District heating in Lyckebo

Investigation of distribution losses

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Abstract

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This study investigates the status and potential of the low temperature district heating system in Lyckebo, focusing on the distribution losses in the culvert system and in the heat exchangers. The Lyckebo system was built in the 1980’s as a test system with heating from a solar field and an electrical boiler. The unique features with this system were a cavern for storage of excess heat combined with a low temperature system. Today, the solar field has been substituted with two pellet boilers, but the cavern is still in service.

Low temperature district heating systems are built in order to lower the losses, due to a smaller temperature difference between the medium in the culvert and the soil. This technology is used in newly built energy efficient residential areas, which makes it interesting to investigate the status of a system that was built in the 1980’s, in comparison to the possibilities of low temperature systems today.

A simulation model has been developed to calculate the theoretical losses in the culvert system with production data from 2013. The total instantaneous losses in the culvert system were between 210-280 kW and the highest losses in W/m can be found in the secondary system. There are heat exchangers in the system that has a return temperature of approximately 8°C lower than the return temperature in the system, which leads to the conclusion that many of the exchangers in the system probably have poor energy utilization.
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1. Introduction

Emissions caused by heating of buildings have historically been a significant, environmental issue in Sweden. However this is not the case in the modern Swedish society today, since most buildings are heated up by district heating. These kinds of systems enable heating on a larger scale, at one place, with improved purification and tall chimneys to keep the contaminants from the living space (SVENSK FJÄRRVÄRME).

Even though district heating has improved the well being of the society in Sweden and many other countries, it is not an ideal system. There are losses throughout the system and the heat is often produced from non-sustainable fuels (BERC, 2008, pp.1-2). District heating systems are constantly challenged by new technologies such as heat pumps, and the demand decreases when buildings become more energy efficient. Our goal for a sustainable society and the competition from other, more environmentally friendly energy sources put new demands on district heating (TRAD, Sonya, 2015).

The technology must be improved in order to reduce losses and enable the possibility of applying other heating sources that may be renewable. One way to reduce the losses and enable low temperature heating sources is to implement a low temperature distribution system. Lower temperatures equals less distribution losses due to a smaller temperature difference to the soil (OLSEN, Peter Kaarup et al., 2014, p.10). Such a low temperature system was implemented in Lyckebo, Storvreta, as a unique test facility in the 1980’s. The facility consisted of a field with solar panels, a cavern for seasonal storage of heat, an electric boiler and a distribution system. Today, the solar field has been substituted with two pellets boilers, but the cavern and the distribution system are still in service (ÅSBERG, Cay, 2011).

There are several newly built low temperature district heating systems in Sweden, and it is therefore interesting to examine the status of the 30 years old distribution system in Lyckebo.

1.1 Aim

This study intends to map and investigate the status and potential of the low temperature district heating system in Lyckebo, focusing on the distribution losses in the culvert system and in the heat exchangers. A simulation model will be developed in order to calculate the losses in the pipes. This model will also be used in a sensitivity analysis where different parameters are altered in order to determine how possible changes could affect the system. The losses that are calculated from the Lyckebo system will then be compared with losses from newly built low temperature systems.
1.1.1 Thesis questions

- What are the energy losses in the distribution system?
- To what extent could the efficiency increase if the Lyckebo system was upgraded?

1.2 Limitations

This study will only treat the distribution system from the heat supply at the cavern to the heat users. This means that the project will neglect the losses in the heat production system, the heat exchangers to the culvert system and the heat exchangers to the rock cavern. The study is limited to investigate the system by using data from the year 2013.
2. Background

In this section an overview of the background information about district heating and the Lyckebo system will be presented.

2.1 District Heating

The idea of district heating is to use resources that would otherwise go to waste in order to fill customer’s heating demands. There are some different kinds of district heating systems, but they all have three common elements, a heat source that uses some kind of available fuel, a local heat demand and a distribution system with pipes. The procedure of district heating is simple. The heat source supplies energy to a medium, often processed water. This energy carrying medium is then led through the distribution system to the customers and consequently back to the heating source again. The distribution needs to be local because the heat cannot be transported more than a few Scandinavian miles before the losses become too great. District heating systems enable concentrated large-scale heating and can provide a substantial number of buildings. The advantages are many, for example cleaner air, since the heating is located at one place with high chimneys containing effective filters, lowered risk for fire in buildings and also lower investment costs for each facility's own heating equipment (FREDERIKSEN, Svend and Werner, Sven, 2012, pp.16-19).

A district heating system can be divided into two different systems, a primary system and a secondary system. The primary system is used by the facilities that are separately connected to the district heating system with their own heat exchanger. In a secondary system, several facilities are connected to the same heat exchanger located in a control room (SVENSK FJÄRRVÄRME, 2015). The supply temperature is often between 90-120°C but there are some systems that use lower temperatures with the main purpose to reduce the losses in the pipes (SVENSK FJÄRRVÄRME, 2015). Typical heat losses of a district heating system in western and northern Europe are around 8-15% (FREDERIKSEN, Svend and Werner, Sven, 2012, p.70).

2.1.1 Low temperature systems

A low temperature district heating system is similar to a common district heating system, except from the fact that the supply and return temperatures are lower. Instead of temperatures around 120/90 °C, a low temperature system works with temperatures around 70/40 °C (ROSA, Alessandro Dalla, 2012). There are several positive effects of having a low temperature system. When you are dealing with lower temperatures, the temperature difference of the soil and the energy carrying medium will be less, which means reduced energy losses throughout the pipes. A greater span of potential energy resources becomes available when a lower temperature is required and the possibilities for the usage of renewable energy resources increase. A low temperature system also has a longer lifetime than a system with higher temperatures. The reason for this is that
a higher temperature wears parts of the system faster, because the pressure in the pipes generally becomes higher. There are also several aspects that must be included when installing a low temperature district heating system. You will, for example, need a more efficient heat exchanger because the energy transfer medium will contain less energy, which makes it harder to extract (OLSEN, P. K et al., 2008, p.1).

