when the capacity to store energy in a certain volume is increased less volume is needed and reduces the annual storage cost.

Despite having fewer losses with a lower volumetric heat capacity and thus being more efficient, the fact that makes the storage more expensive is a bigger volume, which implies more boreholes and more expensive construction costs.

8.6 Possible Distribution.

Figure 36 shows a possible distribution with an estimated distance of 50 meters to the machinery hut. It is the optimum storage, the model number 12, with 229 boreholes distributed in 15 horizontal rows. Also appears the culvert and manifold diameters.

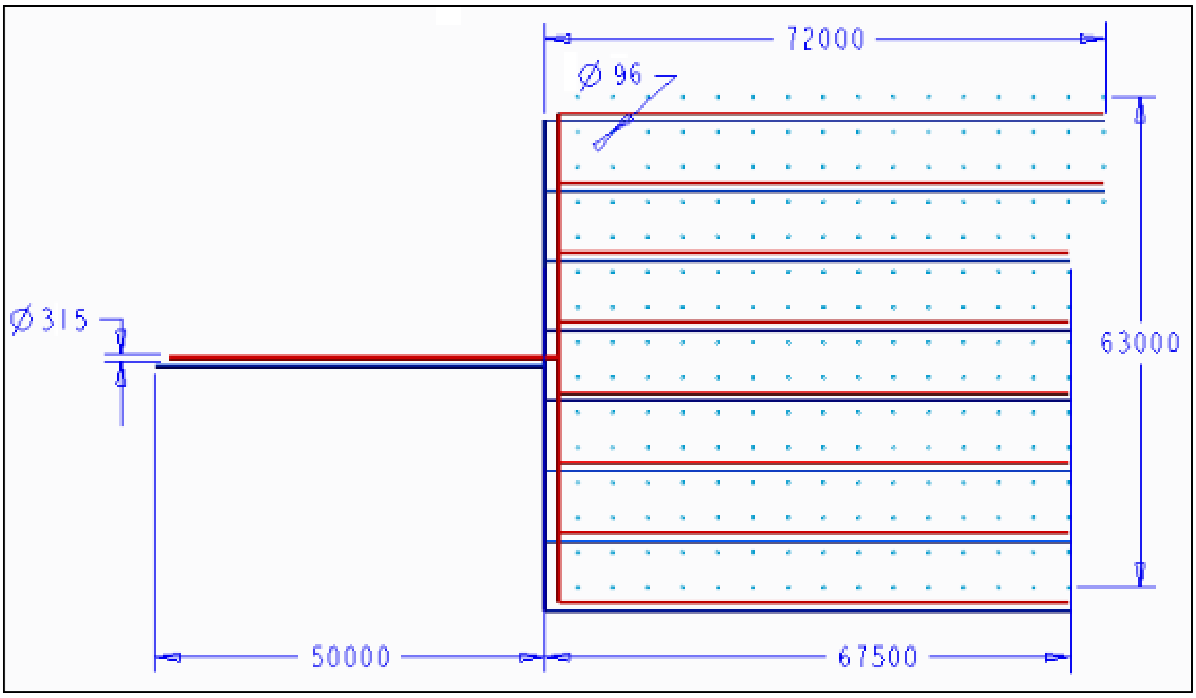

Figure 36. System distribution: pipes and boreholes. (optimum storage: model 12)

9 Conclusions

The significance of the studies in the energy storage field is unquestionable due to the importance of reducing the world energy consumption and fortifying renewable energy.

In a project of this size, handling a large amount of energy, is of utmost importance and for a seasonal storage no better options are available than BTES. The main points are the system efficiency and the payback between 7 and 9 years.

The efficiency (heat recovery) of the BTES is higher than 75% after the fifth year of operation reaching 80% in the tenth year, which means a great ratio of use.

Economically, all the factors influence the storage shape, and all results depend on the injection energy price. A good deal with the energy company would mean an important reduction in the total cost. Most likely the probable cost for the energy will be the one termed “medium price” in the project. Considering that price, 0,15 SEK/kWh, the Annual Cost of the Storage is 4 MSEK during ten years, after which the storage is paid off and the annual cost is reduced to 1 MSEK for maintenance and operation. The total cost of the storage is 40 MSEK.

In the case of the heat source being solar energy, the price of the solar collectors would replace the cost of energy injection. However the injection for the first year must be done with waste heat because in the first year the efficiency of the BTES is below 50% and it needs more than 30 GWh, while the solar system should be planned to supply about 18GWh/year, the annual heat demand.

Although increasing the borehole depth over 150 meters means the storage shape is far from the theoretical optimum shape to reduce the heat loss (cubic), it has been proved that in all cases a depth of 250 meters is better from an economic point of view. Deeper distances should be studied because there are no prices and results on large-scale systems up to now.

It should be noted that the drilling cost function is only valid for a certain limited depth, because the drilling cost is not clear beyond 250 meters. Although the deeper the boreholes the fewer holes are needed, which means it is profitable to continue drilling until the cost reaches the same value as starting a new hole.

The borehole spacing is a most important parameter and it strongly influences the storage shape. It is a little bit higher than expected for the low injection energy cost, being the optimum 4,75 meters. But when the energy cost is higher the optimum borehole spacing gets reduced to 4,25 meters, that is due to the cost of the heat loss. Therefore using a borehole spacing 0,5 meters wider or shorter than the optimum is barely 50 000 SEK/year more expensive. This means that it is possible to play with the parameters to affect other objectives with only slightly increasing the cost.

The importance of the thermal insulation depends on the energy price, but it is not profitable to spend a large amount of money in insulation because the biggest percentage of heat loss is through the storage sides and in to a lesser degree through the bottom. Moreover, the soil layer thickness above the bedrock decreases the heat loss and the necessity to have an insulation layer.

Regarding the bedrock thermal conductivity, the higher it is, the less rock volume (also number of boreholes) is needed and the cost will thus be lower, but it also means a greater heat loss.

Recommendations

The procedure to arrange the BTES in Kronan should follow these recommendations:

Carry out a study of the steel market and analyze the reliability of the steel plant to be confident that their production will not be significantly reduced in the following years. If it is not reliable analyze and discuss other heat sources such as solar energy or waste heat from other processes.

Start with the TRT-test in all the area available to find the best location following the next steps:

- Good bedrock thermal properties.
- Thin soil layer because the soil drilling costs are twice the rock drilling.
- Soil layer with high thermal conductivity: to decrease the losses on the top of the storage.
- Bedrock with high thermal conductivity: as said above it improves the injection and extraction, so the volume and the number of boreholes may be decreased, which would reduce the main cost, the drilling.
- Regarding the borehole filling material consider using a high solids grout to improve the thermal conductivity.

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11 Appendices

A. Heating demand calculation.

B. Different model simulations: basic parameters and costs.

C. Results storage model 8.

D. Results storage model 12.

E. Results storage model 16.

F. Pressure drop calculations.

A. Heating demand calculation

The calculation for the heating demand is made on an hourly basis and due to the long extension (more than 8765 rows) it is not added in this project, but it is attached as Excel file called "Kronan, heat demand.xls" on the project CD-ROM. In Table 23 an example is shown for one day.

Table 23. Heating demand for the first day of January.

Date	Hour	T,air [ºC]	Heat-degree-days [ºC,h]	E,heating [kWh/h]	E,dhw [kWh/h]	E,total [kWh/h]
01/Jan	0-1	0.3	16.7	1.4	0.0	1.4
01/Jan	1-2	-0.2	17.2	1.4	0.0	1.4
01/Jan	2-3	-0.5	17.5	1.4	0.0	1.4
01/Jan	3-4	-1.0	18.0	1.5	0.0	1.5
01/Jan	4-5	-1.4	18.4	1.5	0.1	1.6
01/Jan	5-6	-1.5	18.5	1.5	0.4	1.9
01/Jan	6-7	-2.1	19.1	1.6	1.1	2.7
01/Jan	7-8	-2.7	19.7	1.6	0.4	2.0
01/Jan	8-9	-2.9	19.9	1.6	0.2	1.8
01/Jan	9-10	-3.2	20.2	1.7	0.2	1.8
01/Jan	10-11	-3.0	20.0	1.6	0.3	1.9
01/Jan	11-12	-2.9	19.9	1.6	0.4	2.1
01/Jan	12-13	-2.8	19.8	1.6	0.4	2.0
01/Jan	13-14	-2.7	19.7	1.6	0.3	1.9
01/Jan	14-15	-2.8	19.8	1.6	0.3	1.9
01/Jan	15-16	-1.2	18.2	1.5	0.4	1.9
01/Jan	16-17	-0.8	17.8	1.5	0.6	2.0
01/Jan	17-18	-0.5	17.5	1.4	1.2	2.6
01/Jan	18-19	-0.2	17.2	1.4	2.1	3.5
01/Jan	19-20	-0.3	17.3	1.4	1.2	2.6
01/Jan	20-21	-0.3	17.3	1.4	0.4	1.8
01/Jan	21-22	-0.5	17.5	1.4	0.1	1.5
01/Jan	22-23	-0.7	17.7	1.5	0.0	1.5
01/Jan	23-24	-0.3	17.3	1.4	0.0	1.4

The three first columns are easy to understand, the fourth represents the difference between the ambient temperature and the limit temperature when the heat must be supplied, in this case 17 degrees.

In the calculations for the space heating and district hot water energy the values are estimated proportionally to the total energy consumed by a new house in Luleå. These values are the following:

Table 24. Energy consumption for a single house in Luleå.

Data		
Total Space Heating Energy	8,400	kWh/year
	23,01	kWh/day
Total District Hot Water Energy	3,600	kWh/year
	9,9	kWh/day

Then the heating energy for each hour is calculated multiplying the ratio of the degrees difference over the total degrees difference for the whole year per space heating total energy that appears in Table 24.

