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Seasonal Low Temperature Borehole Thermal Energy Storage

Utilizing excess heat for district heating in Gothenburg.

Master's Thesis in Innovative and Sustainable Chemical Engineering

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Abstract

Occasionally during summer the heat load in the district heating (DH) network of the Gothenburg region exceeds the heat demand of the customer, i.e. there is an excess of heat in the DH-network. Nowadays, this excess heat is cooled against a river or in a cooling tower at a waste incineration plant. The aim of this study is to store this excess heat in the ground instead of cooling it against a river and use this excess heat during occasions when the heating demand is higher, during winter. This excess heat will be stored in a borehole thermal energy storage (BTES). The studied BTES will be connected to existing heat pumps at Ryaverket owned by Göteborg Energi AB. The conditions, regarding temperature and volumetric flow rate, of the heat source of the heat pumps, treated sewage water, will be improved with the aid of a BTES. When these previously mentioned conditions of the sewage water are improved more heat can be generated by the heat pumps. An increased heat generation by the heat pumps will replace heat generated by other, more expensive, heat generation units. To evaluate the economic profitability of such a system the net present value has been calculated. Designs for BTES, storing 50GWh and 25GWh of waste heat, are found with the aid of a software named GLHEpro and the investment cost for these designs are calculated. To reach economic profitability for this project the savings made by this new system, when heat generated by the heat pumps is increased, should meet the extent of the investment cost. To be able to calculate the savings, a software named Martes is used. The investment cost of a BTES is ten times larger than the savings ever will be in the most probable scenario regarding the investment cost of a BTES. Economic profitability is only reached if the investment cost of the BTES is in the minimum price range, if subsidies to cover 40% of the investment cost from Horizon2020 is gained, if an interest rate of 5% is used for economic calculations and when the availability of the heat pumps is increased by 15%. Economic profitability can also be gained for a scenario when the prices for the investment cost are in the minimum price range and an interest rate of 0% is used for economic calculations. It seems rather unlikely to gain all these privileges for this case study to become economically profitable.

Acknowledgements

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Contents

Nomenclature

AS	Sewage
ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
B_u	Shank spacing
CF	Total cash flow
CTES	Rock cavern storage
COP	Coefficient of performance
Cp	Heat capacity
DH	District heating
DTH-drilling	Down the hole drilling
HP	Heat pump
IC	Investment cost
LT-BTES	Low-temperature thermal energy storage
NPV	Net present value
r_b	Borehole radius
r_p	Radius of u-pipe
S	Present value of savings
SEK	Swedish krona
SV	Salvage value
UTES	Underground thermal energy storage
λ	Thermal conductivity of ground
λ_b	Thermal conductivity of borehole filling
λ_p	Thermal conductivity of pipe material

1

Introduction

District heating (DH) is an energy service that provides customers with heat by transportation of pressurized water. It is a suitable technique for space heating as well as for providing heat to industrial processes [1].

In the Gothenburg region, DH is provided by Göteborg Energi AB, supplying about 90% of all the apartment buildings, 12000 residential buildings, a lot of stores, office spaces and other properties with heat [2].

In the DH-network waste heat from two fuel refineries and a waste incineration plant in the Gothenburg region is used to some extent. Occasionally during summer the customers heating demand decreases. Since shutting down the operation of the fuel refineries and waste incineration plant is a time consuming process, this results in an load of excess heat in the DH-network due to the sudden reduction in the heating demand of the customer. Nowadays when this occurs, the water in the DH-network is cooled against a river or in a cooling tower located at the waste incineration plant. However, instead of cooling this excess heat against a river by seasonal storage, this heat can be utilized during some other occasion when the heating requirement in the DH-network is higher, e.g. during winter [3].

Borehole thermal energy storage (BTES) is one type of seasonal storage. The principle of BTES is to use a system of several boreholes to load/unload the ground with heat. These boreholes are drilled 20-300 meters deep into the ground and supplied with vertical heat exchangers to provide the heat transfer into the ground. The heat is stored in the ground until the heating demand has increased and it is desirable to use this heat [4].

Sweden and Norway are leading countries regarding usage of BTES for space heating. Heat pumps utilizing heat from BTES provides 20% of heat for space heating in Sweden. As heat sources usually excess heat or solar energy is used for example in Anneberg, Stockholm a solar heating system stores 1000 MWh during summer and provides space heating and heat to tap water for 60 single-family houses during winter [5].

1.1 Project aim

Göteborg Energi AB is interested in investigating the possibilities of adding a low temperature borehole thermal energy storage (LT-BTES) (storage temperatures > 10°C) as a supplement to a current heat pump system at Ryaverket owned by Göteborg Energi AB. These heat pumps generates heat for DH purposes and the idea is to increase the heat load generated by these heat pumps by adding a LT-BTES to the system. In the current system treated sewage water is used as the heat source for the heat pumps at Ryaverket. The heat pump system at Ryaverket consists of four heat pumps that transfers heat from treated sewage water into the DH-network. The purpose of such a LT-BTES is to increase the temperature of the sewage water since an increased temperature of the heat source will increase the heat generation by the heat pumps. An increased heat generation by the heat pumps will replace heat generated by more expensive heat generation units. This way some money can be saved. To be able to decide if economic profitability of such a system can be gained the net present value has been calculated.

1.2 Project formulation

This study is aiming at answering the following questions:

- How should a LT-BTES be designed as a supplement to the heat pumps at Ryaverket? What will the geometrical properties and size of such a LT-BTES be?
- Is it economically profitable to add a LT-BTES system as a supplement to the already existing heat pump system at Ryaverket? To be able to investigate this the investment cost of the LT-BTES is calculated. To gain economic profitability this investment cost should meet the amount of money saved with this new system when the heat pumps are supplemented with a LT-BTES compared to a case without a LT-BTES.
- What energy flows will be replaced? What will the consequences on the greenhouse gas emissions be?
- How sensitive will the economy of such a system be to changes in certain parameters?

1.3 Restrictions

Different sizes and configurations of the LT-BTES will be tested to the extent that time permits. Sensitivity analysis will also be tested on some, rated as important by the author, parameters contributing to the economy of the heat pump system connected to a LT-BTES. The primary focus is to make a first evaluation of such a system where the heat generation by the heat pumps is increased by improving the conditions of the heat source for the heat pumps. The physical location of such a LT-BTES and the impact on the surrounding region will not be investigated in this study.

1.4 Disposition

In the theory section some common information about heat storage and different technologies will be presented, then some more focus is put on the borehole thermal energy storage. Basic principles of a heat pump and economical concepts will also be discussed.

In the methodology section a thorough review of the practical work for this study is made. At first the work on how the thermal energy generation by the heat pumps was increased and then the approaches to the softwares Martes and GLHEpro will be described. Lastly, the procedure when calculating the economics of a LT-BTES and the sensitivity analysis performed will be explained.

In the results section the results obtained from the practical work of this study will be presented and these results will then be discussed in the discussion section. At last some conclusions will be drawn.

2

Theory

Using renewable energy sources for heating purposes can be problematic due to the intermittent nature of the energy sources, hence makes it hard to meet the energy demands solely with renewables. To be able to utilise renewables as much as possible thermal energy storage could be a good solution. With seasonal thermal energy storage excess heat can be moved to seasons when the need for heat is higher. Thermal energy storage can be divided into two categories depending on the extent of the storage time; short-term storage and long-term storage. Short-term storage implies heat storage that extends from one hour to a week and long-term storage implies storage that extends from a week up to a year [6]. Long-term thermal energy storage or seasonal storage is of particular importance for this study.

2.1 Thermal energy storage technologies

There are three types of thermal energy storage technologies; latent heat storage, thermochemical storage and sensible heat storage.

2.1.1 Latent heat storage

The principle for latent heat storage is thermal energy stored in materials that changes phases during the storing process. This process is nearly isothermal and as storage material usually solids that become liquids are used, liquids vaporizing during a storage process is not that unfamiliar either. These storage materials are conveniently called phase changing materials [7]. Advantages with latent heat storage is that it does not require as much storage volume as the other technologies and provides a high energy density. However this technology has only been applied for short-term storage, for long-term storage this technology is still on lab-scale mostly due to lack-of knowledge regarding the capacity of the phase changing materials in the long-run [8].

2.1.2 Chemical reaction heat storage

Chemical reaction heat storage is a storage method with a large energy density and small heat losses. In this technology, the heat to be stored originates from reaction enthalpies of reversible reactions or from absorption and adsorption processes [8]. However this technology is still in the research phase, but it is desirable to make progress with it since it is advantageous in the sense that heat can be stored for a long time. In other words this would be a suitable technology for seasonal storage. Another advantage with this technology is that it is flexible, for example the storage temperature can easily be changed by varying the pressure [9].

2.1.3 Sensible heat storage

Sensible heat storage is the technology that will be analysed in this study. The principle of sensible heat storage is to increase the temperature of the storage material by heat injection and when needed this heat can be extracted and used. The heat stored is proportional to the temperature difference between the material and the temperature of the heat transferring fluid and to the properties of the storage material like heat capacity and density. The latter properties implies that this technology requires large storage volumes [7].

The advantage of a sensible heat storage is that it is a well-known technology that has been applied for a long time. This technology is also relatively cheap, mostly due to that the storage material can already be found in the nature. Storing materials could be for example rock, water or soil. This technology has a big drawback and as previously mentioned this storage technology requires large storage volumes. Large long-term storage indicates also heat losses [8].

2.2 Different storage systems

Underground thermal energy storage (UTES) is a suitable system to use for sensible heat storage. There are several types of UTES; rock cavern storage (CTES), storage in aquifers (ATES) and borehole thermal energy storage (BTES) to mention a few. All these types of storage systems can extend to large inexpensive storage volumes which is a requirement for seasonal storage [10][11].

2.2.1 Rock cavern storage

Rock cavern thermal energy storage or CTES is as the name implies a large cavern situated underground. Heat is stored as water in this storage type and it is easy to maintain a stratified temperature profile. This storage system is advantageous when fast variations, or high power, of the loading and unloading loads are required [10]. However this technology is more expensive compared to ATES and BTES discussed in the preceding sections [12].

2.2.2 Storage in aquifers

Storage in aquifers implies storage in the water or the minerals of the aquifer where ground water is the heat transferring medium and heat is transferred by letting the groundwater flow through the permeable layers of the aquifer [11][13]. To extract the heat from the aquifers hydraulically coupled wells are drilled and to be able to extract the heat these wells should be placed a suitable length from each other. Heat storage in aquifers is a technology attractive from an economic point of view and suitable for building applications for storage of solar heat and waste heat [10][13].

2.2.3 Borehole thermal energy storage

In this study the sensible heat storage system that is analysed is a borehole thermal energy storage (BTES). The principle of BTES is drilling boreholes into rock and implementing heat exchangers in these boreholes, these heat exchangers will provide the heat transfer from the heat transferring medium into the rock. The dimensions of such boreholes are usually in the following range: 10-15cm in diameter and 20-300m deep [4]. At depths over 10m into the ground some stratification of the ground temperature will be felt. The ground temperature is said to hold the mean annual air temperature the first 10m from the ground surface, further into the ground the temperature increases with 1-3°C every 10m. The reason behind this phenomena is the thermal inertia of the ground which causes a time-lag between the ambient air temperature and the temperature of the ground. During summer the ground temperature will be lower than the temperature in the outside air and winter the temperature of the ground will be higher than the temperature of the outside air [14].

The empty space between the borehole walls and the heat exchanger is usually filled with grout or water, water is the most common filling material in Sweden. This filling material fulfills a purpose of obtaining stability in the borehole as well as reducing the thermal resistance in the hole. Grout would be a suitable filling material since it also restricts the vertical movement of water in the hole and this way prevents polluted water from entering the hole, grouting also hinders drainage of soil layers near the ground surface [4]. Since in Sweden the boreholes are usually filled with water casing could be used to avoid polluted water from entering the hole [15].

The heat transfer phenomena is to a large extent heat conduction, however if the borehole filling is water even heat convection should be considered, except if the heat storage is in crystalline granite. Experiments have shown that in crystalline granite the heat convection factor is hardly significant [11].

The boreholes could be drilled in the storage system in a hexagonal pattern or square pattern. Both systems are advantageous in some way, the hexagonal pattern is better regarding heat transfer but the square pattern is easier to drill. The hexagonal pattern also gives less heat losses but the square pattern makes it easier to connect the holes to each other. A distance of 6-8m is a standard distance between the holes in Scandinavian rock type [4][11].

The boreholes and also the piping are believed to have a lifetime of at least 100 years [16].

2.3 Technical overview of BTES

The preceding sections will in closer detail describe some of the technicalities of a BTES.

2.3.1 Ground heat exchangers

The BTES can be considered as a heat exchanger, an open type or a closed type. The first mentioned is an open system in which the heat carrying fluid will be in direct contact with the heat storage material. Although this method shows good properties considering the heat transfer between the heat carrying fluid and the storage material this kind of system shows problems with water chemistry, for example scales can be formed in the piping system and heat exchangers [4][11]. An open type heat exchanger will not be investigated in this study.

A closed type heat exchanger consists of tubes that will be placed in the boreholes, the heat transferring fluid will flow through these tubes and will be in indirect contact with the heat storage material. The pipe material for such heat exchanger pipes is usually polyethylene with a thermal conductivity of 0.42 W/mK [17][18].

There are different closed type heat exchangers suitable for boreholes, for example an u-pipe heat exchanger and a coaxial pipe heat exchanger.

Coaxial heat exchanger

A coaxial heat exchanging tube can have a couple of different designs. One example is a design where an inner pipe is inserted into a larger pipe. The heat carrying fluid will be flowing down the inner pipe and up the outer pipe and the heat will be transferred into the walls of the borehole. In this case it is important to insulate the inner pipe to prevent thermal short-circuiting (i.e. heat is transferred through the pipe walls directly into the upwards flowing fluid) [4]. A second type of design is a centered pipe surrounded by several smaller pipes attached to the borehole walls. The water will first flow downwards the centered pipe, then directed to the smaller pipes surrounding and heat will be transferred to the borehole walls when the fluid is flowing upwards. The flow through these pipes is laminar due to the small dimensions of the pipes but the heat transfer becomes good due to the pipe placement close to the borehole wall [11]. Due to the laminar flow heat convection becomes an important transport phenomena.

U-pipe

The second type, the u-pipe heat exchanger, works in the following way; the heat carrying fluid flows down the pipe to the bottom of the hole, makes a U-turn at the bottom and flows back to the top of the hole. The flow can be kept turbulent and this will eliminate the importance of heat convection and only heat conduction needs to be accounted for [17]. Sometimes double or triple u-pipes are used in one hole in order to improve the heat transfer to a relatively cheap price [4].

2.3.2 Briefly about borehole drilling

The drilling of a borehole consists usually of two parts. The first part is called ODEX-drilling and is the part that penetrates the ground surface and drills through the soil, usually also one meter down into the bedrock. The second part is called Down The Hole or DTH-drilling and continues into the rest of the bedrock until the desired depth is reached. Sometimes the bedrock cracks during drilling and to prevent water movement thermal bentonite is injected into the holes to seal the cracks [16][19].

The deeper the boreholes are the harder it will be to drill them straight and deviations from straightness implies degraded heat transfer properties of the boreholes. At the borehole thermal energy storage built at Xylem in Emmaboda some analysis on the borehole drilling straightness was made. They measured the straightness every 10m down the hole and the results were the following; the deviation from straightness at a depth of 150m could vary between 4m and 32m with an average of 18m. The deviations were for most parts in the same direction and the reason for this was a changing rock structure down the hole. However in particularly this case the thermal properties were probably not influenced that much since the deviations were in the same direction for the most part [19].

2.3.3 The loading and unloading process

When there is an excess of heat in the DH-network the water in the DH-network is circulated through the heat exchangers placed in boreholes to load the ground with heat. The available waste heat load could go up to 200GWh, but at least 50GWh of heat will be available each year, this is the heat load cooled in a cooling tower at the waste incineration plant when the excess heat load is at the lowest [20].

Heat is transferred into the ground mainly through conduction when a temperature gradient is created due to the temperature difference between the cold ground and the hot circulating fluid. The heat will be stored in the ground until it can be used for heating purposes, e.g. during winter. When unloading, the process is reversed and a cold fluid is circulated through the heat exchangers to gather the heat stored in the ground.

The studied storage system consists of several boreholes connected in series or parallel through a central piping system [4].

Some important properties regarding heat extraction process should be considered.

The volumetric flow rate of the circulating fluid should not exceed $2\frac{m^3}{h}/borehole$ and the heat extraction and injection rate should be around $50\frac{W}{m}$ [21].

2.4 Storage heat losses

The untouched ground holds a natural ground temperature which is about the average ambient air temperature throughout the year [11]. In Gothenburg the average ambient temperature is about 8-10°C [22]. Injection of heat into the ground will obviously increase the ground temperature which implies that temperature gradients are created around the boundaries of the storage system. These temperature gradients will cause heat losses through the storage boundaries due to heat transfer to the colder surroundings. This heat loss can be expressed by Fourier's law

$$q_{cond} = -\lambda \nabla T \tag{2.1}$$

Fourier's law states that the conductive heat, q_{cond}, is proportional to the temperature gradient, ∇T, in the storage material and the heat conduction, λ, of the storage material [11]. During the extraction period a temperature gradient is now created towards the boreholes, when a colder fluid is flowing through the boreholes, and this implies that the heat losses through the storage boundaries decreases or could be totally reversed [11]. With every loading period the heat losses to the surroundings will decrease since the heat is left in the ground from the former loading period. If the operating conditions for the second loading period are the same as for the first the temperature gradients in the ground are not as large as in the previous loading period and this leads to decreased heat losses. With every loading period heat will accumulate in the ground and the heat losses will decrease for every period until after years of operation a steady-state is reached. Steady-state heat losses are the ones to be considered when comparing different heat storages to each other [11].

