MODELING ENERGY LOSSES AND GAINS IN LOW TEMPERATURE BI-DIRECTIONAL HEATING AND COOLING GRIDS

A CASE STUDY OF E.ON'S ECTOGRID™

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LUND UNIVERSITY

Department of Mathematics

Olivia Arnfalk

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Abstract

Energy for heating and cooling purposes is essential for many industrial processes, as well as something we all rely on to provide us with warm water and a pleasant indoor climate. As much as half of all energy consumed in the EU is used for heating and cooling [1]. District heating and cooling grids are common ways in which the energy is delivered and distributed, and due to the large quantities of energy in the systems it is of importance that the efficiency is high. One way to optimize the grids are by minimizing the energy losses of the pipes. In conventional district heating the pipes are insulated and losses are always negative, and many models have been developed to predict and calculate these losses.

This thesis analyses the energy gains and losses on the 5th generation district heating and cooling grid, E.ON ectogrid™. Since the models on energy losses in conventional district heating or district cooling are not applicable for this type of 5th generation uninsulated grids with low temperature and bi-directional flows, this thesis attempts to find other ways of quantify and predict the energy-losses. The approach is primarily data-driven, by calculating and modeling the energy gains and losses based on empirical data collected from an ectogrid™. In developing a model, the energy losses were studied separately for the warm and the cold pipe of the grid. The temperature changes of the water in the pipes were also studied.

The results suggest that energy loss varies based on energy demand, temperature of the pipe and its surroundings, and the grid layout. There are primarily energy losses from the warm pipe, which is expected as the temperature of this pipe is typically warmer than the outside temperature. The cold pipe experienced gains in cooling energy during the winter, but losses during the summers when cooling is needed the most. The implications of these losses are analysed, in regards to how they relate to grid design, and when losses are actually beneficial to the system. Based on the findings of the temperature change on the pipes, the warm pipe heats up the cold pipe, and the cold pipe cools the warm pipe more than expected.

For more energy efficient grids it is suggested to add insulation to the warm pipe or separate the pipes. Energy losses might be further reduced if the temperature difference between the pipes is smaller. One of the most significant findings was that some of the data collected from the ectogrid™ proved to have large variance and was unreliable, introducing a lot of uncertainty into the models. For further studies it is therefore recommended that more sensors are installed on the grid.

Acknowledgements

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Definitions

DEFINITIONS	
ectogrid^{TM}	The grid studied in this thesis. A 5th generation district heating and cooling grid, operating at low temperatures and with bi-directional flow in the pipes. The desired temperatures are delivered to consumers with the help of heat pumps [2].
Topology	Refers to the layout of the grid.
Heat pump	A machine that ”applies external work to extract an amount of heat”, in this case in the form of water from the grid, and delivers heating to the consumer [3].
Chiller	A heat pump that is ”reveresed”, that extracts heat from the consumer and delivers it to the grid.
Heat exchanger	”a device that is used to transfer thermal energy (enthalpy) between two or more fluids [...]” [4].
Free cooling	”using colder ambient air [...] to perform cooling rather than the refrigeration cycle of the chiller.” [5]
Substation	”[...] component in a district heating system that connects the main network to a building’s own heating system.” [6]. A substation inside a building contains the heat pumps or chillers.
Supply temperature, Supply line	In conventional district heating, the supply line refers to the pipes of the grid which supplies the usually warm water to the consumers. The supply temperature is the temperature of the supply line.
Active Balancing Unit	A producer of heating or cooling energy in a 5th generation district heating and cooling grid. An active balance is used when the energy in the grid is unbalanced.
Passive Balance Unit	A supplier of heating or cooling energy in a 5th generation district heating and cooling grid. Unlike the active balance, the passive balance does not require supplementary energy, but instead relies on stored energy.
Setpoint temperature	The temperatures that heat pumps, chillers and active balances are programmed to return to the grid on either the warm or the cold pipe. Used for the temperatures in ectogrid^{TM}, and can change
Energy losses	The difference in thermal energy produced and consumed. Negative energy losses are also referred to as gains, and used interchangeably.

DEFINITIONS

White-box models	Are purely theoretical models based in physics, and made with assumptions and equations describing how different aspects of a network are expected to behave. One of the main advantages of a white-box model is the explainability and adaptability.
Black-box models	Are data driven. A black-box model makes no assumptions for how a system is supposed to work, but instead analyses the data and makes predictions and finds connections based on it. A data driven model can have some explainability, which is common in linear regression, but can also be hard to make any commentary on which is commonly the case for some machine learning methods, such as artificial neural networks.

SYMBOLS

$\boldsymbol{E}$ (J or kWh)	Energy
$\boldsymbol{P}$ (W)	Power
$\boldsymbol{T}$ (^{o}C)	Temperature
$\boldsymbol{Q}$ (m^3/h)	Flow
$\boldsymbol{V}$ (m^3)	Volume
$\boldsymbol{m}$ (kg)	Mass
$\boldsymbol{t}$ (h)	Time
$\boldsymbol{\rho}$ (kg/m^3)	Density
$\boldsymbol{c_p}$ (kJ/kgK)	Specific heat capacity

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1 Introduction

In the EU, half of the energy consumption goes towards heating and cooling usage [1]. Our way of life is dependent on having functioning systems that supply heating and cooling to our homes and industries, as many of us do not have the capacity to produce it for ourselves. However, our dependency on unreliable trading partners to supply this energy has recently been brought to the forefront of the public's attention, and many are searching for more predictable and domestic energy sources to solve the problem. The energy is also often dependent on non-renewable resources, as 90% of all heating produced world-wide came from fossil fuels in 2020 according to the international energy agency [7]. The demand for heating and cooling will not disappear, however the technical solutions currently in use will have to be replaced with new technology that is more reliable and sustainable, both economically and environmentally. Heating and cooling solutions at the forefront of technology are therefore more efficient, by minimizing losses and maximizing utilization.

This thesis analyses the energy flow of one such solution; a 5th generation district heating and cooling network developed by E.ON called *ectogrid^{TM}* [2], by studying the energy and temperature gains and losses on the water in the pipes of the grid. The main differences between an ectogrid$^{\text{TM}}$ and more conventional district heating and cooling system is that an ectogrid$^{\text{TM}}$ combines have lower temperatures, the flow is bi-directional, and the pipes are uninsulated environment. Additionally, instead of the four pipes that would be needed in a conventional system, one supply and one return for both heating and cooling, an ectogrid$^{\text{TM}}$ only relies on one warm and one cold pipe. In 5th generation grids the energy delivery does not rely on heat exchange in the buildings, but instead utilizes heat pumps to deliver the desired temperatures to the consumers.

Using a data-driven approach, the energy difference between the energy entering the pipes and the energy extracted from the pipes is calculated, analysed and a prediction model is developed. The temperature difference is also investigated, as it relates to the energy losses.

The studied grid is a first prototype, with no data driven approaches at quantifying energy distribution loss in the pipes having been conducted prior to this thesis. Findings relating to this thesis could be considered in the design, expansion and operations of current and future ectogrids$^{\text{TM}}$, in order to have more effective energy heating and cooling solutions.

1.1 Objectives

(a) How big are the energy distribution losses on the warm and the cold pipe and what influences them?

(b) What is the change in temperature of the water going into a pipe and coming out of that pipe?

Figure 1.1: Illustrations of the two main problem formulations of this thesis.

The objective of this thesis is to investigate the energy distribution losses and gains in the pipes of a low temperature, bi-directional heating and cooling grid; ectogrid^{TM}, using a data-driven approach. The losses can be both positive (net energy losses) and negative (net energy gains), which is made possible by the design of the grid. These losses will affect the warm and a cold pipe of the grid differently, and it is of interest to know how much each pipe was impacted. The energy gains or energy losses on the pipes of the grid were calculated as the difference between energy input and energy output. Since the thermal energy in the grid is based on the temperature of the grid, the change of the water temperature in the pipes was also investigated.

This leads us to the main research questions of this thesis, illustrated in part by figure 1.1, with the formulations that follow:

- What are the energy distribution losses in the pipes of ectogrid^{TM}?

- Is it possible to predict the daily energy gains and losses with the available data, and what are the most influential factors?

- What are the change in temperature between the water put into the pipes and the water taken out of the pipes?

In order to answer these questions, both theoretical and data-driven approaches were taken, where results and analysis were made based on the specifications of the studied ectogrid^{TM}. This grid is a prototype installation, and the findings from it are to be used in the future iterations. The current assumption of ectogrid^{TM} is that there are no energy losses during distribution, and the findings from this thesis show how this is not the case. Understanding and being able to predict the energy losses can be largely beneficial when it comes to designing and optimizing an ectogrid^{TM}.

The findings were analysed and the implications were discussed in terms of how they relate to the extra energy that has to be produced in order to compensate for any energy losses, and whether this compensation is needed on the cooling or the heating side. It was investigated when energy losses are beneficial and when they are disadvantageous, which in turn could act as an indication as to whether future grids should or should not be insulated. The findings could be of importance when deciding the optimal temperatures in the grid, which is a decisive factor when developing a more energy efficient system.

In order to model the energy losses, a number of other problems and questions also had to be addressed. These include the reliability and relative error of the signals from the grid, and identifying which other factors that influence the energy losses.

The findings suggest that the negative effects of the energy losses would not outweighed by the positive effects of energy gains on the grid. It was found that the data used in this thesis was not sufficiently reliable to fully explain the energy gains and losses. Some of the variance of the data was explained by the models, but most was not. More tests would have to be run at different temperature setpoints to investigate energy dissipation from and between the pipes further. These are some of suggestions for further research, that could build on the results from this thesis.

1.2 Methodology

In order to answer the questions of how large the temperature changes and energy losses are, the overarching workflow presented in figure 1.2 guided the process. Data science however is typically not a linear process, and it was not the case in this thesis either, as many revisions were made. This thesis is a case-study, and the approach to try to answer the research questions was mainly data-driven. All results and subsequent models are based on the measured data from the grid. However, some comparisons were made to theoretical models based in thermodynamics, in order to get a more insightful analysis.