The district hot water calculation is also used a proportion of the total value, but in this case the daily average of consumption on an hourly basis is known, as shown in Table 25.

Table 25. Daily percentage of district hot water consumption in Luleå.

h	% dhw
0-1	0.0 %
1-2	0.0 %
2-3	0.0 %
3-4	0.0 %
4-5	0.8 %
5-6	3.8 %
6-7	11.4 %
7-8	3.8 %
8-9	1.9 %
9-10	1.9 %
10-11	3.0 %
11-12	4.5 %
12-13	3.8 %
13-14	3.0 %
14-15	3.0 %
15-16	3.8 %
16-17	5.7 %
17-18	12.1 %
18-19	21.2 %
19-20	11.7 %
20-21	3.8 %
21-22	0.8 %
22-23	0.0 %
23-24	0.0 %

The data is given by Kjell Skogsberg from the company Snowpower.

As explained before in section 5.2, during the warmer months the storage is only charging and the heating demand would be directly supplied from the heat source and thus the electricity consumption for the heat pumps is subtracted from the total heat demand for the BTES. Thereby the heating demand is summarized in Table 26.

Table 26. Energy demand for the 1500 houses and the energy supplied by the BTES.

Month	E. space heating [MWh/month]	E dhw heating [MWh/month]	E. dhw electricity [MWh/month]	Total Energy [MWh/month]	BTES Heat Demand [MWh]
January	2 418	344	115	2 877	2 762
February	2 489	311	104	2 903	2 799
March	1 655	344	115	2 113	1 999
April	810	333	111	1 254	1 143
May	321	344	115	780	0
June	25	333	111	469	0
July	4	344	115	463	0
August	73	344	115	531	0
September	377	333	111	821	0
October	806	344	115	1 264	1 150
November	1 906	333	111	2 350	2 239
December	1 718	344	115	2 177	2 062
TOTAL	***12 600***	***4 050***	***1 350***	***18 000***	***14 153***

B. Storage models: parameters and costs

The results shown in the following tables are the characteristics of each BTES model and the capital cost to build it.

Table 27. Parameters and costs of storage models 1 to 4.

	Storage Model 1	**Storage Model 2**	**Storage Model 3**	**Storage Model 4**
Volume (m3)	1 366 000	1 372 000	1 379 000	1 386 000
Spacing (m)	5,00	5,00	5,00	5,00
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	25,00	25,00	25,00	25,00
Number of boreholes	312	274	245	222
Total surface (m2)	7806	6860	6129	5544
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,64	0,73	0,82	0,90
Steady heat loss (MWh)	3 437	3 536	3 655	3 782
Transient heat loss (MWh)	9 770	10 291	10 769	11 225
COSTS				
Cost drilling+piping (kr)	18 848 792	18 080 922	17 569 369	17 173 007
Insulation cost (kr)	1 876 494	1 649 144	1 473 385	1 332 778
Land movements cost (kr)	858 629	754 600	674 178	609 840
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 258 391	2 148 467	2 071 693	2 011 562
CONTRUCTION COST	**24 842 306**	**23 633 133**	**22 788 625**	**22 127 187**
Transient heat losses cost (SEK)	1 465 500	1 543 650	1 615 350	1 683 750
TOTAL INVESTMENT COST	**26 307 806**	**25 176 783**	**24 403 975**	**23 810 937**
Maintenance (SEK)	248 423	236 331	227 886	221 272
Operation (SEK)	248 423	236 331	227 886	221 272
Steady heat losses cost (SEK)	515 550	530 400	548 250	567 300
Annual Storage Cost (10years)	**4 419 377**	**4 263 571**	**4 164 449**	**4 093 469**
TOTAL COST 10 years	**44 193 773**	**42 635 712**	**41 644 489**	**40 934 690**

Table 28. Parameters and costs of storage models 5 to 8.

	Storage Model 5	**Storage Model 6**	**Storage Model 7**	**Storage Model 8**
Volume (m3)	1 246 000	1 251 000	1 258 000	1 265 000
Spacing (m)	4,75	4,75	4,75	4,75
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	22,56	22,56	22,56	22,56
Number of boreholes	316	277	248	224
Total surface (m2)	7120	6255	5591	5060
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,63	0,72	0,81	0,89
Steady heat loss (MWh)	3 322	3 422	3 544	3 672
Transient heat loss (MWh)	9 448	10 242	10 726	11 186
COSTS				
Cost drilling+piping (kr)	18 816 367	18 061 759	17 575 384	17 200 556
Insulation cost (kr)	1 711 648	1 503 702	1 344 103	1 216 424
Land movements cost (kr)	783 200	688 050	615 022	556 600
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 231 121	2 125 351	2 053 451	1 997 358
CONTRUCTION COST	**24 542 336**	**23 378 862**	**22 587 960**	**21 970 938**
Transient heat losses cost (SEK)	1 417 200	1 536 300	1 608 900	1 677 900
TOTAL INVESTMENT COST	**25 959 536**	**24 915 162**	**24 196 860**	**23 648 838**
Maintenance (SEK)	245 423	233 789	225 880	219 709
Operation (SEK)	245 423	233 789	225 880	219 709
Steady heat losses cost (SEK)	498 300	513 300	531 600	550 800
Annual Storage Cost (10years)	**4 351 025**	**4 207 505**	**4 116 963**	**4 052 851**
TOTAL COST 10 years	**43 510 254**	**42 075 047**	**41 169 633**	**40 528 515**

Table 29. Parameters and costs of storage models 9 to 12.

	Storage Model 9	Storage Model 10	Storage Model 11	Storage Model 12
Volume (m3)	1 143 000	1 148 000	1 154 000	1 160 000
Spacing (m)	4,50	4,50	4,50	4,50
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	20,25	20,25	20,25	20,25
Number of boreholes	323	283	253	229
Total surface (m2)	6531	5740	5129	4640
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,62	0,71	0,79	0,87
Steady heat loss (MWh)	3 231	3 334	3 455	3 582
Transient heat loss (MWh)	9 680	10 202	10 696	11 161
COSTS				
Cost drilling+piping (kr)	18 992 284	18 256 544	17 774 994	17 403 384
Insulation cost (kr)	1 570 155	1 379 896	1 232 985	1 115 456
Land movements cost (kr)	718 457	631 400	564 178	510 400
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 228 090	2 126 784	2 057 216	2 002 924
CONTRUCTION COST	**24 508 986**	**23 394 624**	**22 629 373**	**22 032 164**
Transient heat losses cost (SEK)	1 452 000	1 530 300	1 604 400	1 674 150
TOTAL INVESTMENT COST	**25 960 986**	**24 924 924**	**24 233 773**	**23 706 314**
Maintenance (SEK)	245 090	233 946	226 294	220 322
Operation (SEK)	245 090	233 946	226 294	220 322
Steady heat losses cost (SEK)	484 650	500 100	518 250	537 300
Annual Storage Cost (10years)	**4 336 896**	**4 195 884**	**4 109 222**	**4 048 019**
TOTAL COST 10 years	**43 368 962**	**41 958 842**	**41 092 219**	**40 480 194**

Table 30. Parameters and costs of storage models 13 to 16.

	Storage Model 13	Storage Model 14	Storage Model 15	Storage Model 16
Volume (m3)	1 048 000	1 052 000	1 058 000	1 063 000
Spacing (m)	4,25	4,25	4,25	4,25
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	18,06	18,06	18,06	18,06
Number of boreholes	332	291	260	235
Total surface (m2)	5989	5260	4702	4252
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,60	0,69	0,77	0,85
Steady heat loss (MWh)	3 150	3 253	3 376	3 503
Transient heat loss (MWh)	9 674	10 201	10 702	11 161
COSTS				
Cost drilling+piping (kr)	19 275 908	18 539 070	18 075 828	17 703 910
Insulation cost (kr)	1 439 653	1 264 504	1 130 414	1 022 181
Land movements cost (kr)	658 743	578 600	517 244	467 720
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 237 430	2 138 217	2 072 349	2 019 381
CONTRUCTION COST	**24 611 734**	**23 520 392**	**22 795 835**	**22 213 192**
Transient heat losses cost (SEK)	1 451 100	1 530 150	1 605 300	1 674 150
TOTAL INVESTMENT COST	**26 062 834**	**25 050 542**	**24 401 135**	**23 887 342**
Maintenance (SEK)	246 117	235 204	227 958	222 132
Operation (SEK)	246 117	235 204	227 958	222 132
Steady heat losses cost (SEK)	472 500	487 950	506 400	525 450
Annual Storage Cost (10years)	**4 339 991**	**4 202 518**	**4 122 375**	**4 063 234**
TOTAL COST 10 years	**43 399 909**	**42 025 176**	**41 223 753**	**40 632 339**

Table 31. Parameters and costs of storage models 17 to 20.

	Storage Model 17	Storage Model 18	Storage Model 19	Storage Model 20
Volume (m3)	963 000	967 000	972 000	977 000
Spacing (m)	4,00	4,00	4,00	4,00
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	16,00	16,00	16,00	16,00
Number of boreholes	344	302	270	244
Total surface (m2)	5503	4835	4320	3908
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,58	0,66	0,74	0,82
Steady heat loss (MWh)	3 080	3 186	3 309	3 438
Transient heat loss (MWh)	9 681	10 214	10 718	11 184
COSTS				
Cost drilling+piping (kr)	19 739 310	19 012 267	18 545 467	18 186 401
Insulation cost (kr)	1 322 887	1 162 334	1 038 528	939 483
Land movements cost (kr)	605 314	531 850	475 200	429 880
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 266 751	2 170 645	2 105 919	2 055 576
CONTRUCTION COST	**24 934 262**	**23 877 096**	**23 165 114**	**22 611 341**
Transient heat losses cost (SEK)	1 452 150	1 532 100	1 607 700	1 677 600
TOTAL INVESTMENT COST	**26 386 412**	**25 409 196**	**24 772 814**	**24 288 941**
Maintenance (SEK)	249 343	238 771	231 651	226 113
Operation (SEK)	249 343	238 771	231 651	226 113
Steady heat losses cost (SEK)	462 000	477 900	496 350	515 700
Annual Storage Cost (10years)	**4 377 846**	**4 246 049**	**4 167 845**	**4 113 456**
TOTAL COST 10 years	**43 778 463**	**42 460 491**	**41 678 450**	**41 134 558**

Table 32. Parameters and costs of storage models 21 to 24.

