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Seasonal Storage of Distant Industrial Excess Heat for District Heating

Master's Thesis in Innovative and Sustainable Chemical Engineering

IDA FRIBERG

Department of Division of Building Services Engineering
Civil and Environmental Engineering
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MASTER'S THESIS

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Master's Thesis within the Innovative and Sustainable Chemical Engineering Programme

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Abstract

Large parts of district heating used in Gothenburg originates from excess heat generated from industries near the city. There is potential to utilise more excess heat in Gothenburg from distant industries. This will however require a connecting pipeline of considerable length with high investment cost. This thesis investigates whether the economical benefits of such a pipeline can be increased by installing an additional borehole thermal energy storage (BTES) and an electricity driven heat pump. Investigations have been made for two locations, western Gothenburg and Kungälv. The behaviour of the BTES has been analysed with the *Duct Storage Model* using the software *PILESIM 2*. The district heating system has been simulated with the software *Martes*. Simulation data including prices of fuels, taxes and political instruments used for this study are based on the forecasts of the local district heating company, *Göteborg Energi AB*. The investment cost of the BTES is based on previously performed master thesis project at *Göteborg Energi AB*. The results indicate that the potential to make profits from the proposed BTES and the heat pump system under the prescribed project restrictions is rather poor, especially for Kungälv. Western Gothenburg qualifies as an better location from an economical point of view. The COP of the heat pump and electricity price have large impact on the economical results. The choice of interest rate also has a large influence on the economical feasibility of the project.

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Ida Friberg, Gothenburg, 10/06/2015

Abbrevations

BHE .... Borehole Heat Exchanger

BTES .... Borehole Thermal Energy Storage

COP .... Coefficient of Performance

FV .... Future Value

NPV .... Net Present Value

PV .... Present Value

SEK .... Swedish Krona (*currency*)

SV .... Salvage Value

TES .... Thermal Energy Storage

Contents

Chapter 1: Introduction

THE DISTRICT HEATING capacity in Sweden has steadily increased since the first small scale system was installed in Karlstad in 1948. The initial fuel mixture included large parts of fossil fuels. However, the use of other fuels including wood/peat based fuels, industrial excess heat, heat from waste incineration and heat pumps have increased gradually over time [1]. Today, cooling and heating represent almost half of the energy consumption within buildings [2], which underlines the importance of having efficiently operated cooling and heating systems.

The emissions of carbon dioxide per unit of district heating have decreased significantly during the last decades [1]. However, the concern of negative environmental impact is more relevant today than ever before. The desire to develop sustainable heat supply systems and to improve the energy efficiency of existing industries have grown across the world. Nevertheless, economic competitiveness is the driving force in today's society. Hence, technologies which combine environmental benefits with economic competitiveness have clear advantages.

Industrial excess is a heat source that is often not fully exploited. It may be described as heat which cannot be used internally by the industry itself. Hence, it must either be utilised externally or dissipated to the ambient. Heat from electricity generation processes is sometimes not regarded as excess heat. It is estimated that around half of the industrial excess heat in Sweden (approximately 4480 GWh/year) is utilised, which is a large part from a global perspective. In Germany around 900 GWh/year of industrial excess heat is used. In France and Italy the excess heat being used is around 300 and 30 GWh/year, respectively [3].

International Energy Agency (*IEA*) has mentioned energy storage as a potential solution to reduce atmospheric carbon and to enhance energy security and accessibility. Energy storage technologies can be used to make up for the differences between energy demand and energy generation. Large scale thermal energy storage (TES) systems can increase utilisation of resources which are not fully exploited today [2]. These technologies allow for both long- and short-term storage cycles. A seasonal TES system enables heat generated during summer to be used in winter. Thus TES appears as an attractive option to make the heat generation system more independent of fluctuations in heat demand. It may even be possible to utilise heat which will otherwise go waste during periods of low heat demand [4].

Several countries, including Sweden, have climates with significant seasonal fluctuations. In Gothenburg, the minimum and maximum recorded temperatures in 2013 were -14.4 °C and +29.4 °C, respectively [5]. In other words the temperature gradient over the year 2013 was close to 45 °C. Due to the temperature variations, the annual heat demand in Gothenburg also exhibited large fluctuations with maximum reaching during the winter season. Seasonal TES is one way to deal with these types of seasonal fluctuations in heat demand.

1.1 Background

Gothenburg has a relatively large district heating system managed by the municipal company *Göteborg Energi AB*. Today, district heating is supplied to around 12 000 apartment buildings, 90 % of single family houses and numbers of office blocks, industries etc. in Gothenburg. The district heating system covers a widely spread area and the total pipe length for the heating network measures up to approximately 1200 km [6]. The district heating system of Gothenburg is also connected to the district heating system of the neighbouring city Kungälv. The district heat is generated in several plants using oil, natural gas, bio fuels, electricity and industrial excess heat [3].

Approximately 23% of the district heat in Gothenburg comes from industrial excess heat generated at oil refineries and around 26% comes from excess heat from waste incineration. The location of Gothenburg offers further options to increase excess heat utilisation from other energy intensive industries further away, for example the chemical industries in Stenugnsund and the paper pulp industry in Värö (near Varberg) [3]. The Gothenburg county is more densely populated (540 789 citizens, year 2014) than Stenugnsund (25 227 citizens) and Varberg (60 382 citizens) [7] and has a higher demand of district heating. For implementing the distant industrial heat possibilities in reality, the key question is whether it is economical feasible to transfer excess heat from these locations to Gothenburg. Due to the considerably long distances, the excess heat projects from Stenugnsund/Värö are associated with high investment costs [3]. One idea is to combine the pipeline with a low temperature TES and heat pump system. A potential solution is a borehole thermal energy storage (BTES) system. The intention is to better utilise the excess heat from the distant industries throughout the year with help of seasonal storage system. It is also desired to have stable heat generation despite a seasonally fluctuating heat demand. The normalised heat demand for the Gothenburg region is shown in Figure 1.1.

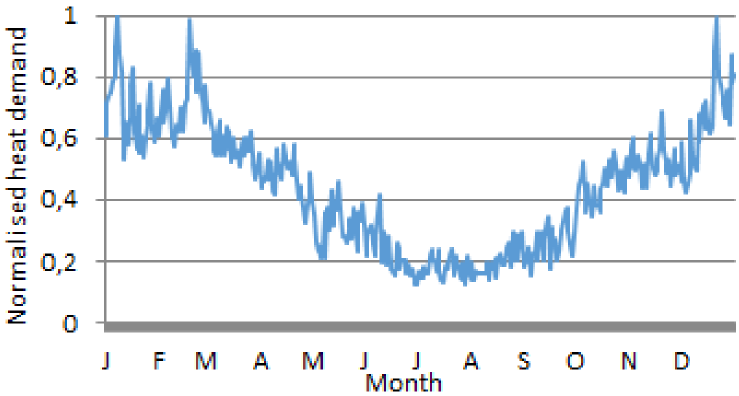

Figure 1.1: Normalised heat demand curve for the Gothenburg region (source: *Göteborg Energi AB*).

1.1.1 Chemical industries of Stenugnsund

There are several chemical industries in the Stenugnsund region located approximately 50 km away from Gothenburg. Today, only a fraction of the excess heat generated in these industries is used as district heat of Stenugnsund. An interest has grown to investigate a connecting pipeline between these industries and Kungälv (city north of Gothenburg, closer to Stenugnsund). The district heating system of Kungälv is already connected to the district heating system of Gothenburg. Kungälv imports around 40 GWh/year of district heating from Gothenburg. The excess heat pipeline from Stenugnsund to Kungälv will decrease the heat generation from current plants in both Kungälv and probably also reduce district heating import from Gothenburg to Kungälv [3].

Morandin et al. [8] have studied the potential of district heating distribution from the chemical industries of Stenugnsund. For a delivery temperature of 93°C and a return temperature of 50°C, the estimated theoretical upper limit of district heat delivery is approximately 70 MW from one single plant or 235 MW from the entire industry cluster. The last mentioned value assumes a collaboration between the industries within the cluster. However, the industries can also choose to optimise the internal heat usage instead of delivering external district heating. A maximum district heating delivery of around 42 MW from a single plant or 110 MW from the entire industry cluster can be expected if the internal heat utilisation is optimised to reduce the fuel consumption dedicated for heating within the industries is reduced by 50%. In order to enable district heating distribution from these industries, significant investments are needed. However, despite the investments good economical potential has been indicated [8].

1.1.2 Södra Cell Värö

Södra Cell Värö is a kraft pulp mill located approximately 60 km south of Gothenburg. A considerable amount of excess heat is generated in their paper pulping process every year. Today, *Södra Cell Värö* delivers district heat to a nearby city Varberg. In year 2012 the delivered heat was 145 GWh/year [3]. Currently, the mill is being expanded to increase the pulp production from the current level of 425 000 ton pulp/year to 700 000 ton pulp/year [9]. There have been discussions to connect the district heating system of Kungsbacka (city south of Gothenburg) to *Södra Cell Värö*, but so far no decisions have been made [3].

1.2 Purpose and aim

This project aims to investigate whether the profitability of the proposed excess heat pipelines between Stenugnsund and Kungälv/western Gothenburg can be increased with a borehole thermal energy storage and a heat pump system. The study also aims to suggest suitable designs of borehole thermal energy storage system. Another objective is to evaluate the limitations and to find key parameters that may influence the technical and economical performance of such a system. This project seeks to address the following questions.

- Would it be profitable to invest in the BTES system in addition to the distant excess heat pipeline?
- How can the BTES system be designed to meet the district heating system requirements?
- Which limitations such a BTES system will have and what are the critical parameters of the BTES system to be profitable?

1.3 Limitations

This study does not intend to investigate the profitability of the excess heat pipeline itself but focuses only on the economic feasibility of an additional BTES system. The economical evaluation compares the installation and operation cost of the BTES to the operating cost of the district heating system. Costs of maintenance are disregarded. Fuel prices, taxes and political instruments used in the analysis are forecasted future values. The project does not prescribe a specific location of the BTES system.

Chapter 2: Theory

2.1 Underground thermal energy storage

The principle of ground-source heat extraction using heat pump systems has a documented history of at least one century. However, market development of this technology was restricted during the first three quarters of 20^{th} century due to popularity of fossil fuels. The interest in the systems grew after the oil crisis in 1970s [10]. Since then, the technology to store larger capacities of heat in longer cycles has been actively developed [4].

Ground TES include systems storing heat in different ground elements including rock, soil, sand and ground water [4]. When the heat from an external heat source is transferred into the storage, the process is commonly referred to charging of the storage or simply heat injection. Similarly, when the heat is transferred out from the TES, the process is called discharging or heat extraction [11].

Ground TES systems include both high- and low-temperature storages as well as long- or short-term storage systems. These can also be divided into three main groups, borehole, aquifer and cavern storages. The first mentioned rely on the principle of circulating heated fluid in the boreholes in order to heat the surrounding ground. For aquifer storages, the thermal energy is stored in water and solids within aquifers. Cavern storages store the heat in water which fills the underground rock caverns [4]. This study only deals with borehole thermal energy storages (BTES).

2.2 Borehole thermal energy storage

A BTES system consists of a ground volume penetrated with a number of vertical or slightly inclined boreholes [11]. The driving force for the heat injection/extraction is the temperature difference between heat carrier fluid and the ground. [12]. A BTES is rather inflexible to changes in thermal power demand but is relatively inexpensive to construct [11].

2.2.1 Principle and construction of BTES

The boreholes are arranged in a certain pattern, for example quadratic or hexagonal. Inclined boreholes are preferred in cases with limited land area since it is possible to achieve a larger storage volume with lesser ground area [11]. A typical heat extraction rate for a standard borehole is 50 W/m [13]. The borehole diameter is usually between 100-150 mm and the drilled depth may vary between 20-300 m. Water is the most commonly used heat carrier fluid, sometimes mixed with an anti-freezing agent. The heating carrier fluid flows indirectly through the boreholes via pipes placed within the boreholes (closed system). In some cases the heat carrier fluid may also flow directly in the boreholes (open system). The pipes in a closed system are called ground heat exchangers or borehole heat exchangers (BHE) [4].

An open system offers low installation costs and good heat transfer rate since the heat carrier fluid is in direct contact with the ground. However, it may provide problems with, for instance, scaling that arises from chemical reactions between heat carrier fluid and compounds in the rock. This difficulty is avoided when a closed system is selected. However, this is done at the expense of reduced heat transfer since the heat carrier does not directly touch the borehole surface [11].

The BHEs in a closed system can either be coaxial or U-shaped, see Figure 2.1. A simple coaxial pipe consists of a inner pipe which is surrounded by a larger outer pipe. The coaxial pipe can also be of more complicated designs, called complex coaxial pipe. A complex coaxial pipe consists of a inner pipe which is surrounded by several smaller pipes. In an U-shaped heat exchanger, the heat carrier fluid flows through a single or a double U-pipe. High-density polyethylene or polypropane is commonly used as pipe material [14].

In a closed system, the material which surrounds the BHE within the borehole is called filling/grouting material. This material aims to enhance the thermal transport between the heat carrier and the surrounding ground. The selection of grouting material is crucial as it determines the thermal resistance of the borehole. It is important that the grouting materials is easy manageable, attach to the surrounding surfaces and retain its initial volume [4]. However, grouting of boreholes is not necessary in Sweden since the underground structure allows the borehole to be naturally filled with groundwater [15].

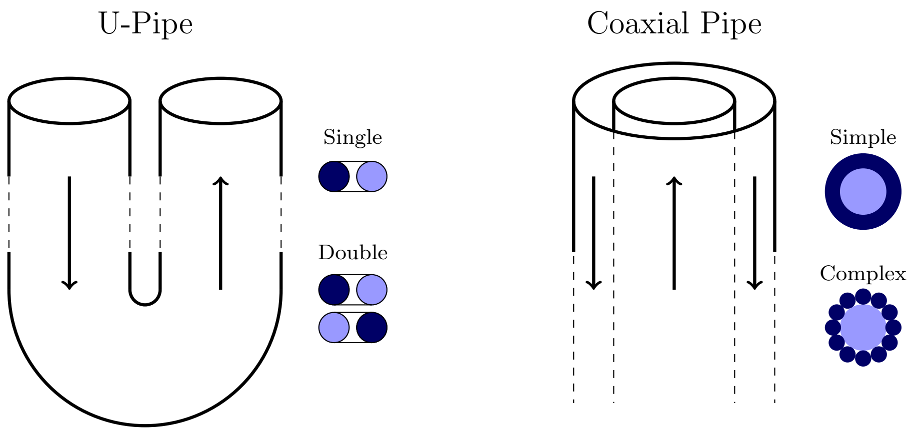

Figure 2.1: Simple sketch of single/double U-pipe and simple/complex coaxial pipe (after *Florides* and *Kalogirou* [14]).