2.5 Heat Pump theory

As previously mentioned the purpose of this study is to improve the operating conditions of the existing heat pumps at Ryaverket and this way increase the generated heat by these heat pumps. This section will present the convenient parts of a heat pump in operation.

2.5.1 Principle of a heat pump

The basic idea of a heat pump is to convert 100kWh of electrical energy into 300kWh useful thermal energy, by using 200kWh of available thermal energy, at a lower temperature, as a heat source. In other words, the heat load generated by the heat pump will be larger than the load of electrical energy input needed to operate the heat pump [23].

Figure 2.1 shows a sketch of a simple heat pump.

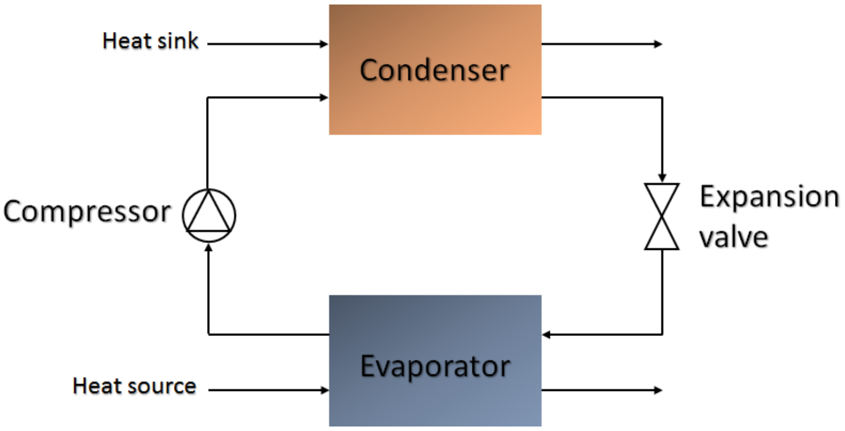


Figure 2.1: The principle of a heat pump.

The heat pump consists of four components; an evaporator, a compressor, a condenser and an expansion valve. Some sort of fluid, could be water or some refrigerant, is circulated through the heat pump to obtain heat transfer. The circulating fluid extracts heat during an evaporation process. Heat is gained from an external heat source which is denoted as heat source in figure 2.1. During heat extraction the circulating fluid increases in temperature, usually becomes saturated steam or superheated steam [24].

After leaving the evaporator the saturated or superheated steam is compressed in a compressor and as a result the pressure and temperature of the steam is increased. This step requires work input, simply to work the compressor. The work input will be in the form of electrical energy [23].

When the circulating fluid is compressed the heat concentration of the fluid becomes higher. The fluid enters a condenser and will create a concentration gradient towards an opposing fluid, which works as a heat sink in this case, denoted heat sink in figure 2.1, since the thermal energy concentration of this fluid is much lower. This concentration gradient will give rise to heat transfer towards the opposing fluid and the circulating fluid will condensate [23]. The heat gaining fluid will after heat extraction be directed towards the heating aim.

After condensation the circulating fluid will pass an expansion valve which results in released pressure and a lower heat density of the circulating fluid. Due to the low density the heat concentration gradients will now be directed towards the circulating fluid when entering the evaporator yet again and resulting in more heat extraction. The whole process described will be repeated as long as the heat pump is in operation [23].

The governing heat balances and working principles of each component in a heat pump will be briefly presented below.

Evaporator

The power of the evaporator is proportional to the mass flow and the temperature difference of the heat source entering and exiting the evaporator

$$\dot{Q}_{evap} = \dot{m} \cdot C_p \cdot \Delta T \tag{2.2}$$

$\dot{m}$ is the mass flow of the heat source, C_p is the heat capacity of the circulating fluid under the operating conditions and ΔT is the temperature difference between the circulating fluid entering and leaving the evaporator. In the evaporator the heat is transferred to the circulating fluid and it becomes saturated or superheated as mentioned before. The presented equations below regards a case with saturated steam.

For an ideal heat exchanger the amount of heat extracted by the circulating fluid is the same as the heat omitted by the heat source. The evaporator power on the steam side can be expressed as

$$\dot{Q} = \dot{m} \cdot \Delta H_{vap} \tag{2.3}$$

where $\dot{m}$ is the mass flow of the circulating fluid and ΔH_{vap} is the heat of vaporization of the fluid [25].

Equation 2.2 and 2.3 equals to each other and $\dot{Q}$ is the transferred heating power over the evaporator.

The evaporator power can also be expressed as

$$\dot{Q} = UA\Delta T_{LM} \tag{2.4}$$

where A is the heat transfer area of the evaporator, U is the overall heat transfer coefficient of the process and ΔT_{LM} is the logarithmic mean value of the temperature over the evaporator. The logarithmic mean value is defined as

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{ln(\frac{\Delta T_1}{\Delta T_2})} \tag{2.5}$$

If the evaporator is a heat exchanger that works counter currently ΔT_1 is the temperature difference between the entering heat source and the exiting steam and ΔT_2 is the temperature difference between the exiting heat source and the entering condensate entering the evaporator, see figure 2.2.

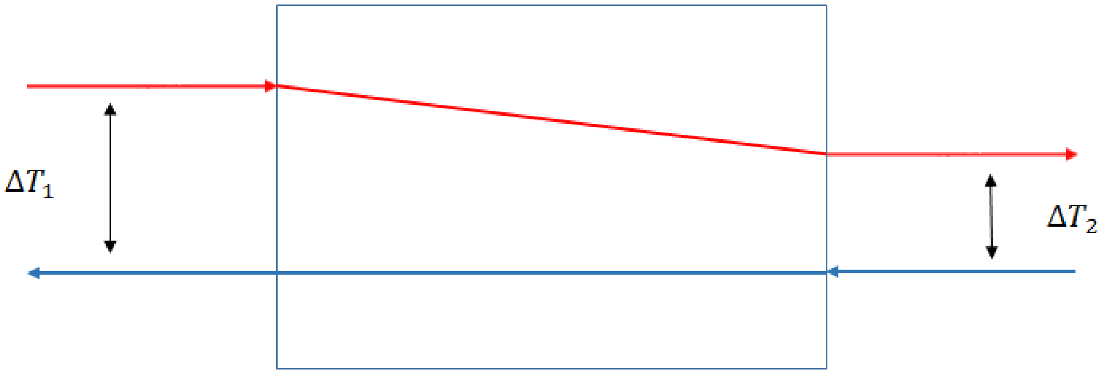


Figure 2.2: A temperature profile over an evaporator.

The overall heat transfer coefficient and the heat transfer area is usually expressed as one variable, UA, and the equation for this one is dependent on the type of the heat exchanger. For example for a geometry where the heat exchanger is a concentric pipe inside another the following equation is used

$$\frac{1}{UA} = \frac{1}{A_i h_i} + \frac{ln(r_o/r_i)}{2\pi\lambda L} + \frac{1}{A_o h_o} \tag{2.6}$$

and by inverting equation 2.6 a value of UA is obtained. A_i and A_o are the inner and outer heat transfer areas respectively, h_i and h_o are the inner and outer heat convection coefficients and λ is the heat conduction coefficient through the wall between the inner and outer pipe [26]. The heat convection coefficients, h_i and h_o, are temperature dependent and obtained from a geometry specific correlation of the Nusselt number.

Compressor

The compressor serves a purpose and that is to increase the pressure (and temperature) of the steam before the steam enters the condenser. This way the energy density of the steam will be higher and temperature gradients will be formed, which are necessary for heat transfer.

The work a compressor exerts can be expressed as

$$W = \int V dP \tag{2.7}$$

where V is the volume of the steam entering the compressor and dP is the differential in the pressure that the compressor will accomplish.

Condenser

After the steam is compressed it is aimed at a condenser which purpose is to transfer heat to a heat carrying medium that will be aimed at end use purposes. At the same time as the heat sink, see figure 2.1, is extracting heat the circulating fluid will condensate. In some cases sub cooling could also be obtained but that is not described in this study. The same heat balances, equation 2.2, 2.3 and 2.4, as for the evaporator will also apply here but instead of heat of vaporization in equation 2.3 a heat of condensation will be more accurate (though, this heat will be the same in both cases under the same operating conditions).

If the condenser is a concurrent heat exchanger the following will apply for equation 2.5; ΔT_1 will denote the temperature difference between the entering steam and the entering cold fluid, heat sink, and ΔT_2 will denote the temperature difference between the exiting condensate and the exiting cold fluid, see figure 2.2.

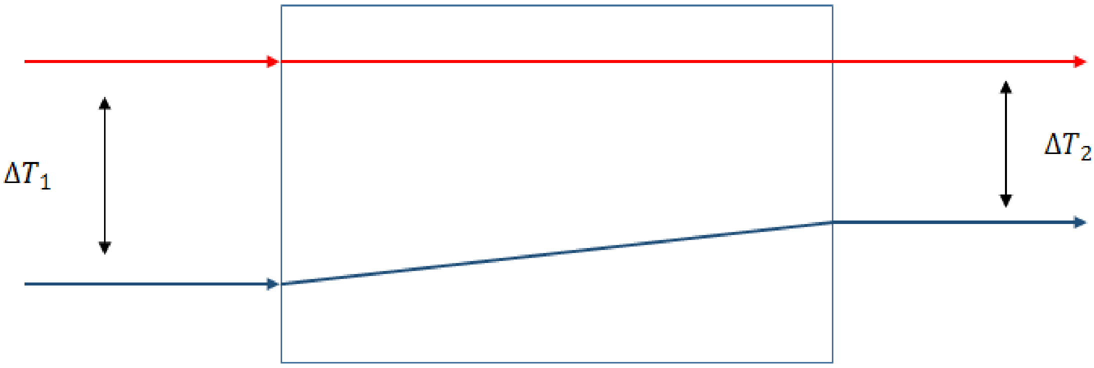


Figure 2.3: Temperature profile over a condenser.

Figure 2.3 shows a temperature profile of a condenser that only obtains condensation of the circulating fluid, i.e. no sub cooling of the circulating fluid.

Expansion valve

After the condenser an expansion valve follows to release on the pressure of the circulating fluid. A decrease in pressure results in a lower energy density of the circulating fluid and this means that the fluid is now able to extract even more heat when entering the evaporator once again.

2.5.2 Coefficient of performance

Probably the most important feature and design parameter of a heat pump is the coefficient of performance, COP, which by definition is the ratio between useful thermal power output and the electric power consumption of the heat pump [27]. The COP can be expressed by the following relations

$$COP = \frac{\dot{Q}_{out}}{\dot{W}_{in}} \tag{2.8}$$

$$COP = \frac{\dot{Q}_{out}}{\dot{Q}_{out} - \dot{Q}_{in}} \tag{2.9}$$

$$COP = \frac{T_H}{T_H - T_C} \tag{2.10}$$

where $\dot{Q}_{out}$ is the useful thermal power output of the heat pump, $\dot{W}_{in}$ is the electric power consumption of the compressor, $\dot{Q}_{in}$ is the thermal power consumption of the evaporator, T_H and T_C are the temperatures of the circulating fluid entering and exiting the condenser and evaporator respectively [23].

2.6 Current heat pump system

This section will briefly describe the technicalities of the existing heat pump system at Ryaverket in Gothenburg, which is the heat pump system that this study is aiming to improve. A simple sketch of the current system can be seen in figure 2.4.

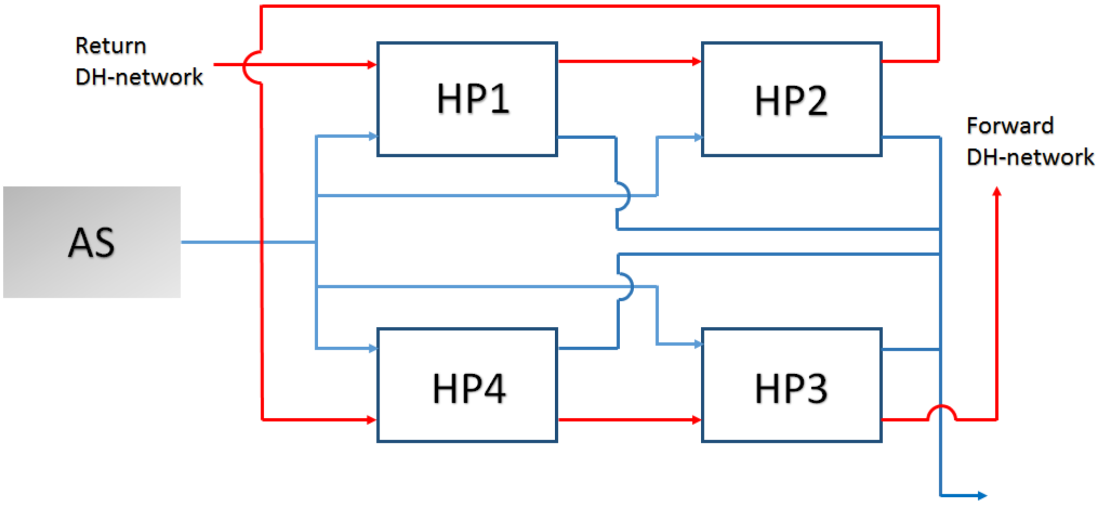


Figure 2.4: An overview of the heat pump system at Ryaverket in Gothenburg. The evaporators of the heat pumps are connected in parallel and the condensers are connected in series.

This current heat pump system consists of four heat pumps, denoted HP1, HP2, HP3 and HP4 in figure 2.4. These heat pumps have different properties regarding size and COP-values.

Treated sewage water is the heat source for the heat pumps, denoted as *AS* in figure 2.4, and the returning water from the district heating network, see figure 2.4 will be the heating aim for the heat pumps, the heat sink. The heat pumps are connected in parallel to the heat source (sewage water) which means that the water entering the evaporators of the heat pumps is divided into different flows and the entering temperature into the evaporators for each heat pump will approximately be the same.

From the heat extraction point of view the connections between the heat pumps are a bit trickier. In general the heat pumps are connected in series, easily seen in figure 2.4, but this is only a much simplified picture. However, if all the heat pumps are in operation the heat extraction will occur in series. The return from the DH-network will at first enter HP1 then HP2 and HP4 and at last HP3. The water will be heated in steps. Though, sometimes some of the heat pumps are out of operation and control devices are used to bypass a heat pump that is out of operation. However, as far as possible the heat will be extracted according to the steps described previously.

2.7 Economical concepts

To make an economical evaluation of the LT-BTES added as a supplement to the heat pump system at Ryaverket in Gothenburg, some economical concepts are applied. There are two parts that contribute to the economy; the first part is be the investment cost of the LT-BTES and the second part is the annual savings when operating the LT-BTES and utilising more waste heat for DH compared to a case when no LT-BTES is in use.

A net present value (NPV) will be calculated and the minimum criteria for an investment to be economically profitable is that the NPV should at least be zero. The NPV of an investment is defined as the investment cost subtracted from the present value of the total cash flow during the whole investment [28].

The calculation of the net present value will be performed as presented below.

$$NPV = CF - IC \tag{2.11}$$

where IC is the investment cost of the LT-BTES and CF is the total cash flow during the considered investment period. The investment cost will be further discussed in section 3.4. In this study the cash flow is divided into two parts

$$CF = S + SV \tag{2.12}$$

where S is the present value of the savings made when utilising the LT-BTES during the period of investment and SV is the salvage value of the LT-BTES. Equation 2.13 gives a definition of the salvage value.

$$SV = \frac{R}{(1 + (p + k))^n} \tag{2.13}$$

In equation 2.13 R is the value of the LT-BTES at the end of the investment period, p is the interest rate, k is the inflation rate and n is the amount of years considered for the investment period.

Each year, by utilising even more waste heat in the DH-network by storage in LT-BTES, some savings will be made, S, see equation 2.12. To be able to compare the amount of savings to the investment that is today made into a LT-BTES, the present value for these savings needs to be calculated and summarized and this is done according to the equation below.

$$S = \sum_{i=1}^{n} \frac{a_i}{(1 + (p + k))^i} \tag{2.14}$$

In equation 2.14 a_i is the amount of money saved year i, p is the interest rate, k is the inflation rate and n is the amount of years considered for the investment.

3

Methodology

The main task of this study is to investigate how the heat pumps at Ryaverket in Gothenburg can be improved and to evaluate how much economic profitability can be obtained by doing so. How this will be done is described in the preceding sections.

3.1 Power output from heat pumps

Angelbratt et al. [29] created a model to describe how the consumption of electric power in the heat pumps at Ryaverket is depending on the prevailing temperature and volumetric flow rate of the sewage water, i.e. the heat source of the heat pumps. In reality, the maximal electric power consumption of the heat pumps is influenced by several factors, however in the study (temperature and volumetric flow rate of sewage water disregarded) the other factors are assumed to be optimal from an electric power consumption point of view.

According to experts at Ryaverket the COP-value of the heat pumps are already the best possible, this is simply due to the design of the heat pumps and the COP-value cannot be regulated manually, and this value can thereby be regarded as constant. This means that by increasing the electric power consumption of the heat pumps the thermal power output from the heat pumps will also increase.

The electric power consumption of the heat pumps increases with improved conditions of the sewage water, increased temperature or volumetric flow rate, and this is due to that there is a restriction on the heat source exiting the heat pumps. This sets demands on the evaporators of the heat pumps. The sewage water, heat source, should not fall below about 3°C in temperature since in that case the water will freeze. That is why a higher temperature or volumetric flow rate of the sewage water entering the heat pumps can increase the electricity consumption since the power of the evaporator can also be higher.