	Storage Model 21	Storage Model 22	Storage Model 23	Storage Model 24
Volume (m3)	883 000	887 000	892 000	896 000
Spacing (m)	3,75	3,75	3,75	3,75
Borehole depth (m)	175	200	225	250
Surface/borehole (m2)	14,06	14,06	14,06	14,06
Number of boreholes	359	315	282	255
Total surface (m2)	5046	4435	3964	3584
Flow (m3/s)	0,2	0,2	0,2	0,2
Flow x borehole (l/s)	0,56	0,63	0,71	0,78
Steady heat loss (MWh)	3 009	3 116	3 241	3 369
Transient heat loss (MWh)	9 689	10 424	10 750	11 221
COSTS				
Cost drilling+piping (kr)	20 325 430	19 606 475	19 153 004	18 785 678
Insulation cost (kr)	1 212 990	1 066 174	953 052	861 594
Land movements cost (kr)	555 029	487 850	436 089	394 240
Pumps+HE+valves+control	1 000 000	1 000 000	1 000 000	1 000 000
Design and admin. Cost (SEK)	2 309 345	2 216 050	2 154 215	2 104 151
CONTRUCTION COST	**25 402 794**	**24 376 549**	**23 696 360**	**23 145 663**
Transient heat losses cost (SEK)	1 453 350	1 563 600	1 612 500	1 683 150
TOTAL INVESTMENT COST	**26 856 144**	**25 940 149**	**25 308 860**	**24 828 813**
Maintenance (SEK)	254 028	243 765	236 964	231 457
Operation (SEK)	254 028	243 765	236 964	231 457
Steady heat losses cost (SEK)	451 350	467 400	486 150	505 350
Annual Storage Cost (10years)	**4 437 399**	**4 314 299**	**4 237 690**	**4 183 708**
TOTAL COST 10 years	**44 373 993**	**43 142 989**	**42 376 904**	**41 837 081**

C. Storage model 8

The main parameters of storage 8 are shown in Table 33:

Table 33. Storage model 8 parameters.

Drilling pattern	Quadratic	
Borehole installation	Closed, Double U-pipe	
Borehole diameter	0,115	m
Borehole spacing	4,75	m
Number of boreholes	224	m^2
Storage land area	5060	m^2
Storage volume	1265000	m^3
Insulation thickness	0,4	m
Ins. Thermal conductivity	0,13	W/m,K
Soil layer	10	m
Soil thermal conductivity	1,4	W/m,K
Soil volumetric heat capacity	2,5E6	J/m^3K
Bedrock layer	1000	m
Bedrock thermal conductivity	3,45	W/m,K
Bedrock volumetric heat capacity	2,16E6	J/m^3K
Borehole pipe diameter	32,6	mm
Borehole pipe thickness	3	mm
Borehole pipe thermal conductivity	0,42	W/m,K

The results obtained with DST are in Table 34, the simulation starts in May and it goes on for ten years.

Table 34. Storage model 8, results.

t [days]	Tin [°C]	Tout [°C]	Tmean storage [°C]	Tair [°C]	Qdem [kW]	Injection [GJ]	Extraction [GJ]	Losses Top [GJ]	Losses Side [GJ]	Losses Bottom [GJ]
30	75	60,2	17,4	10,4	6 300	36 343	0	8	1 282	108
60	70	58,8	26,5	15,9	6 300	63 412	0	23	3 499	280
91	70	60,7	33,7	18	6 300	85 930	0	43	6 078	479
121	75	66,1	40,4	16	6 300	107 366	0	66	8 953	700
152	80	71,4	46,7	10,6	6 300	127 961	0	97	12 103	942
182	33	40,5	44,3	3,1	-1 576	128 219	4 085	134	14 674	1 131
213	23,6	35	40,8	-4,4	-3 068	128 219	11 647	174	16 508	1 265
243	28,3	35	38,4	-9,9	-2 825	128 219	16 522	218	17 991	1 372
273	31,4	35	36,8	-12	-3 783	128 219	19 280	267	19 323	1 469
304	33,4	35	35,8	-10	-3 833	128 219	20 656	319	20 577	1 560
334	34,8	35	35,1	-4,6	-2 738	128 219	21 127	369	21 785	1 647

365	34,7	34,7	34,7	2,9	-1 568	128 219	21 143	414	22 958	1 733
395	75	66,4	41,6	10,4	6 300	149 184	21 143	456	24 826	1 879
425	70	63,8	46,1	15,9	6 300	163 936	21 143	497	27 156	2 057
456	70	64,8	49,6	18	6 300	176 443	21 143	536	29 636	2 247
486	75	69,5	53,4	16	6 300	189 709	21 143	574	32 287	2 450
517	80	74,2	57,4	10,6	6 300	203 610	21 143	618	35 130	2 669
547	43,8	51,3	55	3,1	-1 576	203 786	25 227	666	37 545	2 849
578	29,4	44,1	51,3	-4,4	-3 068	203 786	33 236	717	39 353	2 983
608	27,9	41,4	48	-9,9	-2 825	203 786	40 668	773	40 772	3 087
638	17	35	44	-12	-3 783	203 786	50 576	830	41 828	3 162
669	23,6	35	40,7	-10	-3 833	203 786	58 496	888	42 614	3 217
699	27,9	35	38,6	-4,6	-2 738	203 786	63 517	942	43 315	3 267
730	30,7	35	37,2	2,9	-1 568	203 786	66 620	990	43 997	3 315
760	75	67	43,8	10,4	6 300	223 454	66 653	1 034	45 438	3 430
790	70	64,3	48	15,9	6 300	237 038	66 653	1 076	47 385	3 581
821	70	65,2	51,3	18	6 300	248 522	66 653	1 117	49 512	3 745
851	75	69,8	54,9	16	6 300	260 888	66 653	1 157	51 833	3 924
882	80	74,5	58,7	10,6	6 300	273 995	66 653	1 201	54 369	4 121
912	45,2	52,7	56,4	3,1	-1 576	274 160	70 737	1 251	56 513	4 281
943	31	45,6	52,8	-4,4	-3 068	274 160	78 745	1 304	58 089	4 398
973	29,5	43	49,6	-9,9	-2 825	274 160	86 176	1 360	59 302	4 487
1003	18,6	36,7	45,6	-12	-3 783	274 160	96 082	1 420	60 174	4 550
1034	21,1	35	42	-10	-3 833	274 160	105 352	1 478	60 750	4 590
1064	26	35	39,5	-4,6	-2 738	274 160	111 536	1 533	61 210	4 621
1095	29,2	35	37,9	2,9	-1 568	274 160	115 402	1 582	61 655	4 652
1125	75	67,2	44,5	10,4	6 300	293 443	115 446	1 627	62 875	4 751
1155	70	64,5	48,6	15,9	6 300	306 660	115 446	1 670	64 623	4 887
1186	70	65,3	51,9	18	6 300	317 806	115 446	1 710	66 555	5 037
1216	75	70	55,5	16	6 300	329 860	115 446	1 751	68 693	5 203
1247	80	74,7	59,2	10,6	6 300	342 677	115 446	1 796	71 054	5 387
1277	45,7	53,3	57	3,1	-1 576	342 838	119 533	1 846	73 037	5 536
1308	31,6	46,2	53,5	-4,4	-3 068	342 838	127 540	1 899	74 472	5 642
1338	30,1	43,6	50,3	-9,9	-2 825	342 838	134 972	1 956	75 563	5 722
1368	19,4	37,4	46,3	-12	-3 783	342 838	144 880	2 016	76 317	5 776
1399	19,9	35	42,6	-10	-3 833	342 838	154 548	2 075	76 763	5 807
1429	25	35	40	-4,6	-2 738	342 838	161 198	2 131	77 078	5 829
1460	28,3	35	38,4	2,9	-1 568	342 838	165 293	2 179	77 382	5 851
1490	75	67,3	44,9	10,4	6 300	361 882	165 343	2 225	78 480	5 941
1520	70	64,6	49	15,9	6 300	374 872	165 343	2 268	80 103	6 068
1551	70	65,4	52,3	18	6 300	385 809	165 343	2 309	81 915	6 209
1581	75	70,1	55,8	16	6 300	397 670	165 343	2 350	83 930	6 366
1612	80	74,7	59,5	10,6	6 300	410 307	165 343	2 395	86 174	6 542
1642	46,1	53,6	57,3	3,1	-1 576	410 466	169 425	2 445	88 056	6 684
1673	32	46,6	53,8	-4,4	-3 068	410 466	177 438	2 498	89 399	6 783