2.2 Distribution System

This section carries out the main distribution components of a district heating system and their properties.

2.2.1 Culverts

The technique to distribute heat and cooling through a culvert system has through the years been developed and made the process easier, better and cheaper (SVENSK FJÄRRVÄRME, 2015).

Most of the culvert systems are built as a two-pipe system, with a supply and a return pipe. The heat transfer medium used is water, because of its many appealing features. It is cheap, accessible and not particularly corrosive. There have been three distinctive generations of distribution systems that have been developed along the timeline. The first one is distribution of steam arranged in culverts inside of ducts, the second is instead distribution of hot water in concrete culverts and the third one is distribution of hot water in pipes that are directly placed underground without the duct (FREDERIKSEN, Svend and Werner, Sven, 2012, pp.238-239). Plastic jacket pipes became dominant on the market in the second half of the 1970’s and this dominance has persisted for today. The characteristics of third generation pipes are the reduction of dimensions by burying it in the soil and also the reduction of the components needed for distribution (FREDERIKSEN, Svend and Werner, Sven, 2012, p.248).

The first types of culverts were made of a steel pipe placed in channels of concrete under the ground. The pipes were often isolated by mineral wool and had shells of polyurethane or cellular concrete. Another type that was common was the ACE-culvert, with a jacket made of asbestos, although it disappeared in the production due to the prohibition of this material in Sweden in the 1970’s. ACE-culverts are today still in drift in many district heating systems (SVENSK FJÄRRVÄRME, 2015).

In the late 1970’s, the first design of the third generation distribution system was introduced. The pipes were called directly foamed plastic jacket pipe and was made up by a steel pipe with isolation of polyurethane (PUR) and a jacket of high-density polyethylene (HDPE). There are also other medium pipes used, made of both copper and plastic material of cross-linked polyethylene (PEX). These pipes are so-called all-bonded pipe, where the insulation is bonded to both the carrier pipe and the jacket pipe. These are found in both rigid and flexible types. The rigid ones are available in many diameters and consist largely of a carbon steel carrier pipe, insulation of PUR and jacket
pipe of HDPE. The flexible ones are available solely with small diameters and there are ranges of different materials used in various designs. The most significant difference between this generation and the others is that the third generation does not need to be installed in a duct in the soil (FREDERIKSEN, Svend and Werner, Sven, 2012, p.249). The term culvert can be referred as both a duct and a pipe, from now on the term will refer to only a pipe without a duct.

Plastic jacket pipes are best suited for district heating systems working at relatively low temperatures. (FREDERIKSEN, Svend and Werner, Sven, 2012, p.248) These pre-isolated, third generation culverts are today delivered with straight pipes, fittings, joints and a monitoring system. Productions of these distribution systems are regulated with European standards, which in Sweden are given out by the Swedish Standards Institute, SIS (SVENSK FJÄRRVÄRME, 2015).

### 2.2.2 Forefront culverts

Some of the pipe producers on the market are specialized on low temperature pipes that have the purpose to lower the losses as much as possible. It is today theoretically possible to build a low temperature district heating system that supplies 130 buildings with maximum culvert losses of 7 W/m (SVENSK FJÄRRVÄRME). These kind of systems uses a supply temperature in the summer of approximately 62 °C and in the winter approximately 75°C (SVENSK FJÄRRVÄRME).

### 2.2.3 Polyurethane foam

Polyurethane is an organic polymer which as a flexible foam is used for instance as insulation in buildings and technical applications (THE ENGINEERING TOOLBOX). A common value for the heat conductivity of polyurethane is 0.03 $W/mK$ (FREDERIKSEN, Svend and Werner, Sven, 2012, p.65). The heat conductivity changes by time. A report investigated the aging of 40 mm PUR insulation with an initial value of 0.023 $W/mK$ which increased till 0.0263 $W/mK$ after 15 years in service. The heat conductivity was raised during the first three years before it reached its equilibrium and became invariable for the rest of the time (NIEUWENHUYSE, E. Van, 2006, p.10).

### 2.2.4 Mineral Wool

Mineral Wool is an insulation material that is made by melted minerals that undergoes a spinning process, which results in an isolative material (LINZANDER, Schubert). The heat conductivity for mineral wool can be estimated to 0.04 $W/mK$ (FREDERIKSEN, Svend and Werner, Sven, 2012, p.65).
2.2.5 Heat conductivity for soil

The heat conductivity for the soil depends highly on its water content and density (SUNDBERG, Jan, 1991, p.9). The soil type in Sweden consists to 75 % of moraine (STATENS GEOTEKNISKA INSTITUT, 2015). Moraine alters in heat conductivity from 0.6-2.4 W/mK in unfrozen soil (SUNDBERG, Jan, 1991, p.9). A general presumption that could be made for the heat conductivity coefficient in the soil is 1.5 W/mK (FREDERIKSEN, Svend and Werner, Sven, 2012, p.66).

2.2.6 Joints and Valves

For a substantial time, the focus points of improvement have considered the joints of the culverts, which repeatedly have represented the weak link of the distribution system (FREDERIKSEN, Svend and Werner, Sven, 2012, p.254).

Valves are used for insulation and regulation of flows in district heating systems. They block normal flows enable pipe venting, and pipe emptying (FREDERIKSEN, Svend and Werner, Sven, 2012, p.256).