The electric power consumption of the heat pumps in MW, can the calculated by

$$P_{el} = \beta_0 + \beta_1 \cdot t + \beta_2 \cdot t^2 + \beta_3 \cdot t^3 + \beta_4 \cdot q + \beta_5 \cdot q^2 + \beta_6 \cdot q^3 \tag{3.1}$$

where t is the temperature and q is the volumetric flow rate of the sewage water entering the evaporators of the heat pumps in °C and $\frac{m^3}{h}$ respectively. The parameter values of equation 3.1 are shown in table 3.1.

Table 3.1: A list of the parameter values of equation 3.1.

β_0	$-2.13688583 \cdot 10^2$
β_1	$4.07027834 \cdot 10^1$
β_2	-2.82231057
β_3	$6.17631824 \cdot 10^{-2}$
β_4	$1.63786584 \cdot 10^{-2}$
β_5	$-1.23637685 \cdot 10^{-6}$
β_6	$3.16205646 \cdot 10^{-11}$

There are some restrictions for the model, equation 3.1;

- if $t \leq 6°C$, $P_{el} = 0$
- if $q < 5000\frac{m^3}{h}$, $P_{el} = 0$

The following also applies;

- The volumetric flow rate of the water entering the heat pumps should not exceed $16000\frac{m^3}{h}$ since the pumps in the system are not capable of pumping through a larger water volume [29].
- A small analysis performed on the model, equation 3.1, shows that the maximum electric power consumption of the heat pumps is obtained if the water entering the heat pumps holds a temperature of 11.72°C and at the maximum flow rate of $16000\frac{m^3}{h}$. A higher water temperature than 11.72°C will result in as much electricity consumption as for a temperature of 11.72°C however the model cannot handle higher temperatures in a correct manner [29].

It is worth mentioning that the model, equation 3.1, has an uncertainity of about 10% regarding the electric power consumption of the heat pumps but has been proved to work fairly well at a diurnal basis.

A further analysis shows that depending on the initial values on the temperature and volumetric flow rate of the sewage water the maximum electric power consumption of the heat pumps will sometimes be obtained 1. without and sometimes 2. with maximizing the flow rate of the water entering the heat pumps ($16000\frac{m^3}{h}$) (the comparison is made in a manner that the heat load extracted from LT-BTES will be the same in both cases). Figure 3.1 shows how the heat from the LT-BTES should be extracted to maximize the electric power consumption of the heat pumps. In the figure Ryaverket denotes all the four heat pumps.

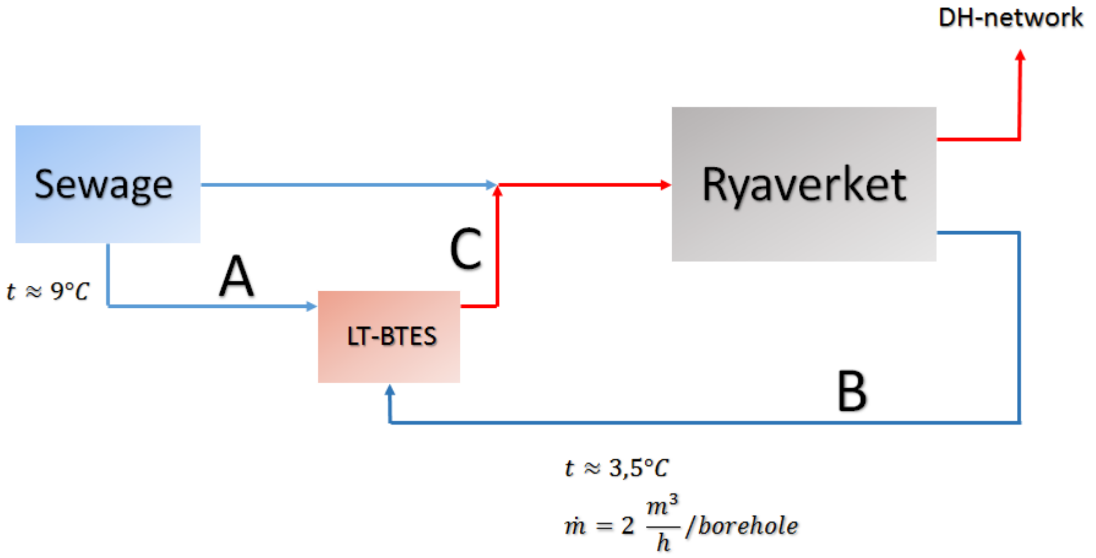


Figure 3.1: A technical overview of how to connect LT-BTES to the heat pumps when maximizing the power output from the heat pumps. ”Ryaverket” denotes all the four heat pumps.

- Approach 1: Path A-C in figure 3.1. The volumetric flow rate of sewage water is kept at its initial value and the sewage water will extract a heat load, Q_0, by letting a suitable amount (according to guidelines mentioned in section 2.3.3) of sewage water flow through the LT-BTES and then mix with the rest of the sewage water.
- Approach 2: Path B-C figure 3.1. The volumetric flow rate is maximized to $16000\frac{m^3}{h}$ by adding water from the exit of the heat pumps and then mix it with the sewage water. The temperature of the additional water will be set as 3.5°C, this is approximately the temperature of the water exiting the heat pumps. This water will extract the same amount of heat, Q_0, from LT-BTES as in approach 1 described above and then mixed with the sewage water. This will result in a bit lower temperature of the water entering the heat pumps but a higher volumetric flow rate compared to approach 1.

For approach 1 the heat load extracted from the LT-BTES to improve the conditions of the sewage water is calculated by the heat balance preceding

$$Q_{extr} = \dot{m}_{AS} \cdot C_p \cdot (T_{in,HP} - T_{AS}) \tag{3.2}$$

where $\dot{m}_{AS}$ and T_{AS} is the initial mass flow and temperature of the sewage water in $\frac{kg}{s}$ and °C respectively, C_p is the heat capacity of the sewage water in $\frac{J}{kgK}$ and $T_{in,HP}$ is the temperature of the water entering the heat pumps (11.72°C is the desired temperature to maximize the thermal power output from the heat pumps).

If the maximum electric power consumption is reached by adding colder water from the exit of the heat pumps and this way maximizing the volumetric flow rate of the sewage water entering the heat pumps, approach 2, the following heat balances applies

$$Q_{extr} = \dot{m}_{exit,HP} \cdot C_p \cdot (T_{out,LT-BTES} - T_{exit,HP}) \tag{3.3}$$

where $\dot{m}_{exit,HP}$ is the amount of additional water needed to reach the maximum volumetric flow rate of the water entering the heat pumps, $T_{exit,HP}$ is the temperature of the water exiting the heat pumps (a mean value over the year is about 3.5°C). To find the heat load extracted from LT-BTES, Q_{extr} in equation 3.3, a heat balance over the mixing point of the water exiting the LT-BTES and the sewage water is made, see equation 3.4. This will give the needed temperature of the water exiting LT-BTES and thus solve the equation 3.3.

$$\dot{m}_{max} \cdot C_p \cdot (T_{in,HP} - T_{ref}) = \dot{m}_{exit,HP} \cdot C_p \cdot (T_{out,LT-BTES} - T_{ref}) + \dot{m}_{AS} \cdot C_p \cdot (T_{AS} - T_{ref}) \tag{3.4}$$

Some further reasoning on the model describing the electric power consumption will precede. Figure 3.2 describes how the electric power consumption of the heat pumps is depending on the initial temperature and the volumetric flow rate of the sewage water, the heat source of the heat pumps.

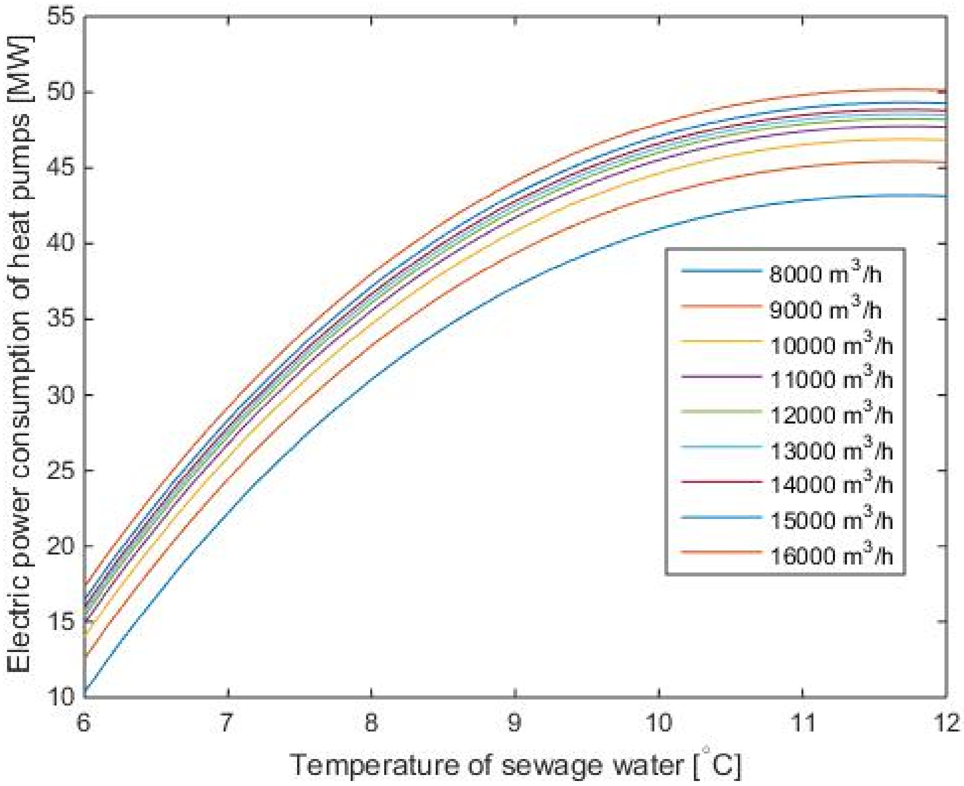


Figure 3.2: This figure shows how electric power consumption of the heat pumps is dependening on temperature and volumetric flow rate of the sewage water.

It is clear that the electric power consumption of the heat pumps is more dependent on the temperature of the sewage water than on the volumetric flow rate, especially at rather cold temperatures (<9°) and when the flow rate exceeds 11000 $\frac{m^3}{h}$. A small change of temperature from for example 7°C to 8°C can increase the electric power consumption by almost 10MW for a constant volumetric flow rate, but an increase of volumetric flow rate from for example 12000$\frac{m^3}{h}$ to 16000$\frac{m^3}{h}$ at a constant temperature gives at most an increase by about 3MW in electric power consumption.

Figure 3.3 and 3.4 describes in closer detail how the heat from the LT-BTES should be extracted, Approach 1 or Approach 2, for some initial temperatures on the sewage water to reach the maximum electric power consumption of the heat pumps. The title in the figures tells which initial temperature the sewage water holds, the x-axis describes different initial volumetric flow rates of the sewage water. Note that the blue line in the figures describes approach 2, e.g. the volumetric flow rate of the water entering the heat pumps is maximized to 16000$\frac{m^3}{h}$ but the x-axis is the value of the initial volumetric flow rate of the sewage water before it is mixed with colder water from the exit of the heat pumps.

The red line in the figures 3.3 and 3.4 describes Approach 1, the case where the sewage water flow rate is kept the same throughout the whole process. The y-axis in the figures describes the electric power consumption of the heat pumps.

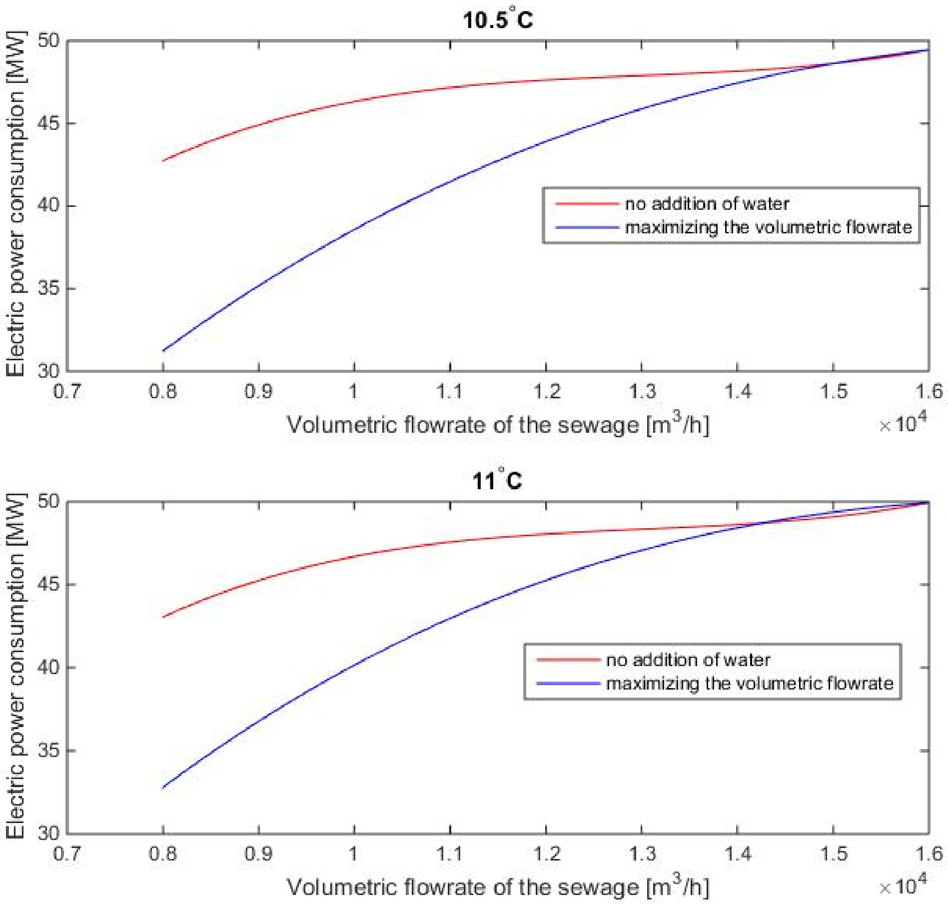


Figure 3.3: This figure describes how the electric power consumption is maximized, with or without maximizing the volumetric flow rate of the water entering the heat pumps. The initial temperature of the sewage water (before heat extraction) is 10.5°C and 11°C respectively.

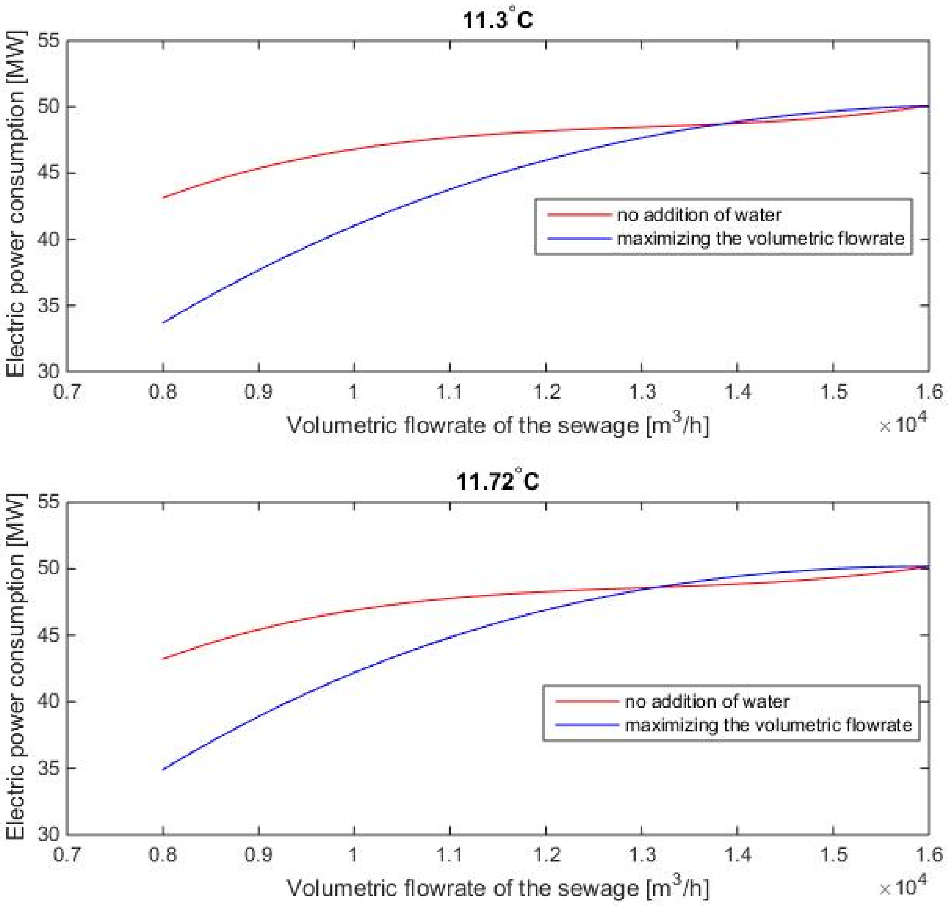


Figure 3.4: This figure describes how the electric power consumption is maximized, with or without maximizing the volumetric flow rate of the water entering the heat pumps. The initial temperature of the sewage water (before heat extraction) is 11.3°C and 11.72°C respectively.

From figures 3.3 and 3.4 it is evident that for the most part the highest electric power consumption is obtained when heating the existing sewage water and not trying to maximize the flow rate (reach $16000\frac{m^3}{h}$ by adding cold water at ~3.5°C from the exit of the heat pumps), when the same amount of heat is added into the sewage water in both cases. However at rather high initial sewage water flow rates ($>13000\frac{m^3}{h}$), and high initial sewage water temperatures (>10.5°C) maximizing the volumetric flow rate is maximizing the electric power consumption of the heat pumps.