1703	30,5	44	50,7	-9,9	-2 825	410 466	184 876	2 556	90 402	6 857
1733	19,8	37,9	46,8	-12	-3 783	410 466	194 787	2 616	91 073	6 905
1764	19,1	35	43	-10	-3 833	410 466	204 646	2 676	91 439	6 930
1794	24,3	35	40,4	-4,6	-2 738	410 466	211 542	2 731	91 669	6 946
1825	27,6	35,1	38,8	2,9	-1 568	410 466	215 691	2 781	91 897	6 962
1855	75	67,3	45,2	10,4	6 300	429 317	215 748	2 826	92 910	7 046
1885	70	64,7	49,3	15,9	6 300	442 130	215 748	2 870	94 450	7 166
1916	70	65,5	52,5	18	6 300	452 907	215 748	2 911	96 181	7 301
1946	75	70,1	56	16	6 300	464 620	215 748	2 952	98 118	7 453
1977	80	74,8	59,7	10,6	6 300	477 121	215 748	2 997	100 285	7 623
2007	46,3	53,9	57,6	3,1	-1 576	477 278	219 829	3 047	102 092	7 759
2038	32,2	46,9	54,1	-4,4	-3 068	477 278	227 843	3 101	103 368	7 854
2068	30,9	44,4	51	-9,9	-2 825	477 278	235 280	3 159	104 306	7 923
2098	20,1	38,2	47,1	-12	-3 783	477 278	245 191	3 219	104 916	7 967
2129	18,4	35	43,3	-10	-3 833	477 278	255 154	3 279	105 222	7 988
2159	23,7	35	40,7	-4,6	-2 738	477 278	262 199	3 335	105 384	7 999
2190	27,9	35,4	39,1	2,9	-1 568	477 278	266 353	3 384	105 544	8 010
2220	75	67,4	45,5	10,4	6 300	495 964	266 409	3 430	106 496	8 089
2250	70	64,7	49,5	15,9	6 300	508 631	266 409	3 474	107 974	8 205
2281	70	65,6	52,8	18	6 300	519 276	266 409	3 515	109 642	8 336
2311	75	70,2	56,2	16	6 300	530 870	266 409	3 556	111 515	8 483
2342	80	74,8	59,9	10,6	6 300	543 262	266 409	3 602	113 617	8 649
2372	46,5	54,1	57,8	3,1	-1 576	543 418	270 491	3 652	115 370	8 781
2403	32,5	47,1	54,4	-4,4	-3 068	543 418	278 504	3 706	116 594	8 872
2433	31,1	44,6	51,3	-9,9	-2 825	543 418	285 934	3 764	117 481	8 938
2463	20,4	38,5	47,4	-12	-3 783	543 418	295 846	3 825	118 043	8 978
2494	17,9	35	43,6	-10	-3 833	543 418	305 868	3 885	118 304	8 996
2524	23,3	35	40,9	-4,6	-2 738	543 418	313 005	3 941	118 425	9 004
2555	28,1	35,6	39,3	2,9	-1 568	543 418	317 162	3 991	118 541	9 012
2585	75	67,5	45,7	10,4	6 300	561 963	317 219	4 036	119 447	9 088
2615	70	64,8	49,7	15,9	6 300	574 507	317 219	4 080	120 873	9 200
2646	70	65,6	52,9	18	6 300	585 043	317 219	4 122	122 491	9 327
2676	75	70,2	56,4	16	6 300	596 538	317 219	4 163	124 315	9 471
2707	80	74,9	60,1	10,6	6 300	608 840	317 219	4 209	126 371	9 633
2737	46,7	54,2	58	3,1	-1 576	608 994	321 312	4 259	128 078	9 762
2768	32,6	47,3	54,5	-4,4	-3 068	608 994	329 314	4 313	129 259	9 850
2798	31,3	44,8	51,5	-9,9	-2 825	608 994	336 739	4 371	130 104	9 913
2828	20,6	38,7	47,6	-12	-3 783	608 994	346 651	4 432	130 628	9 950
2859	17,4	35	43,8	-10	-3 833	608 994	356 704	4 493	130 853	9 966
2889	22,8	35	41,1	-4,6	-2 738	608 994	363 897	4 549	130 941	9 971
2920	28,4	35,9	39,5	2,9	-1 568	608 994	368 058	4 599	131 024	9 977
2950	75	67,5	45,9	10,4	6 300	627 419	368 115	4 644	131 890	10 050
2980	70	64,8	49,9	15,9	6 300	639 858	368 115	4 689	133 278	10 159
3011	70	65,7	53,1	18	6 300	650 300	368 115	4 730	134 856	10 283

3041	75	70,3	56,5	16	6 300	661 712	368 115	4 771	136 641	10 424
3072	80	74,9	60,2	10,6	6 300	673 936	368 115	4 817	138 656	10 583
3102	46,9	54,4	58,1	3,1	-1 576	674 090	372 208	4 867	140 325	10 710
3133	32,8	47,5	54,7	-4,4	-3 068	674 090	380 210	4 921	141 459	10 795
3163	31,5	45	51,6	-9,9	-2 825	674 090	387 635	4 980	142 254	10 856
3193	20,8	38,9	47,8	-12	-3 783	674 090	397 546	5 041	142 738	10 891
3224	16,9	35	44	-10	-3 833	674 090	407 613	5 101	142 923	10 904
3254	22,4	35	41,3	-4,6	-2 738	674 090	414 837	5 158	142 968	10 907
3285	28,6	36,1	39,7	2,9	-1 568	674 090	419 001	5 208	143 002	10 911
3315	75	67,6	46,1	10,4	6 300	692 408	419 058	5 254	143 823	10 981
3345	70	64,9	50,1	15,9	6 300	704 755	419 058	5 298	145 184	11 089
3376	70	65,7	53,2	18	6 300	715 116	419 058	5 339	146 725	11 210
3406	75	70,3	56,7	16	6 300	726 454	419 058	5 381	148 470	11 349
3437	80	74,9	60,3	10,6	6 300	738 612	419 058	5 427	150 450	11 505
3467	47	54,5	58,2	3,1	-1 576	738 764	423 151	5 477	152 087	11 629
3498	32,9	47,6	54,8	-4,4	-3 068	738 764	431 153	5 531	153 187	11 713
3528	31,6	45,1	51,8	-9,9	-2 825	738 764	438 578	5 590	153 954	11 771
3558	21	39	47,9	-12	-3 783	738 764	448 489	5 651	154 411	11 805
3589	16,8	35,1	44,2	-10	-3 833	738 764	458 556	5 712	154 569	11 816
3619	21,9	35	41,5	-4,6	-2 738	738 764	465 791	5 768	154 592	11 818
3650	28,7	36,2	39,9	2,9	-1 568	738 764	469 959	5 818	154 615	11 820

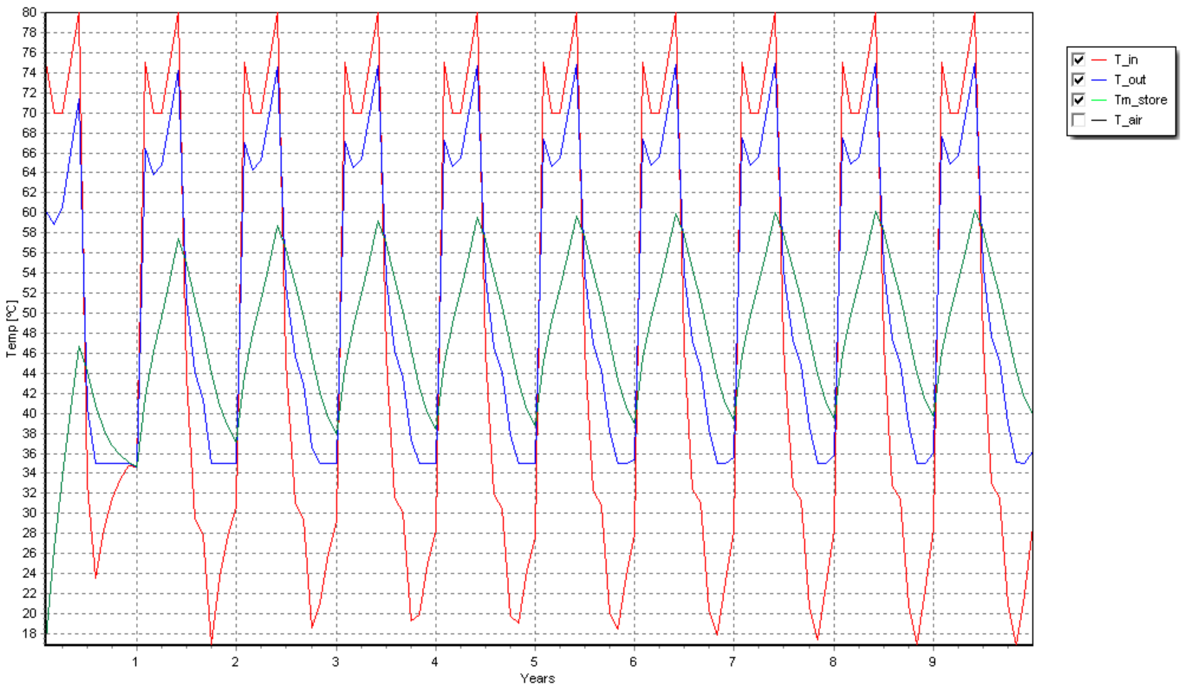

Figure 37. Storage model 8, temperature graph with Inlet T (red line), Outlet T (blue line) and Mean Storage T (green line)

D. Storage model 12

The main parameters of storage 12 are shown in Table 35:

Table 35. Storage model 12 parameters

Drilling pattern	Quadratic	
Borehole installation	Closed, Double U-pipe	
Borehole diameter	0,115	m
Borehole spacing	4,5	m
Number of boreholes	229	m^2
Storage land area	4640	m^2
Storage volume	1160000	m^3
Insulation thickness	0,4	m
Ins. Thermal conductivity	0,13	W/m,K
Soil layer	10	m
Soil thermal conductivity	1,4	W/m,K
Soil volumetric heat capacity	2,5E6	J/m^3K
Bedrock layer	1000	m
Bedrock thermal conductivity	3,45	W/m,K
Bedrock volumetric heat capacity	2,16E6	J/m^3K
Borehole pipe diameter	32,6	mm
Borehole pipe thickness	3	mm
Borehole pipe thermal conductivity	0,42	W/m,K

The results obtained with DST are in Table 36 and Figure 38, the simulation starts in May and it goes on for ten years.