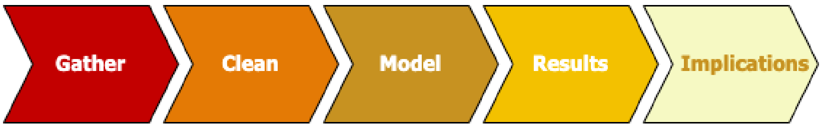


Figure 1.2: Illustration of the workflow used in this thesis

The initial phase was to gather domain knowledge on district heating and cooling as well as data from the grid. Domain knowledge was gathered from sources such as published papers and other literature on the topic, and through discussions with domain experts at E.ON. Findings were cross-validated through other publications. The data gathering consists of obtaining and choosing which data to use, and to motivate these choices in regards as to how they can be used in the calculation of temperature and energy differences.

Data filtering and cleaning was needed, due to working with real data. The methods used in the data cleaning include filtering the data and removing outliers, recalculating data from faulty meters through estimations, and then evaluating the quality of the data. A deeper analysis into the estimation and recreation of data from the grid's accumulator tank was also performed, as the signals from the tank differ from what is expected from theoretical calculations, and the tank operates differently to other buildings and active balancing units. The combined flow-signals to and from the grid were also investigated, as they provided an indication of the reliability of the data.

All the data-driven approaches utilize the cleaned data to model and predict the behaviour of the grid. All inconsistencies found during data cleaning were evaluated in terms of how much they affected the models. Another measure to accurately depict only the pipes of the grid was to exclude internal processes within the buildings, which is why the substations in the buildings were modeled to only take into account their impact on the pipes. The subsequent data-driven models utilize this method for including substations in the calculations and models.

Both the temperature changes in the pipes and the energy losses on the pipes were studied, using the methods described below:

Temperature changes

The thermal energy in a system is determined by its temperatures, and energy losses can be quantified in terms of degrees gained or lost. In order to calculate the change in temperature between incoming and outgoing water to the grid, the weighted average temperature to the grid was compared to the weighted average temperature from the grid. Due to there being no temperature sensors inside of the ectogrid^{TM} pipes, the actual internal temperatures of the pipes are not measured. Instead the temperature sensors are placed at the entry and exit points of the heat pumps and chillers in the buildings, as well as the temperatures to and from the active balances. These are the temperatures that the findings are based on, and the results were analysed and interpreted in regard to how they relate to the operations of the bi-directional grid. The calculated changes in temperatures were done for the grid as a whole, since the nature of the bi-directional grid makes temperature comparisons between buildings difficult to asses.

Energy losses

The energy difference was calculated as the energy input to the grid subtracted by the energy output from the grid. Each energy in- or output was calculated manually.That is how the energy dissipation from the warm pipe and the cold pipe were calculated independently from each other. The magnitude of the energy differences was modeled using linear regression, and the model was tested on unseen data. The results and limitations of the model were discussed, as well as the possibility for other kinds of models.

A theoretical model for energy difference based on a steady state scenario between two pipes was also implemented, with equations by Petter Wallenstén [8] was applied to the ectogrid^{TM}-scenario and used as a reference for comparison to the results based in data.

The implications of the findings are also analysed in relation to ectogrid^{TM} and its demand profile. Findings were also discussed in terms of data quality and future sensor requirements.

1.3 Structure of the Thesis

Chapter 2 supplies the theoretical background on district heating and cooling, ectogrid^{TM} and thermodynamics that this thesis is based on. Chapter 3.1 on data gathering and data cleaning discusses how the data used in this thesis was obtained, and the methods used for data cleaning. Section 3.1 discusses where the data came from and how it was chosen. In Section 3.2 the filtering and removal of outliers is described, while recreation of data from faulty meters is discussed in Sections 3.3 and 3.4, and a more thorough discussion on the accumulator tank is found in Section 3.5. In addition, a discussion on the inconsistencies in flow and how it relates to the overall data quality is presented in Section 3.6.

After the chapter on the data cleaning follows Chapter 4 on the calculations and models. The theory for the substations is presented in Section 4.1. The following sections are targeting the research question, beginning with the modeling of the temperature difference in the grid in Section 4.2 together with the resulting findings in Section 4.2.1. The next model presented is the grid energy-model, which is presented in Section 4.3, along with the findings, predictions and discussion about the reliability of the model. Section 4.4 describes the theoretical model and its implications.

In Chapter 5 the findings are compared. Their respective benefits and drawbacks are discussed. In Chapter 6 the main implications and recommendations are discussed. This includes how the results should be interpreted and how ectogrid^{TM} and similar grids could be built and operated in order to optimize usage. Some of the sources of error and recommendations for further studies are also presented.

The final Chapter 7 summarizes the main findings of this thesis.

2 Heating and Cooling Grids

District Heating (DH) is the term for a network with a shared system providing heating for purposes such as creating a comfortable indoor climate and warm water to showers, but also for industrial processes and manufacturing. A district cooling (DC) grid similarly provides cooling to its customers. These grids rely on some basic thermodynamic principles, as described below:

2.1 Thermodynamics of Heating and Cooling

The heating or cooling energy, E, in a grid is in the form of thermal energy, which utilizes a temperature difference. The power, P, extracted from a grid at any point is proportional to the temperature difference of the mass-flow, as seen in equation (2.1) [9]. c_p is the specific heat capacity of the material, in district heating and cooling usually water.

$$P = \Delta T \cdot c_p \cdot \dot{m} \tag{2.1}$$

During a given period the energy extracted from a system is:

$$E = \Delta T \cdot c_p \cdot m = \int (\Delta T)_t \cdot c_p \cdot \dot{m}_t \, dt \tag{2.2}$$

Heating energy is then proportional to how much the water is cooled down, and cooling energy will in this report be defined by how much the water is heated up. "In order to understand the basics of cooling, it is important to understand that cooling involves the removal of heat, not the addition of cold. Technically speaking, there is no such thing as cold, only an absence of heat/energy."[10]. Cooling energy is then calculated as the negative value of the heating energy.

2.2 Basic Concept of District Heating and District Cooling

In a district heating grid, the heating energy is supplied in the form of water or pressurized steam, and is usually obtained from one or many centralized points, such as a power plant, a waste-to-energy plant or natural geothermal sources [9]. It can also involve the burning of fossil fuels. District cooling (DC) operates from a similar principle but works by actively removing heat from the consumer, for example by using air conditioning for comfort cooling or keeping the freezers at the needed temperatures in supermarkets [9]. The supply temperatures of the cooling grid are much lower than those in the heating case and can be around 4 ^oC, and the return temperature is commonly around 10 ^oC higher [11].

The grids discussed in this report are so called 5th generation district heating and cooling, and are at the forefront of technology and innovation within the field. They combine cooling and heating in one system, storing both heating and cooling energy in one grid, and they are also developed to be more energy efficient than their predecessors. These grids are developed based on the insights from earlier iterations, combined with more precise equipment and the expected demands of coming generations.

2.3 Brief History of District Heating and Cooling

District heating networks have existed since the 1880s, where they where first introduced in the US and reached the European market in the early 1900s [9]. These networks used steam as the carrier of heat, which also meant that the temperatures far exceeded 100 ^oC. These 1st generation networks were widely implemented in the US and Europe, with high heating losses and great risk of harm in case of bursting pipes [9]. There are still some steam-based DH-networks in e.g. New York and Paris, but they where not as widely used after the introduction of the lower temperature 2nd generation DH technology.

The 2nd generation DH systems still operates at temperatures above 100 ^oC, but are pressurised in order to stay in liquid form. The networks were mainly put into production between the 1930s and 1970s. In the 1960s district cooling systems using a similar technology but with low temperatures started to emerge, meeting the demand for district cooling [12].

The 3rd generation of DH networks, sometimes called "Scandinavian district heating networks" due to Scandinavian companies being in the forefront of developing and selling the components for these systems [9], where introduced in the 1970s. The temperatures in the pipes were lower compared to the previous generation and kept under 100 ^oC, but still pressurised. After the two oil crises of 19734-1974 and 1979 [13], the demand for heating from alternative fuels such as coal and biomass increased and these were more widely used in the construction of 3rd generation networks [12].

When it comes to the 4th generation of district heating networks, they too follow the trend of lower temperatures. The supply temperatures can be as low as 45 - 55 ^oC, delivering heating as warm water heating at temperatures of 40-50 ^oC to the consumers. However the temperatures may be as high as 70 ^oC. These networks will largely rely on smart solutions such as peak-shaving and network performance indicators, as well as more energy efficient buildings [14]. The energy losses in 4th generation network are lower, and more renewable energy sources are utilized, which makes these networks more environmentally friendly than their predecessors [12]. The expected timeline for these grids to become the main approach for newly implemented systems is expected to be 2020-2050 [14].

As the development progresses in district heating the temperatures continuously decrease, as shown in figure 2.1. There are several reasons as to why the temperatures have decreased, partly it is due to the damage a ruptured pipe can cause if the temperatures are high, but the main reason is to utilize energy as efficiently as possible. Waste energy from mostly industrial processes can be recovered and recycled in a grid, if the temperatures in the grid match those of the excess. The losses to the surroundings from the DH pipes is also one of the main driving factors to utilize energy efficiently. Higher temperature difference between the DH temperatures and its surroundings will lead to a larger energy losses. This is costly for the energy producers since some or much of the product is not delivered to the customer, and is of utmost importance to minimize the losses. The leakage of energy is also detrimental to the environment as additional energy has to be produced to bridge the gap caused by the losses, resulting in the need for more resources.

The losses in a district heating grid are often directly to the soil surrounding the pipes, and cannot be repurposed. That is why traditional DH grids are generally well insulated to minimize these losses. But energy dissipation from DH pipes could potentially make its way somewhere else, besides the surrounding soil. Theoretically, in systems where pipes are close together some of the dissipating energy might reach and be absorbed by the other pipe. A return-pipe close to the supply-line can also force the supply-temperatures to go down as the interaction between pipes create a heat exchanger. Since these effects are unwanted, the pipes are insulated from each other as well as their surroundings [9].