2.2.7 Heat Exchangers

It is the heat exchangers that enable heat to travel between closed culvert systems as efficient as possible. There are some different types of heat exchangers such as shell-and-tube heat exchangers and gasket type plate heat exchanger, but the most common in northern Europe are plate heat exchangers. The reason for this is that they are compact and cheaper than the others and they have also proven to be very reliable (FREDERIKSEN, Svend and Werner, Sven, 2012, pp.333-335).

The standard design of plate heat exchangers consists of a pack of corrugated metal plates with holes in it that enables the two different fluids to pass through. This is where heat exchange takes place. The hot water passes through the holes on one side where it heats up the plate, the plates are constructed to lead the heat to the other side where the cold water pass through. The total amount of plates is determined by the temperature program, the pressure drop, the physical properties of the fluids and by the flow rate (ALFA LAVAL, 2015).

2.3 Lyckebo district heating system

The 1970’s oil crisis gave incentive for the municipality of Uppsala to invest in a sustainable system for heat production at the time. The choice fell on solar heating which was considered to have the best potential. A test system was set up in Lyckebo, in the community Storvreta, located 15 km north of Uppsala. The construction started in 1981 and the system was taken into drift in 1983, by the time working as a research project (ÅSBERG, Cay, 2011, p.15).
Uppsala Kraftvärme AB (UKAB) was the commissioner of the project and had the responsibility for the drift and maintenance of the facility. The cost of the project was estimated to 39 million SEK in 1983 and the funding of the project was made possible due to a loan of 18.5 million SEK from the Swedish state council for building research (HILLSTRÖM, Carl-Gunnar and Årstrand, Lars, 1985, p.11). HSB national association and Skanska contributed with 2 million SEK each and the rest 16.5 million SEK, was funded by UKAB. (HILLSTRÖM, Carl-Gunnar and Årstrand, Lars, 1985, p.14) There were also other parties involved with research of the facility due to its originality (ÅSBERG , Cay , 2011, p.9).

The district heating system was constructed to cover approximately 550 homes that were supplied with heat and hot water from a separately district heating system which was built as a low temperature distribution system, unique at the time, working with temperatures of maximum 70 °C during winter and 55 °C during summer (HILLSTRÖM, Carl-Gunnar and Årstrand, Lars, 1985, p.1). It was at the time a modern and unique facility with solar collectors, a cavern for seasonal heat storage and telescope legs for input and output of water in the cavern and also for maintaining an optimal thermocline in the cavern.

Two different sources supplied the system with energy. These were on the one hand a 4320 m² field with solar collectors and on the other hand an electricity boiler, providing 6 MW of energy to the system. The solar field was intended to provide 15 % of the annual energy demand of 8 GWh. To simulate a full-scale sun energy production, an electricity boiler provided the rest of the demand during the night. This local heating system was also customized for energy storage. A cavern was dug for seasonal storage and also for equalizing power peaks (ÅSBERG , Cay , 2011, p.9).

The system was constructed with three different liquid circuits, the solar field-, the cavern- and the distribution circuit, all separated by heat exchangers. The solar field circuit contained a refrigerant that transferred energy to a heat exchanger (ÅSBERG , Cay , 2011, p.14). From here the hot water was led to a distribution tunnel above the cavern, where the pumps, heat exchangers, electricity boiler and a room for control technology were placed. The input and output of water of the cavern occurred through the two pairs of telescope legs. One of them short, reaching down to 15 m, and the other one reaching deeper in the cavern. The purpose of these telescope legs was to make sure that the thermocline in the water maintained narrow. Each telescope leg was provided with a heat exchanger and also a temperature sensor in order to make sure that input and output of water were performed with the right temperatures (ÅSBERG , Cay , 2011, p.12).

In the initial ten years of the trial period, the facility was used as intended with a mixture of solar energy, compensated with electrical energy during night time. This drift was intended to simulate 24 hours of solar heating. The next ten years followed by solely electrical heating and during the last years the heating source has been changed into two pellets boilers (ÅSBERG , Cay , 2011, p.15). Vattenfall took over the
ownership in 2000 and decided not to reinvest in the solar panels (ÅSBERG, Cay, 2011, pp.7,16).

When the solar field was replaced by the pellets boilers, the drift temperature was changed to approximately 95°C. Today the hot water is led to the distribution tunnel where it is either stored in the cavern or mixed through valves with the return temperature from the buildings of approximately 50 °C (NILSSON, Mattias, 2015). From here the supply temperature is at least 67 °C, and peaks at 78 °C during a cold winter day (KARLSSON, Anna, 2015).

The Lyckebo system is also coupled with a high temperature distribution system called the City-system (ÅSBERG, Cay, 2011, p.14). The two pellets boilers and the cavern are thereby supplying heat to both systems. The City-system also contains an oil boiler placed at Ärentunaskolan in Storvreta, which runs as a reserve source if the heat supply in Lyckebo would need some complement. Valves separate these two different systems (NILSSON, Mattias, 2015).

![Diagram](image_url)

**Figure 1: A schematic picture of the Lyckebo system.**

### 2.3.1 Culverts in Lyckebo

The culvert from the solar field to the cavern is 492 m long and constructed in steel with an inner diameter of 0.200 m and an outer insulation diameter of 0.355 m, consisted of polyurethane foam (LINDBERG, Elisabeth, 2015). The transfer capacity is limited to 5 MW due to temperature difference and flow rate (ÅSBERG, Cay, 2011, p.41).
The primary distribution system from the cavern is constructed with many different pipe types. What separates them are their pipe material, dimensions and insulation. There are two kinds of materials used in the pipes. Copper pipes with mineral wool as insulation and steel pipes with polyurethane foam as insulation. The depth, which the culverts in Lyckebo are buried, is unknown. A common depth is between 0.5-1.0 m.