The bedrock is often covered by a soil layer on top. This provides an insulating effect since soil typically has a lower thermal conductivity than the underlying rock. The thermal conductivity of soil is often around 1.0 W/(m·K) whereas the thermal conductivity of rock typically ranges between 1.7-7.0 W/(m·K), see also Table 2.1 and Table 2.2. The soil layer, however, increases the construction cost of the BTES as the drilling cost in soil is higher then bedrock [11]. The technique for drilling in soil is called ODEX-drilling and the drilling technique in rock is called DTH-drilling [16].

2.2.2 Ground conditions

The ground can be divided in three temperature zones [17]. The temperature in the first meter depth, called the surface zone, is highly dependent on the short-term fluctuations of the ambient temperature. In the next zone, called shallow zone (down to 8-20 m), the temperature is somewhat dependent on the seasonal fluctuations but maintains a value around the annual average outdoor temperature. Finally, in the deep zone, the temperature remains constant over the year [17]. In the deep zone, the temperature exceeds the ambient outdoor temperature during the winter period whereas the opposite can be seen during the summer period [14].

Thermal properties of soils are significantly affected by their porosity and water content. The thermal conductivity of soils with higher water content increases when the temperature falls below the freezing point of water [18]. Thermal conductivity and volumetric heat capacity of clay, sand/gravel and silt can be seen in Table 2.1.

Table 2.1: Thermal conductivity and volumetric heat capacity of clay, sand/gravel and silt [19].

	Thermal conductivity [W/(m ·K)]	**Volumetric heat capacity [MJ/(m^3·K)]**
Clay with high clay content	0.85-1.1	3.0-3.6
Sand, gravel	0.4-1.1	1.2-1.7
Silt	1.2-2.4	2.4-3.3

Different rock types also have somewhat different thermal properties, depending on mineral content, porosity, temperature, density, cracks etc. [19]. Higher thermal conductivity is observed in rock types with larger quartz content, whereas rock types with higher composition of organic compounds and clay shows the opposite [14]. In this context one may differ between crystalline and sedimentary rocks. The properties of the first type depends much on mineral composition whereas the properties of the later one are more dependent on the water content and the degree of porosity. In general, the influence of the mineral composition is higher in non-porous rock types. Crystalline rock types do not exhibit any extensive porosity but there are hollow spaces between the rock solids due to crack formation. Sedimentary rocks, have a more porous like structure [18].

The transport of heat in soil and rock occurs mainly via four mechanisms, thermal conduction, thermal convection, radiation and diffusion of steam. In crystalline rocks, conduction is so dominant that other mechanisms can usually be neglected. For these rocks, the thermal conductivity and the heat transport increase further at higher temperatures. In porous rock types, convection is also an important heat transport mechanism. In these rocks, diffusion of steam may also occur at elevated temperatures. Rocks may also be inhomogeneous to varying extent, meaning that the minerals are not evenly distributed in the rock volume. Consequently, the heat is transported more rapidly through parts with, for example, higher quartz content. Rocks can also express anisotropic properties due to its structure. Thus heat may not be evenly conducted in all directions [18]. Different rock types exhibit different structures depending on mechanism of their formation. Finally, it is worth mentioning that thermal conductivity is significantly larger for water than gases which results in greater heat transport when porous bedrock is saturated with water. However, as discussed before, the influence of porosity and water content is mild, at least for crystalline rock types [19].

The dominating rock types in Sweden are granite and gneiss. These have rather similar thermal heat conduction properties [19]. According to the map from SGU (Geological Survey of Sweden), see Figure C.1, Appendix C, the bedrock in Gothenburg typically consists of granite, granodiorite and monzonite. Thermal conductivity for these rock types can be found in Table 2.2.

Table 2.2: Mean value for thermal conductivity of some rock types [19], and air and water [12].

	Mean thermal conductivity [W/(m ·K)]
Granite	3.49
Granodiorite	3.28
Monzonite	2.68
Water	0.6
Air	0.024

2.2.3 Environmental impact of closed loop BTES

There is a risk that the heat carrier fluid, typically water with additional anti-freezing agent, will leak to the surroundings. However, many commonly used anti-freezing agents are quickly degraded and/or are rather harmless to the environment. It should be emphasised that a borehole always involves a risk that contaminants above the ground will reach the ground water [20].

The ground temperature increases when a BTES is installed. However the elevated temperature zone is rather local and centralized around the BTES, typically upto 10-20 m from the BTES border. Elevated temperatures can result, for example, in vapour migration, drying of land mass and somewhat enlarged bedrock volume. High temperatures can also increase the solubility of gases and solid compounds [20].

Some risk may also be associated with the heat carrier fluid below the freezing temperature of water. Prolonged freezing periods may result in frost heave effects on the surface layer. Alternated freezing and melting of sediment structures may separate small sized particles from larger ones resulting in breakup of land mass [20].

2.2.4 Simulation of BTES

Optimisation of the BTES system has a significant impact on the economical and technical performance of the system. Several approaches to characterise the flow of thermal energy within and outside the BTES have resulted in a number of models with different levels of detail. A description of noteworthy methods for modelling of BTES systems is given in [21] and [22]. The primary objective of modelling of BTES is to obtain the temperature of the heat carrier fluid at the outlet of the BHE pipes and to estimate the amount of injected or extracted heat. The analysis is generally carried out by studying the heat transfer both within and around the BHE. The heat transfer problem outside the borehole is treated transiently, while there are different approaches to account for heat transfer inside the borehole [10].

Kelvin's Line Source model, *Cylindrical Source model*, *Eskilson's g-functions* and *Finite Line Source model* are some famous models which treat the heat transfer problem outside the borehole [23]. The heat transfer within the boreholes can be described with one-, two- or quasi-three-dimensional models [10].

So far, the *Duct Storage model* (*DST-model*), developed by *Hellström* [12], has not been mentioned. *Hellström* divides the ground heat transfer problem in a local and a global problem. The final temperature profile of the BTES is obtained by superposition of these solutions [12]. This model is discussed more thoroughly below.

Duct storage model

The local problems includes the volume inside the borehole and the ground in the direct vicinity of the borehole. Thermal resistances, R_b and R_a, describe the relation between the temperature of the heat carrier and the surrounding ground. R_b [K/(W·m)] denotes the thermal resistance between the ground and the heat carrier fluid. It summarises several elementary heat transfer processes such as convection within the pipe, conduction through pipe wall and grouting material etc. R_b would be sufficient to describe the temperatures within the local volume in case of a single duct, as seen in the equation below [12].

$$q_{fluid-ground} = \frac{T_{fluid} - T_{borehole}}{R_b} \tag{2.1}$$

It is obvious from Equation 2.1 that R_b greatly influences the heat transport from the BHEs. It is also important to take into account the interaction between the pipes of the BHE. The resistance, R_a, provides a measure of the total internal thermal resistance of the BHE [12].

The transient heat extraction/injection in the local region is obtained from the temperature difference between the heat carrier fluid and the enclosing ground [24]. However, during periods of steady-flux, a steady-state value of the thermal resistance is used. As the model assumes a symmetrical borehole pattern, a zero heat flux boundary is set between the boreholes, see the dashed square in Figure 2.2. Consequently, the temperature within this region is steadily increased/decreased during heat injection/extraction in the steady-flux regime [12]. The computational cost is reduced by applying the steady-flux regime [25].

The global process involves heat transport at a larger scale and consists of three major parts in the *Duct Storage Model*. The first part describes the steady-state heat losses which occur at the vertical outer edges and at the top and at the bottom of the BTES. Note that losses also occur at the insulated surfaces in case of an insulated BTES. The steady-state heat losses are calculated based on the difference between the constant temperature at the BTES surfaces and the temperature of the surrounding ground/atmosphere. The second part includes heat losses based on the average ambient temperature. The final part describes the transient process called thermal build-up, where the BTES goes towards steady-state temperature levels from an initial undisturbed ground temperature. The thermal build-up is most significant during the initial operating cycles whereas it decreases in importance near steady-state [12].

The final temperature profile is obtained by the superposition of all underlying thermal processes described above [12]. The finite difference method is applied both for solving both the transient local and global parts while the steady-flux local part is solved analytically [25].

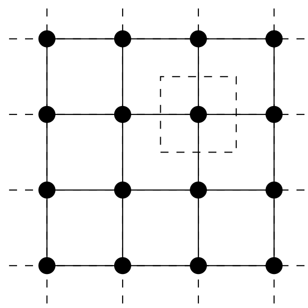

Figure 2.2: A quadratic borehole pattern. The dashed square indicates zero heat flux line due to symmetry [12].

2.3 Heat pumps

Heat pumps are mechanical systems to provide heating by raising the temperature of the supplied medium. The term *heat pump* is often used for electricity driven vapour compression machines [26]. However, other types like absorption heat pumps also exist [27]. A heat pump lifts the temperature of a low-temperature heat source by using an energy source of higher grade, like thermal or electrical energy [26]. The heat produced by the ground-source heat pump system can be used in district heating systems or within a single household.

2.3.1 Vapour compression cycle

A simple sketch of the vapour compression cycle is seen in Figure 2.3. The fundamental components are compressor, evaporator, condenser and expansion valve. The refrigerant flows through the cycle where it is alternately expanded and compressed. The maximum pressure in the cycle is obtained at the condenser side and the lowest is at the evaporator side. Heat of evaporation is provided from an external low-temperature heat source (e.g. ground) whereas the heat of condensation is transferred to a heat sink at a higher temperature (e.g. building). Electric power is required to create the pressure difference between the evaporator and the condenser [26]. In other words, the design principle is to provide conditions that allow phase transition so the that latent heat can be utilised [27].

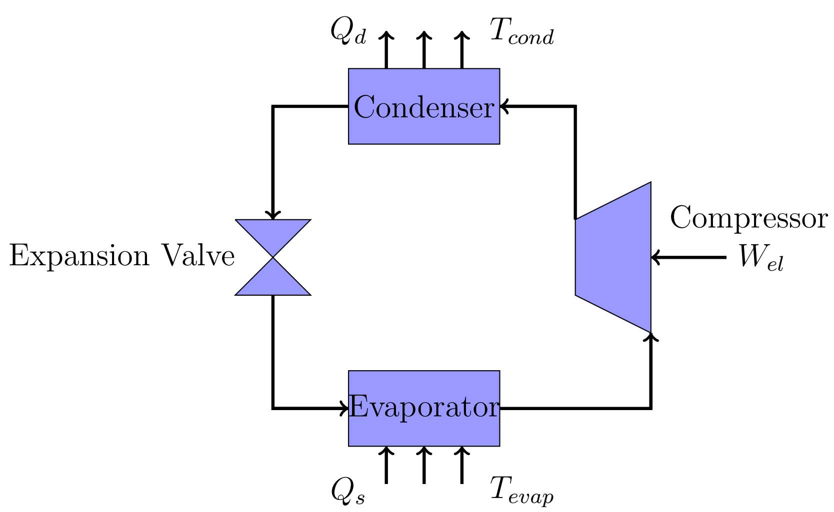

Figure 2.3: Basic illustration of a vapour compression machine.

The efficiency of a heat pump is specified as coefficient of performance, COP, which is the ratio of delivered heat, Q_d, to electricity supplied to the compressor, W_{el} [28].

$$COP = \frac{Q_d}{W_{el}} \tag{2.2}$$

The heat delivered equals the sum of heat supplied from the low quality heat source, Q_s and , W_{el} [25].

$$Q_d = W_{el} + Q_s \tag{2.3}$$

A high COP is desired from an economical point of view, since less electricity is consumed per unit of Q_d. A low COP can be expected, for instance, in cases of large temperature differences between evaporator and condenser [27].

Only the most basic design of closed compression cycle heat pump has been discussed. Many variants, for instance with several compressor stages, sub-cooling and in combination with economisers are possible [27] but not discussed here. After this point heat pump refers to an electrically driven vapour compression machine.

2.4 Heat losses in district heating pipes

Despite being insulated, district heating pipes have certain heat losses. Moreover, an ageing district heating pipe can also be expected to have degraded insulation and higher temperature losses [29]. Heat losses and corresponding temperature drop is related as Equation 2.4 [30]. Here C_p [J/(K·kg)] is the heat capacity, T [K] is the temperature and $\dot{m}$ [kg/s] is the mass flow rate.

$$\dot{Q} = \dot{m} \int_{T_{final}}^{T_{initial}} Cp(T)dT \tag{2.4}$$

For small temperature differences, ΔT, it is convenient to assume a constant value of C_p in Equation 2.4, which yields:

$$\dot{Q} \approx \dot{m} Cp \Delta T \tag{2.5}$$

Jarfelt [29] has used the multi-pole method to describe the steady-state heat losses, $\dot{q}_h$ and $\dot{q}_c$ [W/m], from adjacent hot and cold pipe surrounded by a thick layer of soil, see Figure 2.4.

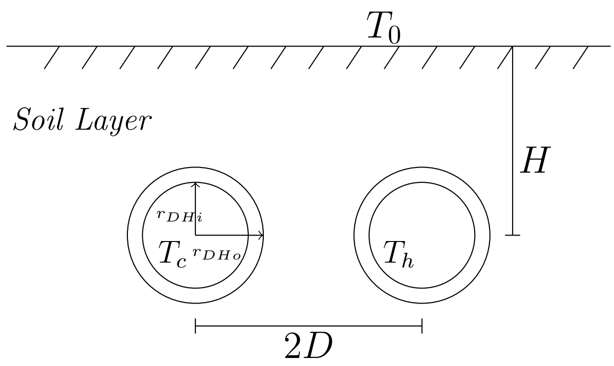

Figure 2.4: Illustration of two adjacent, identical pipes for the hot and cold district heating lines (after *Jarfelt* [29]).