Since the demands from the consumers on a DH grid varies over time, the DH will adapt to meet the demands whilst optimizing production not to over-produce. The way in which a conventional DH network adapts to demand is to increase the flow in the pipes up until a threshold based on the network specifics.

2.4 5th Generation District Heating and Cooling

5th generation networks follow the trend of lower grid temperatures, spanning as low as 5-30 ^{o}C. They are built around the idea of utilizing the excess heating and cooling as the grid most commonly consists of a warm and a cold pipe [16], to which consumers of both heating and cooling are connected. This is unlike previous district heating and cooling grids that cannot be combined due to the high temperatures. Every building connected to a 5th generation grid is equipped with heat pumps to ensure that the right temperatures are delivered, in regards to their demand [17]. If there is a demand for cooling, the heat pump is used for extracting energy from the building and delivering it to the grid. A heat pump used for cooling is called a chiller.

Unlike conventional district heating or cooling where, power is usually supplied by centralized power stations [18], all connected buildings act as both consumers and producers. The water that is returned from a heat pump or chiller would in earlier generations be considered as waste heat, but can now be utilized directly. The residual

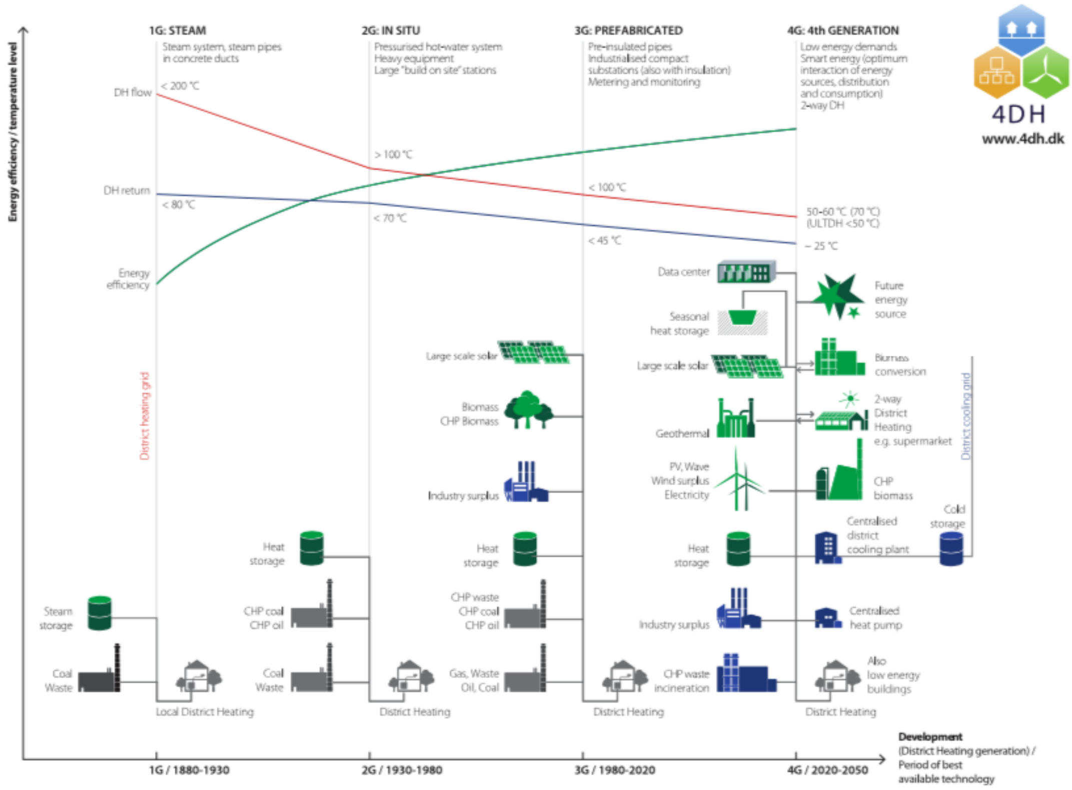


Figure 2.1: Illustration of how temperatures have changed in district heating networks, image borrowed from Henrik Lund et al [15]

heating or cooling is repurposed as it goes back into the pipes for utilization. This design results in a decreased demand for external energy to be brought into the system, and the utilization of residual energy will most likely be the future of district heating. The grid can be either an ambient loop or bi-directional [17]. In an ambient loop the water travels in one direction from building to building in a circular grid. Bi-directional means that unlike other district heating and cooling systems the direction of the flow in the pipes is not in a predetermined direction, making the need for circulation pumps in the grid obsolete. These grids are usually intelligent, utilizing data to predict demand and optimize the systems.

An example of how a 5th generation district heating and cooling grid could operate, is to envision a data center needing a considerable amount of cooling power in order to maintain their operations. The constant cooling will in turn be generating residual heat, which then could be used by a residential house in need of comfort heating. Under optimal circumstances the residual heat from industries and the heating demand would be equal, and the system would balance itself, re-purposing both the residual heating and cooling without any additional energy.

Because of varying demands both during a regular 24 hour period, but especially over the course of a year, the system will not always be fully balanced. To bridge this gap active and passive balances can be used. Active balances actively add or remove heating from the system, based on current or predicted future demands. An example of this is a reversible heat pump with the ability to produce both cooling and heating for the system. Another example of an active balance is to use district heating from another larger grid, however this is an undesirable scenario for a grid that should be self-sufficient. An example of a passive balance is an accumulator tank where water is stored in an insulated tank with minimal mixing of the temperatures and minimal heat dissipation. Such a tank can build up a buffer during periods of low demand, that can be used in periods of high demand. It can be thought of as a thermal battery, that can be charged with warm or cold water to be used at a later point in time when the grid is unbalanced.

An illustration of a small 5th generation district heating and cooling grid can be seen in figure 2.2, which shows how buildings as well as an active and a passive balancing unit are connected to a warm and a cold pipe, red and blue respectively. The direction of the flow is dynamically determined by demand, as several of the connected buildings and balancing units both consume and produce heating and cooling. The figure shows a scenario with the two buildings to the left requiring both heating and cooling, which could be the case for an office building or a supermarket, followed by a building only needing cooling which could be the case for a data center. Furthest to the right is a building exclusively needing heating, for example a residential building. The active and passive balancing bridges gap in the balancing.

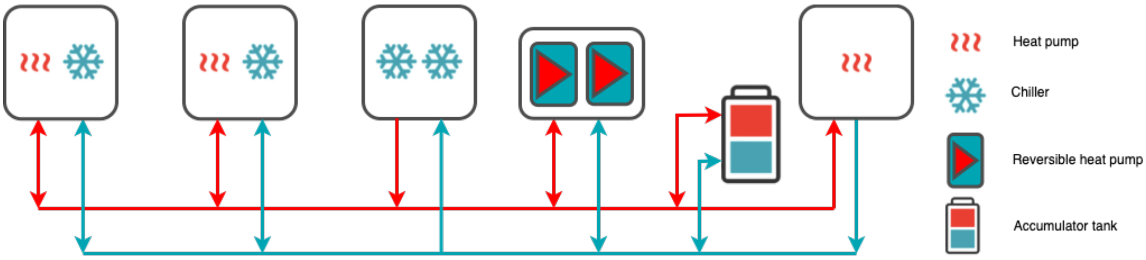


Figure 2.2: A representation of a small 5th generation district heating and cooling grid with active and passive balancing units.

One of the main reasons that the 5th generation networks are being developed is that the equipment and control systems have become sufficiently reliable and precise. In addition, data and algorithm-driven systems are available to ensure that the 5th generation grids are able to optimize and control the energy production and consumption in real time [17]. Other benefits of a 5th generation network is that the losses are small due to the low temperature difference between ground and pipe temperature. It also means that pipes can be less insulated, possibly even uninsulated as in the case for ectogrid™ [16].

2.5 E.ON ectogrid™

This thesis is based on data from the first E.ON ectogrid™, a 5th generation district heating and cooling network. The grid is situated in Lund, Sweden and has been operating in part since 2018 [2]. More ectogrids™ are currently in production in different locations around Europe [2]. All grids are based on the same principles but have different specifications and demand profiles. The name ectogrid™ is derived from the word ectothermal, referring to animals such as lizards that are able to adjust their body temperatures based on their surroundings. An ectogrid^{TM} is able to change its operating temperatures dynamically based on current demand and surroundings, which in turn optimizes efficiency [19]. The mean temperature in the grid can vary between 10 and 40 ^{o}C. Data from the grid in Lund makes the basis for this thesis.

Since its initialization the ectogrid^{TM} in Lund has expanded to include more buildings and balancing units, and the combined length of the pipes has grown with it. Not only that, the grid has gone from linear to circular during the studied period, changing the topology. For the studied ectogrid^{TM} in Lund, there is typically a dominant demand for heating in the winter, and for cooling in the summer. This shifting demand is normally due to the need for comfort heating during the colder winter months, while some consumers, mainly businesses, have a more stable demand throughout the year to maintain their processes.

Demand is met through the influx of warm or cold water to substations containing heat pumps or chillers, which are located in the buildings. The heat pumps utilize the temperature difference ΔT between the warm and the cold pipe, by extracting the energy released from cooling a volume of water to the lower temperature setpoint. The chiller works by heating up the cold water to the higher temperature setpoint, and by doing so removing heating energy from the building. The amount of extracted energy is in proportion to the volume of water. The temperature difference ΔT between the warm and the cold pipe is determined by the maximal capacity demand. It is determined in relation to the diameter of the pipes and other design aspects, which will set the constraints for the velocity. The velocity and diameter of the pipes is directly related to the volume of the body of water that is able to pass through a pipe during a set time interval. The ΔT then has to be large enough to supply the maximum energy demand, given the constraints set by the flow capacity. As the ΔT increases, so does the thermal capacity of the grid. In the ectogrid^{TM} in Lund the ΔT is typically 10 ^{o}C. A higher ΔT means that there is more thermal capacity of the system, but the ΔT should be as low as possible depending on mode of operation, as it will minimise stagnant water in the pipes, and limit interaction between the pipes.