The Lyckebo distribution system was classified as a (PN6), low temperature system and parts of this distribution circuit was made up of PEX-pipes that are capable of maximum 85 °C (ÅSBERG, Cay, 2011, p.14). The flow of water in the culvert can be maximized to 4 m/s (ÅSBERG, Cay, 2011, p.32).
2.3.2 Production in Lyckebo

![Power from pellet burners, TPC1 & TPC2 (W)](image)

![Charge and discharge from cavern (W)](image)

![Stored heat in cavern (MWh)](image)

**Figure 2**: Production in Lyckebo during the year of 2013, TPC1 and TPC2 represent the pellets boilers. Top1 and Top2 represent the telescope legs in the cavern. (KARLSSON, Anna, 2015)

The production from the two pellet boilers varies over the year. It is possible to see a smaller production during the summer, due to a lower heating demand. There is a charging period in the late months of the year and a discharging period during the first months of the year. This pattern can be seen in the storage heat figure. This figure is used in order to find the periods with no charge and discharge in the cavern. These periods are used in order to estimate the losses in the cavern. We have used the periods 3308-4170 hours and 7546-7910 hours for analysing losses in cavern, in figure 12 and figure 13.
Heat production of the two systems is shown in GWh in figure 2. In this study, it is interesting to compare our results with the distribution efficiency in this figure, but also the losses of the cavern. From this picture it is possible to estimate the losses in the cavern to approximately 52 %. This is obtained by dividing the losses in the cavern by the total energy input during the year.
3. Methodology

In order to gain basic understanding of the system and find useful data, a literature study and a field study were made. The literature study was mostly based on three evaluation reports from the Lyckebo system at different periods, one master thesis and an educational book for district heating. The field study was held in Lyckebo.

3.1 Mapping

One part of the aim of this study was to map the system and find valuable information about the drift, culverts and heat exchangers. This kind of information has been collected through interviews via meetings and emails with people involved in the Lyckebo system.

The following information were collected:

- Drift map of the production
- Area map of Lyckebo
- Models and dimensions of the culverts
- Output power data from the pellet boilers and the cavern
- Supply and return temperatures in the system
- Soil temperatures

3.2 General model

A general model was developed for analysing the losses in the culverts of a district heating system. The model was developed in the calculation program MATLAB and consisted of different equations that were all extracted from the educational book District heating and cooling (FREDRIKSEN, Svend and Werner, Sven, 2012, p.66). These describe the theoretical energy losses in a closed pipe. From each simulation three different plots are generated. These plots describe the different losses in the pipes, the percentage production losses and the total losses, hourly over a year.

3.2.1 Definitions and formulas

The equations below are gathered from the educational book, District heating and cooling, and used in our model (FREDRIKSEN, Svend and Werner, Sven, 2012, p.66).

Definitions:

\( P_{so} \) = The heat loss from the supply line without influence from the return line
\( P_{ro} \) = The heat loss from the return line without influence from the supply line
\( \lambda \) = Heat conductivity for the ground
\( \lambda_i \) = Heat conductivity for insulation
\( t_s \) = Supply temperature 
\( t_r \) = Return temperature 
\( t_a \) = Ambient temperature 
\( \Theta_s = t_s - t_a \) 
\( \Theta_r = t_r - t_a \)

\( L \) = Route length for the pair of pipes (half the pipe length)
\( d \) = Outer pipe diameter, because of small temperature drop through the pipe wall
\( D \) = Outer insulation diameter
\( s \) = Distance between pipe centres
\( h \) = Distance between pipe centres and ground surface

Formulas:

Total heat flow \( P_{hl} \) [W] from supply and return pipe:

\[
P_{hl} = P_{so} + P_{ro} = L \pi d \cdot (\Theta_s + \Theta_r)/(R_i + R_g + R_c)
\]

(1)

Heat flow \( P_s \) [W] from the supply pipe only:

\[
P_s = P_{so} + P_{sr} = L \pi d \cdot ((R_g + R_i)\Theta_s - R_c \cdot \Theta_r)/((R_g \cdot R_i)^2 - R_c^2)
\]

(2)

Heat flow \( P_r \) [W] from the return pipe:

\[
P_r = P_{ro} - P_{sr} = L \pi d \cdot ((R_g + R_i)\Theta_r - R_c \cdot \Theta_s)/((R_g \cdot R_i)^2 - R_c^2)
\]

(3)

Heat flow \( P_{sr} \) [W] from supply pipe to the return pipe:

\[
P_{sr} = L \pi d \cdot (R_c \cdot (\Theta_s - \Theta_r))/((R_g \cdot R_i)^2 - R_c^2)
\]

(4)

The three heat resistances are calculated using these formulas:

Insulation resistance [m²K/W]:

\[
R_i = (d/2\lambda_i) \cdot \ln (D/d)
\]

(5)

Ground resistance [m²K/W]:

\[
R_g = (d/2\lambda) \cdot \ln (4h/D)
\]

(6)

Coinciding temperatures [m²K/W]:

\[
R_c = (d/2\lambda) \cdot \ln ((2h/s)^2 + 1)^{0.5}
\]

(7)

3.3 Data

The data that was used in the simulation was collected hourly during the year 2013. The data from Vattenfall covered the output power from the pellets boilers and the cavern and also the return and supply temperatures of the system. The soil temperatures were obtained from the institution of geology in Uppsala.