In this study the approach will be to by using the model 3.1 find the occasions when the conditions of the sewage water can be improved to increase the electric power consumption and calculate the new electric power consumption from these improved conditions and also the thermal power output from the heat pumps, when the COP of the heat pumps is kept constant.

3.1.1 Prognostics for the future

It is hard to predict the conditions of the sewage water for the future, since it is depending on so many external elements out of control. The best way is to analyse historic data and from this make some prognostic for the future. Conditions, like the temperature and the volumetric flow rate, of the sewage water for years 2011 through 2014 are thoroughly analysed. Since similarities in the temperature of the sewage water can be observed for each year this data will be used to make a forecast for futuristic conditions of the sewage water. In figure 3.5 the temperature of the sewage water each hour over one year, for years 2011-2014, can be seen.

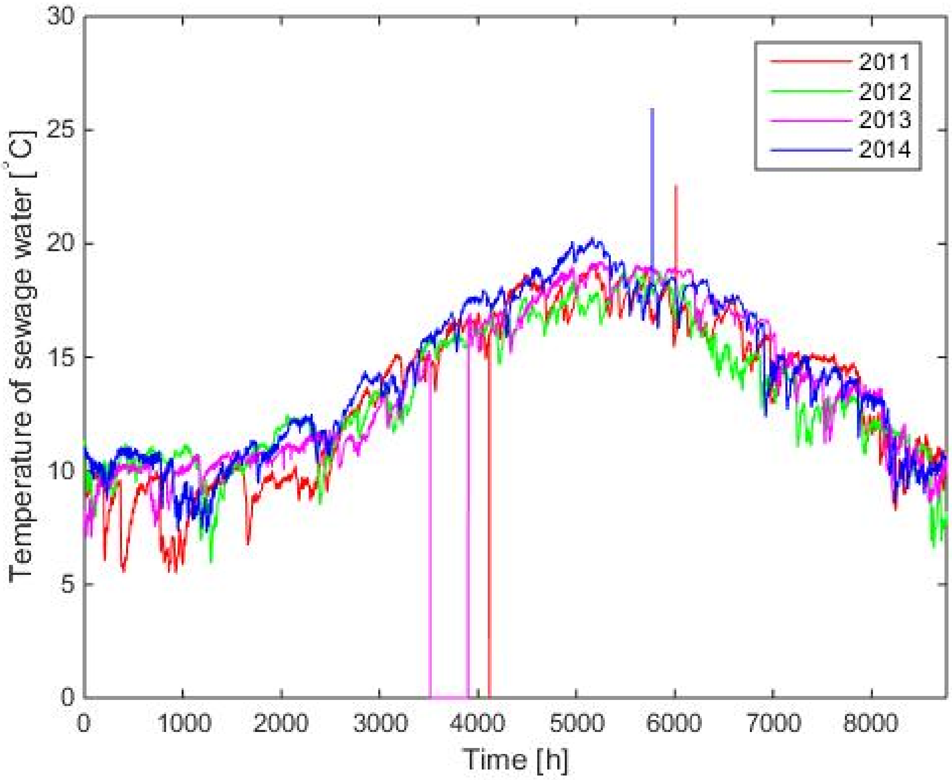


Figure 3.5: The temperature of the sewage water for each hour over the whole year for years 2011-2014.

The volumetric flow rate of the sewage water the second week years 2011 through 2014 can be seen in the figure 3.6. The graph shows the volumetric flow rate of the sewage water each hour over the week.

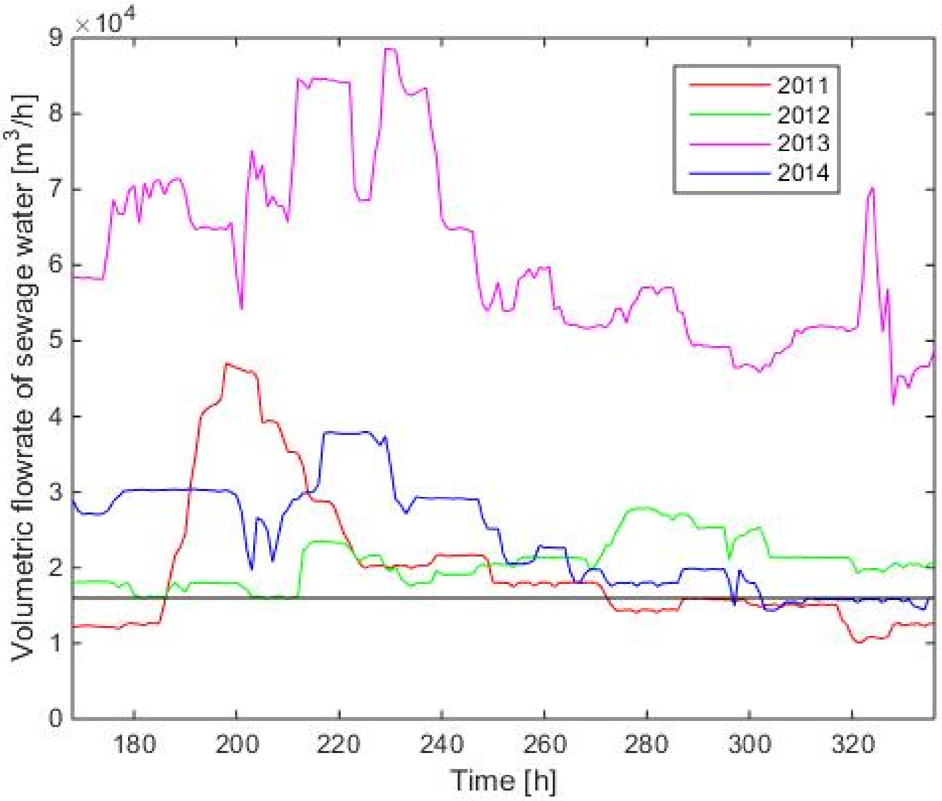


Figure 3.6: The volumetric flow rate of the sewage water for each hour the second week each year for years 2011-2014.

Figure 3.7 shows the averaged volumetric flow rate of the sewage water each day for a whole year the years 2011-2014. The black line in the figure is the restriction on the maximum volumetric flow rate allowed to enter the heat pumps at Ryaverket for the system to be able to pump through the whole water volume.

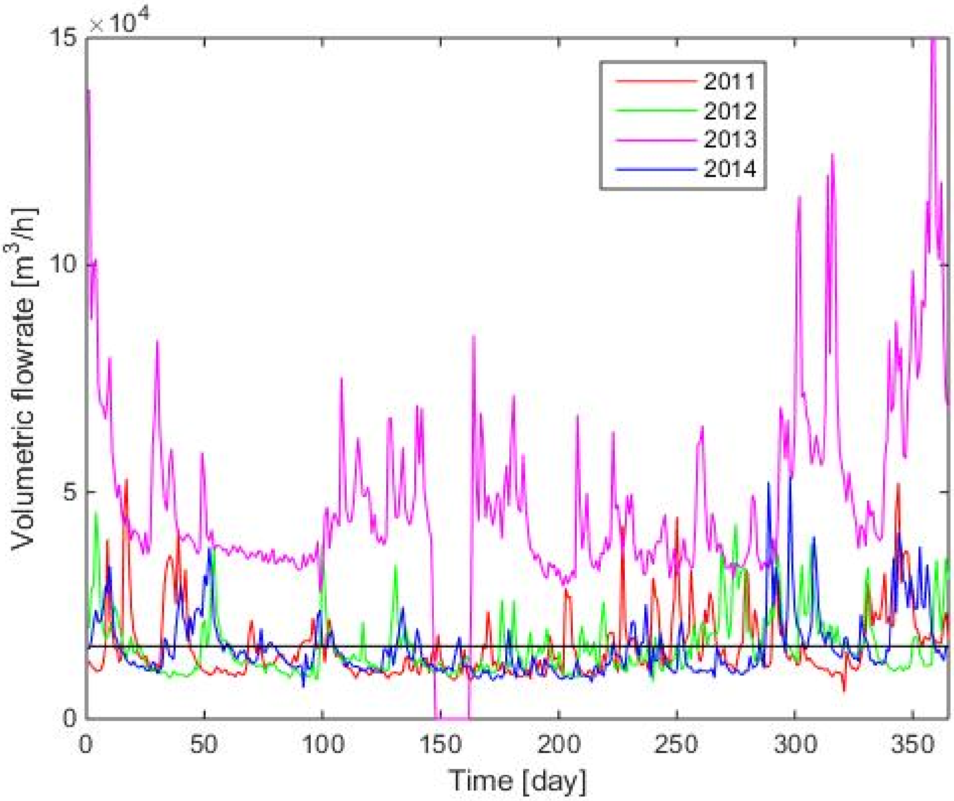


Figure 3.7: The averaged volumetric flow rate of the sewage water for each day the whole year for years 2011-2014.

The volumetric flow rate is differing quite a lot each year. However, by using averaged values on the volumetric flow rates for years 2011-2014 might give an idea of how the sewage water conditions might be in the future. In other words, each hour over the year one averaged value on the volumetric flow rate will be calculated from the years 2011-2014. From figure 3.7 it is clear that the sewage water load year 2013 differs quite a lot from the remaining years. However, when calculating the averaged value for the volumetric flow rate the load of 2013 will only weigh 1/4 of the averaged value. Also, in the future there is a possibility that there will be years when the sewage water load will reach the values of the loads detected in 2013. The averaged values of the volumetric flow rates and the temperatures over the years 2011-2014 will be used when calculating the amount of heat that can be added into the sewage water each hour over the year to improve the conditions of the sewage water before entering the heat pumps. This heat used to improve the conditions of the sewage water will be extracted from LT-BTES.

3.2 Martes

A commercial software named Martes is used to calculate the profitability of investing in a LT-BTES. A brief overview and the approach to the software is described in the text preceding.

3.2.1 Brief overview of the software

Martes is a commercial software that can be used to make detailed simulations and analysis of the heat generation units for the DH-network in Gothenburg. Martes will sort the generation units according to their variable costs and create load duration curves of the heat generation mixes and perform calculations on the economy and environmental aspects for such a generation mix [30].

3.2.2 Input into Martes and assumptions

Göteborg Energi AB has made forecasts for the future regarding heating demand (normal year, cold year and warm year), electricity prices (bought and sold), other fuel prices (natural gas, oil, biofuels, pellet), political instrument like carbon dioxide-tax, other emission allowances, electricity taxes and so on. These will be the input parameters into Martes.

Also the heat generation units contributing to heat generation for DH, disregarding the heat pumps at Ryaverket, will be specified; their sizes, availability and efficiencies. These parameter values are kept the same in each Martes simulation.

The heat pumps are of particular importance for this study, these are the ones that will be alternated. The COP-value is set as the same for all the four heat pumps at Ryaverket. In reality, these heat pumps are rather different from each other and the COP-value will vary quite a bit. The COP-value is calculated as an average of the four heat pumps and for example during occasions when a heat pump with a rather low COP-value is out of operation the averaged COP-value will increase. It is quite hard to foresee how the total COP-value of the heat pumps at Ryaverket will behave in the future so the COP-value will be kept the same each year of simulation.

The availability for HP1 and HP2 will be set as 75% and for HP3 and HP4 the availability will be set as 96%, these availabilities are based on historical data. The availability of a heat pump implies the amount of occasions the heat pump will be operating through the year, disregarding May trough September when these heat pumps are out of operation. Why the availabilities of HP1 and HP2 are lower depends on the fact that when the temperature of the sewage water is too low these pumps are taken out of operation, but HP3 and HP4 will never be taken out of operation for this reason. The availability depends also on occasions when the heat pump is broken and needs to be taken out of operation for reparation. The power output from the heat pumps is the parameter that will be alternated in Martes.

3.2.3 Approach to Martes

Two scenarios will be investigated;

- Scenario without LT-BTES: The power output from the heat pumps will be calculated from the historical data of sewage water.
- Scenario with LT-BTES: The heat pumps at Ryaverket will be supplemented with a LT-BTES. The conditions of the sewage water will be improved, increase in temperature or volumetric flow rate of the sewage water, and the thermal power output from the heat pumps will be calculated from these improved conditions of the sewage water.

At first the scenario without a LT-BTES is run and as a result Martes will produce heat generation mixes for 730 periods (each day and each night) for a whole year each year of simulation. In this study the years 2016-2035 are simulated. In Martes the duration of a day is 16 hours, from 6 a.m. to 10 p.m., and the duration of a night is 8 hours, from 10 p.m. to 6 a.m.. These generation mixes will thoroughly be analysed and noted at which exact occasions the marginal cost of the generation mix is at first the highest and secondly higher than the cost of generating heat by the heat pumps at Ryaverket. At these occasions the amount of heating power that are generated by more expensive heat generation units than the heat pumps will be noted. This is the heat load that can be replaced by increased heat generation by the heat pumps.

As mentioned before the heat load that can be added to the sewage water to improve the conditions is calculated. These heating loads are transformed into averaged values over each day and each night simply to match the resolution that Martes produces and the increased thermal power output from the heat pumps can now be calculated for each day and each night.

The increased thermal power output from the heat pumps is restricted in two ways each day and each night over the year;

- By the heating load that can be replaced under a certain occasion (day/night). The load will be restricted at that occasion to the load of heat generated by more expensive generation units than heat pumps at Ryaverket.
- By the improved thermal power output from the heat pumps. The improved heat pumps can only replace as much heat as the heat pumps can additionally generate. This depends on the heat load that can be added to the sewage water to improve the conditions as much as possible and also on the number of occasions when improvement of sewage water is possible, i.e. when the temperature of the sewage water is lower than 11.72°C or the volumetric flow rate is lower than $16000\frac{m^3}{h}$, c.f. section 3.1.

The scenario without a LT-BTES and the scenario with a LT-BTES will both be run in Martes and the difference between the heat generation costs between these two scenarios will be noted. Martes generates also data of the CO_2-, NOx- and SOx-emissions and the changes in emissions when comparing the scenario without LT-BTES to the scenario with LT-BTES will be analysed.

3.3 Modelling in GLHEpro

The modeling of LT-BTES is performed in a software named GLHEpro. It is a software that can be used for ground loop heat exchanger designs for residential applications. However it is a suitable software for usage in any application for borehole thermal energy storage [31]. GLHEpro bases its borehole modeling on g-functions, which are developed by Eskilson [32]. Basically the g-functions describes how the surrounding ground responds to a heat injection or heat extraction step.

3.3.1 Input, application and assumptions

The input data into GLHEpro required for simulations are; heating and cooling loads, borehole configuration and physical properties of the heat transferring fluid (fluid used for heat extraction and injection) as well as physical properties of the ground.

Heating and cooling loads

The heating and cooling loads will be specified on a monthly basis. Heat extraction from the boreholes will be occurring from October through April. This extracted heat will then be used for heating the sewage water as discussed before. Since there are differences in the heating load requirements of the sewage water over these months an analysis of the heating need, based on simulation results from Martes when the scenario without a LT-BTES is run, over the years 2016-2035 and by noting the historical heating need of the sewage water suitable averaged values are used to decide on the heat extraction loads each month. The heat extraction loads will be weighed in the following way; December through March 17% of the heat will be extracted each month respectively, in November 13% of the heat will be extracted and in October and April 10% of the heat will be extracted both months. The injection of heat will be distributed evenly over five months, May through September.

Two different heat loads will be tested, 50 GWh and 25 GWh. It was previously mentioned that 50 GWh was the waste heat load that at least should be available each year. A heat loss of 10% is assumed which implies that for heat extraction only 45 GWh and 22.5GWh is available.

Borehole configuration

GLHEpro allows its user to choose a configuration regarding how the boreholes should be placed in the borehole field. However, the software is restricted to rectangular- and line-configurations and no hexagonal configuration can be tested. A rectangular configuration as close to quadratic as possible is chosen since this will reduce the heat losses from the storage.

Figure 3.8 is a simple sketch of the borehole to clarify for the terms following in the preceding text. The borehole radius, r_b, is set to 57.5 mm, shank spacing to 36.2 mm, denoted B_u in figure 3.8, the borehole heat exchanger is chosen as the u-pipe type and the inner radius, r_p, is set to 17.7 mm, with a pipe thickness of 2 mm the outer radius results in 19.7 mm. The pipes are set to have a thermal conductivity of $0.42\frac{W}{mK}$ which is the value for polyethylene, a standard material used in borehole heat exchangers [17][18].

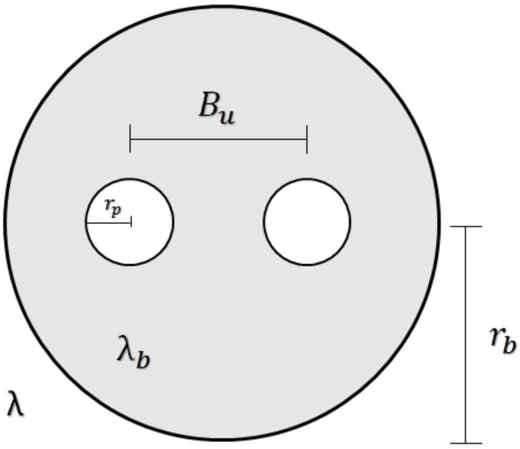


Figure 3.8: Simple sketch of a borehole with a u-pipe inserted.

A borehole depth of 250m is chosen. The depth of the borehole at 250m seems like a suitable choice when carrying on with this study. A depth of 350m would result in a smaller surface area but gives more problems regarding drilling especially when drilling straight. Deviations in the straightness will result in degraded heat transfer properties of the LT-BTES. A less deep borehole of about 150m might give the best heat transfer properties and economy. However, the land area required to fit all the boreholes will be significantly larger than the land area for a borehole depth of 250m larger and it is unclear if there is enough space for a borehole field of this size close to Ryaverket.