The heat losses, $\dot{q}_s$ and $\dot{q}_a$ [W/m], describe the symmetrical and asymmetrical cases and can be expressed with the air temperature at the ground surface, T_0 [K], and the factors h_s [-] and h_a [-] which describe the heat losses.

$$\dot{q}_h = \dot{q}_s + \dot{q}_a \tag{2.6}$$

$$\dot{q}_c = \dot{q}_s - \dot{q}_a \tag{2.7}$$

$$\dot{q}_s = \left(\frac{T_c + T_h}{2} - T_0\right) 2\pi\lambda_{soil} h_s \tag{2.8}$$

$$\dot{q}_a = \left(\frac{T_h - T_c}{2}\right) 2\pi\lambda_{soil} h_a \tag{2.9}$$

Here, T_h and T_c [K] are the temperatures of the hot and cold pipe, λ_{soil} [W/(m·K)] is the thermal conductivity of the soil. The factors h_s and h_a are expressed as:

$$h_s = \left[ln\left(\frac{2H}{r_{DHo}}\right) + \beta + ln\left(\sqrt{1+\left(\frac{H}{D}\right)^2}\right) - \frac{\left(\frac{r_{DHo}}{2D}\right)^2 + \left(\frac{r_{DHo}}{2H}\right)^2 + \left(\frac{r_{DHo}^2}{4(D^2+H^2)}\right)}{\left(\frac{1+\beta}{1-\beta}\right) + \left(\frac{r_{DHo}}{2D}\right)^2} \right]^{-1} \tag{2.10}$$

$$h_a = \left[ln\left(\frac{2H}{r_{DHo}}\right) + \beta - ln\left(\sqrt{1+\left(\frac{H}{D}\right)^2}\right) - \frac{\left(\frac{r_{DHo}}{2D}\right)^2 + \left(\frac{r_{DHo}}{2H}\right)^2 + \left(\frac{r_{DHo}^2}{4(D^2+H^2)}\right)}{\left(\frac{1+\beta}{1-\beta}\right) - \left(\frac{r_{DHo}}{2D}\right)^2} \right]^{-1} \tag{2.11}$$

Where H [m] is the thickness of soil layer above the pipes, $2D$ [m] is the distance between the pipes, r_{DHo} [m] is the outer radius of the pipe and r_{DHi} [m] is the inner radius of the pipe. β [-] is a factor based on λ_{soil} [W/(m· K)] and thermal conductivity of the pipe insulation λ_{insul} [W/(m· K)] together with the radii of the pipes.

$$\beta = \frac{\lambda_{soil}}{\lambda_{insul}} ln \left(\frac{r_{DHo}}{r_{DHi}} \right) \tag{2.12}$$

Assuming constant heat losses over the entire pipe, the final heat losses, $\dot{Q}_h$ and $\dot{Q}_c$ [W] are obtained by multiplying q_h and q_c, respectively, with the length, L [m], of the pipes.

$$\dot{Q}_h = \dot{q}_h L \tag{2.13}$$

$$\dot{Q}_c = \dot{q}_c L \tag{2.14}$$

The corresponding temperature drop can be obtained from $\dot{q}_h$ and $\dot{q}_c$ using Equation 2.5.

2.5 Economic calculations

The future monetary value (FV) at year n can be expressed as a present value (PV) as

$$PV = \frac{FV}{(1+i)^n} \tag{2.15}$$

Net Present Value, NPV, is the sum of the PV of future annual cash flows minus the investment cost, I [28].

$$NPV = \sum_{n=1}^{N} \frac{\xi_{A,n}}{(1+i)^n} - I \tag{2.16}$$

N is the total number of years, e.g. life time of the project

n is the year (with start at year n=1)

i is the interest rate

ξ_A is the annual cash flow

The salvage value (SV_n) of an investment at year n, can be expressed as a present value as:

$$SV_0 = \frac{SV_n}{(1+i)^n} \tag{2.17}$$

It is desirable to obtain a high NPV for an investment. A NPV below zero is unprofitable [28].

2.5.1 Project specific investment and installation costs

Table 2.3 lists data for specific BTES related costs, collected by *Hallqvist* [16] for the year 2014. The data is considered suitable by *Göteborg Energi AB* for estimation of BTES investment costs. The entry ”*Additional BTES installation costs*” includes costs associated to ground preparation, circulations pumps and piping. Additional costs of heat pump and connection to the district heating system also have to be included. *Hallqvist* estimated a salvage value of the BTES at year 20 to be 50 % (maximum 70 %, minimum 30%) of the investment cost of the BTES [16].

Table 2.3: Estimated base costs of BTES related entries, collected by *Hallqvist* [16].

	Estimated Value	Minimum Value	Maximum Value
Borehole fixed cost [kSEK/borehole]	3	2	5
DTH Drilling [SEK/m]	200	150	300
ODEX Drilling [SEK/m]	0.7	1	0.5
Betonite injection [kSEK/m]	17.5	15	20
Pipes [SEK/m]	100	50	150
Additional BTES installation costs [SEK/m]	150	100	200

Chapter 3: Methodology

The methodology adopted for this study can be summarised in two parts, simulation of the BTES system performance and evaluation of the district heating system performance. A sensitivity analysis to study the impact of certain parameters and the involved uncertainties has also been performed.

3.1 Case definition

This study assumes a future scenario of limited access to excess heat, in comparison to present situation. The maximum thermal power from the oil refineries is assumed to be 50% lower then todays' level. Consequently, the excess heat from distant industries will become more attractive. In Section 1.1 possibilities of getting industrial excess heat from two different sources near Gothenburg were mentioned. This study investigates solely the case of getting industrial excess heat from the chemical industries of Stenugnsund. If desired, the second option of *Södra Cell Värö* can also be analysed later using a similar approach. It can be highlighted that this study does not evaluate the technical or economic feasibility of the pipeline required to transfer the excess heat. In fact, it only considers the case of adding a BTES to the pipeline. This is done by comparing the *base case* scenario with an excess heat pipeline without BTES system to a *BTES system case* with excess heat pipeline and a BTES system.

Base Case: A pipeline to transfer 50 MW excess heat from Stenugnsund.

BTES System Case: A BTES system in addition to the *base case* pipeline to transfer 50 MW excess heat from Stenugnsund.

The study investigates Kungälv and western Gothenburg as possible connection points for the pipeline from Stenugnsund to the district heating system. Due to practical reasons, the BTES system must be located close to these locations. However, finding the exact location for the BTES system is beyond the scope of this study.

Figure 3.1 and Figure 3.2 present the charging and discharging phases of the proposed BTES system. The district heating system is supplied with hot water from Stenugsund throughout the year using the connection pipeline. Between May 1 and Sep 30, the return from the district heating system will be used to charge the BTES system before returning back to Stenugnsund. This amounts to 53 days or 3672 hours of charging the BTES. During the proposed charging period the buying cost of the excess heat is generally low. Between Oct 1 and Apr 30 the water supplied from Stenugnsund is returned back directly to Stenugnsund after use in the district heating system. During these months the BTES will be used as a heat source and will be discharged optimally to provide heating to the district heating system. An electrical heat pump will operate with the BTES to lift the temperature of the supply water to 90°C, which is assumed to meet the requirements of the district heating system.

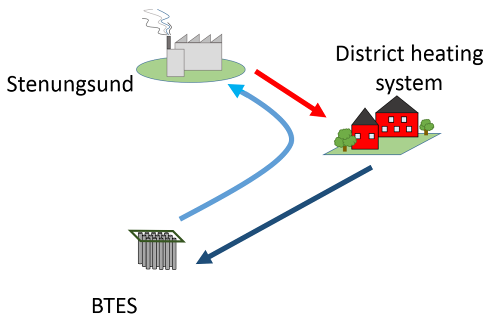

Figure 3.1: Charging period (May 1 - Sep 30)

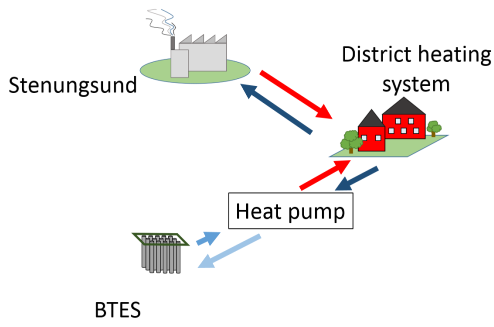

Figure 3.2: Discharging period (Oct 1 - Apr 30).

3.2 System simulation

Figure 3.3 shows an overview of the simulation process. The software *Martes* [31] is used to simulate the district heating system whereas the BTES system is simulated using the software *PILESIM 2* [25].

The district heating fuel mix does not remain identical over the year. Plants are selected differently depending on their operating cost and the heat demand in different system regions. For this study, the heat will only be extracted from the BTES system when it can replace other heat produced at a higher cost. Hence, as a first step the maximum number of yearly profitable hours for extracting heat from the BTES are determined. Next step is to identify the most profitable hours out of these (*Martes*). As these hours will not repetitively occur at the same occasion each year, a typical year is selected for the final BTES simulations in *PILESIM 2*. The final step is to analyse the district heating system and obtain the yearly earnings using *Martes*. Charging and discharging profiles of the BTES system, obtained from *PILESIM 2*, are added to *Martes* prior to the last step. Each of the above-mentioned steps are discussed in further detail in the next coming sections.

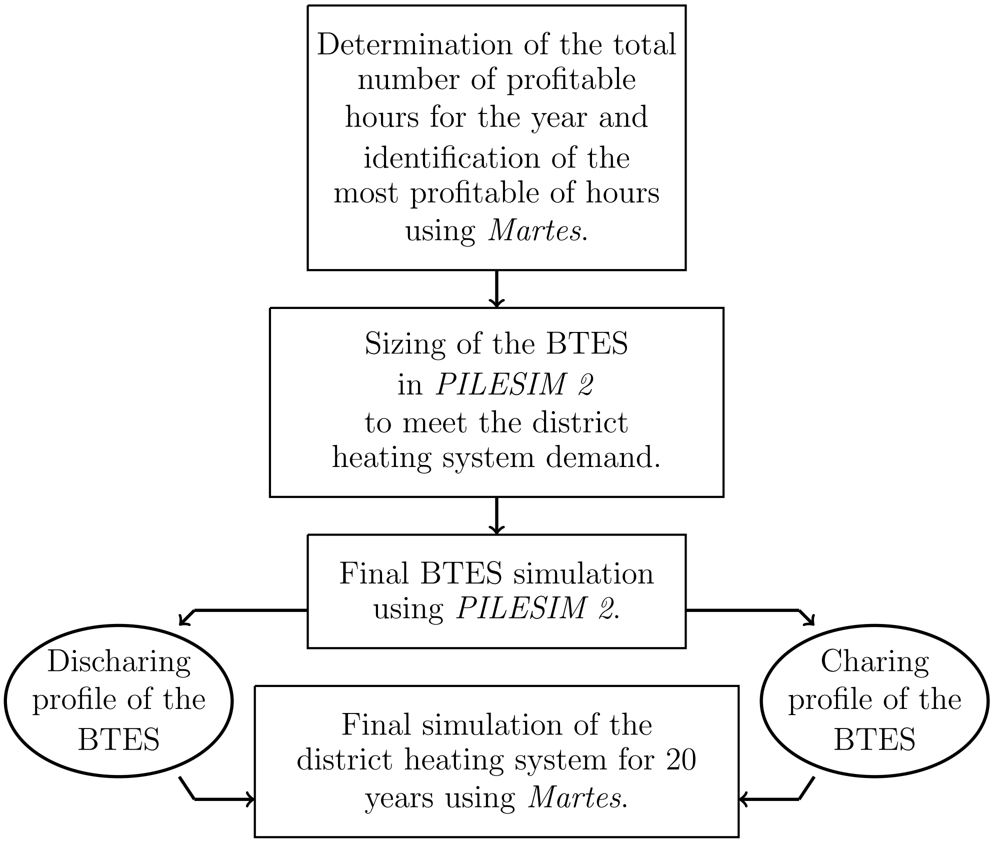

Figure 3.3: Flowchart of the simulation process.

3.2.1 Delivery of excess heat

A 50 MW excess heat pipeline with corresponding mass flow of 239 kg/s is assumed in this study. A single district heating pipeline of type *DN400* in each direction is found suitable for the considered thermal power output and flow rate. The useful thermal power output is determined by considering heat losses from the delivery pipe using Equation 2.5 to Equation 2.14.

Based on the findings of *Morandin et al.* [8], it is assumed that the chemical industries in Stenugnsund have the capacity to handle return temperatures lower than 45°C. Input parameters for heat loss calculations can be found in Table A.1, Appendix A.

3.2.2 Borehole thermal energy storage

The BTES is simulated using the *Duct Storage Model* (*DST-model*) based *PILESIM 2*. This software tool primarily aims at simulating smaller systems connected to buildings. The software offers the possibility to simulate heating using a BTES system as well as geothermal cooling [25]. In this study the heat demand of the district heating system is used in *PILESIM 2* as the building heat demand. The charging of the BTES system is modelled as a direct (i.e. without any heat pump) geothermal process. The results from *PILESIM 2* are obtained using an hourly time-step.

The temperature used for charging the BTES is not know since it depends on many factors, for example position in the district heating system, district heating consumption and activity of other plants in the system. However, a constant temperature of 45°C is considered to be a reasonable assumption. The effect of other temperature levels have been investigated in the sensitivity analysis section. The ambient air temperature assumed for this study is shown in Figure 3.4. This data has been obtained by matching the load curve used in *Martes*, Figure 1.1, with historical data of district heating demand and corresponding outdoor temperatures.

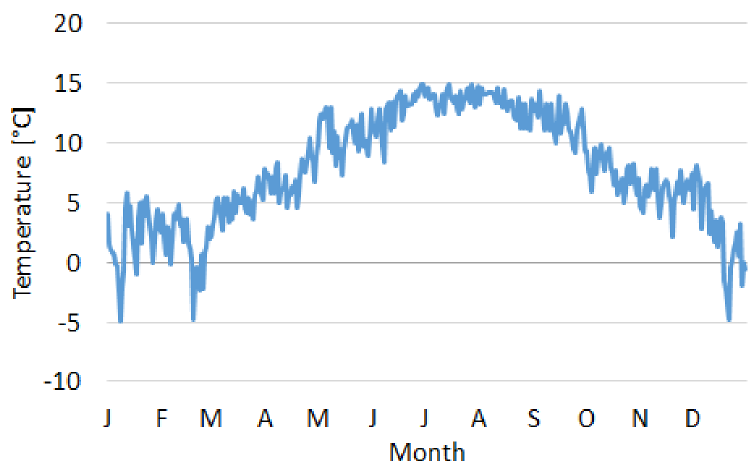

Figure 3.4: Daily average outdoor temperature corresponding to the heat load curve used in *Martes*.

Around 55% of the ground surface at the Swedish west coast consists of bare bedrock [19]. This can be seen in Figure C.2, Appendix C. Therefore bedrock without soil layer is assumed for the simulations. The impact of the soil layer is however evaluated in the sensitivity analysis. Figure C.1, Appendix C, shows that the rock type in the Gothenburg region is primarily composed of granite, granodiorite and monzonite. For simplicity, it is assumed to be pure granite, the most commonly occurring rock type in Sweden [18]. The impact of having different rock types has also been investigated in the sensitivity analysis.

The BTES is assumed to be cylindrical with boreholes arranged in quadratic pattern, see Figure 3.5. The impact of the ground water flow is neglected. The BTES is designed to provide a peak heat extraction of 55 W/m and flow rates of approximately 2m^3/h per borehole. The charging mass flow is assumed equal to the flow through the excess heat pipline, see Section 3.2.1. The boreholes are assumed to be water-filled. Input parameters for BTES simulation are given in Table A.2 to Table A.4, Appendix A.

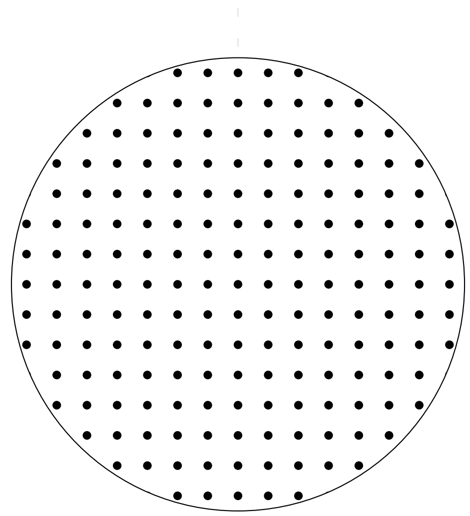

Figure 3.5: Cylindrical BTES configuration with quadratic borehole pattern.