The time selection of the data was made between three different years, 2011, 2013 and 2014. The reason why the choice fell on data from the year 2013 was due to that this year had less data errors compared to the others. The cause of errors might be air bubbles in- and an incorrectly calibration of the measuring equipment (KARLSSON, Anna, 2015). To avoid these errors in the simulation, approximations have been made for these points. These were made by a scaling that used a so called 6th derivative finite
difference coefficient matrix and a scaling that removed single values that differed more than ten percent from the previous value. By doing this, smoother graphs were obtained, which made them easier to understand and process.

### 3.4 Sensitivity analysis

A sensitivity analysis was applied to the simulation, where some parameters in the model were changed for evaluating their impact of the result in the culvert system. The altering in these parameters yielded understanding of how the system responded to changes. This study neglected the fact that some changes might not be economically justifiable.

The parameters treated in the sensitivity analysis:

- The insulating properties of the culvert affect the amount of energy that is transferred to the surroundings and depend on the insulation material and its age. The insulation was simulated with 15% higher heat conductivity.
- The heat conductivity coefficient for the soil is changed. This simulates if the moisture content or density would be affected in some way.
- The depth at which the culvert is buried under the soil affects the soil temperature in the simulation. This parameter is tested due to the depths, which the culverts are buried, are unknown. The new depth was set at 0.4 m instead of 1.0 m.
- The supply temperatures were adjusted by -5°C to simulate a lower medium temperature of the system, to see a possible reduction of losses.
- The return temperatures were adjusted by -8°C to simulate a system with heat exchangers of high efficiency.
4. Results

In the first part of the results, graphs are presented for the losses in the primary and secondary system. These graphs are of three different types, instantaneous losses, instantaneous percentage losses and a bar chart over the instantaneous losses of the different pipe-models. Consequently the losses in the cavern are estimated and the status from a few heat exchangers belonging to the system is presented. The last part of this section presents the results from the sensitivity analysis.

4.1 Primary system

![Graph showing instantaneous losses in the primary system]

*Figure 4: The instantaneous power losses in the primary system hourly over the year of 2013. The black line represents the total losses, the blue line represents the supply pipe losses and the red line represents the return pipe losses.*

By observing the figure above, it is clear that the supply pipe losses are greater than the return pipe losses. This is because of the altering in temperature difference between the medium in the pipe and the ambient soil temperature. The losses are also smaller in the summer due to a reduced temperature difference.
Figure 5: The instantaneous percentage losses in the primary system in relation to the total output power to the Lyckebo system hourly over the year of 2013.

The percentage losses are greater during the summer. This is because of the fraction between the output power and the losses during summer is greater compared to wintertime fraction. The two peaks starting at approximately hour 4600 and hour 6300 are due to data errors. This is explained further in the discussion section.
Figure 6: The power losses per meter for different models of pipes in the primary system. The name and properties of each pipe is described at the x-axis, where the last letter describes the insulation material and the last numbers declare the inner-/outer diameter in millimetre.

It is possible to view which models that leak the most and thereby are the least effective ones. Between the best and weakest model, the difference is approximately 17 W/m.
4.2 Secondary system

Figure 7: The instantaneous power losses in the secondary system hourly over the year of 2013. The black line represents the total losses, the blue line represents the supply pipe losses and the red line represents the return pipe losses.

The losses are almost as great as the losses in the primary system even though the length of this system is approximately half compared to the primary system, which can be seen in appendix A.
Figure 8: The instantaneous percentage losses in the secondary system in relation to the total output power to the Lyckebo system hourly over the year of 2013.

The percentage losses are greater during the summer. This is due to that the factor between the output power and the losses is larger during summer compared to winter. The two peaks starting at approximately hour 4600 and hour 6300 are due to data errors. This is explained further in the discussion section.
Figure 9: The power losses per meter for different models of pipes in the secondary system. The last numbers declare the inner-/outer diameter of the pipe in millimetre.

It is possible to view which models that leak the most and thereby which ones that are the least. Between the best and weakest model, the difference is approximately 18 W/m.
4.3 Total culvert losses

Figure 10: The instantaneous power losses in the whole culvert system hourly over the year of 2013.

From January till the start of April the instantaneous losses increase approximately from 250 kW to 270 kW. After April the figure shows that the total losses start to decrease and reach a minimum around 210 kW in the middle of August. After this point the instantaneous losses once again starts to increase.

The total losses in the culvert system compared to the supplied energy can be calculated as follow:

\[
\frac{Total \, losses \, [W]}{Total \, energy \, [W]} = \frac{2.0833 \cdot 10^9}{10.514 \cdot 10^9} = 0.1986 \approx 19.9\%
\]
Figure 11: The instantaneous percentage losses in the whole culvert system in relation to the total output power to the Lyckebo system hourly over the year of 2013.

The instantaneous losses are greater during the summer month than the rest of the year. The losses are around 40 percentages from middle of April till July, and about 15 percentages from January till March and October till December. Between March and April a fast increase of percentages losses occur and between Augusts till October a fast decrease percentages losses occur. The peak starting at approximately hour 6300 is due to data errors. This is explained further in the discussion section.
4.4 Losses in cavern

Figure 12: The calculated stored heat in the cavern during the hours 3308-4170 during the year of 2013 (total 8760 hours during a year). The equation $y = -0.1673x + 868.15$ is a linear trend line.
Figure 13: The calculated stored heat in the cavern between the hours 7546-7910 during the year of 2013 (total 8760 hours during a year). The equation \( y = -0.3023x + 1927.9 \) is a linear trend line.

It is clear that the trend line decreases at a slower pace in figure 12 compared to the trend line in figure 13. The mean value of stored heat in the cavern is 795,88 kWh in figure 12 compared to the mean value of 1872,62 kWh stored heat in figure 13, which is approximately the double. It is possible to see a relationship between the amount of stored heat and the slope of the trend line, though more stored heat leads to a larger amount of hot water deeper down in the cavern.