Physical properties of working fluid and ground

For heat extraction and injection treated sewage water and water in the DH-network will be used respectively. The physical properties of the heat transferring fluid will be set as water at 20°C (according to the simulation results from GLHEpro the required temperatures on the heat transferring fluid varies between 9 and 35°C). The volumetric flow rate of the water will be kept at $2\frac{m^3}{h}$/borehole.

In most of Sweden the underground structure consists of solid bedrock with a heat transfer coefficient, λ, of about $3.5\frac{W}{mK}$ and this value will be used in the simulations in GLHEpro. In Sweden grouting of the boreholes is often unnecessary since the underground structure allows the boreholes to naturally be filled with groundwater [15]. The groundwater has a heat transfer coefficient, λ_b, of $0.58\frac{W}{mK}$.

A summary of all the geometrical aspects of boreholes and physical properties of the ground and heat transferring fluid are summarized in Appendix 1.

Modelling approach

When all the properties described in the sections above, like heating and cooling loads, geometrical aspects of boreholes and physical properties of ground and the heat transferring fluid are stated in GLHEpro the simulation work can start. The aim will be to find, for a certain size of the borehole field, the temperature of the heat transferring fluid entering the boreholes when extracting and injecting heat each month. A 20 year of simulation is performed. The temperature of the heat transferring fluid GLHEpro states is a restriction that should be fulfilled to be able to extract/inject the desired amount of heat, for a specific month, stated in the setup. However, the water temperature that GLHEpro states each month will vary quite a bit each year, over 20 years, so an averaged value of this temperature a certain month is calculated to find an appropriate size of the borehole field. For heat extraction the lowest temperature requirement (the strictest requirement) on the heat transferring fluid to meet occurs in February, the optimization of the LT-BTES will be done according to this month. Historical data for years 2011-2014 is used to give an estimate of the futuristic averaged temperature of the sewage water in February, this is about 9.2°C. Figure 3.9 shows the averaged variations in the sewage water temperature each day in February for years 2011 through 2014.

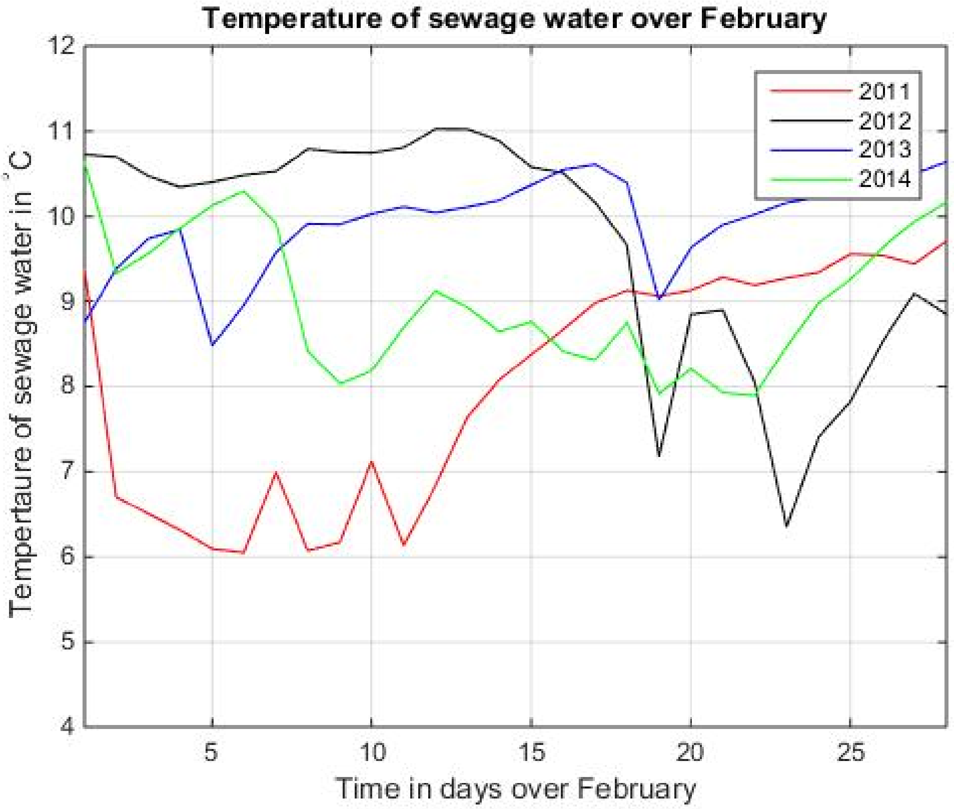


Figure 3.9: The figure shows how the temperature of the sewage water varied over the years 2011-2014 for the month of February.

The temperature of the sewage water over February varies from 6°C to 11°C as can be seen in the figure 3.9. However, since only one temperature restriction of the heat transferring fluid entering the borehole each month is given by GLHEpro an averaged value of the sewage water temperature is calculated and this value is the one used to match the simulation results gained from GLHEpro.

For heat injection the water in the DH-network is used when heat in excess is detected in the DH-network. This water holds a temperature of about 90°C. To be able to inject the desired amount of heat each month into the BTES specified in the setup the temperature of the water never increases 35°C according to GLHEpro. This means that the temperature of the water used for heat injection will never be the restricting factor.

When choosing the size of the borehole field the GLHEpro version available allows simulations of borehole fields of 400 boreholes at maximum. If the amount of boreholes exceeds 400 the software will interpolate the properties of larger borehole fields and the results will be approximate.

3.4 Economics of LT-BTES

Hallqvist [16] made a thorough research for Göteborg Energi AB in 2014 regarding costs for building a borehole thermal energy storage. Hallqvist himself made a correction during the spring of 2015 and stated that the drilling prices were set too high and a 20% reduction of the drilling prices seems more accurate. The economic entries included in the investment cost of building a BTES are given a price range; a minimum, a maximum and a probable value and these will make the base for the economic analysis of implementing a LT-BTES. The prices for the economic entries are presented in table 3.2.

Table 3.2: Presented are the costs of the economic entries included when building a LT-BTES.

Economical entry	Probable price	Mininmum price	Maximum price
Cost of connection [MSEK]	3	1	6
Startup-cost [SEK/borehole]	3000	2000	5000
DTH-drilling [SEK/meter borehole]	160	120	240
ODEX-drilling [SEK/meter borehole]	560	400	800
Overhead drilling expenses [SEK/borehole]	8000	8000	8000
Injection of betonite for sealing purposes [SEK/borehole]	17500	15000	20000
Borehole heat exchanger [SEK/meter borehole]	100	50	150
Ground preparation, pumps and connecting pipes [SEK/meter borehole]	150	100	200
Salvage value [%]	50	70	30

The cost of connection includes costs for all the pipe installations, pumps, electric equipment, control system and other components that are of importance when connecting the LT-BTES to the heat pumps at Ryaverket. Start-up cost is as the name states the cost for starting up the project, ODEX- and DTH-drilling are simply the costs of drilling the boreholes. It is assumed that 5% of the boreholes needs additional sealing due to cracking in the bedrock.

The cost for ground preparation, pumps required to operate the LT-BTES and connecting pipes between the holes are given a common entry which depends on the total depth of the boreholes. The cost for borehole heat exchanger is depending on the depth of the borehole.

Costs including the rent or purchase of land area and also the maintenance cost for the LT-BTES have been overlooked in this economic evaluation and according to Hallqvist [16] these entries should not affect the economics much.

As previously mentioned, in Sweden boreholes are usually filled with water and to avoid polluted water from entering the holes casing is used on the top. However, casing is not considered in this study.

For economic calculations a payback period of 20 years is considered. The economic profitability of supplementing the heat pumps with a LT-BTES is analysed for the years 2016-2035. For economic calculations an interest rate of 7% has been used and an inflation rate of 2%. The salvage value is assumed to be 50%, 70% and 30% of the investment cost for probable, minimum and maximum price scenario respectively.

3.4.1 Sensitivity analysis

The sensitivity of some parameters for the economic profitability is tested. These parameters chosen for sensitivity analysis are believed to change in the future alternatively are hard to give a futuristic value for and are affecting the profitability of the LT-BTES. In this study the tested parameters will be; the availability of the heat pumps, the electricity price, subsidies from Horizon2020 and a lower interest rate.

The availability of HP1 and HP2 will be increased by 6% and 15% and will result in availabilities of 80% and 86%. The electricity price will be decreased and increased by 10%. Subsidies to cover 40% of the investment cost and lower interest rates, 5% and 0%, will also be tested.

A summary of the parameters chosen for sensitivity analysis and a short description is provided in table 3.3

Table 3.3: The parameters chosen for sensitivity analysis.

Parameter	Short description
Heat pump availability	The availability of HP1 and HP2 increased by 6% and 15%
Electricity price	The electricity price is decreased and increased by 10%
Subsidies from Horizon2020	Subsidies to cover 40% of the investment cost
Interest rate	Interest rates of 5% and 0% will be tested

4

Results

This section will at first present the results from Martes simulations, then continue to designs of the LT-BTES and lastly present the results from economic calculations and the sensitivity analysis performed.

4.1 Martes simulations

This section will summarize the most important results and observations from Martes simulations.

4.1.1 Waste heat utilisation and thermal power output from heat pumps

Performing simulations on the scenario without a LT-BTES in Martes showed that for years 2020-2025 and 2034-2035 the heat pumps are already for several occasions working on the margin and that there was not use for the whole waste heat load of 45GWh to improve the conditions of the sewage water, i.e. all waste heat of the larger storage size could not be utilised. In fact, these years only about 20GWh could be used, why it seemed suitable to carry on studies with the half storage size storing 25GWh of waste heat.

The thermal power output of the scenario without a LT-BTES connected to the heat pumps (blue line in figures 4.1 and 4.2) and of the scenario with a LT-BTES as a supplement to the heat pumps (red line in figures 4.1 and 4.2) for years 2016 and 2025 can be seen in figures 4.1 and 4.2. These figures represents the improved thermal power output from the heat pumps connected to a LT-BTES that stores 25GWh waste heat.

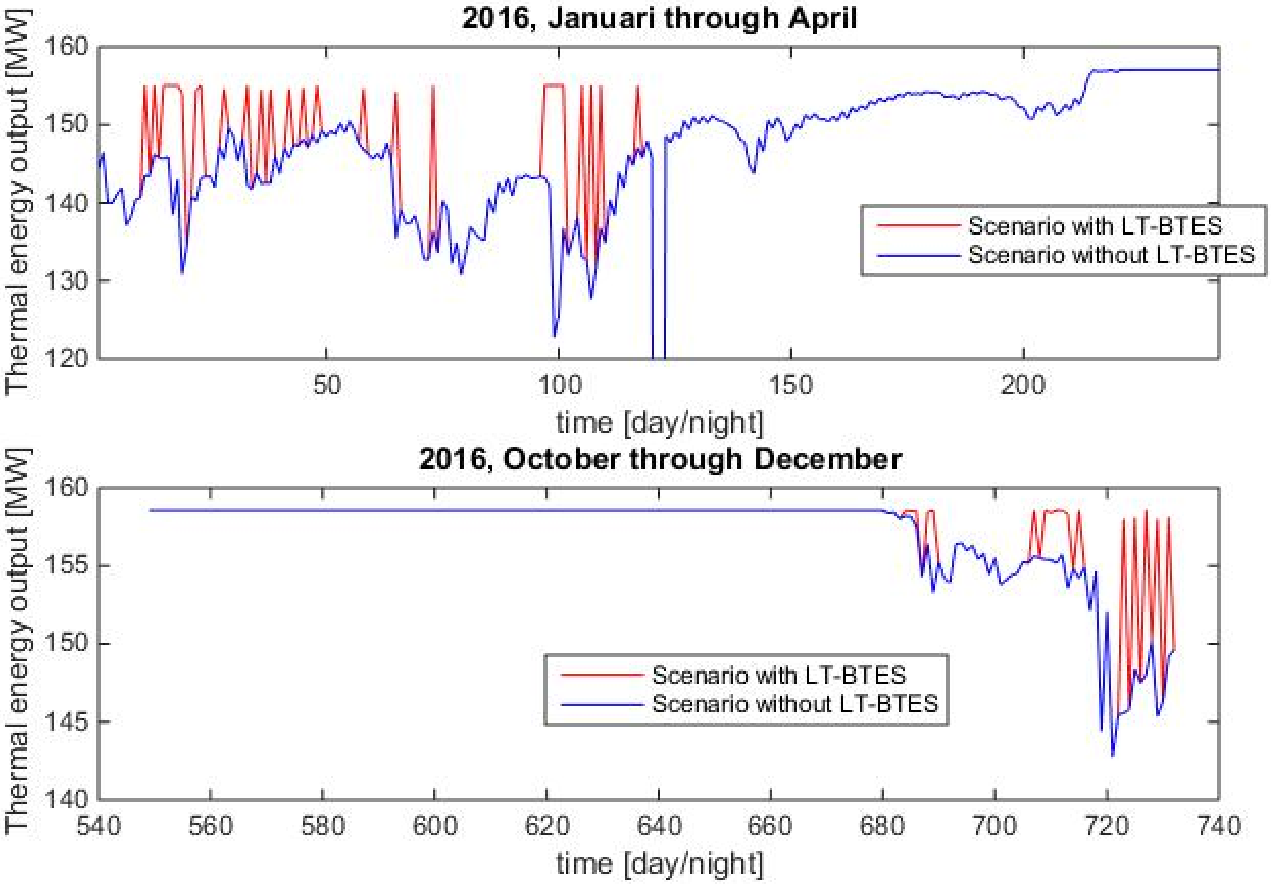


Figure 4.1: Increased thermal power output from heat pumps for the year 2016. The blue line represents the scenario without a LT-BTES and the red line represents the scenario with a LT-BTES.

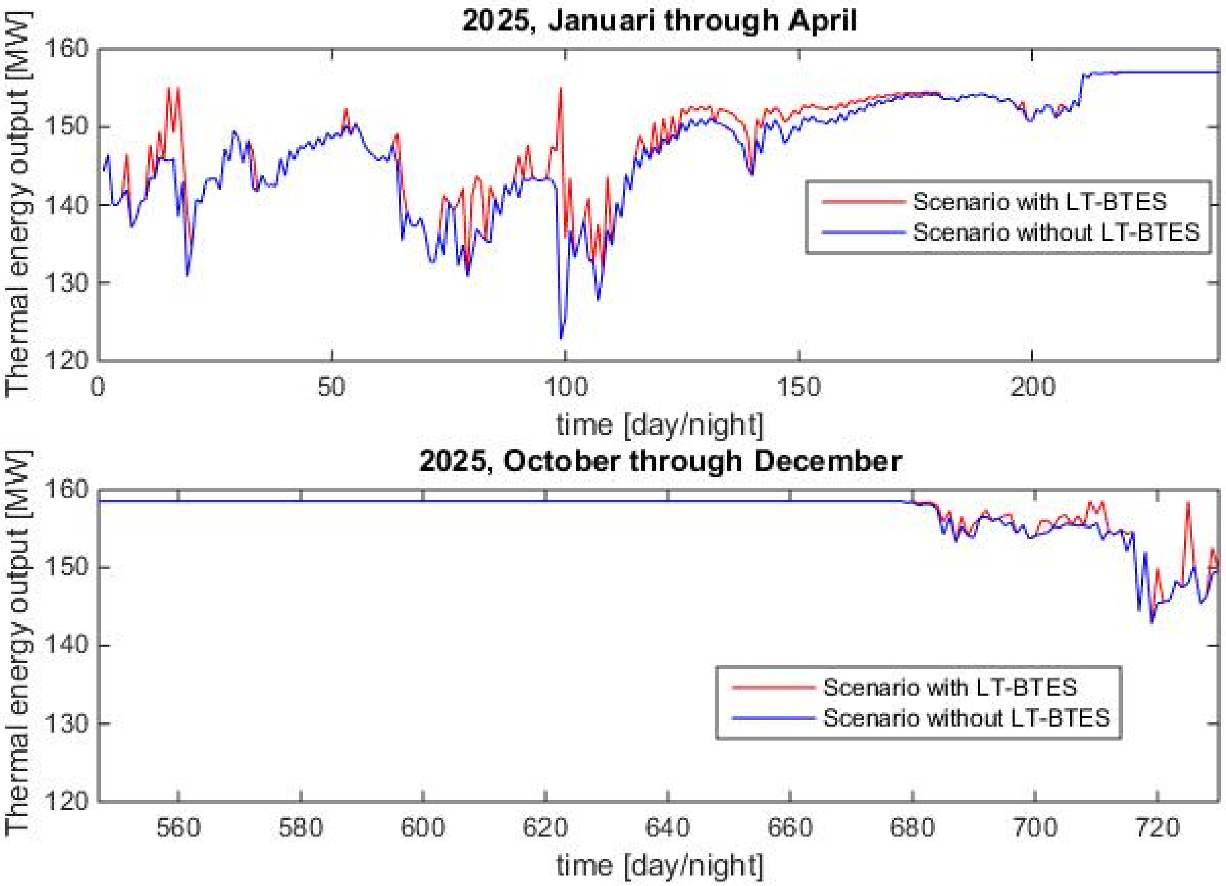


Figure 4.2: Increased thermal power output from heat pumps for the year 2025. The blue line represents the scenario without a LT-BTES and the red line represents the scenario with a LT-BTES.

The resolution of the graphs above is each day and night over one year. As mentioned in section 3.2.3 the duration of the day is 16 hours and the duration of the night is 8 hours. The maximal thermal power output increase is about 20MW at few, maybe only one, occasions. It is evident that the occasions that are most receptive for increased thermal power output occurs in February, March and December. January is also an important month. However there are some variability regarding the most receptive months between different years and the increased thermal power output from the heat pumps the remaining years, not shown here, could have looked rather different.