3.2.3 Heat pump

Two different electricity driven (vapour compression) heat pumps have been considered for this study, see data in Table 3.1. These two heat pumps have different COPs. This way, the impact of the efficiency of the heat pump will be seen in the analysis.

Table 3.1: Heat pump data. Expected costs are based on budgetary prices and estimated installation costs.

	Heat output [MW]	**Elect. input [MW]**	**COP [-]**	**Expected cost [MSEK]**
Heat Pump 1	9.80	3.44	2.85	40.00
Heat Pump 2	9.80	2.80	3.5	40.00

The heat pump is simulated in *PILESIM 2*, using Equation 2.2 and Equation 2.3. The COPs of the heat pumps are assumed to be constant. This is a reasonable assumption as the heat pump will operate under somewhat persistent peak load conditions. The heat pumps are also assumed to be of variable-speed as the BTES will not deliver desired capacity during the first years in operation. However, when heat extraction from the BTES will stabilise, the heat pumps will deliver the maximum thermal power output. All input parameters are given in Table A.3, Appendix A.

3.2.4 District heating system impacts

The feasibility to install an additional BTES system in the district heating system and the resulting impacts are evaluated in *Martes*. This software uses prices of fuels, taxes, electricity certificates and emission allowances together with estimated future heat demand forecasted internally at *Göteborg Energi AB*. An operational model of the existing district heating system has also been supplied by *Göteborg Energi AB*, but has been modified to comply with the case scenario, see Section 3.1. The model includes capacity limitations in district heating pipes between different regions, heat load curves representing the district heating consumption as well as capacities, availabilities, efficiencies etc. of existing heat plants. The connections between different regions in the *Martes* model are shown in Figure 3.6. Note that *Gothenburg*-region consists of several smaller district heating regions but they are simplified to one in the Figure 3.6.

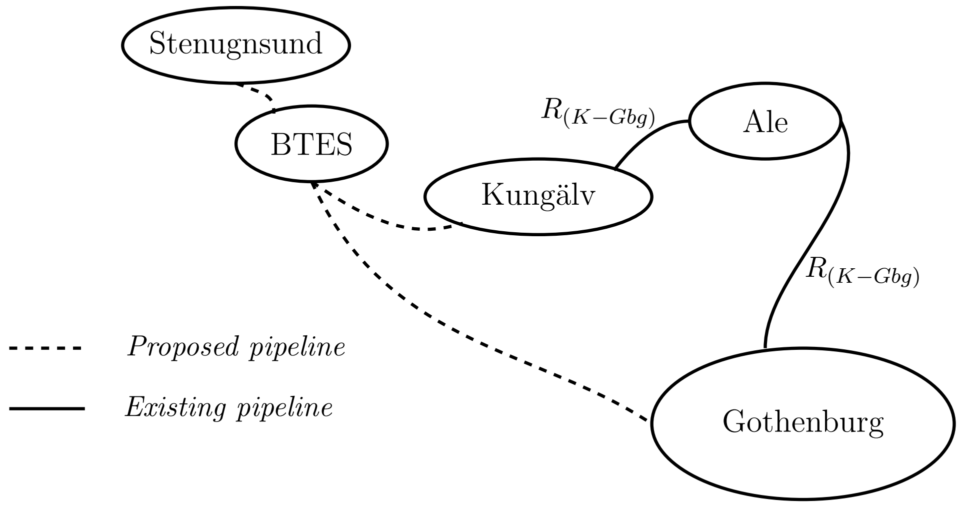

Figure 3.6: Connections assumed between different regions in the model in *Martes*.

The limiting capacity of the pipeline between Kungälv and Gothenburg, $R_{(K-Gbg)}$, which is seen in Figure 3.6, is not constant over the year. Approximate monthly averages of this can be seen in Figure 3.7. The opposite one, $R_{(Gbg-K)}$, has been set to a constant value of 12 MW. Not much heat can be transferred from Kungälv to Gothenburg with existing pipeline configuration. Hence, Figure 3.7 assumes an upgraded pipeline from Kungälv to Gothenburg. Subsequent construction costs of this upgrading are however neglected in this study.

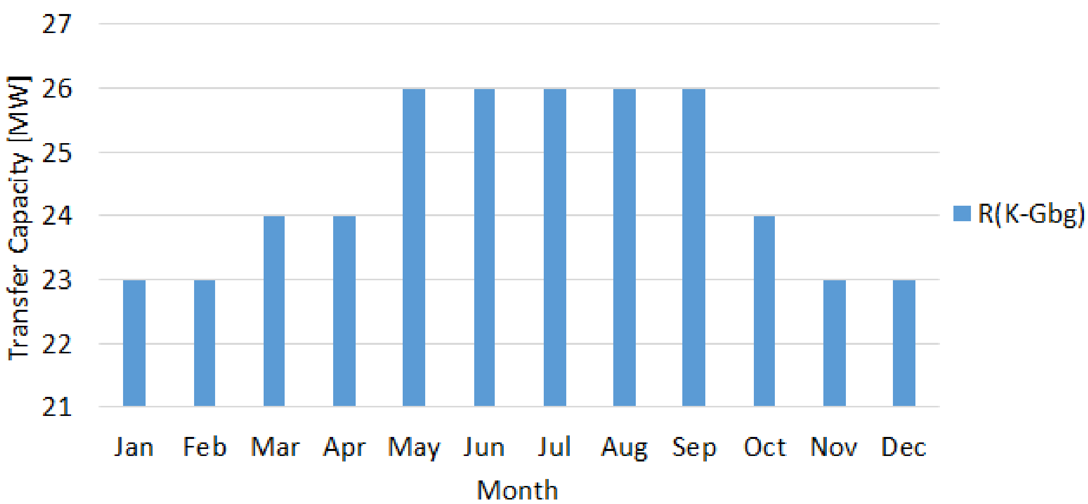

Figure 3.7: Capacity limitation of the district heating pipe between Kungälv and Gothenburg considered for simulations in *Martes*.

For the simulations, the excess heat from Stenugnsund is supplied throughout the entire year. Between Oct 1 to Apr 30, the supply capacity is set to a constant value of 50 MW (minus heat losses). The delivered capacity is higher between May 1 and Sep 30 due to lower return temperatures from the BTES charging[1]. For the discharging period, the BTES system has been added in *Martes* as a heat pump. The COP of the heat pump is set according to Table 3.1. During non-profitable occasions this heat pump is taken out of operation. The thermal power output of the heat pump is reduced during the thermal build-up phase and maximised later. During the charging period, the BTES is added as a region in *Martes* with a heat load profile, which is obtained from *PILESIM 2*. Note that *PILESIM 2* simulates using hourly time-steps whereas *Martes* has day/night time-steps. Hence the results from *PILESIM 2* have been averaged to match the *Martes* resolution and the other way around.

3.3 Economical evaluation

The economical evaluation has been divided into two steps. The first part includes the investment and installation cost of the BTES system. The second part concerns the savings made in the district heating system due to heat generation from the BTES system. Finally, the NPV of the entire investment has been calculated. Also a salvage value of the BTES is accounted for in the end of the 20 year investigated period.

Internal forecasts at *Göteborg Energi AB* including prices of fuel, electricity, taxes, emission allowances and electricity certificates together with future district heating demand have been used in *Martes*. Cost data for BTES construction is approximated based on findings of *Hallqvist* [16]. This cost data is considered reliable enough by *Göteborg Energi AB* to be used in this study. The cost of connecting the BTES system to the district heating system is estimated to be 3.0 MSEK (maximum 1.0 MSEK, minimum 6.0 MSEK). Costs for upgrading the district heating pipe passage from Kungälv to Gothenburg have not been included in the evaluation. Additional costs for maintenance and land acquisition for the BTES are not considered either.

The economical evaluation has been done for a period of 20 years (2015-2034) for which the forecasts from *Göteborg Energi AB* are valid. An interest rate of 7% and an inflation rate of 2% have been used for the NPV calculations. It has been assumed that the salvage value of the heat pump after 20 years will be zero.

[1] A lower return temperature yields a higher energy output for the district heating system.

3.4 Sensitivity analysis

The sensitivity analysis has been carried out to study the uncertainty of the results and to identify the critical parameters. The investigated parameters are presented in Table 3.2 and Table 3.3.

Table 3.2: Parameters investigated for sensitivity analysis of BTES system.

Parameter	Change
Borehole spacing	-3 m , -6 m
Thermal conductivity of bedrock	± 10 % of assumed value
Volumetric heat capacity	± 10 % of assumed value
Soil layer	+ 2 m of sand/gravel, clay
Charging Temperature	± 5 °C

Table 3.3: Parameters investigated for sensitivity analysis of district heating system.

Parameter	Change
Electricity price	- 30 SEK/MWh
Thermal build-up	With, without
Interest rate	7, 4 and 0%
Investment cost of BTES	Decreased

Chapter 4: Results

4.1 BTES system design

An analysis of how many hours a year an additional BTES will generate profits served as a guideline for the BTES design. Prior to this step, the heat losses from the planned excess pipeline were calculated.

4.1.1 Pipeline heat losses

Heat losses from the pipeline between Stenugnsund and Kungälv/western Gothenburg were calculated using Equation 2.5 to Equation 2.14, Section 2.4. Input parameters for the heat loss calculations are given in Table A.1, Appendix A. Resulting temperature drop and heat losses are presented in Table 4.1. Based on these results, 48 MW of useful thermal power is assumed to be available in Kungälv and 46.8 MW[1] in western Gothenburg. The losses from the return pipe serve as cooling in the Stenugnsund industries, hence they do not practically influence the performance of the district heating system in Kungälv and Gothenburg.

Table 4.1: Heat losses from an excess heat pipeline between Stenugnsund and Kungälv/western Gothenburg.

		Total Temperature Loss [K]	**Total Heat Loss [MW]**
Kungälv	**Delivery Pipe**	1.96	1.97
	Return Pipe	0.77	0.77
Western Gothenburg	**Delivery Pipe**	3.21	3.24
	Return Pipe	1.27	1.27

4.1.2 Thermal demands on the BTES system

Figure 4.1 shows the annual number of hours for which it is profitable to extract heat from the BTES, for the 20-year period 2015-2034. These numbers are limited by the heat capacity of other plants with lower operational cost. Using heat from the BTES to replace lower-cost heat from other plants will not result in economic profitability. Note that Figure 4.1 relies on the assumption of no additional costs for charging the BTES. Hence, the results are somewhat overestimated.

[1] 50MW- 1.97MW $\approx$ 48MW, 50MW- 3.24 MW $\approx$ 46.8 MW

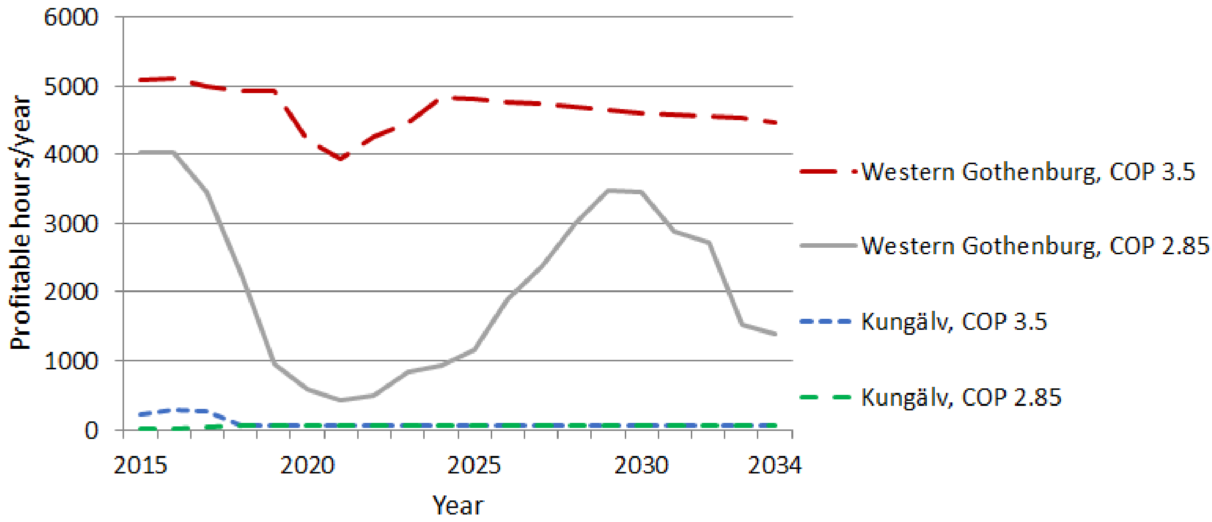

Figure 4.1: Maximum number of hours/year when it is profitable to extract heat from the BTES for the period 2015-2034.

Figure 4.1 indicates that the BTES systems for Kungälv in addition to the 48 MW excess heat pipeline are economically favourable only for a few hours each year. This is due to the relatively low heat demand in Kungälv and Ale, capacity limitations in the district heating pipe between Kungälv to Gothenburg and presence of existing plants with lower operational cost than the BTES system. Therefore, Kungälv was excluded as a potential BTES location for the *base case* scenario in this study.

In western Gothenburg, the BTES system in addition to a 46.8 MW excess heat pipeline is economically favourable during large parts of the years for the 2015-2034 period, as shown in Figure 4.1. The diagram also shows that the economical outcome depends on the COP of the heat pump. The heat pump with a COP of 3.5 has a significantly higher number of profitable hours than the one with lower efficiency. The economic competitiveness of the heat pump with a COP of 2.85 fluctuates during the investigated period. This is due to higher operational costs of the system in comparison to the other plants. A natural gas fired plant, named *Rya KVV*, in the district heating system has a particularly large influence. The decreased economical potential during the period 2018-2027, as seen in Figure 4.1, is the result of the lower operational cost of *Rya KVV* during large parts of these years.

Three different extraction levels, corresponding to 1500, 2000 and 2500 hours of heat extraction per year, have been chosen for further analysis. A maximum yearly heat extraction corresponding to 2500 h/year is reasonable as the capacity of the BTES systems are limited by the charging mass flow given in Section 3.2.1.

Table 4.2: Investigated extraction levels. Heat extraction hours per year with corresponding heat output.

Operation hours per year [h]	**Extracted heat (with heat pump) [GWh/year]**
1500	14.7
2000	19.6
2500	24.5

4.1.3 BTES design

Various BTES designs are made based on the assumptions of Section 3.2.2. Separate designs have been made for each heat pump to comply with the criterion of 55 W/m heat extraction. All input parameters considered for the BTES design are summarised in Table A.2 to Table A.4, Appendix A. The resulting designs can be seen in Table 4.3. The combinations BTES 1/Heat Pump 1 and BTES 2/Heat Pump 2 will be denoted as *System 1* and *System 2* in the remaining report. Data for the heat pumps, Heat Pump 1 and Heat Pump 2, is presented in Table 3.1, Section 3.2.3.