Table 36. Storage model 12, results.

t [days]	Tin [°C]	Tout [°C]	Tmean storage [°C]	Tair [°C]	Qdem [kW]	Injection [GJ]	Extraction [GJ]	Losses Top [GJ]	Losses Side [GJ]	Losses Bottom [GJ]
30	75,0	60,2	18,7	10,4	6 300	36 768	0	8	1 360	110
60	70,0	59,0	28,4	15,9	6 300	63 570	0	24	3 692	283
91	70,0	61,0	36,0	18,0	6 300	85 413	0	44	6 382	481
121	75,0	66,5	42,9	16,0	6 300	105 978	0	68	9 353	700
152	80,0	71,9	49,4	10,6	6 300	125 578	0	99	12 587	938
182	35,6	43,1	46,7	3,1	-1 576	125 821	4 085	136	15 233	1 125
213	21,1	35,7	42,7	-4,4	-3 068	125 821	12 094	175	17 114	1 256
243	25,9	35,0	39,4	-9,9	-2 825	125 821	18 657	217	18 551	1 355
273	30,2	35,0	37,4	-12,0	-3 783	125 821	22 401	263	19 804	1 442
304	32,8	35,0	36,1	-10,0	-3 833	125 821	24 283	311	20 978	1 523
334	34,4	35,0	35,3	-4,6	-2 738	125 821	25 008	357	22 112	1 602

365	34,8	34,8	34,8	2,9	-1 568	125 821	25 080	399	23 220	1 679
395	75,0	66,4	42,4	10,4	6 300	146 979	25 080	438	25 073	1 819
425	70,0	64,0	47,2	15,9	6 300	161 533	25 080	477	27 416	1 991
456	70,0	65,0	51,0	18,0	6 300	173 638	25 080	513	29 903	2 174
486	75,0	69,7	54,9	16,0	6 300	186 424	25 080	551	32 560	2 370
517	80,0	74,5	59,0	10,6	6 300	199 777	25 080	592	35 419	2 581
547	45,3	52,8	56,4	3,1	-1 576	199 944	29 164	638	37 830	2 753
578	30,8	45,5	52,4	-4,4	-3 068	199 944	37 173	687	39 620	2 880
608	29,0	42,4	48,8	-9,9	-2 825	199 944	44 606	738	41 007	2 977
638	17,8	35,9	44,4	-12,0	-3 783	199 944	54 513	792	42 013	3 046
669	23,1	35,0	40,7	-10,0	-3 833	199 944	62 955	845	42 716	3 093
699	28,0	35,0	38,4	-4,6	-2 738	199 944	68 052	895	43 329	3 135
730	31,0	35,0	36,9	2,9	-1 568	199 944	71 027	938	43 930	3 176
760	75,0	66,9	44,3	10,4	6 300	219 962	71 057	979	45 347	3 285
790	70,0	64,4	48,8	15,9	6 300	233 493	71 057	1 019	47 298	3 430
821	70,0	65,4	52,4	18,0	6 300	244 705	71 057	1 057	49 426	3 587
851	75,0	70,0	56,2	16,0	6 300	256 705	71 057	1 096	51 753	3 760
882	80,0	74,8	60,1	10,6	6 300	269 364	71 057	1 138	54 292	3 949
912	46,5	54,1	57,6	3,1	-1 576	269 522	75 141	1 185	56 430	4 103
943	32,2	46,8	53,7	-4,4	-3 068	269 522	83 149	1 235	57 984	4 213
973	30,4	43,9	50,2	-9,9	-2 825	269 522	90 582	1 288	59 159	4 297
1003	19,3	37,4	45,9	-12,0	-3 783	269 522	100 486	1 343	59 979	4 353
1034	20,7	35,0	41,9	-10,0	-3 833	269 522	109 985	1 397	60 482	4 386
1064	26,2	35,0	39,2	-4,6	-2 738	269 522	116 179	1 447	60 859	4 410
1095	29,7	35,0	37,6	2,9	-1 568	269 522	119 902	1 491	61 234	4 435
1125	75,0	67,1	44,9	10,4	6 300	289 198	119 942	1 533	62 432	4 529
1155	70,0	64,6	49,4	15,9	6 300	302 401	119 942	1 573	64 182	4 660
1186	70,0	65,5	52,9	18,0	6 300	313 310	119 942	1 612	66 123	4 805
1216	75,0	70,2	56,6	16,0	6 300	325 030	119 942	1 650	68 265	4 964
1247	80,0	74,9	60,6	10,6	6 300	337 426	119 942	1 693	70 635	5 142
1277	47,0	54,6	58,1	3,1	-1 576	337 581	124 027	1 740	72 617	5 285
1308	32,7	47,4	54,3	-4,4	-3 068	337 581	132 035	1 790	74 034	5 385
1338	31,0	44,5	50,9	-9,9	-2 825	337 581	139 467	1 844	75 091	5 460
1368	20,0	38,0	46,6	-12,0	-3 783	337 581	149 371	1 899	75 793	5 508
1399	19,5	35,0	42,5	-10,0	-3 833	337 581	159 184	1 954	76 169	5 533
1429	25,2	35,0	39,7	-4,6	-2 738	337 581	165 820	2 004	76 410	5 549
1460	28,8	35,0	38,0	2,9	-1 568	337 581	169 822	2 049	76 642	5 564
1490	75,0	67,2	45,3	10,4	6 300	357 037	169 869	2 091	77 717	5 649
1520	70,0	64,7	49,7	15,9	6 300	370 032	169 869	2 131	79 348	5 772
1551	70,0	65,6	53,2	18,0	6 300	380 750	169 869	2 170	81 165	5 908
1581	75,0	70,2	56,9	16,0	6 300	392 292	169 869	2 209	83 190	6 060
1612	80,0	74,9	60,8	10,6	6 300	404 524	169 869	2 252	85 446	6 230
1642	47,4	54,9	58,4	3,1	-1 576	404 676	173 959	2 299	87 326	6 366
1673	33,1	47,7	54,7	-4,4	-3 068	404 676	181 967	2 349	88 653	6 460

1703	31,4	44,9	51,3	-9,9	-2 825	404 676	189 399	2 403	89 622	6 529
1733	20,4	38,5	47,0	-12,0	-3 783	404 676	199 304	2 459	90 243	6 572
1764	18,6	35,0	42,9	-10,0	-3 833	404 676	209 259	2 514	90 542	6 591
1794	24,5	35,0	40,0	-4,6	-2 738	404 676	216 135	2 565	90 693	6 601
1825	28,1	35,0	38,3	2,9	-1 568	404 676	220 254	2 610	90 842	6 611
1855	75,0	67,2	45,5	10,4	6 300	423 958	220 306	2 652	91 834	6 690
1885	70,0	64,7	50,0	15,9	6 300	436 791	220 306	2 693	93 382	6 807
1916	70,0	65,6	53,5	18,0	6 300	447 363	220 306	2 731	95 120	6 938
1946	75,0	70,3	57,2	16,0	6 300	458 771	220 306	2 770	97 068	7 084
1977	80,0	75,0	61,0	10,6	6 300	470 879	220 306	2 813	99 245	7 248
2007	47,6	55,1	58,7	3,1	-1 576	471 029	224 396	2 861	101 056	7 380
2038	33,3	48,0	54,9	-4,4	-3 068	471 029	232 404	2 911	102 316	7 469
2068	31,7	45,2	51,5	-9,9	-2 825	471 029	239 837	2 965	103 221	7 534
2098	20,7	38,8	47,3	-12,0	-3 783	471 029	249 741	3 021	103 783	7 573
2129	17,9	35,0	43,2	-10,0	-3 833	471 029	259 768	3 076	104 025	7 588
2159	24,0	35,0	40,3	-4,6	-2 738	471 029	266 791	3 128	104 122	7 594
2190	27,6	35,1	38,6	2,9	-1 568	471 029	270 941	3 173	104 218	7 600
2220	75,0	67,3	45,8	10,4	6 300	490 157	270 997	3 215	105 149	7 675
2250	70,0	64,8	50,2	15,9	6 300	502 853	270 997	3 256	106 635	7 787
2281	70,0	65,7	53,7	18,0	6 300	513 302	270 997	3 295	108 314	7 914
2311	75,0	70,3	57,3	16,0	6 300	524 599	270 997	3 334	110 198	8 056
2342	80,0	75,0	61,2	10,6	6 300	536 605	270 997	3 377	112 318	8 216
2372	47,8	55,3	58,9	3,1	-1 576	536 754	275 088	3 425	114 072	8 343
2403	33,6	48,2	55,1	-4,4	-3 068	536 754	283 098	3 475	115 281	8 430
2433	31,9	45,4	51,8	-9,9	-2 825	536 754	290 543	3 529	116 137	8 491
2463	21,0	39,0	47,6	-12,0	-3 783	536 754	300 447	3 585	116 652	8 527
2494	17,3	35,0	43,4	-10,0	-3 833	536 754	310 497	3 641	116 853	8 539
2524	23,5	35,0	40,6	-4,6	-2 738	536 754	317 616	3 692	116 903	8 542
2555	27,8	35,3	38,9	2,9	-1 568	536 754	321 769	3 738	116 951	8 545
2585	75,0	67,4	46,0	10,4	6 300	555 744	321 825	3 780	117 835	8 617
2615	70,0	64,8	50,4	15,9	6 300	568 321	321 825	3 821	119 275	8 726
2646	70,0	65,7	53,8	18,0	6 300	578 664	321 825	3 860	120 903	8 849
2676	75,0	70,4	57,5	16,0	6 300	589 867	321 825	3 899	122 741	8 988
2707	80,0	75,1	61,3	10,6	6 300	601 788	321 825	3 942	124 811	9 145
2737	47,9	55,5	59,0	3,1	-1 576	601 937	325 916	3 990	126 521	9 269
2768	33,7	48,4	55,3	-4,4	-3 068	601 937	333 936	4 041	127 690	9 353
2798	32,1	45,6	52,0	-9,9	-2 825	601 937	341 381	4 095	128 505	9 412
2828	21,2	39,3	47,8	-12,0	-3 783	601 937	351 285	4 151	128 984	9 445
2859	16,7	35,0	43,7	-10,0	-3 833	601 937	361 345	4 207	129 149	9 455
2889	23,0	35,0	40,8	-4,6	-2 738	601 937	368 525	4 259	129 163	9 456
2920	28,1	35,5	39,1	2,9	-1 568	601 937	372 682	4 304	129 170	9 457
2950	75,0	67,4	46,2	10,4	6 300	620 806	372 738	4 347	130 017	9 527
2980	70,0	64,9	50,6	15,9	6 300	633 280	372 738	4 388	131 415	9 633
3011	70,0	65,8	54,0	18,0	6 300	643 532	372 738	4 427	133 007	9 753