The increase in thermal power output from the heat pumps is depending on the conditions of the sewage water and how much the conditions can be improved each day and night and also on the heat load that can be replaced by the heat pumps, i.e. the heat load that at that specific occasion is generated by more expensive heat generation units than the heat pumps. This is why the graphs above shows oscillatory behaviour since at some occasions the conditions of the sewage water might already be the best possible and no heat can be added to the sewage water or that the pumps already works on the margin and no increase in thermal power output from heat pumps is possible. Another reason for the oscillatory behaviour is that the primary focus is to replace the heat generated by units that are the most expensive and to first find these exact occasions, and secondly, if there is heat left proceed to replace heat generated by heat generation units that are less expensive to operate.

4.1.2 Replaced energy flows

An increased heat generation by the heat pumps will primarily replace heat generation by natural gas-fired heat only boilers (HOB) located in west and east. Heat generated by the pellet-fired hot water central (HVC) at Rya is also being replaced at occasions.

The figures 4.3, 4.4 and 4.5 will show the heat generation by these units for the scenario without a LT-BTES and the scenario with LT-BTES, for years 2016, 2024, 2028 and 2032. The months May through September are of no interest here since the heat pumps are out of operation these months.

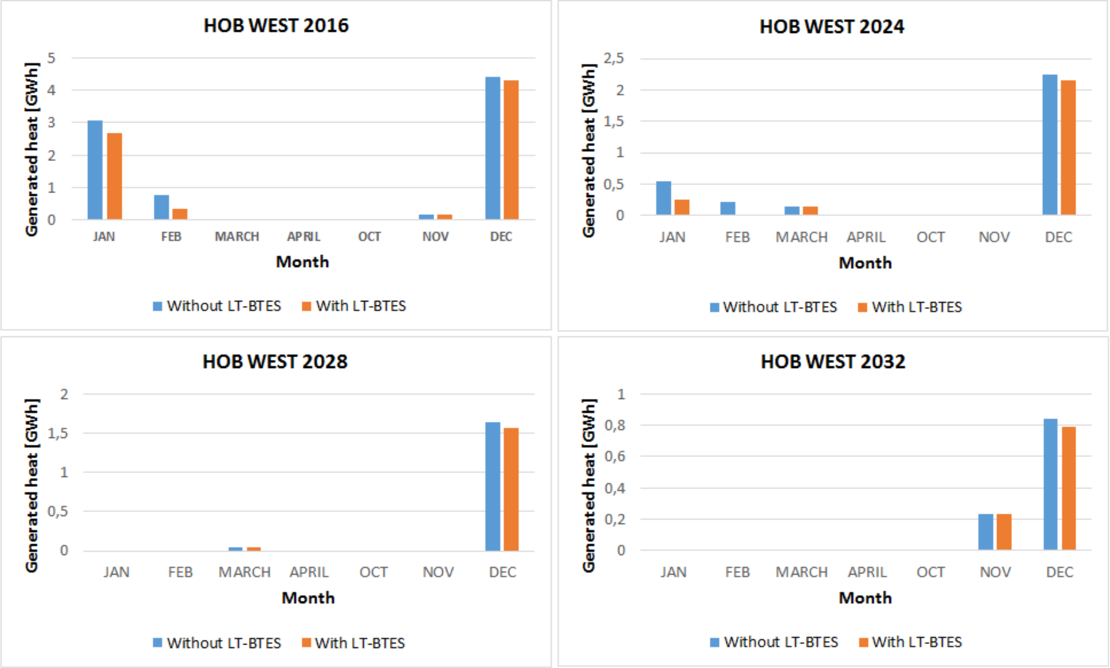


Figure 4.3: This figure shows the generated heat, for the scenario without LT-BTES and the scenario with LT-BTES, by the natural gas-fired HOB WEST.

An increased heat generation by the heat pumps will primarily and the most replace heat generated by the HOB WEST. The largest decrease in heat generation for this unit occurs in the early months of the year, January and February, and the early years, 2016 and 2024. The decrease in percentage when comparing a scenario with LT-BTES to a scenario without LT-BTES is presented in table 4.1.

Table 4.1: Decrease in heat generation by HOB WEST in percentage when adding the LT-BTES as a supplement to the heat pumps at Ryaverket.

Year	January	February	March	April	October	November	December
2016	-12%	-54%	-	-	-	0	-3%
2024	-54%	-100%	0	-	-	-	-4%
2028	-	-	0	-	-	-	-4%
2032	-	-	-	-	-	0	-6%

The resulting decrease in heat generation by HOB EAST is shown in figure 4.4

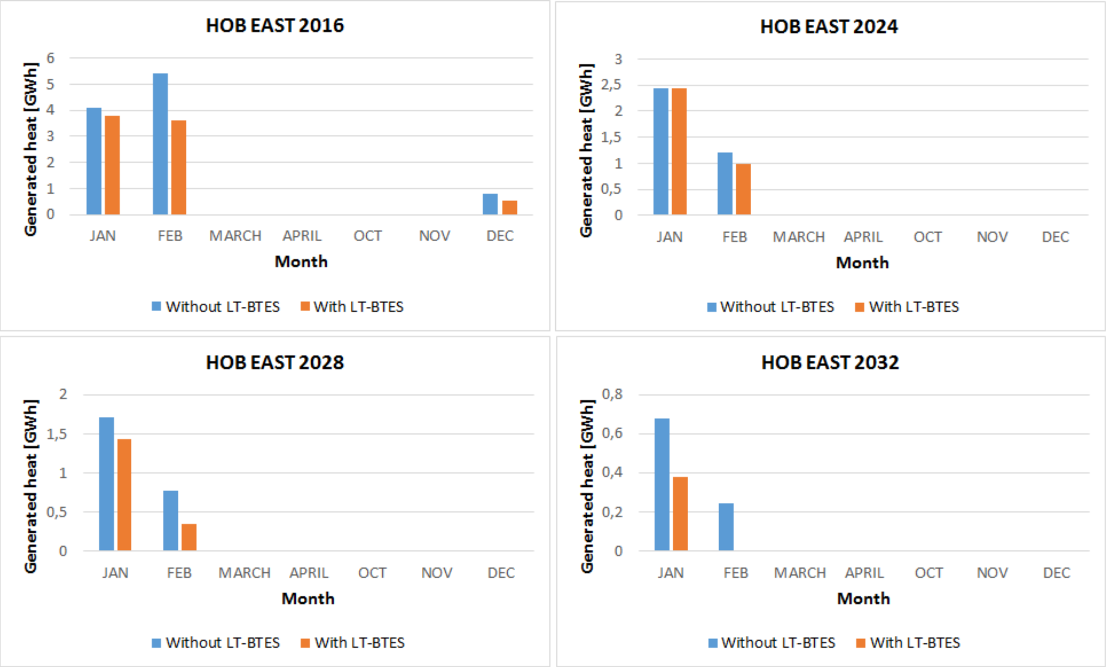


Figure 4.4: This figure shows the generated heat, for the scenario without LT-BTES and the scenario with LT-BTES, by the natural gas-fired HOB EAST.

Similarly as for HOB WEST, the heat generation by HOB EAST decreases the most in January and February. Table 4.2 summarizes the decrease in heat generation in percentage, when comparing a system with LT-BTES to a system without LT-BTES.

Table 4.2: Decrease in generated heat by HOB EAST in percentage, when adding a LT-BTES as a supplement to the heat pumps at Ryaverket.

Year	January	February	March	April	October	November	December
2016	-8%	-33%	-	-	-	-	-31%
2024	0	-19%	-	-	-	-	-
2028	-17%	-54%	-	-	-	-	-
2032	-44%	-100%	-	-	-	-	-

Comparing the results for replaced heat generation of HOB EAST to replaced heat generation of HOB WEST the decrease in heat generation by HOB WEST occurs the most the early months and early years and the decrease in heat generation by HOB EAST occurs more during later years. This has to do with the fact that the HOB WEST has a higher operational cost and during later years when the heat demand in the DH-network decreases this heat generation unit is not needed anymore and hence taken out of operation. In turn HOB EAST will now operate on the margin and heat generated by this unit will be replaced by increasing the operation of the heat pumps.

Figure 4.5 shows the decrease in heat generation by the pellet-fired HVC at Rya.

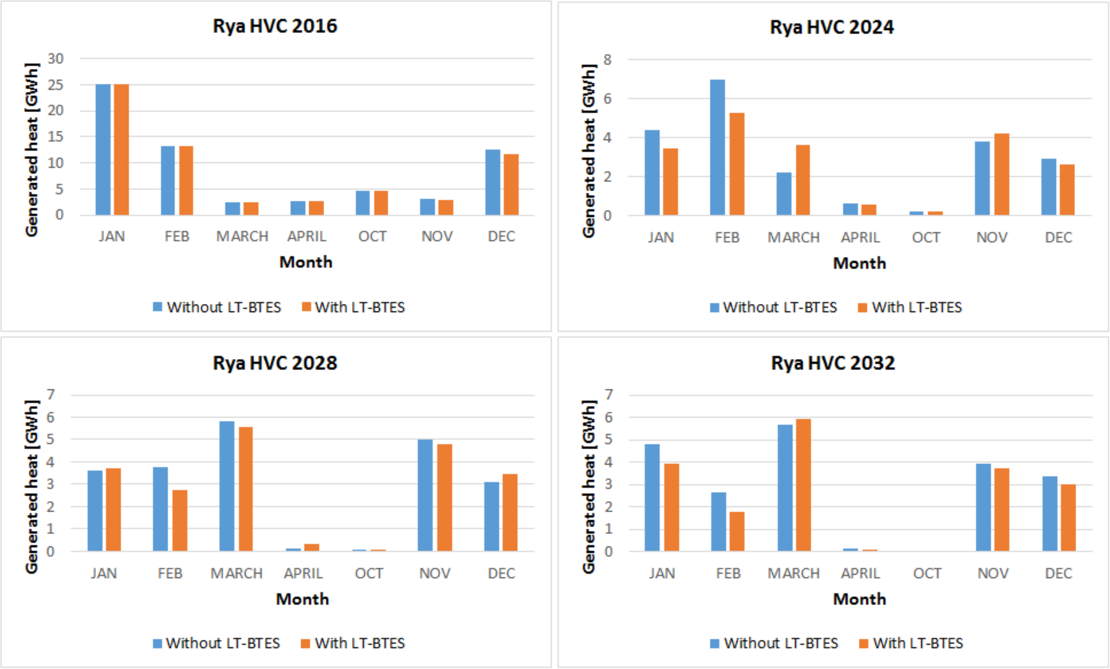


Figure 4.5: This figure shows the generated heat, for the scenario without LT-BTES and the scenario with LT-BTES, by the pellet-fired HVC at Rya.

Table 4.3 shows the changes in heat generation by Rya HVC, when the LT-BTES has been added as a supplement to the heat pumps at Ryaverket, in percentage.

Table 4.3: Change in heat generation by Rya HVC when comparing a system with LT-BTES to a system without LT-BTES.

Year	January	February	March	April	October	November	December
2016	0	-1%	0	0	0	-4%	-7%
2024	-22%	-25%	-62%	-15%	0	+12%	-10%
2028	+4%	-28%	-5%	+71%	0	-4%	+11%
2032	-18%	-33%	+4%	-21%	-	-5%	-11%

The HVC at Rya has a lower operational cost than the HOBs and thus the heat generation decrease is not as extensive for Rya HVC. However, during later years and during months when the heating demand for the DH-network is lower (March, April and November) the HOBs are out of operation and this leads to a decrease in the heat generated by Rya HVC since now this unit is operating on the margin and an increased heat generation by the heat pumps is now replacing heat generated by Rya HVC.

It is interesting that Rya HVC increases in operation at some occasions, year 2024 in November, year 2028 in January, April and December and year 2032 in March.

Reduced emissions

Reductions in CO_2-, NOx- and SOx-emission, for a total of 20 years, are presented in table 4.4.

Table 4.4: A summary of the CO_2-, NOx- and SOx-emissions for scenario without LT-BTES and scenario with LT-BTES.

Emissions in 10^3kg	CO_2	NOx	SOx
Scenario without LT-BTES	$4.99 \cdot 10^6$	$2.82 \cdot 10^3$	588.9
Scenario with LT-BTES	$4.96 \cdot 10^6$	$2{,}80 \cdot 10^3$	588.02
Difference	$-35.12 \cdot 10^3$	-19.59	-0.89

The largest reductions occurs in CO_2- and NOx-emissions. This is due to the fact that the operation of natural gas-fired HOBs are decreased when increasing the operation of the heat pumps. Even though, not presented above, at a few occasions the heating demand reaches peak values and heating oil-fired plants are taken into operation to be able to satisfy this demand. These occasions are rare and almost all of the heat generated by these heating oil-fired plants can be replaced by the heat pumps. A decreased operation of these heating oil-fired plants results in decreased SOx-emissions.

A reduction of CO_2-emissions of $35 \cdot 10^6$kg seems large. However, it is only a reduction of 0.7% when comparing the scenario with a LT-BTES to the scenario without a LT-BTES. The NOx-emissions are also reduced by about 0.7% and the SOx-emissions are reduced by 0.2%.

4.2 Modeling of LT-BTES

The resulting designs for the LT-BTES storing 50GWh and 25GWh of heat are presented in table 4.5. The design parameters of the LT-BTES were chosen as explained in section 3.3.1, see Appendix 1.

Table 4.5: Results from LT-BTES design.

Size of storage [GWh]	50	25
Number of boreholes	1849	961
Storage volume $\cdot 10^6 m^3$	29.58	15.38
Storage area $\cdot 10^3 m^2$	118.34	61.50
Boreholes per GWh	36.98	38.44

From the results above it is evident that doubling the amount of stored heat also doubles the storage volume. This means that the energy density in the both storage sizes is the same.

4.3 Economics

The results from economic calculations of the two LT-BTES, storing 50GWh and 25GWh of waste heat, are presented in table 4.6.

Table 4.6: Economical calculations of LT-BTES designs, storing 50GWh and 25GWh of heat.

Stored heat load	50 GWh			25 GWh		
Economic scenario	Probable	Minimum	Maximum	Probable	Minimum	Maximum
Inv. cost [MSEK]	218.92	148.79	310.83	115.22	77.81	164.43
Savings [MSEK]	17.81	17.81	17.81	17.02	17.02	17.02
Salvage Value	28.29	26.92	24.1	14.89	14.08	12.75
NPV	-172.82	-104.06	-268.91	-83.32	-46.72	-134.67

Neither of the LT-BTES designs gain economic profitability (i.e. the NPV is negative). However, the smaller LT-BTES, storing 25 GWh of waste heat, has larger potential for economic profitability. The relative savings of the LT-BTES storing 25GWh of heat are much larger, 17.02 MSEK, than for the LT-BTES storing 45GWh of heat, 17.81 MSEK.

4.3.1 Sensitivity analysis

Since the LT-BTES storing 25GWh of heat has larger potential for economic profitability sensitivity analysis has been performed on this LT-BTES and the results are presented in this section.

As mentioned in section 3.4.1 the following sensitivities were tested;

- 1. Increased heat pump availability to 80%
- 2. Increased heat pump availability to 86%
- 3. Decreased electricity price by 10%
- 4. Increased elecricity price by 10%
- 5. Subsidies 40%
- 6. An interest rate of 5%
- 7. An interest rate of 0%
- 8. A combination of increased pump availability to 86%, subsidies 40% and an interest rate of 5%

The complete results from the sensitivity analysis are presented in Appendix 3.

Figure 4.6 summarizes the NPV for each sensitivity tested and also the NPV for the basic case, scenario with LT-BTES as a supplment to the heat pumps but without any changes in parameters, can be seen for comparative purposes.

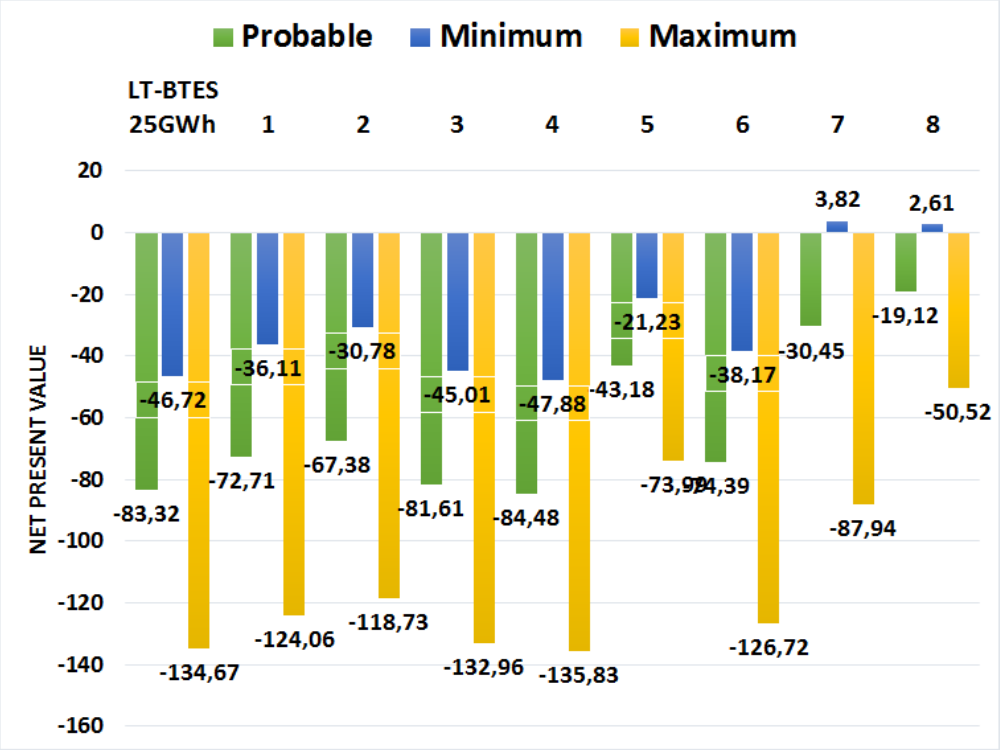


Figure 4.6: Summary of the NPV for the basic case, no changes in parameters, and NPV achieved from the sensitivity analysis.