Table 4.3: BTES designs. BTES 1 satisfies requirements of Heat Pump 1 and BTES 2 satisfies requirements of Heat Pump 2.

	Number of boreholes [-]	**BTES volume [m^3]**	**Surface area [m^2]**
BTES 1	465	9 416 250	37 665
BTES 2	510	10 327 500	41 310

4.2 Performance results

This section aims to present the results for the difference between the *base case* and the *BTES system case* scenario. The BTES behaviour is described first after which the economical analysis based on profits made in the district heating system is presented.

4.2.1 BTES system simulation

Selected output parameters from the simulations are presented in Table 4.4. The flow rate of heat carrier fluid through the BTES pipes is equal for all cases whereas the discharging flow rate is higher for *System 2*. As mentioned, the extraction rate is kept constant close to 55.0 W/m while the injection rate ranges between 34.6 and 48.1 W/m. Table 4.4 also gives the temperature difference of the heat carrier fluid between inlet and outlet of the BTES. This difference has been restricted to not exceed 8 K. A constant temperature difference is obtained during the extraction period. However, during the injection period the temperature difference is largest in the beginning of the period after which it steadily decreases. Therefore, both the highest and the lowest values for ΔT *Inj.* are given in Table 4.4.

Table 4.4: BTES performance of *System 1* and *System 2* for the 20^{th} year.

BTES system	**Heat delivery year 20 [GWh/year]**	**Inj. flowrate [kg/s]**	**Ext. flowrate [kg/s]**	**Inj. rate [W/m]**	**Ext. rate [W/m]**	**ΔT Inj. [K]**	**ΔT Ext. [K]**
System 1	14.7	239.2	209.3	34.6	54.9	7/3.6	8.0
	19.6	239.2	209.3	41.0	54.7	7/4.27	8.0
	24.5	239.2	209.2	47.3	54.8	7/4.9	8.0
System 2	14.7	239.2	230.2	34.6	55.0	7/4.0	8.0
	19.6	239.2	230.2	41.0	54.9	7/4.7	8.0
	24.5	239.2	230.2	48.1	55.0	7/5.5	8.0

Figure 4.2 to Figure 4.4 show the relation between heat injection, extraction and losses during the 20 year period. Highest heat injection is required during the first few years of operation to raise the ground temperature. Also, the least heat is extracted during this period and the heat losses are smallest. Time required to reach the design extraction depends on the heat extraction level. The heat extraction of 14.7 GWh/year is reached after 5 years (Figure 4.2) whereas 24.5 GWh/year is reached after 11 years (Figure 4.4). No significant difference in heat losses is seen between the three different extraction levels.

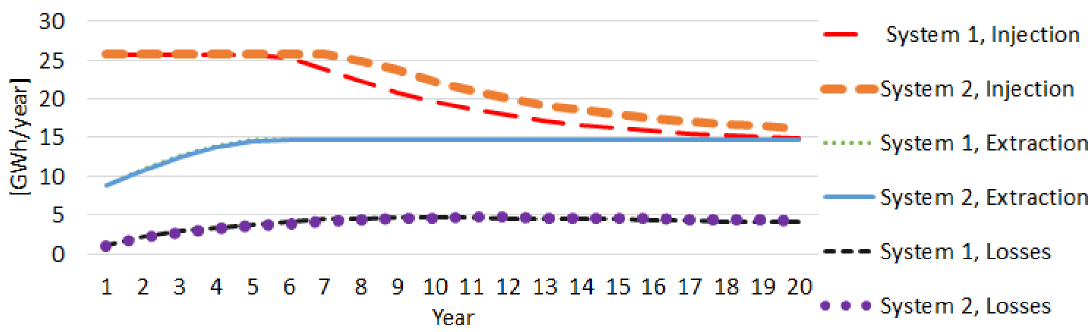

Figure 4.2: Extracted, injected and lost heat for *System 1* and *System 2* with peak heat extraction of 14.7 GWh/year.

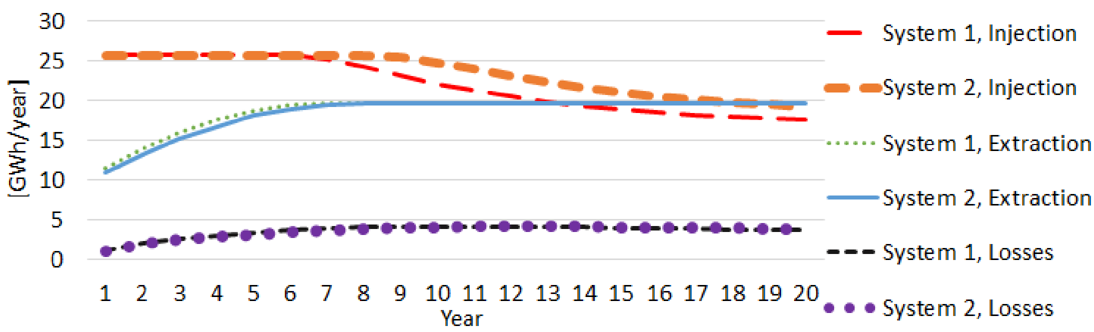

Figure 4.3: Extracted, injected and lost heat for *System 1* and *System 2* with peak heat extraction of 19.6 GWh/year.

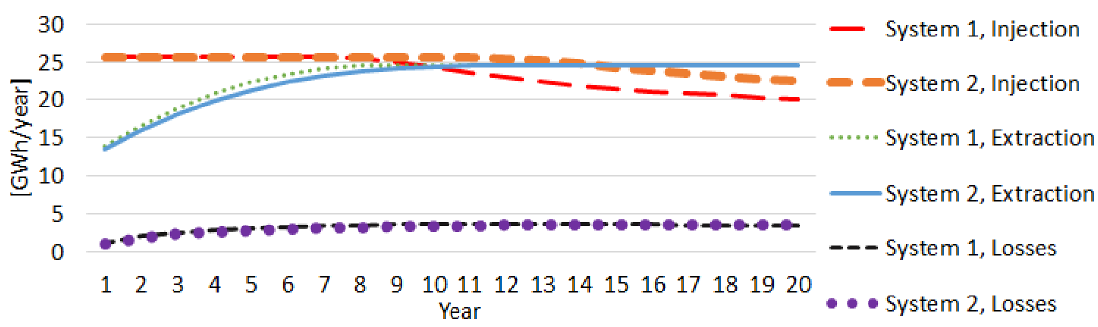

Figure 4.4: Extracted, injected and lost heat for *System 1* and *System 2* with peak heat extraction of 24.5 GWh/year.

Figure 4.5 to Figure 4.10 shows the temperatures of the heat carrier fluid for the 20^{th} year. The blue lines indicate the inlet temperature to the pipes whereas the orange lines represent the outlet temperatures. The diagrams show that for higher extraction rates the heat carrier fluid has lower temperatures. Corresponding power outputs are presented in Figure B.1 to Figure B.6, Appendix B.

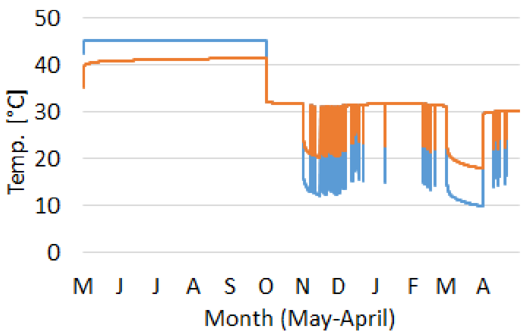

Figure 4.5: 14.7 GWh/year heat extraction with *System 1*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

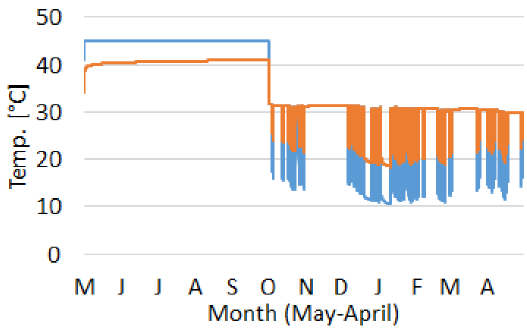

Figure 4.6: 14.7 GWh/year heat extraction with *System 2*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

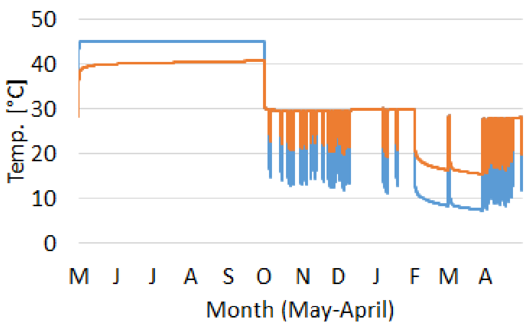

Figure 4.7: 19.6 GWh/year heat extraction with *System 1*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

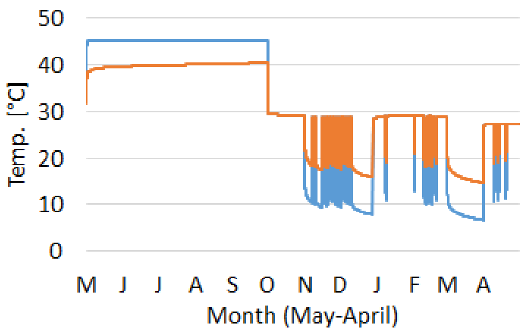

Figure 4.8: 19.6 GWh/year heat extraction with *System 2*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

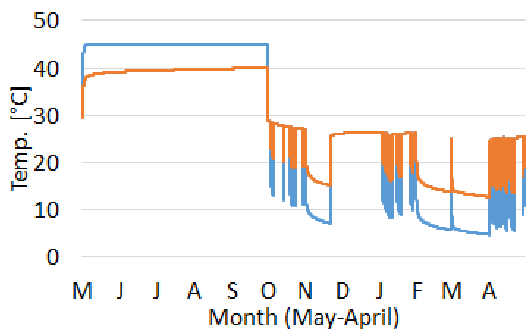

Figure 4.9: 24.5 GWh/year heat extraction with *System 1*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

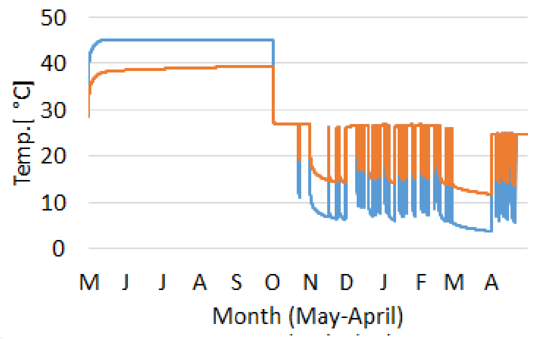

Figure 4.10: 24.5 GWh/year heat extraction with *System 2*. Inlet (blue line) and outlet (orange line) temperature, 20^{th} year.

4.2.2 Economical impact

The construction costs of the BTES designs are calculated according to Table 2.3 and the results can be seen in Table 4.5.

Table 4.5: Estimated construction cost for BTES 1 and BTES 2. Heat pump costs are not included.

	Estimated cost [MSEK]	Min. cost [MSEK]	Max. cost [MSEK]
BTES 1	57.52	37.50	84.82
BTES 2	62.80	41.04	92.44

The NPV of the total investment cost has been calculated using Equation 2.15 to Equation 2.17, Section 2.5, with inputs including BTES construction cost, heat pump initial cost, profits from the BTES system and the salvage value of the BTES. The results are summarised in Table 4.6. None of the analysed cases made enough profits to compensate for the investment cost. *System 2* with heat extraction of 24.5 GWh/year was the most economically feasible case but still with large economical losses.

Table 4.6: Cost summary for *System 1* and *System 2* located in western Gothenburg. Investment cost of the BTES system, salvages values of BTES and profits made from the BTES are included. The estimated (Est.), minimum (Min.) and maximum (Max.) economical results are presented.

		System 1 [MSEK]			*System 2* [MSEK]		
		14.7 GWh	19.6 GWh	24.5 GWh	14.7 GWh	19.6 GWh	24.5 GWh
Est.	Investment cost	- 97.52	- 97.52	- 97.52	-102.80	-102.80	-102.80
	Salvage value	+5.13	+5.13	+5.13	+5.60	+5.60	+5.60
	Profits	+8.26	+8.53	+9.07	+13.42	+14.88	+17.27
	NPV	**-84.13**	**-83.86**	**-83.32**	**-83.78**	**-82.32**	**-79.93**
Min.	Investment cost	- 77.5	- 77.5	- 77.5	-81.04	- 81.04	-81.04
	Salvage value	+4.68	+4.68	+4.68	+5.13	+5.13	+5.13
	Profits	+8.26	+8.53	+9.07	+13.42	+14.88	+17.27
	NPV	**-64.56**	**-64.29**	**-63.75**	**-62.49**	**-61.03**	**-58.64**
Max.	Investment cost	- 124.82	- 124.82	- 124.82	- 132.44	- 132.44	- 132.44
	Salvage value	+4.54	+4.54	+4.54	+4.95	+4.95	+4.95
	Profits	+8.26	+8.53	+9.07	+13.42	+14.88	+17.27
	NPV	**-112.02**	**-111.75**	**-111.21**	**-114.07**	**-112.61**	**-110.22**

4.2.3 Replaced fuels

The heat from the BTES system will replace the thermal energy which is produced at a higher cost. However, as the heat pump operates on electricity, there will be an inevitable increase in the electricity consumption of the district heating system. Figure 4.11 shows the quantity of fuels added to the district heating system due to the installed BTES system. Industrial excess heat from Stenugnsund and electricity are the two fuels added to the district heating system to greatest extent. During some occasions, the BTES system will replace other heat pump units in the district heating system, i.e. electricity will replace electricity. This explains the low increase in electricity which is most obvious during the period 2020-2023. A net increase in wood pellets consumption is also seen for the years 2031-2034. Some plants are required to operate at a certain minimum capacity, for instance, the natural gas fired plant *Rya KVV*. The wood pellets consumption increases for those occasions when it is profitable to replace the entire minimum capacity of *Rya KVV* with heat from the BTES system and wood pellets fired plants.

Figure 4.12 shows the fuels replaced when the BTES system is installed. Natural gas will be replaced to greatest extent but wood pellets are also replaced. Note that both Figure 4.11 and Figure 4.12 are for the most economical feasible case of 24.5 GWh heat extraction with *System 2* located in western Gothenburg. The irregular shapes of Figure 4.11 and Figure 4.12 are due to many factors. For instance, use of fuels with different heating values, plants with different efficiencies, varying demands of district heat, and combined heat and power production from certain plants. It also depends on the minimum operating capacities of some plants and the fact that there are more electricity-driven heat pumps in the system.