4.5 Heat exchangers

Table 1: The working temperatures of two heat exchangers in the Lyckebo system.

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<th>Type</th>
<th>Supply temperature [°C]</th>
<th>Return temperature [°C]</th>
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<tr>
<td>Åskmolnsvägen, heat exchanger supplying 1 house</td>
<td>63</td>
<td>39</td>
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<td>Brf Lyckebo, housing association with a common heat exchanger</td>
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<td>41</td>
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</table>
4.6 Sensitivity analysis

In this section, a sensitivity analysis will be executed in order to examine how possible changes could affect the system.

4.6.1 Insulation

This simulation has been carried out in order to see the impact that an aged insulation has compared to a new insulation. This has been executed by worsening the aged insulation’s heat conductivity by 15%.

Figure 14: The figure shows the difference in loss when comparing a new ideal insulation on the culvert with an aged one. The red line describes the losses for the aged insulation and the blue describes the losses for the ideal new insulation. Our calculations are based on the value of a new insulation (0.03 W/mK).

By subtracting the new insulation losses from the old insulation losses, we obtain the theoretically instantaneous effect that could be saved. This value corresponds to an instantaneous effect around 45 kW, which represents 16% of the total losses.

This corresponds to total losses in the culvert compared to the supplied energy:

\[
\frac{\text{Total losses [W]}}{\text{Total energy [W]}} = \frac{2.0833 \cdot 10^9 + 394.2 \cdot 10^6}{10.514 \cdot 10^9} = 0.2356 \approx 23.6\%
\]
4.6.2 Temperature

In this simulation a comparison has been done between the calculated instantaneous effect losses for two different supply and return temperature vectors. This has been executed by using the current temperature data, the red line and a 5 °C reduction for both the supply and returns temperature, the blue line.

![Graph showing instantaneous losses in the whole culvert]

Figure 15: This figure illustrate a comparison between the losses that are obtained from the original temperature data with the estimated losses that would have occurred if the supply and return temperature were to be decreased by five degrees. The red line describes the losses that occur from the current temperature and the blue describes the estimated losses that would have occurred if the temperature where lowered 5°C.

With only a 5°C reduction, around 22.9 kW instantaneous effect would be saved. This corresponds to 9 % reduction of losses for the whole culvert system.
In this simulation a comparison has been done for two different return temperatures. This has been executed to see how the instantaneous effect losses would differ if the return temperature from all the heat exchangers would have been as for heat exchangers in the study.

![Diagram](image)

**Figure 16:** This figure illustrates the losses that would occur if the return temperature were to be reduced by 8 °C compared to the current temperature data. The red line represents the current losses and the blue line represents theoretically losses that would occur if the return temperatures were to be lowered.

The simulation shows that the losses could be reduced by up to 8 %.
4.6.3 Depth

In this simulation a comparison has been made for how the instantaneous losses will differ depending on which depth the culvert are buried. The simulations show the corresponding losses for the culvert if it was buried at 1.0 m depth, red line and 0.4 m depth, blue line.

![Graph showing instantaneous losses in the whole culvert](image)

**Figure 17:** This figure illustrates a comparison between the losses that are obtained if the culvert were to be buried at 1 m depth respectively 0.4 m depth. The red line represents the losses that theoretically would occur at 1 m depth and the blue line represents the losses that theoretically would occur at 0.4 m depth.

By burying it at 1 m depth instead of 0.4 m, smaller losses occur during the colder month but slightly higher losses occur during the summer and also less mutable seasoning losses are obtained.
4.6.4 Heat conductivity of soil

In this simulation a comparison has been done between three different heat conductivities for the soil, which the culvert are buried within. Here we can see that higher heat conductivity gives greater losses.

![Graph showing instantaneous loss in the whole culvert](image)

**Figure 18:** This figure illustrates how the losses in the culvert were to be changed for different heat conductivity in the soil. The red line represents moist soil with a heat conductivity of 2.4 W/mK, the black line represents common soil with a heat conductivity of 1.5 W/mK and the blue line represents dry soil with a heat conductivity of 0.6 W/mK.

Depending if the culvert is buried in moist soil or dry soil, the losses can differ up to 40 kW. In the rest of our simulations a heat conductivity of 1.5 W/mK has been used.
5. Discussion

This section will discuss aspects about the reliability, heat conductivity, culverts, heat exchangers, the sensitivity analysis and the total losses in the distribution system and the cavern in comparison to Vattenfall’s calculations.

5.1 Reliability

The loss calculations are made from formulas on a theoretical ideal culvert with input data that are measured using equipment that may not be functioning perfectly. This creates two main concerns. The first aspect regards the fact that a real system like the one studied in this report is not ideal and therefore the calculated results may be a bit low. The model uses a fixed value per insulation type in the culvert. The heat conductivity of this insulation may differ a bit depending on the construction method and due to aging of the culverts, especially in the joints. A waterborne system that has been in service for over 30 years may also have water leaks, which increase the losses. The second aspect regards the fact that there may be errors in the measurement equipment as well as calibration errors. Vattenfall has also declared that the appearances of air bubbles in the equipment are errors that affect the measurement data. Errors can also occur due to the human factor.

Missing temperature data were handled by the model, which used a scaling method that gave an appropriate result where obvious data errors existed. However, this scaling method could not handle all the missing measurement data, which gave rise to higher losses than one could expect during a short period of time in figure 8 and 11. We have found production data from 19 hours with the value zero when this error occurs. It is possible to believe that the scaling method did not take care of these values in a way one can expect.