Economic profitability is hard to gain. The largest change in NPV will be achieved with the aid of subsidies covering 40% of the investment cost or if the interest rate is set as 0%. Lowering the investment cost with the aid of subsidies makes an significant impact since the investment cost is about ten times the size of the gained savings and by reducing the investment cost of the LT-BTES extensive changes in the NPV can be obtained. Using an interest rate of 0% for economical calculations increases the savings extensively and the salvage value becomes also significantly higher than for a case with a higher interest rate. This is the reason that economic profitability can be reached for economic calculations for investment cost of the minimum price scenario and with no interest rate at all.

The activity of the heat pumps makes also an obvious impact on the economy. Increasing the heat pump activity by 6% increases the NPV by 13% and increasing the heat pump activity by 16% can increase the NPV by 19%.

A decreased electricity price of 10% increases the savings by 10%. However, an increased electricity price of 10% decreases the savings only by 6.9%.

Economic profitability is also obtained if the economic entries for investment cost are of the minimum price scenario, by increasing the heat pump activities of HP1 and HP2 by 15%, covering 40% of the investment cost with subsidies and using an interest rate of 5% for economic calculations.

5

Discussion

This chapter will discuss different assumptions made when carrying on with the study. The results will also be discussed and improvements that could have been made.

5.1 Electric power consumption of the heat pumps

To be able to maximize the thermal power output from the heat pumps the electric power consumption of the heat pumps, which is depending on the temperature and flow rate of the sewage water, the heat source, was thoroughly analysed as described in section 3.1. It was concluded that at high volumetric flow rates of the sewage water and rather high temperatures (>10.5°C) the electric power consumption of the heat pumps would be higher if the flow rate of the sewage water was maximized by adding cold water from the heat pump exit (at 3.5°C) and ending up with lower temperature of the water entering the heat pumps, Approach 2 c.f. section 3.1, when compared to a case when no additional water was added, Approach 1 c.f. section 3.1. In both cases the heat extraction load from LT-BTES was the same. For sewage water temperatures increasing 10.5°C the initial sewage water flow rate required, to obtain the highest thermal power output from the heat pumps by maximizing the flow rate, is different for every infinitesimal change in the initial sewage water temperature. To simplify things, in this study some discrete intervals, of about 0.45°C, were chosen and the volumetric flow rate required to reach maximal thermal power output from the heat pumps by maximizing this flow rate, for that exact initial sewage water temperature, was chosen according to the lowest temperature in each interval. An infinitesimal division of the temperature intervals would have improved the results but the extent of improvement would not have changed the results significantly.

5.2 Martes simulations

This section will discuss Martes simulations and assumptions made and also the results from Martes simulations regarding generation units and emissions.

5.2.1 Input and approach to Martes

The COP-value for all the heat pumps at Ryaverket is set as the same and kept constant each year of simulation. This is not the case in reality, since the COP-value at Ryaverket is an averaged value of the heat pumps in operation and if one heat pump with a lower relative COP-value is taken out of operation the COP-value at Ryaverket will increase significantly (the COP-values of the heat pumps vary from about 2 to 4). Since it is hard to predict how the heat pumps will be operating in the future the COP-value will be kept the same each year of simulation and this seems like an acceptable approximation.

The input data for preceding years regarding heat demands, fuel prices, availability of generation units and other factors are predicted by experts at Göteborg Energi. However, these parameters are rather hard to predict since it is hard to foresee the future. However using data according to predictions by Göteborg Energi seems acceptable for this study.

5.2.2 Replaced energy flows

The early years and early months, January and February, heat generated by NG-fired HOB WEST is replaced the most by increasing heat generation by the heat pumps. During early years the heating demand for DH is that high that HOB WEST needs to be run however, improving the operational conditions for the heat pumps and thus increasing the operation of these, the expensive HOB WEST can be replaced to large extent. During later years the heat demand for DH is lower and since the operational cost for HOB WEST is the most expensive, this generation unit will not be in operation at all anymore. The HOB EAST shows a similar trend, during early years and months a lot heat generated by this unit can be replaced. However, this unit is also in operation during later years, since this generation unit is slightly lower in operational cost than HOB WEST and during these occasions the increased heat generation by heat pumps implies decreased heat generation by this heat generation unit.

Rya HVC is replaced to a larger extent during later years and this has the same reasoning as for the units described before. Rya HVC is a cheaper heat generation unit than the HOBs but during the later years when the HOBs are out of operation, due to decreased heating demand in the DH-network, heat generated by Rya HVC can be replaced by heat generated by the heat pumps to a larger extent.

Rya HVC is increasing in operation some months, years 2024, 2028 and 2032. The reason behind this is that there is a heat and power plant, Rya KVV, that is slightly more expensive, regarding the operational cost, compared to the heat pumps but less expensive compared to the operational cost of Rya HVC. There is a requirement for minimum heat load generated by Rya KVV for this unit to be in operation. When the heat pumps are increased in operation the residual load might be too low for the Rya

KVV to be taken into operation. This means Martes will produce two heat generation mixes;

- A heat generation mix where the heat generated by the heat pumps is increased. This does not leave enough heat load for Rya KVV to be taken into operation, hence the rest of the heating demand is satisfied by other more expensive heat generation units than Rya KVV and the next unit in operational cost is Rya HVC which means that the operation of this unit is increased.
- A heat generation mix that will include Rya KVV. This means that the operation of the heat pumps will be decreased to fit Rya KVV into the heat generation mix.

Of these two options described above Martes will choose the generation mix that has a lower cost. At times the latter case described above has a lower cost and the operation of the heat pumps will decrease and at times the first option described will be the cheaper mix and this explains why Rya HVC increases in operation at occasions.

Reduced emissions

By supplementing the heat pumps with a LT-BTES reductions in greenhouse gas emissions are obtained. However, this is the result obtained when the system boundaries are drawn to the system generating DH for the Gothenburg region. Energy flows from NG-fired HOBs and pellet-fired HVC are replaced by increasing the heat generation of the heat pumps. Heat pumps consumes electricity and this means that additional electricity will be consumed when increasing the operation of the heat pumps. An increased electricity consumption implies an increased electricity generation. This increased electricity generation will fall outside the system boundaries. Increased electricity generation implies increased emissions, which also falls outside the system boundaries. How much the emissions increase is hard to say and if the emissions, from a global point of view, will in fact decrease or increase.

5.3 Modeling of LT-BTES and heat losses

Some assumptions are made when performing simulations in GLHEpro. The heat injection and extraction loads are set on a monthly basis, which is quite a major approximation. When trying to maximize the power output from the heat pumps, at some occasions, the heating load of the sewage water can reach rather high values and at other occasions the heating loads become low or non-existent, i.e. the heat extraction load is rather oscillatory through the year. The heating loads of the sewage water of the months are also very specific for each year of simulation. To manage to meet the heating demands for each day and night some sort of accumulator tank should be used in the system to obtain this oscillatory behaviour of placing the extracted heat on the desired occasions. In this study the heat extraction loads in GLHEpro are specified as even throughout the whole month. Also the heat load is the same each year of simulation. A larger borehole field could also have been an option to meet this oscillatory behaviour of the heat extraction load.

The optimization aim, when designing the borehole field, was to match the averaged entering temperature of the heat transferring fluid into the LT-BTES with the temperature of the sewage water for the month of February, since the most restricted requirement on this heat transferring fluid occurs during this month. The temperature of sewage water fluctuates quite a lot during February and the aimed value of 9.2°C when modeling is just an averaged value for February calculated from years 2011 through 2014. GLHEpro gives the temperature of the entering fluid into the boreholes every February each simulating year. This temperature is varying a bit each year of simulations. The averaged value for this temperature for February over 20 years of simulation has been calculated to find a design for the borehole field. It is also hard to predict what the temperature is going to be in February for the years to come.

When specifying the heat extraction and injection loads in GLHEpro a heat loss of 10% was assumed. In other words the heat loads injected were 50GWh or 25GWh and the heat loads extracted were 45GWh and 22.5GWh. A 10% heat loss is higher than it would be in reality. Some rough steady-state calculations on the heat losses, equation 2.1, resulted in heat losses of about 7%. In GLHEpro it can also be seen that the heat losses are lower than 10% since the temperature requirements on the heat transferring fluid when extracting heat are less strict later years of simulation. From this can be concluded that the temperature in the ground is increasing each year of simulation, hence not as much heat is extracted and lost from the ground as the heat load injected into the ground each year.

In GLHEpro the maximum amount of boreholes that can be modeled is 400, a larger field can be modeled but the program will interpolate the properties of this larger field. However the error factor that this gives rise to do not seem to be that significant.

5.3.1 Borehole geometry

The value of 250m as the depth of the boreholes is used in the calculations. This has two reasons; A deeper borehole will give a smaller surface area of the borehole field and when building a LT-BTES it might be easier to find a location to fit this field. However the drilling part will be trickier and the deeper the borehole the harder drilling straight will be. Harder to drill implies also higher costs. Deviations from the straightness of the holes will result in degraded heat transfer properties. A less deep hole will result in easier drilling and also imply less costs. However since the geographical location of the LT-BTES has not been investigated in this study it is hard to know how much surface area could be available. So a depth of 250m seems like a suitable choice to use in this study.

5.4 Economics

The savings gained from a LT-BTES storing 25GWh of heat compared to the savings gained from a LT-BTES storing 50GWh of heat does not differ that much. This is because the years 2020-2024 and 2034-2035 all 45GWh waste heat (after 10% of heat losses) could not be utilised for heat pump improvement. The heat pumps are already working on the margin for several occasions these years and only about 20GWh of heat could be used to improve the conditions of the sewage water and hence increase the heat generated by the heat pumps. The second reason to why the relative savings for the larger storage size are much smaller is because the heat load available is high enough to replace heat generated by units that are only slightly more expensive in operational cost than heat pumps, whereas the heat load of the smaller storage size is only enough to replace heat generated by the most expensive units. In this study the optimal storage size (the size that gives the largest relative savings) has not been found but it is possible that the most optimal solution is a LT-BTES storing less heat than 25GWh.

When calculating the savings by implementing a LT-BTES as a supplement to the heat pumps at Ryaverket, the first year of assumed savings occur in 2016. In reality the LT-BTES would not be built that fast, even if the work started today, to be fully operated in 2016. To reach full operation of the LT-BTES some years of only heat injections and hardly any heat extractions are also required. However, since this is a first evaluation of such a system it seems acceptable to assume that the LT-BTES already physically exists and is in full operation. This approximation will result in overestimated savings.

5.4.1 Heat pump availability

A higher availability of the heat pumps HP1 and HP2 will result in a higher amount of savings compared to when other significant parameters for economical sensitivity are varied. As described before, the heating plant at Ryaverket consists of four heat pumps; HP1, HP2, HP3 and HP4 and have availabilities of 75% (HP1 and HP2) and 96% (HP3 and HP4). The reason for the lower availability of HP1 and HP2 is that the temperature of the sewage water, the heat source of the heat pumps, is sometimes too low for these heat pumps to be in operation, however HP3 and HP4 will never be taken out of operation for this reason. By connecting the LT-BTES as a supplement to the heat pumps implies increased conditions, mostly temperature, of the sewage water and this will result in a higher availability of HP1 and HP2.

How large increase in availability with a LT-BTES can be obtained, is hard to predict though. Some calculations could be done to investigate this but unfortunately in this study the timetable is too narrow.

5.4.2 Electricity price

The electricity price for the future is set by experts at Göteborg Energi AB. Market prices, demand and supply, weather and other factors are weighed in when making a prognostics for the futuristic electricity price. However, it is extremely hard to foresee the future and seldom the prices agrees in the end. In this study the electricity price has been increased and decreased by 10% just to see the economic sensitivity to these changes. A decrease of 10% resulted in an increase of savings by 10%. However an increase in electricity price of 10% resulted in a decrease of savings of only 6.8%. This difference might be due to the fact that an increased electricity price might result in a higher operational cost of the heat pumps than for another generation unit that for the initial electricity price had a slightly higher operational cost. Now, when the electricity price increases and the heat pumps bypasses this other generation unit in operational cost the heat pumps are utilised less and the slightly cheaper generation unit is operated instead.

5.4.3 Subsidies

Waste heat storage could be an accurate solution for a sustainable future and as mentioned before LT-BTES can have a lifetime of 100 years. Waste heat that is used as an energy source in this study already exists in the DH-network. When there is an excess of heat in the DH-network, the water of the DH-network is cooled against a river or in a cooling tower at a waste incineration plant to get rid of this excess heat and to be able to meet the heating demand of the customer. By storing this heat (and this way meet the heating requirement of the customer) and later when needed use the stored heat for heat generation purposes less attractive heat generation units, from an environmental point of view, will be replaced at least to some extent. This could be enough motivation to gather subsidies from Horizon2020. How much subsidies will be gained is hard to predict, if at all, but a case where subsidies will consist of 40% of the total investment cost of the LT-BTES was studied. To cut the investment cost in almost half makes a big difference on the economy since it is clear that the investment cost is the most significant contribution to a bad NPV since the savings will never reach the size of the investment cost.

5.4.4 Interest rate

For a first economic calculation an interest rate of 7% was used. This interest rate seems rather tough since this is a long-term investment, a 100 year investment as before mentioned, and a payback period of 20 years for an investment that can reach a lifetime of 100 years seems quite narrow. This is also an investment into a sustainable future as described before and that is why a lower interest rate could be acceptable for calculating the economy for this kind of investment. Interest rates of 5% and 0% are tested. Economic profitability could be gained for an interest rate of 0% if the entries of the investment cost were in the minimum price scenario. However, even though a lower interest rate could be used for a sustainable project like this an interest rate of 0% seems too low to be used.

Economic profitability was hard to gain. However, a combination of an interest rate of 5%, subsidies to cover 40% of the investment cost and an increased availability of the heat pumps by 15% when considering a scenario with the lowest prices for an investment into a LT-BTES could result in economic profitability. Also, a case of an interest rate of 0% for economic calculations and considering a scenario with the lowest prices for an investment into a LT-BTES could result in economic profitability. To be realistic it seems to be rather hard to gain all these privileges.

6

Conclusions

According to prognostics made on the heating demand in the DH-network for preceding years, the size of the LT-BTES should not exceed 25GWh. A 50GWh storage size is also investigated in this study but all the heat from this storage cannot be utilized for increasing the thermal power output from the heat pumps. The relative savings when supplementing the heat pumps at Ryaverket with a LT-BTES are a lot larger for the smaller storage size, storing 25GWh of heat, compared to the larger storage size, storing 50GWh of heat. However, the optimal storage size (the one that generates the most relative savings) has not been investigated in this study and it is possible that the most optimal solution is a LT-BTES storing less heat than 25GWh.

The idea of investing into a LT-BTES is not rather attractive from an economical point of view. A probable price scenario for the investment cost and with heat pump availability increase of 15%, subsidies covering 40% of the investment cost and a lower interest rate results in a NPV-value of -19.12 MSEK. If the economic entries are in the minimum price range economic profitability can be achieved if the improved conditions mentioned before are obtained. Economic profitability could also be gained if an interest rate of 0% is used for the economic calculations and the prices for the investment cost are in the minimum price scenario. It seems rather hard to gain all these privileges to be able to reach economic profitability. The savings obtained when increasing the thermal power output are just too low compared to the size of the investment cost of a LT-BTES. The investment cost regards also a LT-BTES that has been optimized in the way that the heat extractions are evenly distributed over the months. So, in reality the investment cost should be even higher than the one stated in the results of economic calculations.

An investment into a LT-BTES would reduce greenhouse gas emissions. For a period of 20 years the CO_2-emissions will be reduced by 35ktons, NOx-emissions by 19.6tons and SOx-emissions by 0.9tons. These reductions in emissions originates from the reduced operation of generation units that are natural gas-, pellet- or heating oil-fired plants. However the reductions are only that extensive on a local level when the system boundaries have been drawn around the system generating DH in Gothenburg. The change in greenhouse gas emissions on the global level is unsure and not investigated in this study.

Bibliography

[1] S. Frederiksen and S. Werner, "District heating and cooling." European DHC textbook, August 2013.

[2] "Som fjärrvärmeanvändare är du del av ett smart system." *http://www.goteborgenergi.se/Privat/Produkter_och_priser/Fjarrvarme/Om_fjarrvarme*, gathered November 2014.

[3] P. Gustafsson, "An oral dialogue at Göteborg Energi AB."

[4] K. S. Lee, *Underground Thermal Energy Storage.* Springer London, 2013.

[5] K. Lee, "Borehole thermal energy storage," in *Underground Thermal Energy Storage*, Green Energy and Technology, pp. 95–123, Springer London, 2013.

[6] A. Schäfer, F. Grote, and A. Moser, "Optimization of thermal energy storage systems in distributed generation systems," *Zeitschrift für Energiewirtschaft*, vol. 36, no. 2, pp. 135–145, 2012.

[7] K. Lee, "Introduction," in *Underground Thermal Energy Storage*, Green Energy and Technology, pp. 1–13, Springer London, 2013.

[8] J. Xu, R. Wang, and Y. Li, "A review of available technologies for seasonal thermal energy storage," *Solar Energy*, vol. 103, no. 0, pp. 610 – 638, 2014.