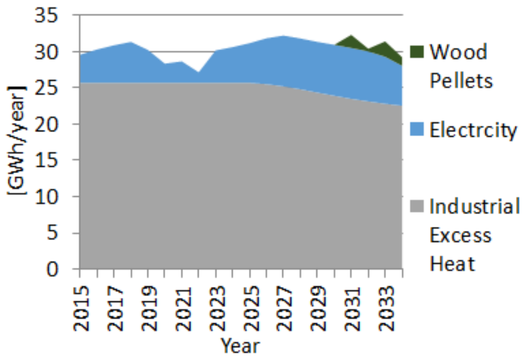

Figure 4.11: Fuel consumption added due to the 24.5 GWh/year *System 2* installed in western Gothenburg.

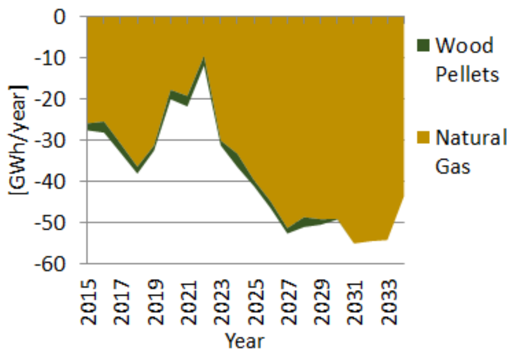

Figure 4.12: Fuel consumption replaced due to the 24.5 GWh/year *System 2* installed in western Gothenburg.

4.3 Sensitivity analysis

A sensitivity analysis has been performed for both *System 1* and *System 2* with desired heat extraction of 24.5 GWh/year. Uncertainties in BTES input parameters are also studied for the most economically feasible case of 24.5 GWh/year heat extraction case with *System 2*, shown in Table 4.6.

4.3.1 BTES design parameters

Five design parameters have been examined in the sensitivity analysis of the BTES system: charging temperature, ground thermal conductivity, ground volumetric thermal capacity, soil layer thickness and borehole spacing. The influence has been evaluated based on resulting yearly average heat output, required heat injection and heat losses over the 20 year period, 2015-2034.

Figure 4.13 shows the impact of different charging temperatures for the 20 years of operation. The quantity of extracted heat remains almost unaffected as the charging temperature is varied between 40 and 50°C. However, both heat injections and heat losses increase with higher charging temperature.

The heat extraction, injection and losses all increase if the thermal conductivity of the bedrock is increased from 3.15 to 3.85 W/(m·K), as seen in Figure 4.14. The effect of ± 10% uncertainty in the assumed value of the ground volumetric heat capacity is shown in Figure 4.15. A higher value of ground volumetric heat capacity results in slightly higher injection and slightly lower extraction. The effect of volumetric heat capacity on heat losses is rather limited within the investigated interval.

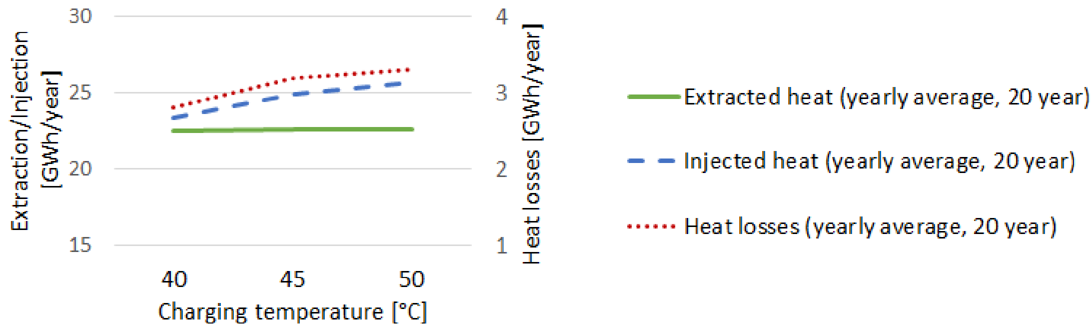

Figure 4.13: Influence of different charging temperatures.

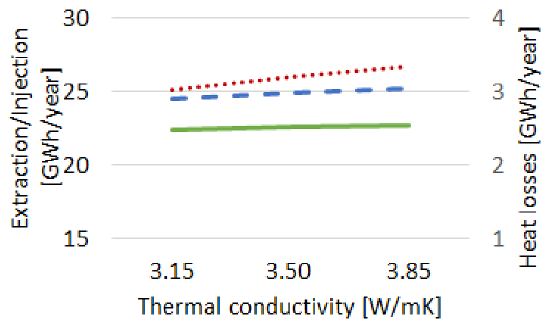

Figure 4.14: Influence of different ground thermal conductivities.

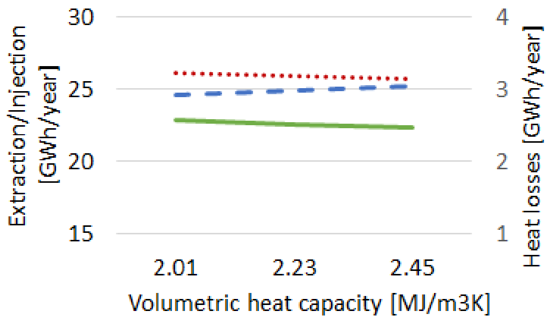

Figure 4.15: Influence of different ground volumetric thermal capacities.

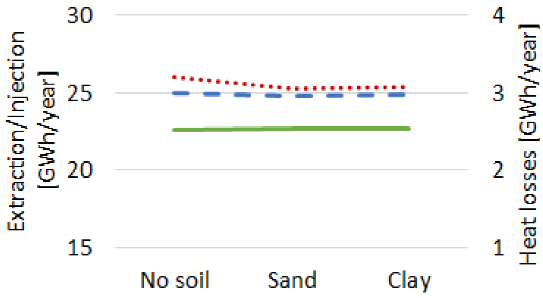

Figure 4.16: Influence of no soil layer, a 2-m thick layer of sand/gravel and a 2-m thick layer of clay.

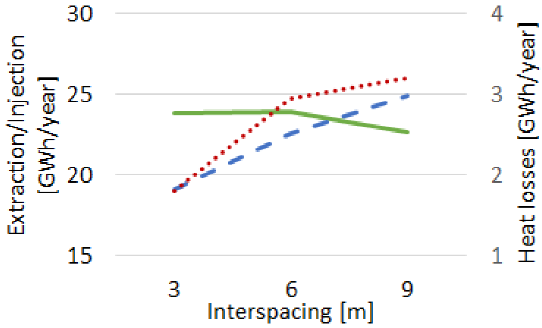

Figure 4.17: Influence of different borehole interspacing.

The effects of having no soil, a 2-m thick sand/gravel layer or a 2-m thick clay layer on top of the BTES are shown in Figure 4.16. The soil/gravel mixture is assumed to have a thermal conductivity of 0.4 W/(m·K) and a volumetric heat capacity of 1.2 MJ/(m^3·K). The thermal conductivity and volumetric heat capacity for clay are assumed to be 1.1 W/(m·K) and 3.6 MJ/(m^3·K), respectively. The results in Figure 4.16 show no major influence on heat extraction, heat injection and heat losses. However, based on data in Table 2.3, the investment cost will increase by 31.9-63.8 kSEK for BTES 1 and 35.7-71.7 kSEK for BTES 2 due to higher drilling costs in soil.

The effect of different borehole spacings of 3, 6 and 9 m are shown in Figure 4.17. It seems that the 3-m spacing is most superior, however, the desired heat extraction of 24.5 GWh/year will not be reached with a 3-m borehole spacing. Figure 4.18 shows that the maximum of 23.9 GWh/year heat extraction is reached after 3 years with the 3-m borehole spacing. With 6- and 9-m borehole spacing, the desired level of 24.5 GWh/year heat extraction is reached after 5 and 11 years, respectively. However, more heat can be extracted during the first years from the BTES with 3-m borehole spacing than from the BTESs with 6- and 9-m borehole spacing. This explains the higher yearly average heat extraction from the BTES with 3-m spacing during the 20-year period, shown in Figure 4.18. Figure 4.19 shows the effect of borehole spacing on heat injections. From the figure it cannot be excluded whether 6-m borehole spacing is more beneficial than 9 m. Using 6-m borehole spacing instead of 9 m will, however, decrease the required land area by 55.6%.

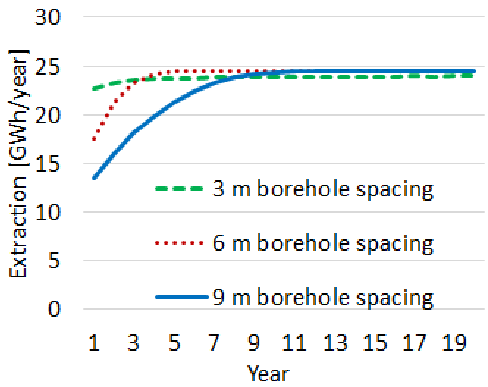

Figure 4.18: Heat extracted over 20 years for 3, 6 and 9 m borehole spacing.

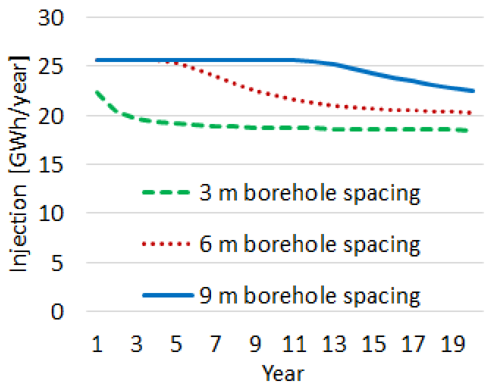

Figure 4.19: Heat injected over 20 years for 3, 6 and 9 m borehole spacing.

4.3.2 District heating system parameters

The sensitivity of the district heating system simulations made in *Martes* has also been analysed in terms of electricity prices, thermal-build up of the BTES, interest rates and decreased investment cost of the BTES system.

Electricity prices

Figure 4.20 shows the annual profitable hours for the period 2015-2034 if the electricity price is lowered with 30 SEK/MWh. In comparison to Figure 4.1, the economic feasibility of both *System 1* and *System 2* will increase. Similarly, for Kungälv the number of profitable hours are still quite low despite the decreased electricity prices.

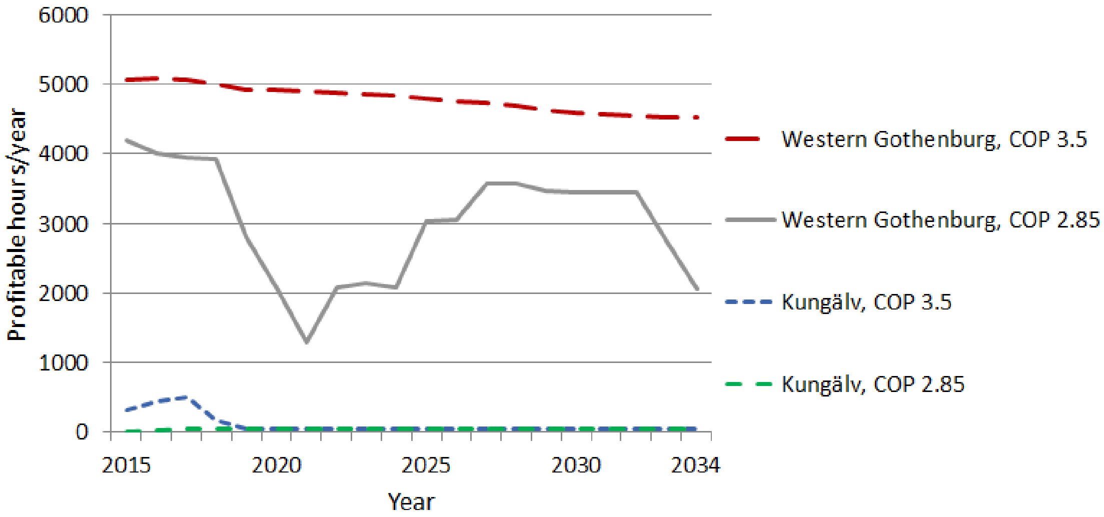

Figure 4.20: Maximum number of hours/year when it is profitable to extract heat from the BTES assuming 30 SEK/MWh reduction in electricity price.

Table 4.7 shows the new NPV of *System 1* and *System 2* for 24.5 GWh/year heat extraction with 30 SEK/MWh reduction in electricity prices. It can be seen from Table 4.7 that more profits are made with the decreased electricity price. The profits increase by 6.29 MSEK for *System 1* and by 5.87 MSEK for *System 2*. Profits for *System 1* increase more since the reduction in electricity price results in more operating hours for *System 1*. This can be seen by comparing Figure 4.20 with 4.1.

Thermal build-up

The impact of having no thermal build-up period has also been analysed. This has been done by assuming a hypothetical situation where it is possible to extract maximum thermal power from year one (9.8 MW). Comparing results from Table 4.6 and Table 4.7 indicate that for a no thermal build-up scenario the profits are marginally increased, which also give higher NPVs.

Table 4.7: Cost summary for *System 1* and *System 2* located in western Gothenburg when the forecasted electricity price is decreased by 30 SEK/MWh and thermal build-up period is neglected. Investment cost of the BTES system, salvages value of the BTES and profits made from the BTES are included. The estimated (Est.), minimum (Min.) and maximum (Max.) economical results are presented.

		Decreased electricity price		**No thermal build-up period**	
		System 1	*System 2*	*System 1*	*System 2*
		24.5 GWh	24.5 GWh	24.5 GWh	24.5 GWh
Est.	Investment cost	-97.52	-102.80	-97.52	-102.80
	Salvage value	+5.13	+5.60	+5.13	+5.60
	Profits	+15.36	+23.14	+11.19	+20.95
	NPV	**-77.03**	**-74.06**	**-81.20**	**-76.25**
Min.	Investment cost	-77.50	-81.04	-77.50	-81.04
	Salvage value	+4.68	+5.13	+4.68	+5.13
	Profits	+15.36	+23.14	+11.19	+20.95
	NPV	**-57.46**	**-52.77**	**-61.63**	**-54.96**
Max.	Investment cost	-124.82	-132.44	-124.82	-132.44
	Salvage value	+4.54	+4.95	+4.54	+4.95
	Profits	+15.36	+23.14	+11.19	+20.95
	NPV	**-104.92**	**-104.35**	**-109.09**	**-106.54**

Interest rate

Until this point, all economic calculations have been made with an interest rate of 7%. Table 4.8 shows the outcome for lower interest rates of 4% and 0%. Note that an inflation rate of 2% is still included in the calculations. The choice of interest rate effects both the profits from the district heating system and the salvage value of the BTES system. An interest rate of 0% increases the savings by 12.96 MSEK for *System 1* and by 22.76 MSEK for *System 2*. Despite the large increase in profits, the NPVs still remain negative for these cases.