The setpoint temperatures for the warm and the cold pipe will take into account if there are any balancing units with the ability to supply energy at a certain temperature, and optimize the usage of such resources. For the Lund grid, the setpoint temperatures in the winter months are usually lower compared to the temperatures used in summer. As these setpoints change, all buildings and active balancing units will have to adapt and produce according to the new setpoints.

The flow in the pipes is bi-directional, meaning that the direction of the flow can change. Apart from this fact and the low temperatures, another major difference of ectogrid^{TM} compared to traditional district heating networks is the fact that the pipes are not insulated. The reason behind this design choice is that it is cheaper and more dynamic to build, but also that some thermal interactivity between the system and outside temperatures were desired at the point of design. Uninsulated pipes allow for the possibility of gaining cooling energy on the cold pipe from the surrounding temperatures, and to lose energy on the warm pipe are desirable which can in some cases be desirable. Energy heating losses would for example be desired in a situation where there is a dominant cooling demand and the excess heat is unfavourable to the grid.

An insulated accumulator tank is the main passive balancing unit of ectogrid^{TM}. It can simultaneously hold a reserve of warm and cold water to use as a buffer when the grid is not in perfect balance. The tank is placed vertically with an inlet/outlet for the warm water on the top, and inlet/outlet for the cold water on the bottom. As heat rises, this allows the temperatures to stay separated. The insulation keeps the energy heat dissipation and therefore also energy losses to the surroundings minimal, which is desirable. The tank is also designed to keep the mixing of water minimal, as the water leaving the tank should optimally have the setpoint temperatures. The accumulator tank also introduces more thermal inertia to the grid, as it holds approximately twice the volume of the grid. During setpoint temperature changes, the tank is likely to contain the prior setpoint temperatures, that will have to be replaced. If going from lower to higher setpoints, the total amount of stored cooling energy will have to be drained, as what is considered warm in the previous scenario will now be closer to the setpoint for the cold pipe. That way, a tank storing only heating energy can go to a tank with solely cooling energy, without any in or outflow of water.

As the grid is the first of its kind, it acts as a test bed for future projects. This has some highly beneficial implications, such as the data being sampled at high frequency using sensors with higher accuracy than what is common in conventional district heating and district cooling systems, as well as more sensors and therefore more sources of data are available than what would be the case for conventional systems. The drawbacks of it being experimental is that there are no similar systems to compare to, and when a signal behaves unexpectedly it is not easily determined whether the data is faulty or correct. It is even possible that the underlying understanding of the system is incorrect, and the lessons learned will be applicable in future grids.

2.6 Modeling Energy Losses in District Heating and Cooling

Due to heating losses being an expensive and unwanted reality in most DH- and DC-systems, there have been plenty of models developed to estimate beyond just the magnitude of such losses. These can be split into white-box (theoretical) and black-box (data-driven). Grey-box models combine data with theoretical models.

At the current state of the theoretical models of ectogrid^{TM}, the length of the pipes are set to zero, hence resulting in zero energy losses on the pipes are. This simplification is based on the proximity between production and consumption and based on the low temperatures, which in turn should keep the losses low. This assumption is being challenged in this thesis, and to do so a more data-driven black-box approach is taken.

In conventional district heating and cooling, energy losses during transmission are often modeled with some of the specifications of the insulation, supply temperature and return temperature, pipe length and diameter, heat conductivity [9]. One entirely white-box formulation for the power heating losses from a pipe can be simulated using a combination of grid-specific constants, formulated as equation (2.3) [20]. The losses on a pipe depend on the thermal conductivity of the insulation of the pipes λ, the length of the pipes L, the outer radius of the insulation divided by the radius of the pipes (D/d) and the temperature difference between the pipe and its surroundings $(T - T_a)$. For a non-changing stable system, the formulation becomes as simple as one constant C multiplied by the length L and temperature difference $(T - T_a)$. To get the cooling losses the equation is multiplied by -1.

$$P_{hl} = C \cdot L \cdot (T - T_a) = 2\lambda\pi L \frac{(T - T_a)}{\ln(D/d)} \tag{2.3}$$

The equation becomes somewhat more convoluted when supply and return-lines are considered in the same system, and different geometries are taken into consideration [8] [9]. But another important aspect is that the temperature in the pipe will change as it gains or loses energy. To calculate the temperature change in the pipe, the mass flow rate, i.e. the mass of the volume passing though an area per unit of time [21] has to be taken into account [9]. For even more in depth analysis of the pipes, the effects of the pressure difference energy, wall friction dissipation and axial diffusion can be included. However, according to van der Heijde et al. [22] "The effects of pressure loss, wall friction and the dissipation of these losses as heat are negligible [...]". These in-depth models for energy loss that include the changing temperature of the pipe are not applicable for the studied grid. In ectogrid™ where the flow is unknown due to the bi-directional nature of the pipes, and the division between producers and consumers are not clear, this kind of model is not applicable.

In larger DH and DC grids a simplified version of the energy loss calculations are commonly used. By retro-fitting the constant C from equation (2.3), a yearly estimation can be used to give a crude estimate for different modes of operation on an existing grid [9]. This way constants like thermal conductivity do not have to be specified, and an estimate for energy losses on a theoretical grid under similar circumstances can be made. This method is more applicable in an ectogrid™-like scenario, but it is still more crude than what would be optimal. More grid specific parameters would be beneficial to know in a bi-directional low temperature grid, which is in part why this case-study was conducted.

For reference, the energy distribution losses in conventional district heating equates to a relative loss of around 8 - 15 % in Western and Northern Europe, where densely populated areas such as cities are on the lower side of the scale as opposed to more rural areas where the losses are typically higher [9]. In Sweden it is common for district heating losses to be around 12% according to studies on existing grids [23]. Energy losses in district heating are typically larger in summers due to the mass flow rate in the pipes being lower and the time that water spends in the pipes is longer [9]. Simulations of uninsulated district cooling pipes in Sweden show the potential for no cooling energy losses and even small potential gains in cooling energy [11].

Despite the expensive insulated pipes in conventional district heating, the energy losses are still typically large. It is of great importance for these systems to minimize losses, and plays a major part in the lowering of temperatures in grid as seen in section 2.3. The ectogrid™ lowers the temperatures and has the additional benefit of no waste energy.

3 Data Gathering and Data Cleaning

3.1 Data Gathering

The data used for analysis in this report is provided by E.ON. It is sampled from sensors and energy meters connected to ectogrid^{TM} and stored as time series data, accessible through a digital platform named ectocloud [24]. The reported values from the ectogrid^{TM}-sensors are updated when a sufficiently large change in the underlying data has occurred, but no more often than the minimum time-resolution. The weather-data is collected by SMHI, the Swedish Meteorological and Hydrological Institute.

An initial analysis of the data was conducted, which aimed at locating the correct signals and deciding which sources of data to use. All signals were examined and cross-validated to ensure the right source of data was chosen. When the correct signals had been located the initialization date at which data-gathering started was noted, creating a timeline for when buildings and balancing units appeared in the grid. This information was used in combination with maps of the grid, to gain an insight into the topology of the grid at different points in time.

In conjunction with the data gathering several domain experts at E.ON were contacted, to get an explanations of the signals and what sorts of behaviour could be expected in the data. This included getting information as to which signals should be used. Additionally, I was advised on data re-scaling data from signals where the reported value differed from the real value by a factor. A visit to the site was also conducted, during which a more in depth understanding of the instruments and the grid was established.

Since the objective of this thesis is to find the energy losses during distribution and in the pipes of the grid, the chosen signals were mainly those that were measuring temperatures and flows to and from the grid, and not taking into account anything happening beyond the heat pump or chiller inside of buildings. This objective includes separating the losses on the warm pipe from losses on the cold pipe to gain a deeper understanding of the system.

One of the main problems for establishing the energy and temperature losses in the pipes is that there are no sensors located in the pipes of ectogrid^{TM}. All relevant data comes from sensorsq placed at inlets and outlets of heat-pumps, chillers and balancing units. That is why the flow in the pipes is unknown, and the same goes for the pipe temperatures. A decision was made to focus on the flow-meters and temperature sensors at the substations instead of the energy meters, as the information from the energy-meter does not give any indication as to how much energy was extracted from or provided to each pipe, but instead only show the energy taken out of the grid.

In reality the flow-meter and the energy meter are the same instrument, and the value on the energy meter is calculated using the flow and temperatures. This meant that if the flow-signal from a meter was incorrect, so was the energy-signal. Some additional parameters such as outside temperature and other weather variables, soil temperatures, and in some cases energy meters on the building-side were also sampled and used in the analysis.

The data used was sampled at a minute frequency, and it was deemed that no significant changes occurred on a smaller time-scale in the system.

One of the largest problems working with real data is that it at times can be unreliable and generate misleading results. Data analysis is only relevant if the data can be trusted. That is why all of the signals studied in this analysis were studied and all diverging behaviour was investigated prior to any modeling. As several issues arose in regard to the quality of the data, having significant relevance for the results and analysis of the thesis, these issues will be addressed and discussed in the following sections.

Data-related issues that emerged in connection to the data include data from sensors scaled incorrectly, extreme outliers and other instances of data from faulty meters. Moreover, some signals were missing from the data-sets.

3.2 Filtering and removing outliers

Using a straight-forward method for removing erroneous data, the flow signals from each building were investigated. In case the flow had no variance for a period of 5 or more hours, the entire data-set for this period was removed from the analysis. This was only done for periods where the absolute value of the flow was larger than zero, since when a building or balancing unit is turned off, the flow is reported as zero.

However, if instead a meter loses connection to the Internet, no new data will be recorded and the value registered in the time series data would remain constant at the last uploaded value, until the connection is re-established. The reason for removing data from the entire grid, and not only from the faulty building or balancing unit is that the grid would not be balanced, if one or more of the contributors were left out of the calculations. Ideally all periods without variance should be removed, not only the periods longer than five hours. However the trade-off between bias and losing a far too much of the data had to be balanced. One such instance can be seen in figure 3.1.