The model uses three kinds of temperatures when calculating the losses, the return, supply and the ambient temperatures. There is a temperature drop of the medium in the distribution pipes and a more precisely model would be to calculate this drop and use the new temperatures for each pipe type. However this has not been possible in this project though we do not know where the different pipes are placed in the system. The medium in the distribution pipes also loses some energy when it is transferred and used by the customers. These facts probably influence the results since the model calculates with slightly higher temperatures than they actually are in reality, which leads to some subtle losses.

The result section shows that the instantaneous losses are smaller during the summer than the winter. This result is in line with the theory, since the heat demand is smaller during the summer, which leads to a lower supply power to the system. Less energy in the culvert system equals less energy to lose. The second reason is that the ambient temperatures are higher during summer. Even if the instantaneous power losses are
lower during summer the percentage losses in relation to the supply power are higher during this period of time. The heat demand is lower during the summer, which means that the heat exchangers transfer less energy. This corresponds to a higher return temperature in the system. This is one of the efficiency problems with today's district heating systems. Users demand water that is warm enough and always available. This means that heat suppliers must maintain a sufficiently high input temperature in the system, although the consumers do not always use this amount of energy.

5.2 Heat conductivity

The values that are used as the heat conductivity for the insulation of the pipes and the soil are fixed values that are estimated. These values do not represent the real conditions in Lyckebo, but are well approximated to do so. Heat conductivity plays an important role in the loss calculations. The heat conductivity of the ground depends, as we have mentioned before, with the level of moisture. This property for the heat conductivity makes it hard to predict, because the moisture in the soil changes over the year. A more accurate calculation could be obtained if data of the heat conductivity was provided hourly and implemented to the model. We still think that the values used are representative because they are an average value.

5.3 Culvert

The total losses in the culvert are approximately 19.9 % during 2013, where the primary system alone stands for 10.3% of the losses. This value is a bit higher than one can generally expect from a low temperature district heating distribution system, though a general district heating system that works with higher temperatures has approximately 10-15% distribution losses. The Lyckebo system consists of many different pipes, which can be a reason for this result.

A larger amount of insulation in relation to the inner pipe diameter leads to smaller losses, according to the graphs that show instantaneous losses per meter of the pipe model. The instantaneous power losses in the primary and secondary systems of Lyckebo are almost equal, this despite the fact that the primary system is approximately twice as long as the secondary system. By comparing the loss in different pipes and the table with total length of each pipe, it is possible to conclude that a large proportion of the secondary system includes pipes with insulation of approximately 100 mm in diameter. The pipes in the secondary system are overall not as energy efficient as the pipes in the primary system.

The different pipe types in the Lyckebo system have different thermal conditions. There are today culverts for low temperature systems that have lower losses in W/m (max 7W/m) than the calculated ones in Lyckebo. There is of course a huge project to replace the pipes in the Lyckebo system, but it can be expected that if the system were to be built today, the distribution losses would be smaller.
Higher temperatures in the system lead to larger losses. The supply and return temperature in Lyckebo is today higher than what the system was designed for, approximately a supply temperature of 55°C and a return temperature of 35°C. The supply temperature curve in a newly built system is also lower, with a supply temperature between 62-75 °C. According to the low heat exploitation during the summer and the fact that the system from the beginning was dimensioned for lower temperatures than the one that is used today, new questions arise about why the temperatures are higher today. This is left for further investigations.

5.4 Heat exchangers

Heat exchangers are one of the key components in an effective district heating system. A high delta T, the difference between supply and return temperature to and from a heat exchanger, means a better heat utilization, which is sought in order to lower the losses and to pursue the most efficient production. The delta T between the supply and return temperature in Lyckebo is approximately 16°C, but we have found heat exchangers in the system that has a delta T of approximately 24°C. This give suspicions about week efficiency of most of the heat exchangers in the system, though the only thing that can explain the high return value is that they are of inferior condition. It could be that the heat exchangers between the primary and the secondary system have a substantial effect of the return temperature. It is possible to suspect this, but it is nothing that we have been able to investigate in this project.

Our study shows that new heat exchangers could be more effective than probably many of those that today are installed in Lyckebo. Most of the heat exchangers in the system are owned by Vattenfall’s customers, which means that it is the heat users that decide whether these should be replaced or not in order to increase the efficiency in the system.

Our heat loss calculations do not consider the losses in the heat exchangers. In general there is probably two heat exchangers in the system between the supply source and the final customer. Heat exchangers usually have an efficiency of about 90%, which leads to approximately 10% in losses due to the heat transferring.

5.5 Total losses

The overall losses in the primary and secondary system, with a mean value of about 19.9 %, plus the losses in the heat exchangers gives total losses of more than 25 % during the year of 2013. This value is greater than the one calculated for the City- and Lyckebo system in figure 3 by Vattenfall. This gives some concerns that our model uses too high heat conductivity values, or that the City system is a lot more effective than the system in Lyckebo.
5.6 Cavern

We can conclude that the energy stored in the cavern is higher during the fourth quarter of a year and that most of this surplus is used in the first quarter the year after, during the cold season in Sweden. Therefore do the loss calculation over one year, January to December, not reflect the overall losses in the cavern. In this study we have instead used a linear trend line of the stored heat in order to see the amount of heat loss during a specific period when no charge or discharge occur. This method gives a more fair view of the losses, but the exact amount of losses cannot be calculated. Beyond the fact that we can see a pattern with charge in the last quarter and a discharge in the first quarter, the cavern is used as a reserve-heating source during the rest of the year. This has an important significance for the system, since it is possible to supply power to the system at sudden drift stop or maintenance of the pellet boilers. It can also be used to cover heat demand tops with energy from biofuel instead of using fossil fuel in the backup oil boiler. Even if the total cavern losses are not calculated here, they are assumed to be significant. Therefore it can be discussed whether it is efficient or not to use the cavern as a backup storage, but this is left for further investigations.