Table 4.8: Cost summary for *System 1* and *System 2* located in western Gothenburg when the interest rate is decreased to 4% and 0%. Investment cost of the BTES system, salvage value of the BTES and profits made from the BTES are included. The estimated (Est.), minimum (Min.) and maximum (Max.) economical results are presented.

		Interest rate 4%		**Interest rate 0%**	
		System 1	*System 2*	*System 1*	*System 2*
		24.5 GWh	24.5 GWh	24.5 GWh	24.5 GWh
Est.	Investment cost	- 97.52	-102.80	- 97.52	-102.80
	Salvage value	+8.97	+8.65	+13.13	+14.33
	Profits	+10.26	+21.78	+14.03	+31.30
	NPV	**-78.29**	**-72.46**	**-70.36**	**-57.17**
Min.	Investment cost	- 77.50	-81.04	- 77.50	-81.04
	Salvage value	+8.18	+8.96	+11.98	+13.11
	Profits	+10.26	+21.78	+14.03	+31.30
	NPV	**-59.06**	**-50.30**	**-51.49**	**-36.63**
Max.	Investment cost	-124.82	-132.44	-124.82	-132.44
	Salvage value	+7.93	+9.79	+11.6	+12.65
	Profits	+10.26	+21.78	+14.03	+31.30
	NPV	**-106.63**	**-100.87**	**-99.19**	**-88.49**

4.3.3 Investment cost of BTES system

The economic impact of a lower construction/investment cost of the BTES storage has also been analysed. Former calculations have been based on cost data from Table 2.3. Table 4.9 presents the scenario if the investment cost of BTES 1 is 27.32 MSEK and BTES 2 is 30 MSEK instead. These costs were obtained directly from drilling companies and are probably better representative of the actual BTES costs. The investment cost of the heat pump system is still assumed to be 40 MSEK in accordance with Table 3.1.

Table 4.9: Cost summary for *System 1* and *System 2* located in western Gothenburg with decreased investment/construction cost of the BTES. Investment cost of the BTES system, salvage value of the BTES and profits made from the BTES are included. The estimated (Est.) is presented presented.

		System 1	*System 2*
		24.5 GWh	24.5 GWh
Est.	Investment cost	- 67.35	- 70.00
	Salvage value	+2.44	+2.67
	Profits	+9.07	+17.27
	NPV	**-55.84**	**-50.06**

Chapter 5: Discussion & Conclusions

This study has analysed the economical feasibility of installing a BTES and an electrical driven heat pump system in addition to an excess heat pipeline from Stenugnsund. It does not consider the profitability of the excess heat pipeline itself but focus only on the additional BTES system. The strength of this combination is above all a decreased return temperature back to Stenugnsund during the charging period, which consequently results in a larger thermal power output from the pipeline. In addition to this, the extracted heat can be used to replace heat generated from other plants with higher operational costs during the discharging period. This also results in lower emissions from plants which are replaced by the BTES system.

5.1 Locating plant in Kungälv

The results show that the potential to increase the economic profitability with a BTES system is low when Kungälv is selected as the connection point of the excess heat pipeline and the BTES system is located there. This can be attributed to cheaper heat production from existing plants, heat transfer limitations from Kungälv to Gothenburg and a relatively low heat demand in Kungälv and Ale. The situation does not change much even if the forecasted electricity prices are decreased by 30 SEK/MWh. This conclusion is not for the excess heat pipeline itself but only for the additional BTES system. Other aspects including shorter distance between Stenugnsund and Kungälv, and lower costs and heat losses keep Kungälv as a location of interest as the connection point of the excess heat pipeline, but probably without the BTES system.

5.2 Locating plant in western Gothenburg

Higher profits are expected when the excess heat pipeline is connected to western Gothenburg and the BTES system is located there. However, the results indicate that the profits made in the district heating system will not exceed the investment cost of the BTES system during the 20 year period of 2015-2034. The feasibility of the investment increases with decreasing electricity price. However, a reduction of the forecasted electricity price by 30 SEK/MWh does not make much difference to the economical results. The profits also depend on the choice of interest rate. However, even considering a 0% interest rate does not make the investment profitable. Another scenario of BTES drilling cost decreased down to 30 MSEK has also been considered. However, the returns from the BTES are not large enough to cover the investment. One reason for these low returns is that the district heating system has enough existing capacity to meet the demand without adding any new system. Hence, the BTES system with both equipment and operational costs is competing with existing systems only having operational costs. If, for some reason, a new plant has to be added to the district heating system or and existing plant has to be overhauled substantially, then the economic competitiveness of the BTES system will be much higher. The feasibility of this investment also depends on the COP of the heat pump. It is shown that the heat pump with a COP of 3.5 can generate profits for more than 4000 h/year throughout the 2015-2034 period. The heat pump with a COP of 2.85 has fluctuating number of profitable hours/year. Least number of profitable hours are obtained during those years when the operational cost of the BTES system is higher than that of the natural gas fired plant *Rya KVV* for large parts of the year. A COP higher than 3.5 will increase the profits further.

Under the *base case* scenario the BTES system mostly replaces heat generated from the natural gas and to a smaller extent from the wood pellet plants. Consequently, emissions related to these fuels are also reduced.

5.3 Uncertainty

Since this study aims at an early stage investigation lower levels of details have been excluded. For instance the profits have been estimated only based on fuel prices, earnings from electricity production, taxes and political instruments. In reality other factors, for example, maintenance will also affect the outcome.

It cannot be emphasized enough that these results are based on forecasted fuel prices, taxes, political instruments and heat demand. Among these forecasts the heat demand is expected to decrease in future due to a more efficiently operated district heating system. Due to complexity in foretelling the future, it is regarded as one of the major uncertainty factors. Other major uncertainties include the scenario of reduced thermal power from the oil refineries and whether the future district heating system retains the identical set-up of plants. Another aspect is that the investigated period was limited to the length of the forecasts, i.e. the 20-year period between 2015-2034. In reality, it will take several years before the BTES system and excess heat pipeline can be taken into operation. Another scenario where one of the existing plants has to be replaced would probably give totally different results. It is also hard to know which delivery temperatures the future district heating system will operate on. Lower delivery temperatures will allow for increased COP of the heat pump system, increasing its economic viability.

The selected BTES designs in this study have a land area requirement of between 36 936 to 41 310 m^2 (which correspond to around 5 to 6 football fields). The sensitivity analysis indicated that a borehole spacing of 6 m would also be feasible. A 6-m spacing between the boreholes would result in between 16 740 to 18 360 m^2 of land area (which corresponds to around 2-3 football fields). In other words, a relatively large land area must be available and authorised for the BTES system. It is also assumed that 90°C delivery temperature from the heat pump will be acceptable by the district heating system. Since the district heating system delivers higher temperatures in winter time, it cannot be excluded that an additional technique will be needed to raise the temperature further.

In the *Martes* simulations the BTES system operated for the most profitable hours during each year. It will be hard to apply this in reality, since it is difficult to predict for which hours the greatest earnings can be made in advance. It is also important to mention that these results are based on an unrealistic assumption of having no additional costs for charging the BTES. Moreover, financial entries like maintenance and cost to purchase/rent land area have been neglected. All of these stated factors contribute to an overestimation of the economical outcome.

Many other factors influence the uncertainty of the analysis. Among technical factors, larger borehole spacing together with higher thermal conductivity of the ground result in higher heat losses from the BTES. Ground with higher value of volumetric heat capacity limits the heat extraction to some extent. The temperature of the heat carrier fluid used for charging the BTES system also affects the thermal performance of the system. However, there are inherent uncertainties in estimating the charging temperature of the heat carrier fluid since it depends on, for example, the position in the district heating system, the heat demand and the other components in the system.

5.4 Conclusions

The economic feasibility of adding a BTES system to an excess heat pipeline from Stenugnsund is very low. The investment is highly infeasible if Kungälv is chosen as the connection point of the excess heat pipeline. Western Gothenburg has a higher economic potential but the returns are still not high enough to justify the investment. The returns on the investment are sensitive to the electricity price, COP of the heat pump and the interest rate.

Bibliography

[1] S. Werner. "*District Heating in Sweden- Achievements and Challanges*". In XIV Polish District Heating Forum, Sept 13-15, 2010.

[2] International Energy Agency. "*Technology Roadmap, Energy Storage*". `https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf`, 2014.

[3] J. Arnell, L. Bolin, K. Holmgren, L. Staffas, I. Adolfsson, and M. Lindblad. "*Förutsättning för ökad nytta av restvärme, Rapport 2012:14*". Fjärrsyn, Svensk Fjärrvärme, 2012.

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

[5] "*Året 2013- Lufttemperatur, SMHI*". `http://data.smhi.se/met/climate/time_series/year/vov_pdf/SMHI_vov_temperature_13.pdf?24851`, Accessed: 2015-01-28.

[6] "*Som fjärrvärmeanvändare är du en del i ett smart system*". `http://www.goteborgenergi.se/Privat/Produkter_och_priser/Fjarrvarme/Om_fjarrvarme`, Acessed: 2015-01-28.

[7] SCB. "Statistiska Centralbyrån, Folkmängsstatistik". `http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/FolkmangdNov/?rxid=335a7767-f6d1-4c22-952d-0632d67ea73f`. Accessed: 2015-02-06.

[8] M. Morandin, R. Hackl, and S. Harvey. "*Economic Feasibility of district heating delivery from industrial excess heat: A case study of a Swedish petrochemical cluster*". *Energy*, 65:209–220, 2014.

[9] "*Södra Cell Värö byggs ut 2014-2016*". `http://www.sodra.com/sv/Massa/Vara-massabruk/Sodra-Cell-Varo/Expansion-Sodra-Cell-Varo/`, Accessed: 2015-02-17.

[10] H. Yang, P. Cui, and Z. Fang. "*Vertical-borehole ground-coupled heat pumps, A review of models and systems*". *Applied Energy*, 87(1):16–27, 2009.

[11] B. Nordell. *"Borehole heat store design optimization"*. PhD thesis, Luleå University of Technology, 1994.

[12] G. Hellström. *"Ground Heat Storage. Thermal Analyses of Duct Storage Systems"*. PhD thesis, Department of Mathematical Physics University of Lund Sweden, 1991.

[13] D. Pahud and B. Matthey. "*Comparison of the thermal performance of double U-pipe borehole heat exchangers measured in situ*". *Energy & Buildings*, 33(5):503–507, 2001.

[14] G. Florides and S. Kalogirou. "*Ground heat exchangers—A review of systems, models and applications*". *Renewable Energy*, 32(15):2461–2478, 2007.

[15] S. Javed and P. Fahlén. "*Thermal response testing of a multiple borehole ground heat exchanger*". *International Journal of Low-Carbon Technologies*, 6(2):141–148, 2011.

[16] K. Hallqvist. "*Högtempererat Borrhålslager för Fjärrvärme*". Master's thesis, Uppsala Universitet, 2014.

[17] C. O. Popiel, J. Wojtkowiak, and B. Biernacka. "*Measurements of temperature distribution in ground*". *Experimental Thermal and Fluid Science*, 25(5):301–309, 2001.

[18] J. Sundberg. "*Termiska egenskaper i jord och berg*". Statens Geologiska Institut, SGI. `http://www.swedgeo.se/upload/publikationer/Info/pdf/SGI-I12.pdf`, 1991.

[19] J. Sundberg. *"Thermal Properties of Soil and Rocks"*. Chalmers University of Technology, University of Gothenburg, 1988.

[20] D. Banks. *"An introduction to thermogeology: ground source heating and cooling"*. 2:nd Edition. Wiley-Blackwell, 2012.

[21] S. Javed. *"Design of ground source heat pump systems. Thermal modelling and evaluation of boreholes, D2010:02"*. Licentiate Thesis. Chalmers University of Technology, 2010.

[22] S. Javed, J. Claesson, and P. Fahlén. "*Analytical modelling of short-term response of ground heat exchangers in ground source heat pump systems*". In 10th REHVA World Congress, Clima 2010, Antalya, Turkey, May 9-12, Proceedings vol. CD-proceedings, 2010.

[23] S. Javed, , P. Fahlén, and J. Claesson. "*Vertical ground heat exchangers: A review of heat flow models*". In Effstock 2009-Stockholm, Sweden, June 14–17. Proceedings vol. CD-proceedings, 2009.

[24] C. Yavuzturk. *"Modeling of Vertical Ground Loop Heat Exchangers for Ground Source Heat Pump Systems"*. PhD thesis, Oklahoma State University, 19.

[25] D. Pahud. "*PILESIM 2, Simulation tool for heating/cooling systems with energy piles or multiple borehole heat exchangers, User Manual*". SUPSI, La Scuola universitaria professionale della Svizzera italiana, 2007.

[26] Hans L. von Cube and F. Steimle. "*Heat pump technology*". Butterworths & Co (Publishers) Ltd., 1981.

[27] M. Eriksson. "*Tekniska möjligheter och potential för högtemperaturvärmepumpar i kommunala och industriella energisystem*". Final technical report. Institutionen för Kemiteknik och Miljövetenskap, Chalmers University of Technology, 2008.

[28] R. Smith. *"Chemical Process Design and Integration"*. John Wiley & Sons, Ltd., 2005.

[29] U. Jarfelt. "*Jämförelse mellan dubbel- och enkelrör. Ackumulerade värmeförluster under 50 års drifttid*". Fjärrvärme Föreningen, Forskning och Utveckling, `http://www.svenskfjarrvarme.se/Global/Rapporter%20och%20dokument%20INTE%20Fj%C3%A4rrsyn/FOU-rapporter%20INTE%20Fj%C3%A4rrsyn/Hetvattenprogrammet,%20rapporter/2002/Jamforelse_mellan_dubbel_och_enkelror_FOU_2002-79.pdf`, 2002.

[30] J. Welty, C. E. Wicks, G. L. Rorrer, and R. E. Wilson. *"Fundamentals of Momentum, Heat, and Mass Transfer"*. Wiley, 5 edition, 2008.

[31] "*Martes - simuleringsprogrammet för strategisk analys av fjärrvärmeproduktion*". `http://www.profu.se/martes.htm`, Accessed: 2015-01-28.

[32] Powerpipe. "*Product Catalogue 2013*". `http://www.powerpipe.se/katalog.htm`, Accessed: 2015-04-13.

[33] J. D. Spitler, S. Javed, and R.K. Ramstad. "*Natural convection in groundwater-filled boreholes used as ground heat exchangers*". Applied Energy (Submitted).

Appendix A: Input parameters

A.1 District heating pipes

Table A.1: Input parameters for heat losses in district heating pipes, type *DN400* single pipe, between Stenugnsund and Kungälv.