Other time-periods studied were when a building unexpectedly displayed no variance in the flow and reporting the value zero for a substantial period of time. However, none of these observations supported the theory of being due to faulty data. One example of such a period can be seen in figure 3.2. The top graph shows an unexpected but correctly reported behaviour of no reported flow during an extended period of time, at the same time as the temperature of the cold pipe (see bottom graph) is drastically higher than the average temperature during this stagnant period. This is due to that

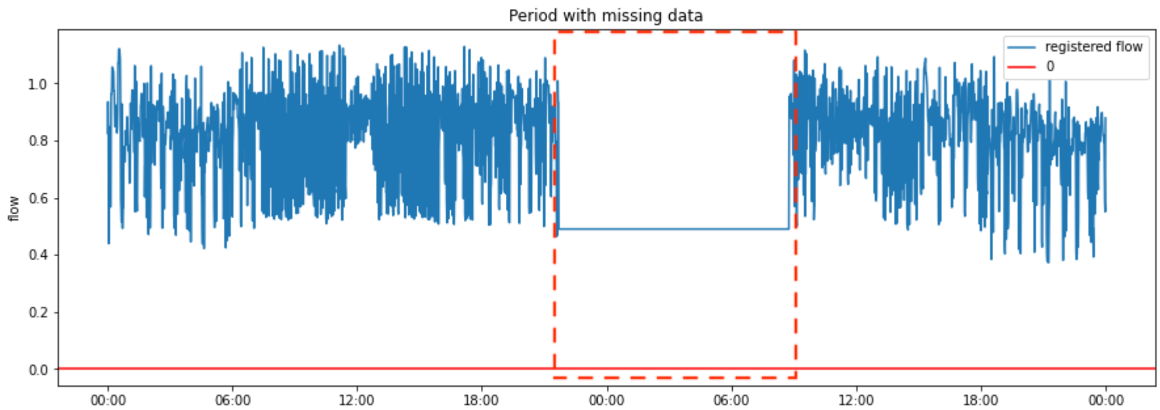


Figure 3.1: Data from a flow-meter during a period without internet connection.

the water being heated by the surroundings in the substation when stagnant for an extended period.

Figure 3.2: An unexpected drop in flow from one of the buildings (top) with a simultaneous raise in temperature in the same building (bottom).

Other periods that were filtered out include data from a few days leading up to a new building or balancing unit showing up in the data-set, as the newly installed building generally would be an active part of the grid for a period of time before any data was stored. This became evident when checking the initial values reported by the energy meters for newly connected entities, as the energy meters did not begin at zero, indicating some time of operation before the initial timestamp of the stored data.

Additionally, any periods with inconsistencies in the data were marked as potential outliers, to make them easily removable in the models. This mainly included periods of unexpected interruptions of operation, and periods when the data from a building or balancing unit was theoretically impossible. It also included filtering out some periods when a large volume of water on either pipe of the grid unaccounted for, which will be discussed to a further extent in section 3.6.

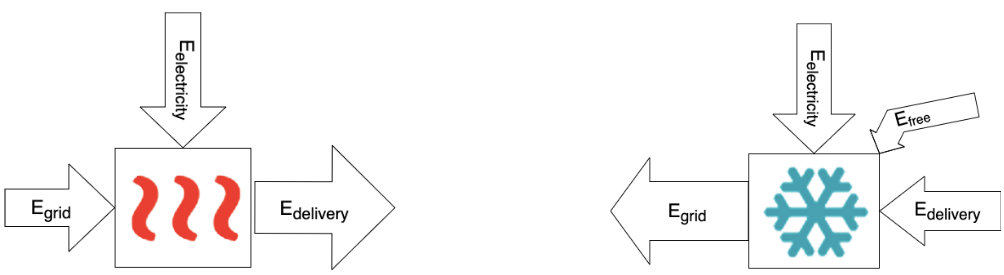
The resulting set of data after filtering and outlier removal consisted of 77 % of the available data for the time period.

3.3 Recreating data from Heat Pumps

The problem with faulty or missing energy-meters was discussed with domain experts. Since some meters were installed incorrectly or simply did not work as intended, the data stemming from such meters was not reliable and had to be recreated. The affected meters or lack thereof affected the flow and energy data by the inlets to heat pumps and chillers.

To recreate these signals, the energy extracted from the grid could be derived from the energy delivered to the building and the electrical energy to the machine. In a system that assumes no losses, the energy equation of a heat pump and a chiller can be seen in equation (3.1) [25], where the energy taken from the grid by the heat pump E_{h_grid} and by the chiller E^c_{grid} is shown, and since the power is the momentary value of energy the equation holds for power as well. In the case of a chiller there might exist an additional component, called free cooling. Illustrations of the energy balances can be seen in figure 3.3.

$$\begin{aligned} E^h_{grid} &= E^h_{delivery} - E^h_{electricity} \\ E^c_{grid} &= E^c_{delivery} + E^c_{electricity} + E^c_{free} \end{aligned} \tag{3.1}$$



(a) The balance of energy of a heat pump **(b)** The balance of energy of a chiller

Figure 3.3: Schematic image of the contributions to the energy of a heat pump and a chiller. The energy delivered is the energy heating to the consumer (house), which is negative for a chiller.

Using this relationship of energy balance in the system, the missing or faulty data from the affected heat pumps and chillers was recreated. The data used came from the the power-signals, which measure the momentary value of energy. Unlike the energy signals which reported values at kWh intervals, the power signals had the additional benefit of not causing problem with discretization. With the calculated values reflecting the momentary energy from grid, combined with the data from the temperature sensors at the in- and outlets, the flow could be established according to equation (3.2), derived from the expression for thermal energy from equation (2.2). With knowledge of the flow, the contribution of energy to and from each pipe can then be calculated individually in accordance with equation (2.2), where the mass of of water for a given flow $m(Q)$ is calculated as the energy from the grid E_{grid} divided by the temperature difference between the warm and cold water entering or leaving the machine $(T^w - T^c)$ times the specific heat capacity for water c_p.

$$m(Q) = \frac{E_{grid}}{(T^w - T^c) \cdot c_p} \tag{3.2}$$

For some affected heat pumps and chillers the faulty meters had been replaced with meter reporting correct values, and new data could validate that also estimations were correct. From the remaining buildings such validation was not possible, but it was assumed that the these signals were correct, since the heat pumps and chillers operated similarly.

One additional factor was included, which was that some water would start flowing from one pipe to the other during a short period before the heat pump or chiller was turned on which is more lenient on the machine. This water would enter the other pipe without being heated up or cooled down, and was unaccounted for in equation (3.2). Signals from circulation pumps were used to determine periods when water was circulated without being processed by the heat pump or chiller. The work performed by the circulation pumps scaled linearly to a control signal, from 0-100%, which was available as data. The work from the circulation pump did scale with the registered or calculated flow, however pressure difference in the pipes would cause variations in in the relationship between flow and control signal. The circulation pump signal compared to the calculated flow can be seen in figures **??** (where one pixel located at around 25% on the y-axis with registered flow close to zero show the affected data-points) and **??**, where this supposed linear relationship can be seen. The relationship found was used to estimate the flow for the affected data-points. The data from periods when the circulation pump was running but no flow was registered was adjusted according to the linear relationships found, however the impact from this was deemed small due to how little of the total flow it affected.

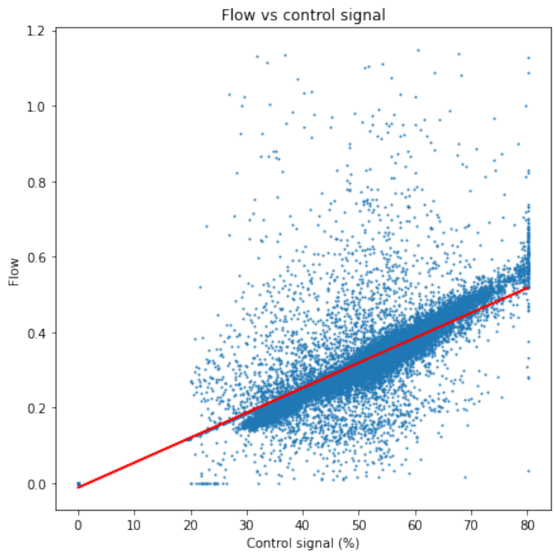


Figure 3.4: Calculated flow vs Circulation pump signal, with fitted line.

The effect these faulty meters had on the grid varied over time, as their recalculated contribution of total consumed energy on the warm pipe made up between 0 and 35% of the total consumed energy. The number varied over time as meters were replaced and new buildings were added to the grid.

3.4 Outliers from Under-Sized Energy Meter

In the case of one active balancing unit, the meter registering flow and energy showed a strange behaviour at times when the flow of water exiting the balancing unit exceeded a certain threshold. The data of registered flow and energy would follow a pattern of smooth peaks that at semi-regular intervals. But at times when the meter registered flow above the threshold, the data would have unreasonably large variance, and register what seemed to be poor estimates of produced energy. These shaky periods were the most prominent during the summer months of the year. The behaviour can be seen in figure 3.5, where the flow is plotted over a smaller period of time, with one of the peaks in flow reaching above the threshold. This is most likely the cause of a meter unable to register above the given threshold, and returning unreliable data.

However, this behaviour could not be seen at every occasion when flow meter registers flow above the threshold. Especially during the winter months, there was a consistent pattern of a sharp peak, after which the registered flow seemed to be more in line with the expected behaviour of more rounded lower peaks. Due to this not being in line with the behaviour of the summer months, these peaks were invested further. The conclusion was that the spikes came directly following defrost cycles of the machines. When a defrost cycle initiates, the active balancing is not producing energy and the flow stops. As the cycle comes to an end, there is a spike in flow as the system restarts and needs an influx of water. These spikes are therefore not due to erroneous sensors and the data does not have to be altered and can be used as is.

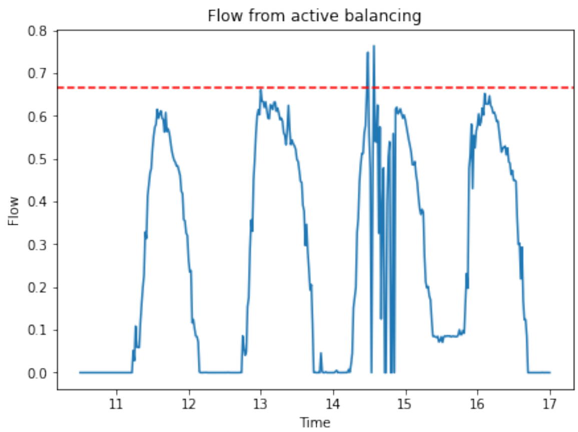


Figure 3.5: Flow from active balancing, with the threshold for the flow meter marked by the red dashed line.