3041	75,0	70,4	57,6	16,0	6 300	654 654	372 738	4 466	134 804	9 890
3072	80,0	75,1	61,5	10,6	6 300	666 503	372 738	4 509	136 834	10 044
3102	48,1	55,6	59,2	3,1	-1 576	666 650	376 829	4 557	138 509	10 166
3133	33,9	48,5	55,5	-4,4	-3 068	666 650	384 849	4 608	139 643	10 247
3163	32,3	45,8	52,1	-9,9	-2 825	666 650	392 293	4 662	140 424	10 303
3193	21,4	39,4	48,0	-12,0	-3 783	666 650	402 198	4 718	140 869	10 334
3224	16,9	35,2	43,9	-10,0	-3 833	666 650	412 258	4 774	140 996	10 343
3254	22,6	35,0	41,0	-4,6	-2 738	666 650	419 471	4 826	140 980	10 341
3285	28,3	35,7	39,3	2,9	-1 568	666 650	423 631	4 871	140 959	10 340
3315	75,0	67,5	46,4	10,4	6 300	685 414	423 687	4 914	141 762	10 408
3345	70,0	64,9	50,7	15,9	6 300	697 796	423 687	4 955	143 134	10 512
3376	70,0	65,8	54,1	18,0	6 300	707 969	423 687	4 994	144 688	10 630
3406	75,0	70,4	57,7	16,0	6 300	719 021	423 687	5 034	146 449	10 764
3437	80,0	75,1	61,6	10,6	6 300	730 806	423 687	5 077	148 448	10 915
3467	48,2	55,7	59,3	3,1	-1 576	730 953	427 778	5 125	150 089	11 035
3498	34,0	48,7	55,6	-4,4	-3 068	730 953	435 798	5 176	151 177	11 115
3528	32,4	45,9	52,3	-9,9	-2 825	730 953	443 242	5 230	151 917	11 169
3558	21,5	39,6	48,1	-12,0	-3 783	730 953	453 147	5 287	152 330	11 199
3589	17,1	35,4	44,0	-10,0	-3 833	730 953	463 207	5 343	152 432	11 205
3619	22,2	35,0	41,1	-4,6	-2 738	730 953	470 435	5 395	152 395	11 202
3650	28,4	35,9	39,5	2,9	-1 568	730 953	474 598	5 440	152 349	11 199

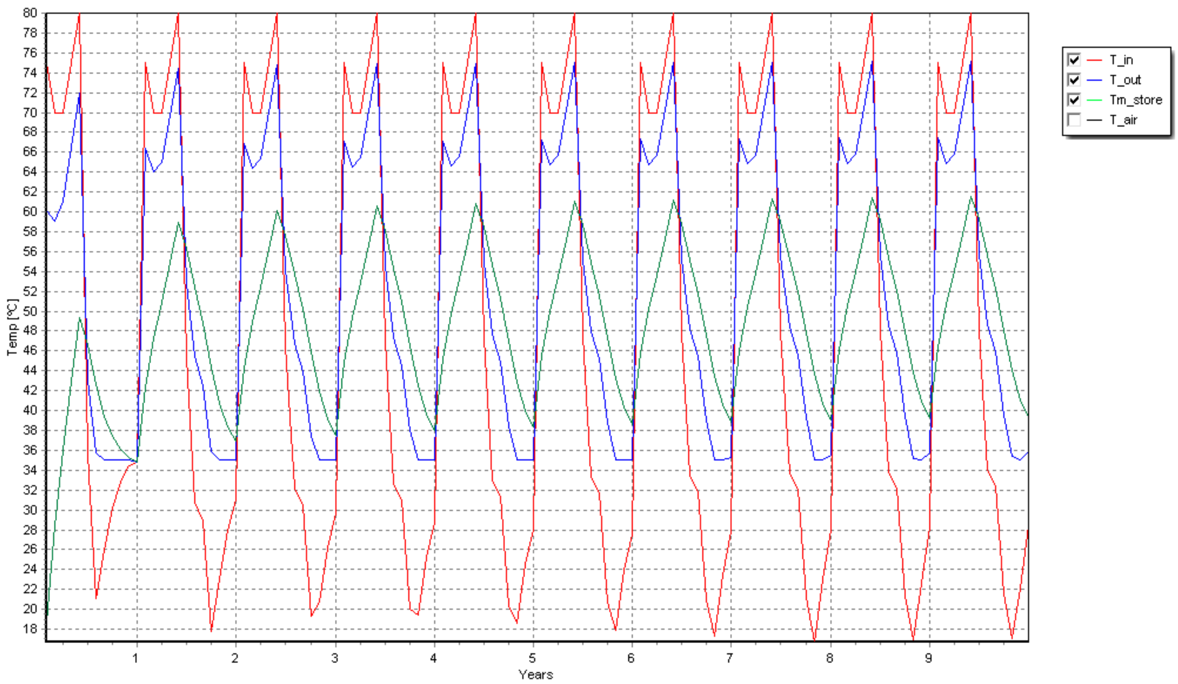

Figure 38. Storage model 12, temperature graph with Inlet T (red line), Outlet T (blue line) and Mean Storage T (green line)

E. Storage model 16

The main parameters of storage 16 are shown in Table 37:

Table 37. Storage model 16 parameters

Drilling pattern	Quadratic	
Borehole installation	Closed, Double U-pipe	
Borehole diameter	0,115	m
Borehole spacing	4,25	m
Number of boreholes	235	m^2
Storage land area	4252	m^2
Storage volume	1063000	m^3
Insulation thickness	0,4	m
Ins. Thermal conductivity	0,13	W/m,K
Soil layer	10	m
Soil thermal conductivity	1,4	W/m,K
Soil volumetric heat capacity	2,5E6	J/m^3K
Bedrock layer	1000	m
Bedrock thermal conductivity	3,45	W/m,K
Bedrock volumetric heat capacity	2,16E6	J/m^3K
Borehole pipe diameter	32,6	mm
Borehole pipe thickness	3	mm
Borehole pipe thermal conductivity	0,42	W/m,K

The results obtained with DST are in Table 38 and Figure 39, the simulation starts in May and it goes on for ten years.

Table 38. Storage model 16, results.

t [days]	Tin [°C]	Tout [°C]	Tmean storage [°C]	Tair [°C]	Qdem [kW]	Injection [GJ]	Extraction [GJ]	Losses Top [GJ]	Losses Side [GJ]	Losses Bottom [GJ]
30	75,0	60,1	20,3	10,4	6 300	37 437	0	8	1 451	112
60	70,0	59,3	30,7	15,9	6 300	64 003	0	25	3 921	288
91	70,0	61,4	38,6	18,0	6 300	85 129	0	46	6 733	486
121	75,0	67,0	45,7	16,0	6 300	104 777	0	71	9 814	703
152	80,0	72,4	52,2	10,6	6 300	123 344	0	102	13 144	938
182	38,4	45,9	49,3	3,1	-1 576	123 572	4 085	138	15 864	1 122
213	23,7	38,3	44,8	-4,4	-3 068	123 572	12 094	176	17 805	1 252
243	21,9	35,0	40,9	-9,9	-2 825	123 572	19 524	217	19 262	1 348
273	28,3	35,0	38,1	-12,0	-3 783	123 572	24 784	260	20 438	1 425
304	32,0	35,0	36,4	-10,0	-3 833	123 572	27 374	304	21 520	1 497
334	34,1	35,0	35,4	-4,6	-2 738	123 572	28 417	347	22 567	1 567