Parameter	**Value**	**Comment, reference**
Insulation thermal conductivity λ_i	0.026 [W/(°C·m)]	Polyurethane foam, [32]
Soil thermal conductivity λ_s	1.1 [W/(°C·m)]	Kungälv, [19]
Pipe length to Kungälv (L_1)	35 000 [m]	Assumed value
Pipe length to western Gothenburg (L_2)	57 500 [m]	Assumed value
District heating pipe inner radius (r_{DHi})	0.711 [m]	Assumed value [32]
District heating pipe outer radios (r_{DHo})	0.900 [m]	Assumed value [32]
Approximate district heating supply temperature (T_h)	100 [°C]	Assumed value
Approximate district heating return temperature (T_c)	45 [°C]	Assumed value
Average ambient temperature (T_0)	10 [°C]	Assumed value
Distance between pipes ($2D$)	1.2 [m]	Assumed value
Depth of district heating pipes (H)	1.0 [m]	Assumed value
Heat capacity, water, 100°C (Cp_{100})	4211 [J/(K·kg)]	[30]
Heat capacity, water, 45°C (Cp_{45})	4177 [J/(K·kg)]	[30] (linear interpolation)

A.2 BTES simulation parameters

Table A.2: BTES design input parameters used in PILESIM 2.

	BTES 1	**BTES 2**	**Comment, reference**
Number of boreholes	465 [-]	510 [-]	Calculated value
Active borehole depth	250 [m]	250 [m]	Assumed value
Soil layer thickness	0.0 [m]	0.0 [m]	Assumed value
BTES volume	9 416 250 [m^3]	10 327 500 [m^3]	Calculated value
Fluid- ground thermal resistance (Rb)	0.10 [W/(m·K)]	0.10 [W/(m·K)]	Calculated value, [33]
Internal thermal resistance (Ra)	0.13 [W/(m·K)]	0.13 [W/(m·K)]	Calculated value, [33]
Borehole radius (r_b)	57.5 [mm]	57.5 [mm]	Assumed value
U-tube wall thickness	2.3 [mm]	2.3 [mm]	Assumed value
U-tube inner diameter	35.4 [mm]	35.4 [mm]	Assumed value
Minimum fluid temperature in BHE	0.0 [°C]	0.0 [°C]	Assumed value
Spacing between boreholes	9 [m]	9 [m]	Assumed value
Borehole pattern	Quadratic	Quadratic	Assumed
Pipe Type	U-Pipe	U-pipe	Assumed
Number of BHE connected in series	1 [-]	1[-]	Assumed value

Table A.3: Heat pump design input parameters for PILESIM 2. Values for Heat Pump 1 are collected from heat pump supplier, values for Heat Pump 2 are assumed

	Heat Pump 1	**Heat Pump 2**
Electric power demand	3.44 [MW]	2.80 [MW]
Constant COP	2.85 [-]	3.5 [-]
Delivered heat	9.8 [MW]	9.8 [MW]
Design inlet temperature to evaporator (Inlet temperature of BHE fluid in evaporator corresponding to specified COP)	12 [°C]	12 [°C]
Design outlet temperature from condenser (Inlet temperature of BHE fluid in evaporator corresponding to specified COP)	90 [°C]	90 [°C]

Table A.4: Ground input parameters for PILESIM 2.

	BTES 1 & 2	**Comment, reference**
Undistrubed ground temp.	8 [°C]	Assumed value
Undisturbed ground temperature gradient	0.0 [°C]	Assumed value
Ground thermal conductivity	3.46 [W/(m·K)]	Granite, [19]
Ground volumetric heat capacity	2.23 [MJ/(m^3·K)]	Granite, [11]
Darcy velocity	0.0 [m/day]	Assumed value

Appendix B: Additional results

Figure B.1 to Figure B.6 show the hourly extracted and injected heat for the 20^{th} year. Corresponding temperature profiles are presented in Figure 4.5 to Figure 4.10, Section 4.2.1.

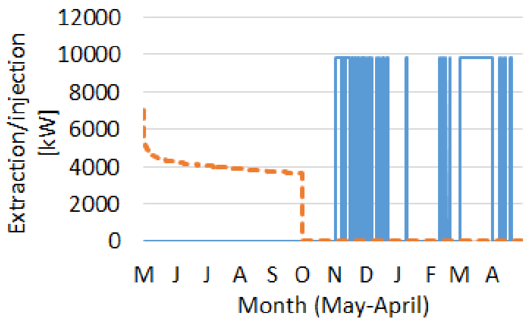

Figure B.1: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

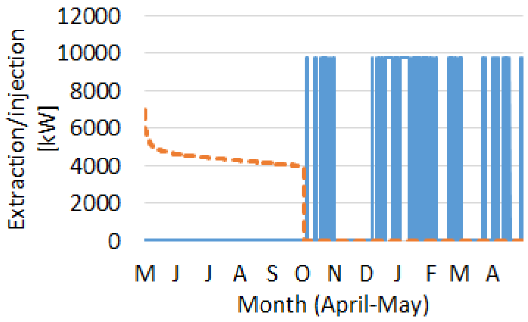

Figure B.2: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

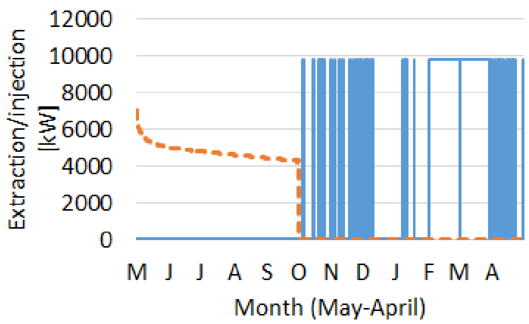

Figure B.3: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

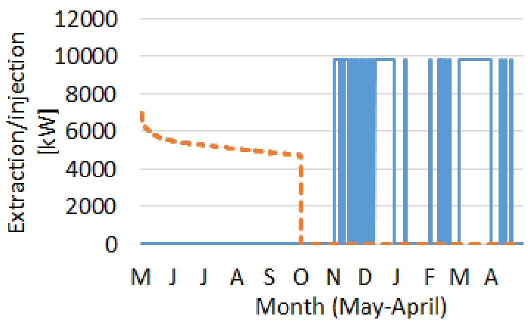

Figure B.4: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

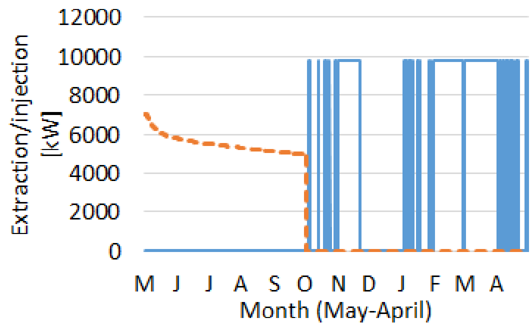

Figure B.5: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

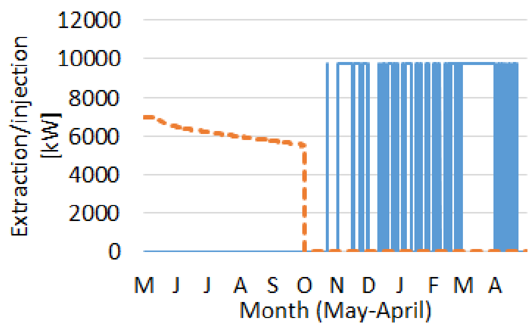

Figure B.6: Injected heat (dashed, orange line) and extracted heat (blue line), 20^{th} year.

Appendix C: Geological maps

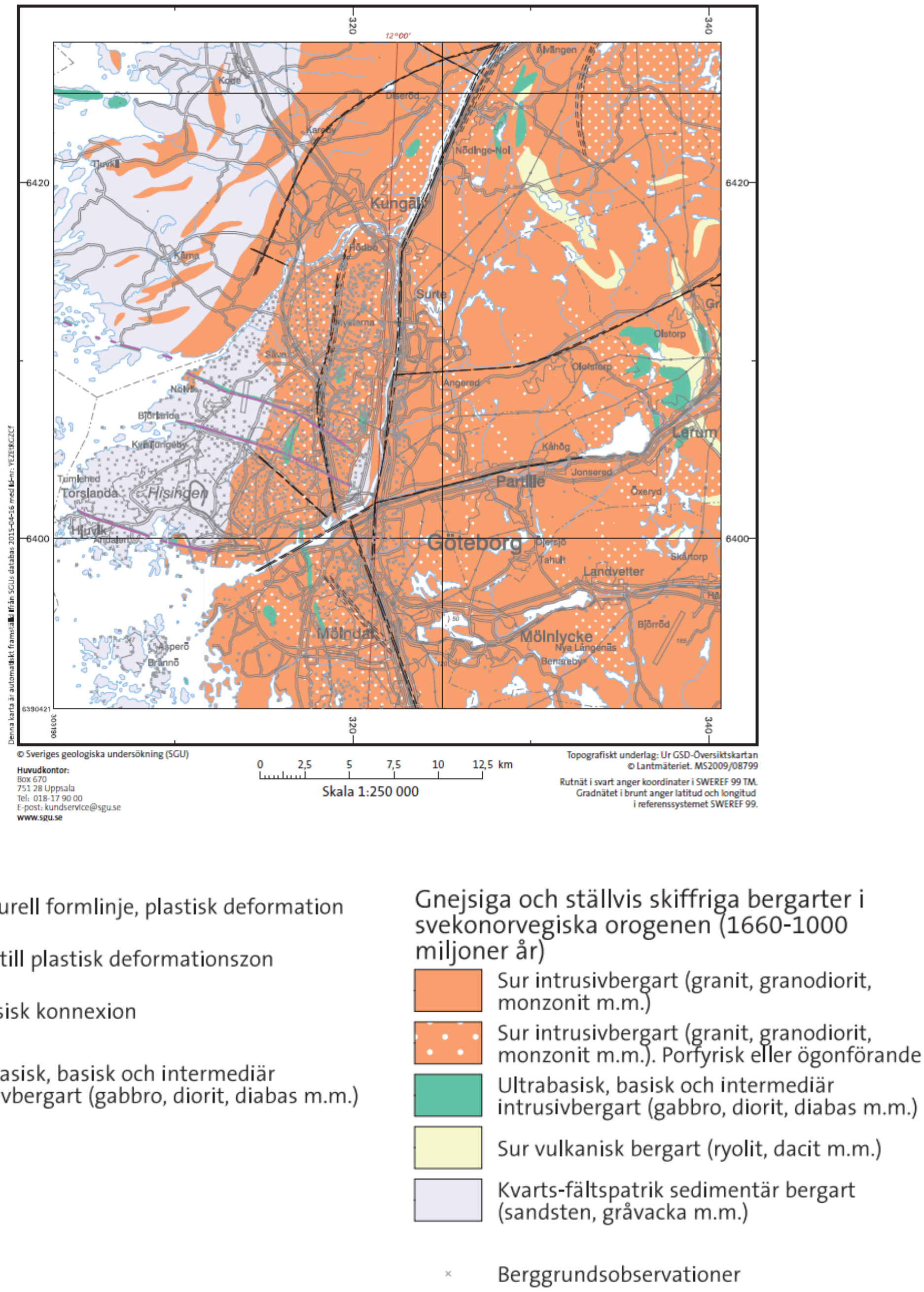

Figure C.1: Bedrock type in the Gothenborg and Kungälv region. ©SGU, Geological Survey of Sweden.

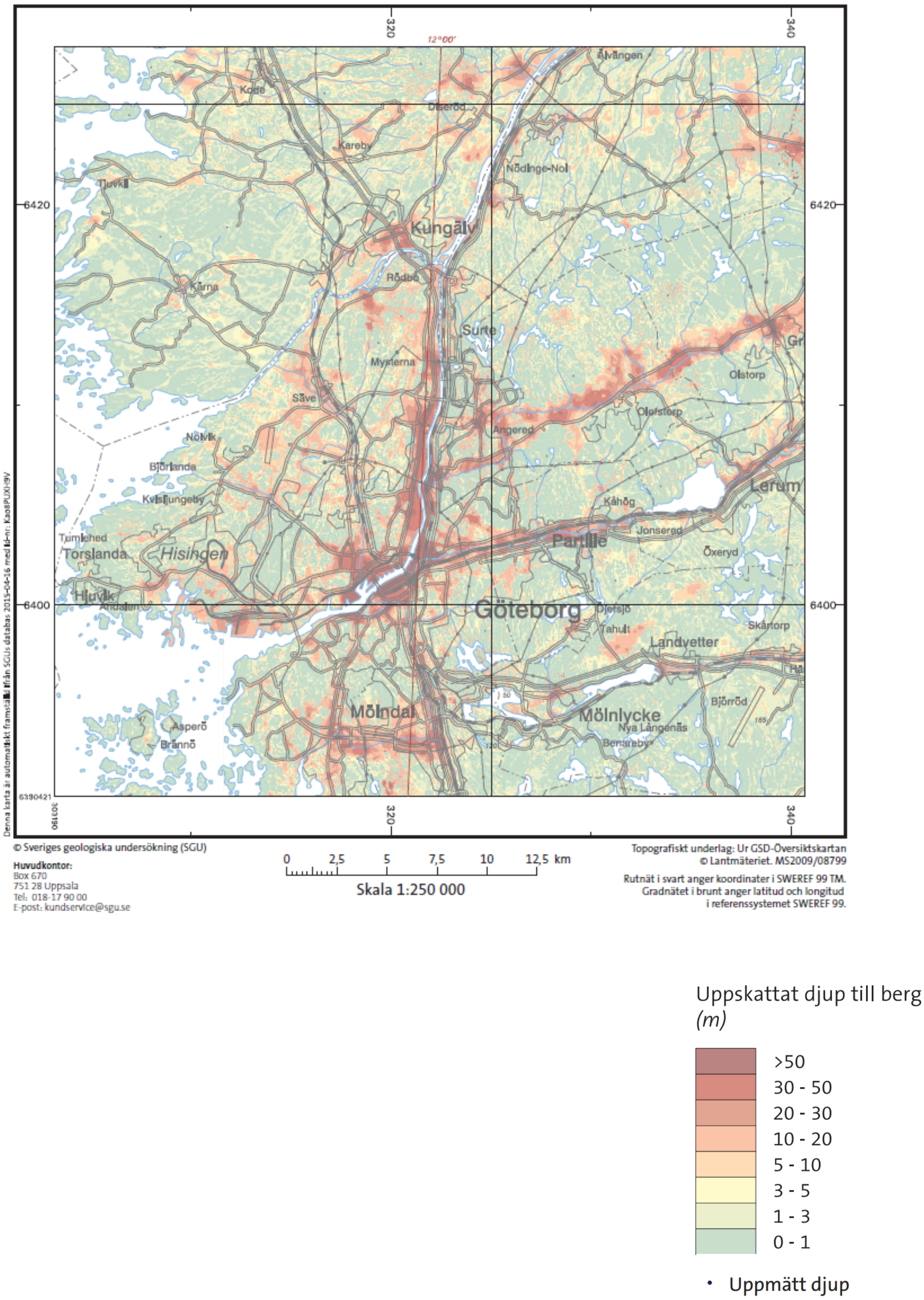

Figure C.2: Soil depth in the Gothenburg and Kungälv region. ©SGU, Geological Survey of Sweden.