Since the contribution from the affected active balancing unit is large, the data was attempted to be recreated based on the idea of a consistent coefficient of performance (COP). The COP is a performance indicator showing how much energy that can be extracted from a system given a certain amount of added electricity [25]. If there is a linear relationship between the electricity usage and the produced energy, this could be used to interpolate values to replace the suspicious data.

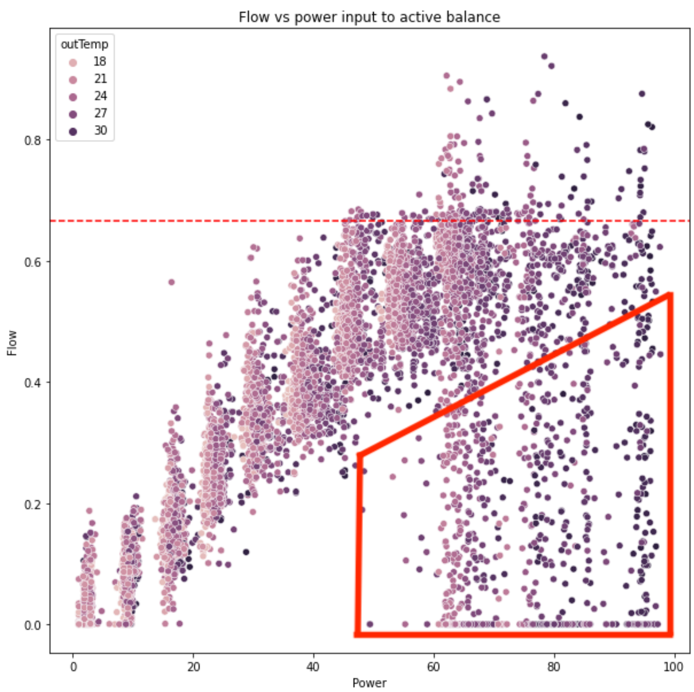
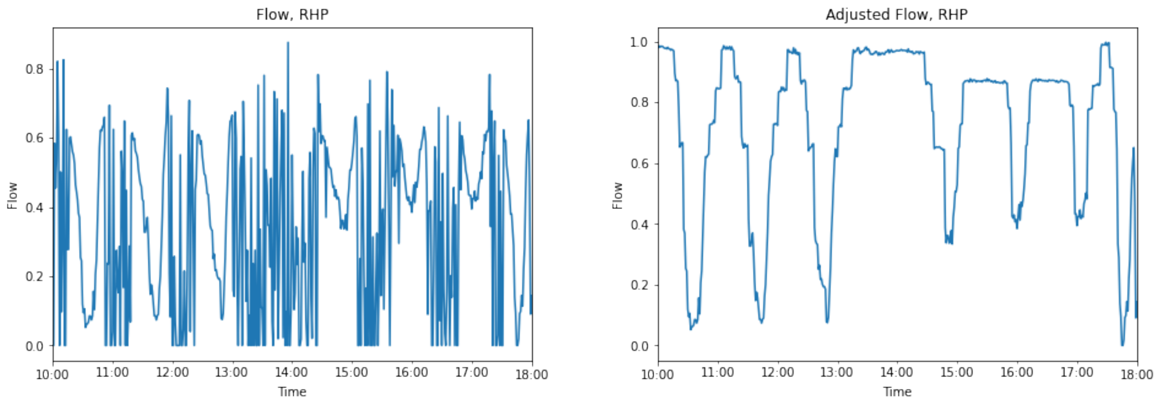


Figure 3.6: The image shows how the flow (y-axis) from the active balance correlated to the power input (x-axis). The filtered data makes up 4% of the data during the period and is located within the area marked in red, and the threshold is marked by the dashed line.

The relationship between the flow from the active balancing unit and the power electricity usage during a period with stable setpoints, can be seen in figure 3.6. In the



(a) The measured flow from active balance

(b) Adjusted flow of the same time period

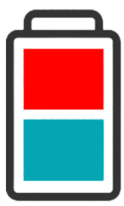
Figure 3.7: Comparison of flow-data before and after being adjusted.

plot the area containing suspicious data is marked in red and make up around 4% of the data for this period. Since the incoming and outgoing temperatures are deemed to be fairly stable, these are excluded from the calculations. A linear model was fitted on the stable linear data, and the data-points in the red-marked area are then fitted to this linear model. A comparison of the data before and after the linear fit can be seen in figure 3.7. The linear model does not render the peaks as smooth as the observed peaks during stable periods, and may also be overestimating the flow, but the model was considered to be sufficiently good at calculating the flow, and that the potential over-estimation overall would be insignificant.

3.5 Re-creating data from the Accumulator tank

The accumulator tank is one of the most important components for operating the ectogrid^{TM}. It is a passive balancing unit that stores both warm and cold water, and adjusts any temporal imbalance on the grid. Its importance lies not only with its ability, but also its capacity for storing energy, as the tank holds the equivalent of approximately twice the total volume of the grid in stored water. It works as a thermal battery, that can be charged with either warm or cold water.

However, the sensors used at the inlet/outlet of the accumulator tank are proven faulty. The missing data include the temperature sensors of the water going into and out of the tank, as well as the energy going into and out of the tank. For a large proportion of the time, the water flow data is also missing. Due to the significant impact of the accumulator tank on the grid, an attempt to recreate these signals was made.



The signals that are obtainable from the tank are temperature sensors inside the tank measuring the temperatures at certain height intervals, and a functioning flow meter placed there in October year 2. Figure 3.8 show how much of the total flow to the warm pipe of the grid was registered to come from the accumulator tank, a number that on average varies between 10 - 30%.

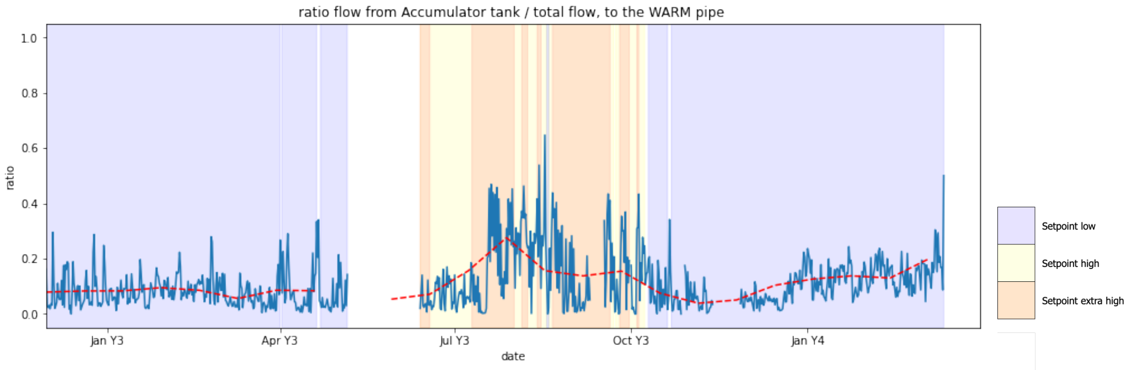


Figure 3.8: The ratio of flow from the accumulator tank to the total flow, to the warm pipe

3.5.1 Energy from the Accumulator Tank

Since the energy in the tank is in proportion to the temperature of the water in the tank, the change of the energy in the tank is proportional to the temperature difference in the tank. This change is then a measure of how much energy comes from or goes to the grid. From the thermometers mounted on the inside the tank, separated at 1 meter intervals, the mean temperature T^{mean} of the tank was calculated. The energy to the grid during a given period of time equals the negative energy difference in the tank, in accordance with equation (3.3) [26], derived from equation (2.2) where $m(V^{ACC}) = V^{ACC} \cdot \rho$.

$$E^{ACC}_{diff} = (T^{mean}_2 - T^{mean}_1) \cdot c_p \cdot m(V^{ACC}) = -E_{to\,grid} \tag{3.3}$$

That is assuming that there are no energy losses in the tank, and that all energy comes from and leaves to the grid. The energy difference can then be attributed to the temperature difference of the in and outflow of water, and the mass of that flow, in accordance with the equation for thermal energy equation (2.2). The energy difference in the tank over time is then described by equation (3.4)

$$E^{ACC}_{diff} = E_{in} - E_{out} = (T_{in} - T_{out}) \cdot c_p \cdot m(Q_{to\,tank}). \tag{3.4}$$

If the energy difference of the tank E^{ACC}_{diff} is positive and the mean tank temperature is raised, the tank has taken water from the warm pipe of the grid and outputted cold water on the cold pipe, and if the energy to grid is negative, the opposite holds true. This in and output of water will cause an energy shift on both pipes. The energy to the warm and the cold pipe of the grid from the accumulator tank, given the flow Q to the warm pipe, is shown in equation (3.5). The temperatures T^w and T^c are the warm and cold temperatures of the water leaving or entering the accumulator tank, and T^w_{sp} and T^c_{sp} are the setpoint temperatures.

$$\begin{aligned} E^{ACC}_{to\ warm\ pipe} &= (T^w - T^c_{sp}) \cdot c_p \cdot m(-Q_{from\ warm\ pipe}) \\ E^{ACC}_{to\ cold\ pipe} &= (T^w_{sp} - T^c) \cdot c_p \cdot m(Q_{from\ warm\ pipe}) \end{aligned} \tag{3.5}$$

However, the actual energies from equation (3.5) cannot be calculated using the available data, since the temperatures of the water leaving and entering the tank; T^w and T^c, are unknown throughout the entirety of the period and the flow Q is unknown for some of the period. The temperatures could potentially be estimated using the temperature sensors closest to the inlets and outlets, but these sensors will only provide a rough estimate. A different approach to estimating the energy to and from the grid was instead chosen. Assuming that there is no mixing of the water in the tank and that the water going into the tank has the setpoint temperature, the energy leaving the tank is the same energy that was previously stored there. These assumptions of $T^w = T^w_{sp}$ and $T^c = T^c_{sp}$ will cause the energy estimates to the warm pipe to be $-E^{ACC}_{diff}$ and the energy to the cold pipe to be E^{ACC}_{diff}.