365	34,9	34,9	34,9	2,9	-1 568	123 572	28 585	385	23 602	1 636
395	75,0	66,4	43,4	10,4	6 300	145 065	28 585	422	25 446	1 770
425	70,0	64,1	48,5	15,9	6 300	159 437	28 585	459	27 805	1 937
456	70,0	65,2	52,4	18,0	6 300	171 121	28 585	494	30 308	2 113
486	75,0	70,0	56,5	16,0	6 300	183 412	28 585	530	32 978	2 302
517	80,0	74,7	60,7	10,6	6 300	196 207	28 585	570	35 845	2 506
547	47,0	54,5	57,9	3,1	-1 576	196 366	32 670	613	38 257	2 671
578	32,4	47,0	53,5	-4,4	-3 068	196 366	40 678	659	40 032	2 791
608	30,2	43,7	49,7	-9,9	-2 825	196 366	48 110	708	41 386	2 883
638	18,8	36,8	44,9	-12,0	-3 783	196 366	58 016	758	42 342	2 946
669	22,5	35,0	40,7	-10,0	-3 833	196 366	66 955	806	42 962	2 985
699	28,1	35,0	38,1	-4,6	-2 738	196 366	72 150	852	43 479	3 018
730	31,4	35,0	36,7	2,9	-1 568	196 366	74 969	892	43 999	3 052
760	75,0	66,8	44,9	10,4	6 300	216 888	74 996	930	45 396	3 157
790	70,0	64,5	49,9	15,9	6 300	230 385	74 996	968	47 359	3 297
821	70,0	65,5	53,6	18,0	6 300	241 304	74 996	1 004	49 499	3 449
851	75,0	70,2	57,6	16,0	6 300	252 920	74 996	1 040	51 833	3 615
882	80,0	75,0	61,7	10,6	6 300	265 116	74 996	1 081	54 383	3 798
912	48,1	55,6	58,9	3,1	-1 576	265 267	79 082	1 125	56 519	3 945
943	33,6	48,2	54,7	-4,4	-3 068	265 267	87 094	1 172	58 054	4 050
973	31,4	44,9	50,9	-9,9	-2 825	265 267	94 529	1 222	59 195	4 128
1003	20,1	38,2	46,2	-12,0	-3 783	265 267	104 435	1 273	59 961	4 178
1034	20,1	35,0	41,8	-10,0	-3 833	265 267	114 165	1 322	60 388	4 205
1064	26,4	35,0	38,9	-4,6	-2 738	265 267	120 395	1 368	60 672	4 222
1095	30,2	35,0	37,2	2,9	-1 568	265 267	123 951	1 409	60 963	4 241
1125	75,0	66,9	45,4	10,4	6 300	285 481	123 988	1 447	62 145	4 331
1155	70,0	64,6	50,3	15,9	6 300	298 683	123 988	1 485	63 911	4 458
1186	70,0	65,7	54,1	18,0	6 300	309 327	123 988	1 522	65 864	4 597
1216	75,0	70,4	58,0	16,0	6 300	320 687	123 988	1 558	68 021	4 752
1247	80,0	75,1	62,1	10,6	6 300	332 644	123 988	1 599	70 404	4 923
1277	48,5	56,1	59,4	3,1	-1 576	332 791	128 074	1 644	72 385	5 060
1308	34,1	48,7	55,2	-4,4	-3 068	332 791	136 086	1 691	73 788	5 156
1338	32,0	45,5	51,5	-9,9	-2 825	332 791	143 521	1 741	74 810	5 226
1368	20,8	38,8	46,9	-12,0	-3 783	332 791	153 433	1 792	75 461	5 268
1399	18,8	35,0	42,4	-10,0	-3 833	332 791	163 383	1 843	75 768	5 288
1429	25,4	35,0	39,4	-4,6	-2 738	332 791	170 042	1 889	75 918	5 297
1460	29,3	35,0	37,6	2,9	-1 568	332 791	173 923	1 930	76 072	5 307
1490	75,0	67,0	45,8	10,4	6 300	352 800	173 965	1 968	77 134	5 389
1520	70,0	64,7	50,6	15,9	6 300	365 808	173 965	2 007	78 780	5 508
1551	70,0	65,7	54,3	18,0	6 300	376 274	173 965	2 043	80 613	5 640
1581	75,0	70,4	58,2	16,0	6 300	387 470	173 965	2 080	82 654	5 787
1612	80,0	75,2	62,3	10,6	6 300	399 273	173 965	2 121	84 925	5 951
1642	48,8	56,3	59,7	3,1	-1 576	399 419	178 052	2 166	86 810	6 082
1673	34,4	49,1	55,6	-4,4	-3 068	399 419	186 064	2 213	88 122	6 172

1703	32,4	45,9	51,9	-9,9	-2 825	399 419	193 499	2 263	89 061	6 236
1733	21,2	39,2	47,3	-12,0	-3 783	399 419	203 411	2 315	89 632	6 273
1764	17,8	35,0	42,8	-10,0	-3 833	399 419	213 447	2 366	89 865	6 288
1794	24,7	35,0	39,7	-4,6	-2 738	399 419	220 342	2 412	89 939	6 292
1825	28,7	35,0	37,9	2,9	-1 568	399 419	224 389	2 453	90 009	6 297
1855	75,0	67,1	46,0	10,4	6 300	419 262	224 437	2 492	90 986	6 373
1885	70,0	64,8	50,9	15,9	6 300	432 118	224 437	2 530	92 552	6 486
1916	70,0	65,8	54,6	18,0	6 300	442 448	224 437	2 567	94 307	6 613
1946	75,0	70,5	58,4	16,0	6 300	453 519	224 437	2 604	96 271	6 755
1977	80,0	75,2	62,5	10,6	6 300	465 207	224 437	2 645	98 466	6 914
2007	49,0	56,6	59,9	3,1	-1 576	465 351	228 523	2 690	100 282	7 040
2038	34,6	49,3	55,8	-4,4	-3 068	465 351	236 535	2 738	101 530	7 126
2068	32,7	46,2	52,1	-9,9	-2 825	465 351	243 970	2 788	102 406	7 186
2098	21,5	39,5	47,6	-12,0	-3 783	465 351	253 882	2 840	102 920	7 220
2129	17,0	35,0	43,1	-10,0	-3 833	465 351	263 948	2 891	103 099	7 231
2159	24,0	35,0	40,0	-4,6	-2 738	465 351	270 988	2 938	103 118	7 231
2190	28,1	35,0	38,1	2,9	-1 568	465 351	275 115	2 979	103 132	7 232
2220	75,0	67,2	46,3	10,4	6 300	485 050	275 167	3 018	104 049	7 304
2250	70,0	64,8	51,1	15,9	6 300	497 777	275 167	3 056	105 554	7 414
2281	70,0	65,8	54,7	18,0	6 300	507 992	275 167	3 093	107 250	7 536
2311	75,0	70,5	58,6	16,0	6 300	518 960	275 167	3 130	109 153	7 675
2342	80,0	75,3	62,6	10,6	6 300	530 555	275 167	3 171	111 291	7 830
2372	49,2	56,7	60,1	3,1	-1 576	530 697	279 254	3 216	113 054	7 953
2403	34,8	49,5	56,0	-4,4	-3 068	530 697	287 266	3 264	114 251	8 035
2433	32,9	46,4	52,4	-9,9	-2 825	530 697	294 700	3 314	115 079	8 092
2463	21,7	39,8	47,8	-12,0	-3 783	530 697	304 600	3 366	115 549	8 123
2494	16,9	35,2	43,3	-10,0	-3 833	530 697	314 680	3 417	115 685	8 131
2524	23,5	35,0	40,2	-4,6	-2 738	530 697	321 821	3 464	115 657	8 129
2555	27,6	35,1	38,4	2,9	-1 568	530 697	325 982	3 506	115 625	8 127
2585	75,0	67,2	46,5	10,4	6 300	550 263	326 038	3 545	116 496	8 196
2615	70,0	64,9	51,3	15,9	6 300	562 874	326 038	3 583	117 954	8 303
2646	70,0	65,9	54,9	18,0	6 300	572 988	326 038	3 620	119 602	8 423
2676	75,0	70,6	58,7	16,0	6 300	583 865	326 038	3 657	121 457	8 558
2707	80,0	75,3	62,8	10,6	6 300	595 380	326 038	3 699	123 547	8 709
2737	49,4	56,9	60,2	3,1	-1 576	595 521	330 113	3 744	125 267	8 830
2768	35,0	49,7	56,2	-4,4	-3 068	595 521	338 125	3 791	126 424	8 909
2798	33,1	46,6	52,6	-9,9	-2 825	595 521	345 559	3 842	127 212	8 964
2828	21,9	40,0	48,0	-12,0	-3 783	595 521	355 459	3 894	127 647	8 993
2859	17,1	35,4	43,5	-10,0	-3 833	595 521	365 539	3 945	127 748	8 999
2889	23,0	35,0	40,4	-4,6	-2 738	595 521	372 735	3 993	127 686	8 995
2920	27,8	35,3	38,6	2,9	-1 568	595 521	376 900	4 034	127 620	8 991
2950	75,0	67,3	46,7	10,4	6 300	614 965	376 956	4 073	128 455	9 058
2980	70,0	64,9	51,4	15,9	6 300	627 472	376 956	4 112	129 873	9 162
3011	70,0	65,9	55,0	18,0	6 300	637 498	376 956	4 149	131 482	9 279