5.7 Sensitivity analysis

By changing the insulation parameter to simulate an aged insulation material, the losses could be raised by 16%. A possible solution for reducing the losses would thereby be to upgrade the culverts with new materials. If this is not possible for the whole system, one way would be to replace just a few pipe models that have the largest losses from our results (See figure 6 & 9).

By altering the supply and return temperatures of the Lyckebo system by -5 °C, we could reduce the losses of approximately 9% in the distribution system. It might not be practically feasible because the buildings need to be more energy efficient in order to be provided with sufficient heat and hot water with a lower supply temperature. In the early stage, the Lyckebo system had a supply temperature of 55°C during the summer which is a difference of -12 °C from today. This raise might imply that distribution system has become less effective during these 30 years, which is reasonable and also that the buildings were not that energy efficient as expected from the beginning.

Consequently the return temperature of the Lyckebo system was reduced by 8°C, which lowered the theoretically losses by 8%. By studying two different heat exchangers in Lyckebo, we saw that the return temperature was approximately 8°C lower than the average return temperature of the system. This gave us the reason to believe that a possible way to reduce the losses is to upgrade the heat exchangers. However, this is something that is up to the heat users, since Vattenfall’s customers own most of the heat exchangers.
The results of the parameter regarding the culvert’s depth showed that it had a minor impact on the losses, which differed irregularly during the year. Figure 12 shows that the losses during the winter were lower at 1.0 m compared to 0.4 m and that the losses were slightly lower at 0.4 m during the summer. Spread over a year it would be more energy efficient to bury it at 1.0 m, which can be explained due to the fact that the temperatures are not as mutable deeper down in the soil. The reason why a sensitivity analysis is performed with the depth of 0.4 m is that we do not know the depth of where the culvert is buried.

In this study a presumption has been made that the soil was moraine and thereby the heat conductivity coefficient could differ from 0.6-2.4 $W/mK$. A general value to implement is 1.5 $W/mK$ and this was set as our default value in the calculations. What we could see by altering this parameter to 0.6 $W/mK$ and 2.4 $W/mK$, was that the losses were lowered by using 0.6 $W/mK$ and raised by using 2.4 $W/mK$. The interval of these two coefficient changes is the same from the default value, but the difference in loss did not correspond to equal changes. The reason for this could be explained by the equations in our model, because the heat conductivity coefficient of the soil affects parts of the calculations quadratic and thereby the difference will not be linear. We have no information of how this parameter alters in Lyckebo, but we know that a lower value equals dryer soil, and a higher value corresponds to more moisture soil. This is a constant that depends on the climate and it is therefore interesting to have in consideration if the climate would change in the future.
6. Conclusions

During the year of 2013 the instantaneous losses in the primary system differed between 110-150 kW and in the secondary culvert 100-130 kW, which gave raise to a total loss between 210-280 kW. This corresponds to a total loss of 2.08 GWh, which equals 19.9% of the total production, 10.5 GWh. The largest losses per meter in the culvert were localized in the secondary system, where the pipe type AWK 88.9/189, with a total length of 108 m, had a theoretically loss of 30 W/m. The lowest losses could instead be found in the primary culvert where the pipe type 1FPSP 20/125, with a total length of 89 m, had the theoretically lowest loss of 11 W/m.

It is clear that the amount of insulation in relation to the inner diameter of the pipes have the greatest impact on the losses. The eminent losses in the secondary system can be explained though approximately two thirds of the system consists of pipes with high losses, over 17 W/m. It is not possible to see a relationship between the pipes that uses mineral wool and the pipes that use polyurethane foam as insulation, even though polyurethane foam has lower heat conductivity than mineral wool.

This study has shown that the return temperature in Lyckebo is quite high, but that some heat exchangers in the system have a good heat utilization and send back temperatures lower than 40°C. This indicates that there are components in the system that works poorly. The medium in the distribution pipes pass through a minimum of one heat exchanger, either between the primary- and secondary system or at the heat consumers. The most likely reason for the high return temperatures are therefore these heat exchangers.

By replacing the heat exchangers in the system, we believe that the return temperature could be lowered by approximately 8°C, which would affect the distribution losses with approximately 8% according to figure 12. It is possible to supply a distribution system of 130 buildings with pipes that have a maximum loss of 7W/m. Lyckebo consist of about 500 buildings which means that it may not be possible to supply the whole net with this kind of low loss pipes. But it is possible to upgrade all the pipes in the smaller secondary systems with this kind of pipes, which could lower the losses further.
Bibliography

Literature


FREDERIKSEN, Svend and Sven WERNER. 2012. *District heating and cooling*.


Electronic sources


Interview


NILSSON, Mattias. 2015. Uppsala. Mail correspondans and interview.
Appendix A

Total length of each pipe type in the primary and the secondary system.

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th></th>
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<tbody>
<tr>
<td>1FPKM</td>
<td>Pipe of copper with 1 outer casing (twin)</td>
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<tr>
<td>2FPKM</td>
<td>Pipe of copper with 2 outer casings (single)</td>
</tr>
<tr>
<td>1FSPS</td>
<td>Pipe of steel with plastic casing (twin)</td>
</tr>
<tr>
<td>2FSPS</td>
<td>Pipe of steel with plastic casing (single)</td>
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<td>IXSM</td>
<td>Indoor pipe</td>
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<td>Nominal inner diameter 18mm, outer diameter 128mm</td>
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