3.5.2 Flow from the Accumulator Tank

Because of the faulty flow-meter registering of the water entering and exiting the accumulator tank, this signal was attempted to be calculated manually. The flow in to and out of the tank is problematic to estimate since there are several unknown parameters. However, under ideal circumstances it can be derived from the temperature difference in the tank in combination with the temperatures of the water leaving and entering the tank, as seen in figure 3.9. The problem however remains that the temperatures of the water entering and leaving the tank are unknown.

Combining the expressions for the energy difference in the tank in equation (3.4) with the energy leaving and entering the tank from equation (3.5), an expression containing only the temperatures and mass of the water can is found, in accordance with equation (3.6). The flow can then be found using the relationship from equation (3.7).

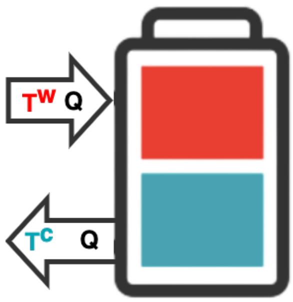


Figure 3.9: Illustration of flow into and out of the accumulator tank, where T^w is the water temperature to and from the warm pipe, T^c the temperature to and from the cold pipe and Q if the flow from the warm pipe and to the cold pipe, which can be negative.

$$T_2^{mean} = \frac{T_1^{mean} \cdot m(V^{ACC}) + m(Q_{from\ warm\ pipe}) \cdot T^w - m(Q_{from\ warm\ pipe}) \cdot T^c}{m(V^{ACC})} \tag{3.6}$$

$$Q = Q_{to\ warm\ pipe} \propto m(Q_{to\ warm\ pipe}) = \frac{(T_2^{mean} - T_1^{mean}) \cdot m(V^{ACC})}{(T^w - T^c)} \tag{3.7}$$

There were several attempted methods for estimating the flow from the accumulator tank, which are presented below:

1. **No flow**: In this model the impact of the accumulator tank is considered to be none over a larger period pf time. This is supported by the mean tank temperature staying somewhat consistent when the setpoints are stable. Temporary variations will even out as long as the time-scale is sufficiently large.

$$Q = 0 \tag{3.8}$$

2. **Setpoint temperatures**: The assumption in this model is that the temperatures T^w and T^c are consistent with the setpoint-temperatures of the grid. Hence, the calculated flow is in proportion to that of:

$$m(Q) = \frac{\Delta T^{mean} \cdot m(V^{ACC})}{(T^w_{setpoint} - T^c_{setpoint})} \tag{3.9}$$

3. **Highest and lowest tank temperatures**: In this iteration of the model, the temperatures to and from the grid are assumed to be those of the topmost and bottom-most of the temperature sensors in the tank. In this case, the temperatures of the water entering and exiting the tank are assumed to be the same temperatures measured at the sensors closest to the inlets. A few different variations for the temperatures $T^{top}_{measured}$ and $T^{bottom}_{measured}$ were taken into consideration, with rolling averages of the temperatures tested as well as the momentary values. The method with the best performance was based on a rolling average of the two sensors closest to the outlet.

$$m(Q) = \frac{\Delta T^{mean} \cdot m(V^{ACC})}{(T^{top}_{measured} - T^{bottom}_{measured})} \tag{3.10}$$

4. **Highest and lowest tank temperatures with closest building temperatures:** This method is closely related to the previous method, except the flow coming into the accumulator tank is assumed to keep the temperatures measured at the in- and outlets of the closest building:

$$T_{in} = T^{closest}_{measured} \tag{3.11}$$

Based on if the flow to the accumulator tank was determined to be from the warm or the cold pipe, the T_{in} would switch between T^w and T^c.

5. **Highest and lowest tank temperatures with closest building temperatures updated:** An updated version of the previous method was also tested, where the incoming temperatures were set to be the mean of the temperatures at the closest building, the closest sensor in the tank, and the setpoint temperature.

$$T_{in} = (T^{closest}_{measured} + T^{tank}_{measured} + T_{setpoint})/3 \tag{3.12}$$

The models (1-5) were tested on against a period in time where the flow-meter of the accumulator tank was in use, and the models could be validated against the actual data. The calculated root mean square errors (RMSEs) and overall trends in flow for the period are presented in table 3.1.

Table 3.1: The RMSEs of the different techniques for estimating the accumulator flow

Method	RMSE	Trend (Actual 1.3)
1. No flow	4.6	0.0
2. Setpoint	4.1	0.0
3. Tank temp measured	4.1	-0.2
4. Closest building	172.8	6.5
5. Closest building update	3.8	0.7

As indicated in the table, the suggested methods of estimating the flow out of the accumulator tank have high root mean square errors. Some of the methods outperform the "No flow" alternative when it comes to the RMSE scores, but it is not vastly different, with the best estimate being method 5. An unwanted consequence of the calculated flows arises when a longer period of time is examined, and the trend can be seen. The average flow to the accumulator tank during this period was 1.3 m^3/h, which was not reflected in the data for any of the methods. The conclusion was that none of the methods for calculating the flow from the accumulator tank were sufficiently accurate, and no calculated values from the flow were introduced during the periods when there was no sensor.

3.5.3 Analysis of the Accumulator Tank

Because of diffusion, the water cannot stay perfectly separated in the tank, even when efforts are made to minimize these effects. There will be some kind of temperature gradient in the tank, and heating as well as cooling energy will be lost. This energy loss due to diffusion will also cause an imbalance in the volume of warm to cold water. If a volume of warm water lay directly on top of cold water, it will decrease in temperature as the eat dissipates to the cold volume.

In regards to whether the in and outgoing temperatures to the tank stay consistent with the setpoint temperatures, this can also be dismissed, as seen in figure 3.10. The temperatures in the tank seldom reach the setpoint temperatures. During colder periods of winter, the top part of the tank storing warm water is significantly lower than the set-point temperatures, and the bottom of the tank storing cold water is slightly warmer than the setpoint. During the periods with the higher setpoints, the cold water is typically significantly higher than the setpoint for the cold pipe.

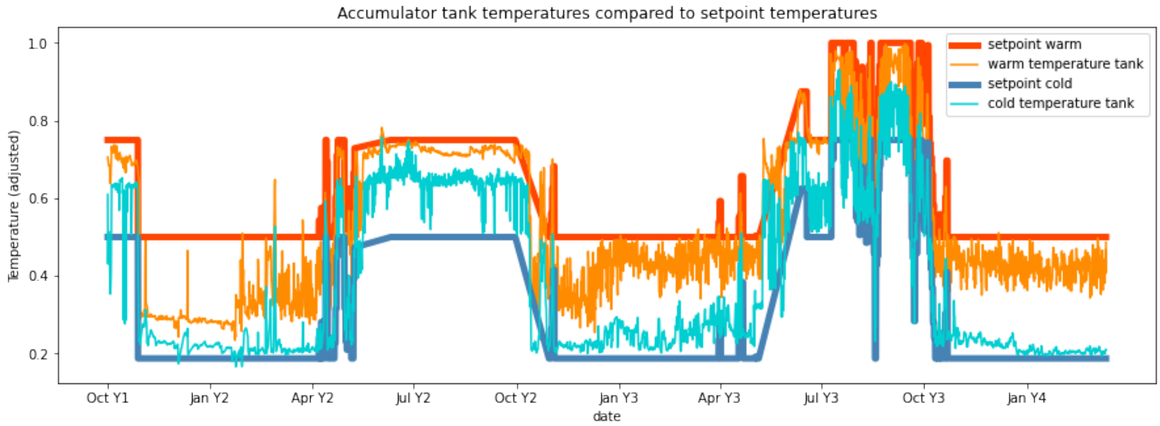


Figure 3.10: The temperatures at the top and bottom of the accumulator tank, compared to the setpoints

Some of this difference might be due to energy losses to the surroundings, and a small discussion about this can be seen in section A of the Appendix. However, losses from the accumulator tank to the outside temperatures were deemed small in comparison to the shift in temperatures. It is more likely that the temperatures entering the tank are not those of the setpoints, and that there is internal mixing of the temperature as heat diffuses.

Since the grid expanded over time to include more buildings and balancing units, the demand for heating and cooling has shifted. It is possible that the addition of more buildings causes larger volume flow in the pipes, which could potentially lead to the water staying in the pipes and in the tank for a shorter period of time, making the mixing of temperatures less prevalent.

3.6 Combined Flow

Since ectogrid™ is closed-circuit, the water that is in the pipes gets re-circulated and no new water is added is added to the system. Hence, the expectation is that when the data from all flow meters from the substation and balancing units are summed up, the value should be around zero, as the volume of water to a pipe should be as large as the volume from a pipe. The flow is measured at the inlets to the heat pumps and chillers, and the same body of water is then returned back to the grid on the other pipe. The overall water input minus the overall water output should be equal, or else there are volumes of water that are unaccounted for.

The flow to the warm pipe subtracted by the flow from the warm pipe was calculated. The difference was then divided by the total flow to the warm pipe, to obtain a ratio of how much of the flow was unaccounted for. The results can be seen in figure 3.11.