[9] M. Haider and A. Werner, "An overview of state of the art and research in the fields of sensible, latent and thermo-chemical thermal energy storage," *e & i Elektrotechnik und Informationstechnik*, vol. 130, no. 6, pp. 153–160, 2013.

[10] B. Nordell, "Large-scale thermal energy storage," *Winter Cities 2000*, 2000.

[11] B. Nordell, *Borehole heat store design optimization.* PhD thesis, Luleå tekniska universitet, 1994.

[12] I. Dincer and M. A. Rosen, *Thermal Energy Storage (TES) Methods*, pp. 83–190. John Wiley & Sons, Ltd, 2010.

[13] K. Lee, "Aquifer thermal energy storage," in *Underground Thermal Energy Storage*, Green Energy and Technology, pp. 59–93, Springer London, 2013.

[14] G. Florides and S. Kalogirou, "Ground heat exchangers—a review of systems, models and applications," *Renewable Energy*, vol. 32, no. 15, pp. 2461 – 2478, 2007.

[15] S. Javed, *Thermal modelling and evaluation of borehole heat transfer.* PhD thesis, Chalmers University of Technology, 2012.

[16] K. Hallqvist, "Högtempererat borrhålslager för fjärrvärme," Master's thesis, Uppsala University, 2014.

[17] J. Acuña, *Distributed thermal response tests : New insights on U-pipe and Coaxial heat exchangers in groundwater-filled boreholes.* PhD thesis, KTH, Applied Thermodynamics and Refrigeration, 2013.

[18] G. Hellström, "Thermal performance of borehole heat exchangers," in *The Second Stockton International Geothermal Conference*, Stockton International Geothermal Conference, 1998.

[19] O. Andersson and L. Rydell, "The HT-BTES plant at Xylem in Emmaboda, Sweden - Experiences from design, construction and initial operation."

[20] L. Hjalmarsson, "An oral dialogue at Göteborg Energi AB."

[21] D. Pahud and B. Matthey, "Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ," *Energy and Buildings*, vol. 33, no. 5, pp. 503–507, 2001.

[22] "Årsmedeltemperatur." $http://www.smhi.se/klimatdata/meteorologi/kartor/monYrTable.php?par=tmpYr\&month=13$, gathered March 2015.

[23] A. M. Omer, "Ground-source heat pumps systems and applications," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 344 – 371, 2008.

[24] H. Madani, J. Claesson, and P. Lundqvist, "Capacity control in ground source heat pump systems: Part i: modeling and simulation," *International Journal of Refrigeration*, vol. 34, no. 6, pp. 1338 – 1347, 2011.

[25] J. R. Elliott and C. Lira, *Introductory Chemical Engineering Thermodynamics.* Prentice-Hall international series in the physical and chemical engineering sciences, Prentice Hall PTR, 1999.

[26] J. Welty, C. Wicks, G. Rorrer, and R. Wilson, *Fundamentals of Momentum, Heat and Mass Transfer.* Wiley, 2007.

[27] B. Sanner, C. Karytsas, D. Mendrinos, and L. Rybach, "Current status of ground source heat pumps and underground thermal energy storage in europe," *Geothermics*, vol. 32, no. 4–6, pp. 579 – 588, 2003. Selected Papers from the European Geothermal Conference 2003.

[28] "Net present value." Oxford University Press, 2010.

[29] J. Angelbratt and P. Gustafsson, "Prognostrisera eleffekt i rya värmepumpar." February 2015.

[30] Profu, *Martes, Simuleringsprogrammet för strategisk analys av fjärrvärmeproduktion*, December 2000.

[31] "Ground loop heat exchanger design software." https://www.hvac.okstate.edu/glhepro/overview, gathered February 2015.

[32] J. Claesson and P. Eskilson, "Conductive heat extraction to a deep borehole: Thermal analyses and dimensioning rules," *Energy*, vol. 13, pp. 509–527, June 1988.

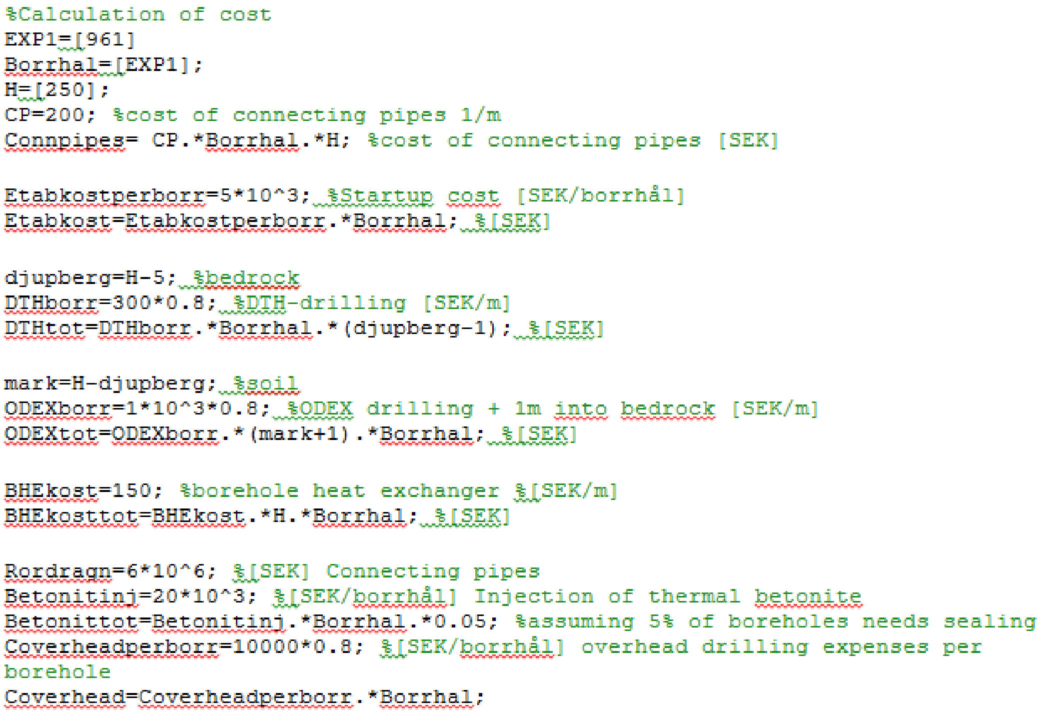
Appendix

1 Summary of input parameters in GLHEpro simulations

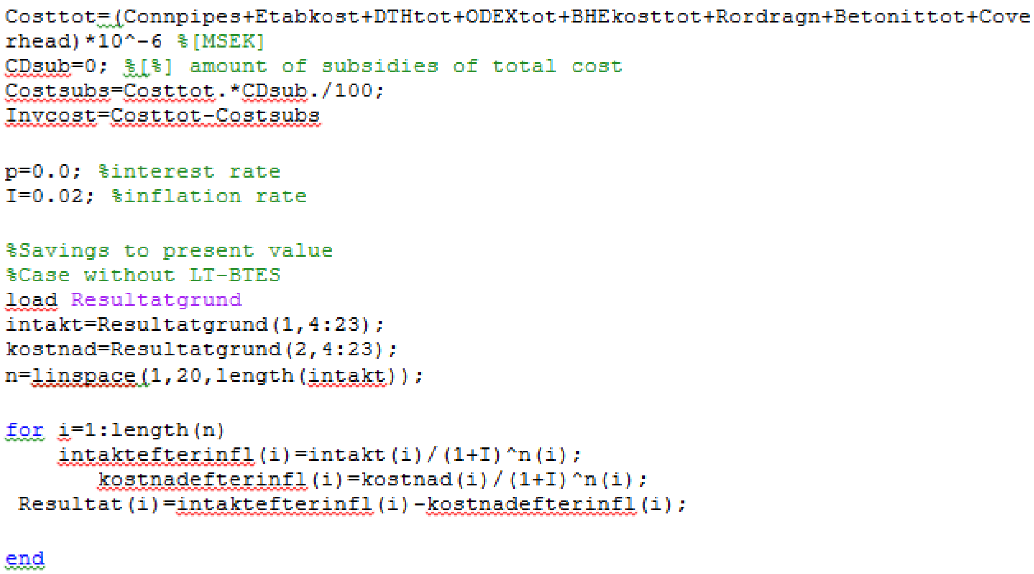
A summary of the geometrical properties of boreholes, borehole field and the physical properties of the surrounding ground and working fluid is presented below.

Borehole field configuration	Rectangular
Spacing between boreholes	8m
Borehole depth	250 m
Borehole radius	57.5 mm
Type of borehole heat exchanger	U-pipe
Pipe inner radius	17.7mm
Pipe outer radius	19.7 mm
Shank spacing	36.2 mm
Thermal conductivity of pipe material	0.42 $\frac{W}{mK}$
Flow rate of heat transferring fluid	2 $\frac{m^3}{h}/borehole$
Thermal conductivity of ground	3.5 $\frac{W}{mK}$
Borehole filling	Water
Thermal conductivity of water	0.58 $\frac{W}{mK}$

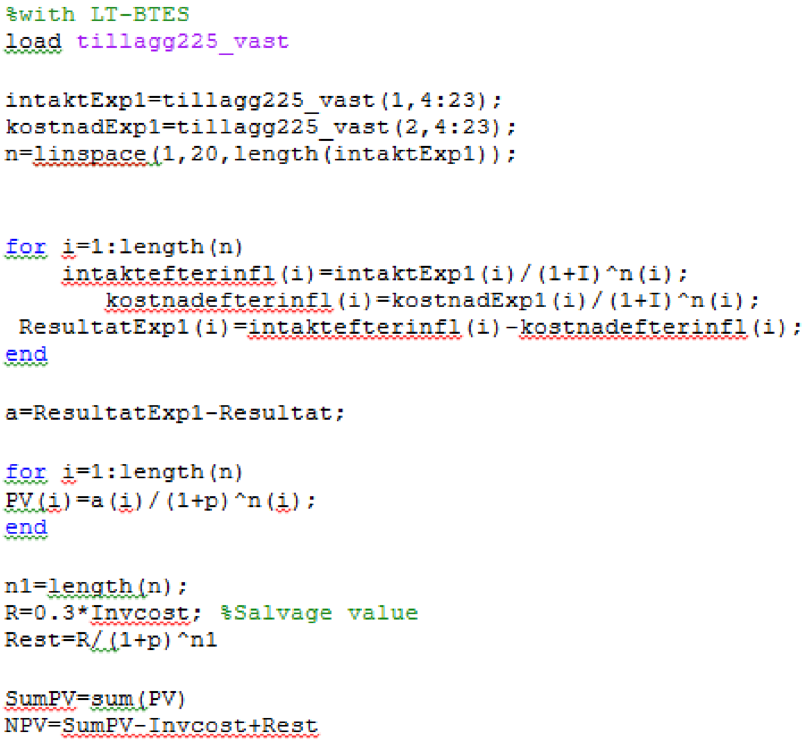
2 Code for calculating the economy



```
%Calculation of cost
EXP1=[961]
Borrhal=[EXP1];
H=[250];
CP=200; %cost of connecting pipes 1/m
Connpipes= CP.*Borrhal.*H; %cost of connecting pipes [SEK]

Etabkostperborr=5*10^3; %Startup cost [SEK/borrhål]
Etabkost=Etabkostperborr.*Borrhal; %[SEK]

djupberg=H-5; %bedrock
DTHborr=300*0.8; %DTH-drilling [SEK/m]
DTHtot=DTHborr.*Borrhal.*(djupberg-1); %[SEK]

mark=H-djupberg; %soil
ODEXborr=1*10^3*0.8; %ODEX drilling + 1m into bedrock [SEK/m]
ODEXtot=ODEXborr.*(mark+1).*Borrhal; %[SEK]

BHEkost=150; %borehole heat exchanger %[SEK/m]
BHEkosttot=BHEkost.*H.*Borrhal; %[SEK]

Rordragn=6*10^6; %[SEK] Connecting pipes
Betonitinj=20*10^3; %[SEK/borrhål] Injection of thermal betonite
Betonittot=Betonitinj.*Borrhal.*0.05; %assuming 5% of boreholes needs sealing
Coverheadperborr=10000*0.8; %[SEK/borrhål] overhead drilling expenses per
borehole
Coverhead=Coverheadperborr.*Borrhal;
```



```
Costtot=(Connpipes+Etabkost+DTHtot+ODEXtot+BHEkosttot+Rordragn+Betonittot+Cove
rhead)*10^-6 %[MSEK]
CDsub=0; %[%] amount of subsidies of total cost
Costsubs=Costtot.*CDsub./100;
Invcost=Costtot-Costsubs

p=0.0; %interest rate
I=0.02; %inflation rate

%Savings to present value
%Case without LT-BTES
load Resultatgrund
intakt=Resultatgrund(1,4:23);
kostnad=Resultatgrund(2,4:23);
n=linspace(1,20,length(intakt));

for i=1:length(n)
    intaktefterinfl(i)=intakt(i)/(1+I)^n(i);
       kostnadefterinfl(i)=kostnad(i)/(1+I)^n(i);
 Resultat(i)=intaktefterinfl(i)-kostnadefterinfl(i);

end
```

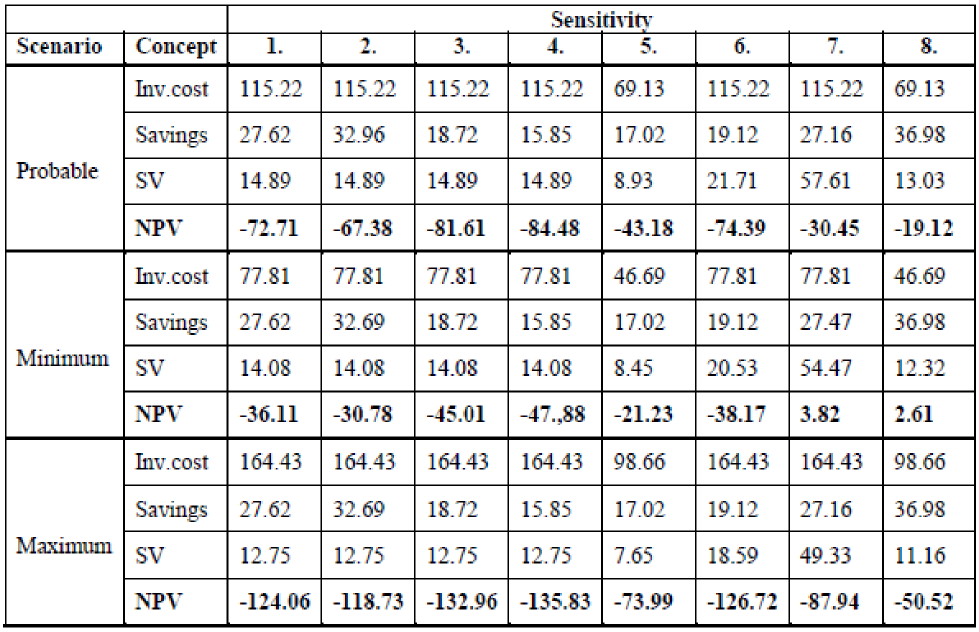


```
%with LT-BTES
load tillagg225_vast

intaktExp1=tillagg225_vast(1,4:23);
kostnadExp1=tillagg225_vast(2,4:23);
n=linspace(1,20,length(intaktExp1));


for i=1:length(n)
    intaktefterinfl(i)=intaktExp1(i)/(1+I)^n(i);
       kostnadefterinfl(i)=kostnadExp1(i)/(1+I)^n(i);
 ResultatExp1(i)=intaktefterinfl(i)-kostnadefterinfl(i);
end

a=ResultatExp1-Resultat;

for i=1:length(n)
PV(i)=a(i)/(1+p)^n(i);
end

n1=length(n);
R=0.3*Invcost; %Salvage value
Rest=R/(1+p)^n1

SumPV=sum(PV)
NPV=SumPV-Invcost+Rest
```

3 Results from sensitivity analysis

The results from the sensitivity analysis are presented below.

- 1. Increased heat pump availability to 80%
- 2. Increased heat pump availability to 86%
- 3. Decreased electricity price by 10%
- 4. Increased elecricity price by 10%
- 5. Subsidies 40%
- 6. An interest rate of 5%
- 7. An interest rate of 0%
- 8. A combination of increased pump availability to 86%, subsidies 40% and an interest rate of 5%



		Sensitivity							
Scenario	**Concept**	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**
Probable	Inv.cost	115.22	115.22	115.22	115.22	69.13	115.22	115.22	69.13
	Savings	27.62	32.96	18.72	15.85	17.02	19.12	27.16	36.98
	SV	14.89	14.89	14.89	14.89	8.93	21.71	57.61	13.03
	NPV	**-72.71**	**-67.38**	**-81.61**	**-84.48**	**-43.18**	**-74.39**	**-30.45**	**-19.12**
Minimum	Inv.cost	77.81	77.81	77.81	77.81	46.69	77.81	77.81	46.69
	Savings	27.62	32.69	18.72	15.85	17.02	19.12	27.47	36.98
	SV	14.08	14.08	14.08	14.08	8.45	20.53	54.47	12.32
	NPV	**-36.11**	**-30.78**	**-45.01**	**-47.,88**	**-21.23**	**-38.17**	**3.82**	**2.61**
Maximum	Inv.cost	164.43	164.43	164.43	164.43	98.66	164.43	164.43	98.66
	Savings	27.62	32.69	18.72	15.85	17.02	19.12	27.16	36.98
	SV	12.75	12.75	12.75	12.75	7.65	18.59	49.33	11.16
	NPV	**-124.06**	**-118.73**	**-132.96**	**-135.83**	**-73.99**	**-126.72**	**-87.94**	**-50.52**