3041	75,0	70,6	58,9	16,0	6 300	648 298	376 956	4 186	133 299	9 411
3072	80,0	75,3	62,9	10,6	6 300	659 743	376 956	4 228	135 351	9 561
3102	49,5	57,0	60,4	3,1	-1 576	659 884	381 031	4 273	137 035	9 679
3133	35,2	49,8	56,3	-4,4	-3 068	659 884	389 042	4 321	138 158	9 756
3163	33,2	46,7	52,7	-9,9	-2 825	659 884	396 477	4 371	138 914	9 809
3193	22,1	40,1	48,2	-12,0	-3 783	659 884	406 377	4 424	139 319	9 836
3224	17,3	35,6	43,7	-10,0	-3 833	659 884	416 457	4 475	139 391	9 840
3254	22,6	35,0	40,6	-4,6	-2 738	659 884	423 685	4 522	139 304	9 834
3285	28,0	35,5	38,8	2,9	-1 568	659 884	427 853	4 564	139 207	9 828
3315	75,0	67,3	46,8	10,4	6 300	679 222	427 909	4 603	140 012	9 893
3345	70,0	65,0	51,6	15,9	6 300	691 640	427 909	4 642	141 398	9 994
3376	70,0	65,9	55,1	18,0	6 300	701 589	427 909	4 679	142 971	10 109
3406	75,0	70,6	59,0	16,0	6 300	712 322	427 909	4 716	144 754	10 240
3437	80,0	75,4	63,0	10,6	6 300	723 706	427 909	4 758	146 773	10 387
3467	49,6	57,1	60,5	3,1	-1 576	723 846	431 984	4 803	148 425	10 503
3498	35,3	49,9	56,4	-4,4	-3 068	723 846	439 995	4 850	149 503	10 579
3528	33,4	46,8	52,8	-9,9	-2 825	723 846	447 430	4 901	150 220	10 630
3558	22,2	40,3	48,3	-12,0	-3 783	723 846	457 330	4 954	150 588	10 655
3589	17,4	35,7	43,9	-10,0	-3 833	723 846	467 410	5 005	150 631	10 658
3619	22,2	35,0	40,8	-4,6	-2 738	723 846	474 653	5 053	150 515	10 650
3650	28,2	35,7	39,0	2,9	-1 568	723 846	478 823	5 094	150 401	10 643

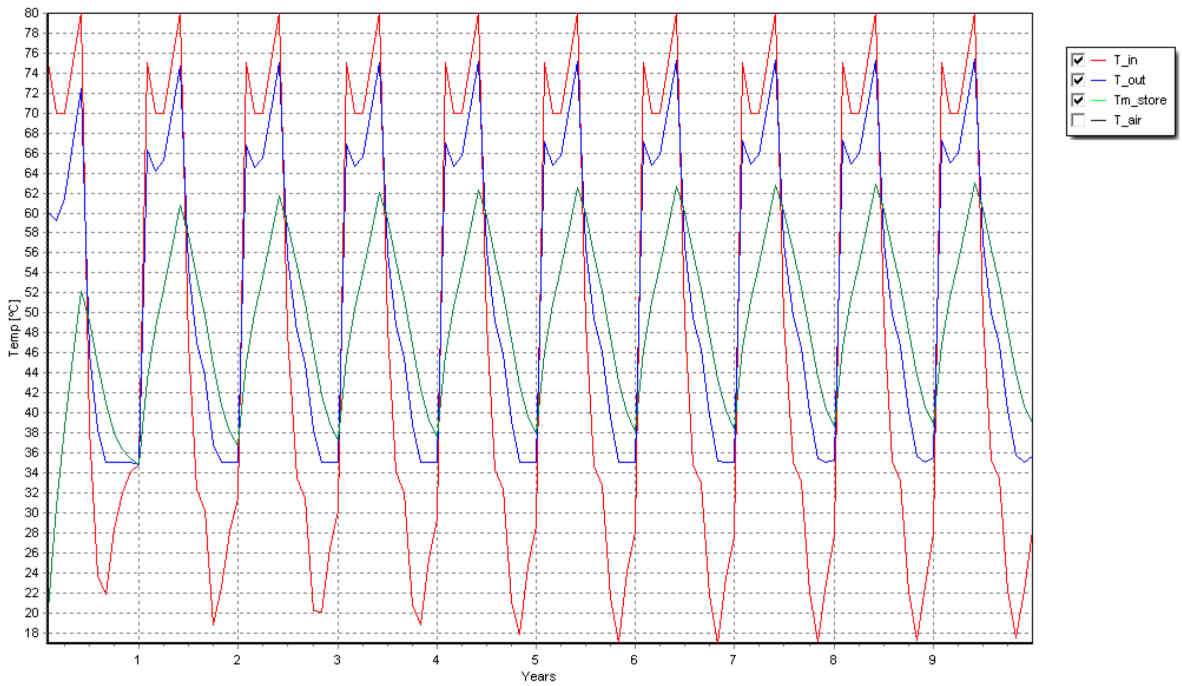

Figure 39. Storage model 16, temperature graph with Inlet T (red line), Outlet T (blue line) and Mean Storage T (green line)

F. Pressure drop as a function of flow rate

In order to find the optimum injection flow rate the pressure drop is calculated, because higher pressure drop means a bigger pump is necessary.

The pipe installation wherein the boreholes are connected in parallel and there is no high difference between the pumping point and the end point reduces the system total pressure drop.

Calculate the pressure drop consists in a few steps with different equations because the installation has different pipes: borehole pipe, connection between boreholes, manifold and culvert. Each pipe has different diameter and the only one condition is the flow must be turbulent because of better heat transfer.

The length of each pipe is calculated depending on the storage model parameters, mainly the borehole spacing and depth. Except the culvert length, it is assumed to be twice one storage side plus 50 meters, these 50 meters is the estimation for the machinery house location.

Hence, the calculation is the following:

$$v = \frac{Q}{A} = \frac{4 \cdot Q}{D^2 \cdot \pi} \tag{A 1}$$

$$Re = \frac{v \cdot D}{\upsilon} \tag{A 2}$$

With equation (A 1) the velocity is calculated by the flow rate Q, in the case of the borehole pipe the total flow rate is divided for the number of boreholes. Then equation (A 2) is used to confirm the flow is turbulent, when Reynolds number is over 4000.

The losses are divided in two: the major losses caused by friction along the pipe length and the minor losses caused by pipe components. The total pressure drop h is the sum of the major h_L and minor losses h_d, see equation(A 3).

$$h = h_L + h_d \tag{A 3}$$

$$h_L = \frac{f \cdot L \cdot v^2}{2 \cdot D \cdot g} \tag{A 4}$$

$$h_d = K \cdot \frac{v^2}{2 \cdot g} = K \cdot \frac{Q^2}{2 \cdot g \cdot A^2} \tag{A 5}$$

The minor loses depend on the coefficient K for each component (see Table 39), while the major loses depend on the friction factor f. The friction factor is estimated with the Colebrook-White approximation equation (A 6).

$$f = \frac{1.325}{\ln\left(\frac{k}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)^2} \quad \text{(A 6)}$$

Table 39. Local loss coefficient in PE pipes.

K (Local loss coefficient)	
Bend 90 oC	0.48
T rounded entrance 315mm	*0.05*
T rounded exit 315 mm	*1*
<u>Branch flowing asunder</u>	
Main pipe	0.02
Branching pipe	0.95
<u>Branch flowing together</u>	
Main pipe	*0.15*
Branching pipe	*0.8*

The result obtained is illustrated in Figure 32, it shows how the pressure loss increases when the flow rate growths. Also, the borehole pipe losses are the most important because of the pipe length, which is twice the borehole depth, 500 meters.

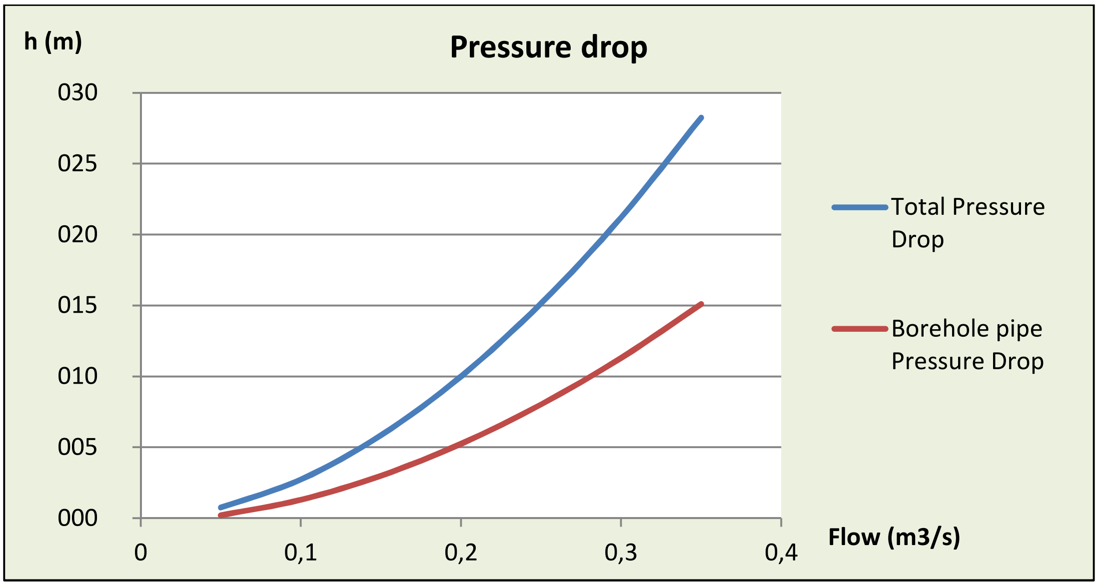

Figure 40. Total and borehole pipe pressure drop

A summary of the results is shown below in Table 40. These results and the chart above correspond to the calculations made for the optimum model, storage model the number 12 with 229 boreholes, 4.5 m of borehole spacing and 250 m depth , more data in page- 87 -.

Table 40. Pressure drop calculations for the optimum storage (model 12) with injection flow of 0.2m/s.

	Borehole pipe	**Section pipe**	**Collector pipe**
Diameter (m)	3.26E-02	9.68E-02	3.15E-01
Flow (m^3/s)	4.37E-04	1.33E-02	2.00E-01
Area (m^2)	8.35E-04	7.36E-03	7.79E-02
Velocity (m/s)	0.52	1.81	2.57
Re	2.59E+04	2.67E+05	1.23E+06
f	2.43E-02	1.49E-02	1.13E-02
$h_{majorloss}$ (m)	5.21	1.76	2.27
$h_{minorloss}$ (m)	0.04	0.32	0.41
Total h		***10.01***	