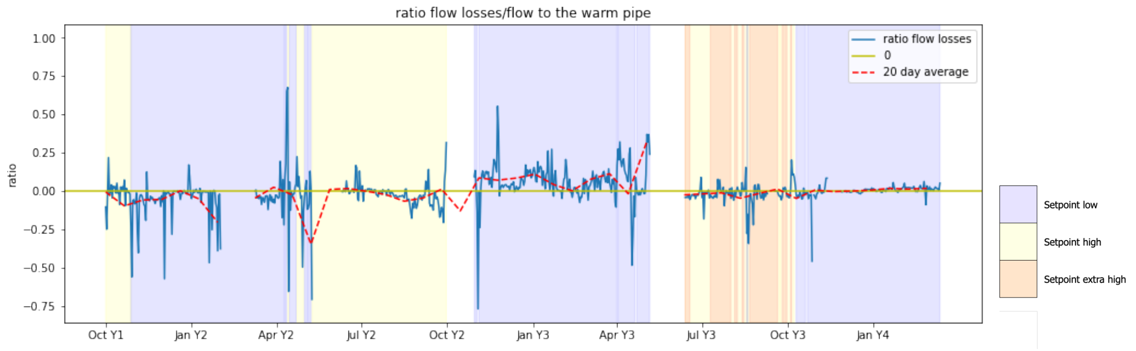


Figure 3.11: The ratio of flow unaccounted for to the input flow.

However, when the data was summed up and an hourly mean was calculated, the result showed that this assumption was not necessarily true. There could be several reasons for this, including the following eight possible explanations:

1. **Exclusion of accumulator tank:** The most obvious reason for the discrepancy in the first part of the data is that the impact of the accumulator tank is not taken into consideration. . The affected period lasts until October year 2. Since it has one of the largest impacts on the grid, and the impact would be even more prevalent during the periods with less actors on the grid, it is probably responsible for a major part of the discrepancy. The flow from the accumulator tank when a functioning flow meter had been installed registered as approximately 10% of the total flow to the warm pipe, as seen in figure 3.8. But the contribution from the tank is volatile, and the mean contribution can in some periods be around 40% during extended periods. It is possible that the entire discrepancy in flow during this period could be attributed to the accumulator tank.

2. **Manually calculating the flow:** From certain buildings the flow had to be calculated manually, as seen in section 3.3. This calculation is flawed in the sense that it is merely an estimation, with no chance of validation. The calculated contribution from the affected buildings is around 10% during the periods of October year 2 - May year 3, after which the contribution dips during the summer months when the heating demand for these buildings is low. During October year 3 - March year 4 these buildings made up 25 - 35% of the total flow of water used for heating, meaning that if they are on average scaled wrong by 10%, the impact on the flow is 2.5 - 3.5% during the period, which would explain the entire flow loss ratio from figure 3.11. This proportionality is also seen in the energy usage by these houses.

3. **Expansion of water:** A volume of water will expand when heated up, and the density will drop. If the ΔT of the system is approximately 10 degrees, the mass of the water on the cold pipe will be larger than the mass of the water on the warm pipe. At 10 degrees the density ρ^{10} is 999.70 kg/m^3, and at 20 degrees ρ^{20} is 998.21 kg/m^3. The ratio $\rho^{10}\ /\rho^{20} = 999.70/998.21 \approx 1.0015$, or a 0.15% decrease in volume. Between 20 and 30 degrees the ratio is 0.26% [27]. In a scenario where ectogrid^{TM} is operating at temperatures 20 and 30 degrees, consider all of the water inputs to the warm pipe are measured directly and the

water at the outlets are measured indirectly as being the same as the inlet flow from the cold pipe. The expansion of water would cause a 0.26% discrepancy. This does not account for the entire difference.

4. Expansion unit on the grid: There is an expansion unit on the grid, installed with the purpose of storing excess water on the grid caused by expansion. This in in place to ensure the pipes will not burst if the volume of the water increases. The reason to not include the expansion unit in the calculations is partly that the meter for the expansion unit only shows flow from the grid and not back to the grid, but mainly because the impact of the expansion unit is small in comparison to the total flow. During all of year 2, the flow registered going into the expansion unit was just over 20 m^3. Per hour that equals 0.002 m^3/h. The impact of the expansion unit is overall next to none.

5. Faulty meters: One of the more likely reasons behind the discrepancy is that the flow meters are not returning an accurate estimation of the flow. These could be scaled incorrectly or have some other bias that is unknown. The impact on the total flow that faulty meters may have is completely unknown.

6. Under-sized meters: As discussed in section 3.4, there are meters that cannot register flows above a certain threshold. Although accounted for, the flow estimations will not be a perfect representation of the actual flow during unstable periods. The impact this has on the grid is different depending on season, and will affect more data during certain periods of time and no data during others. During the most affected period of June and July of year 3, the data that was altered due to strange behaviour was 4% of the data, and cannot be solely responsible for the difference, but will likely impact this period somewhat.

7. Buildings on the grid in operation but no data: When new buildings or balancing units are installed, on the grid, they might operate for a period of time before the data is stored. It can be concluded that such is the case when checking the first stored value of the energy meter. The energy meter is cumulative and shows every kWh consumed. Most of the energy meters from the grid do not start at zero, indicating that they were being active components on the grid from before there is accessible data.

8.Incorrect calculations: There is always the possibility for incorrect calculations or estimations that could cause the difference.

The flow losses are the most consistently problematic during the period between October year 2 until May year 3, where a trend emerges of more water reportedly flowing to the warm pipe than water leaving the warm pipe. The flow from the accumulator tank is included in this period and should not be the cause, the impact of "hidden buildings" should also be small since not that many buildings were added during the period, and the impact of buildings where the flow is calculated manually is relatively small. It appears that this discrepancy in flow is most logically caused by faulty meters that have not been addressed.

Table 3.2: The potential impact of different aspects possible of causing the flow-imbalance

Source	Impact	Comment
1. Accumulator tank	0 - 40 %	Only until October year 2
2. Calculating flow	0 - 40 %	Mainly from October year 3
3. Expansion of water	0.3 %	
4. Expansion vault	0 %	No significant impact
5. Faulty meters	unknown	
6. Under-sized meter	0 - 4 %	Mainly summer year 2
7. Hidden buildings	unknown	Mainly during year 3
8. Incorrect calculations	unknown	

The implications of this calculation is that there is a high level of uncertainty in the data, not only when it comes to the flow. Since the energy is calculated using the flow, the same uncertainty is introduced in the overall energy losses. Differences in the flow will result in unexpected energy differences, that could be impossible to predict.

4 Calculations and Models for Gains and Losses on ectogrid$^{\text{TM}}$

The following sections discusses the research questions by modeling the grid, calculating and quantifying different aspects of the gains and losses on the pipes, and make predictions based on the findings.

4.1 Substations on the Grid

In order to specify where the energy losses occur, the warm and the cold pipe of ectogrid$^{\text{TM}}$ were handled as separate systems. This was achieved by calculating the energies based on the flow into/out of the building and the temperature of the water according to equation (2.2). The flow was provided by a meter connected to the heat pump or chiller, as well as the temperatures of water going into and out of the machine. For buildings with substations containing both chillers and heaters, the temperature of the water taken from the grid had to be calculated based on the ratio of water coming from the ectogrid$^{\text{TM}}$ pipes and the return-water from the other machine. A schematic illustration of such a substation can be seen in figure 4.1.

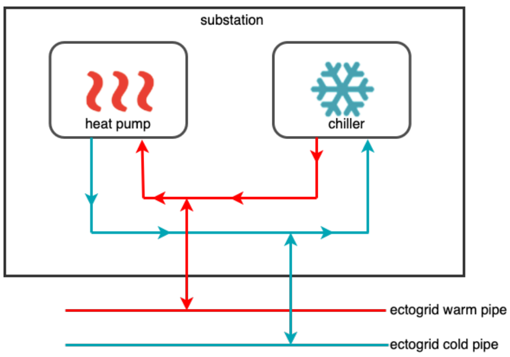


Figure 4.1: A building with both cooling and heating demand, chiller and heat pump in the same substation.

The net-flow of water from the warm pipe in ectogrid$^{\text{TM}}$ to a substation at a certain moment in time is equal to the water flow to the heat pump subtracted by the water flow out of the chiller and vice versa, as per equation (4.1). A dominant cooling demand will result in a negative net-flow of warm water to the substation, and the temperature of the water entering the heat pump and the ectogrid$^{\text{TM}}$ warm pipe will be the return temperature of the chiller. If instead there is a dominant heating demand, as is mostly the case in the chosen period, the net-flow will be positive and the temperature of the water going into the heat pump will be a weighted average of the temperature in the ectogrid™ warm pipe and the return temperature from the chiller. This can be seen in equation (4.2).

The net-flow from the warm pipe of the grid to a substation is

$$Q_{net} = Q_{HP} - Q_C \tag{4.1}$$

Note that the net-flow can be negative, if flow to the chiller is larger than the flow to the heat pump. The delivered temperatures to the heat pump is a mixture of the return temperature from the chiller and the water from the warm pipe of the grid, and is formulated as

$$T_{HP} = \begin{cases} T_C^{return} & Q_C > Q_{HP} \\ \frac{T_{grid} \cdot (Q_{net}) + T_C^{return} \cdot Q_C}{Q_{HP}} & Q_C < Q_{HP} \end{cases} \tag{4.2}$$

From equation (4.2) one can find the actual temperature of the water from or to the grid, as seen in equation (4.3):

$$T_{grid} = \begin{cases} T_C^{return} & Q_C > Q_{HP} \\ \frac{T_{HP} \cdot (Q_{HP}) - T_C \cdot Q_C}{Q_{net}} & Q_C < Q_{HP} \end{cases} \tag{4.3}$$

The same calculation is then done for the cold pipe, with the variables from the heat pump and chiller switching places. This model assumes perfect mixing of the return temperature and the temperature from the grid, which might not be reflected in the real life scenario, and it also assumes reliable meters. During periods when the Q_{net} is small, inconsistencies in the meters will be blown out of proportion. That is why the calculations on ectogrid™ were made with an adjustment, see equation (4.4), where the temperature from the grid is set to be the temperature registered at the heat pump when the net-flow is smaller than a constant k. This constant was chosen to be large enough to avoid the temperatures of being blown out of proportion, but small enough to affect as little of the data as possible.

$$T_{grid} = \begin{cases} T_C^{return} & Q_C > Q_{HP} \\ T_{HP} & 0 < Q_{HP} - Q_C < k \\ \frac{T_{HP} \cdot (Q_{HP}) - T_C \cdot Q_C}{Q_{net}} & Q_{HP} - Q_C > k \end{cases} \tag{4.4}$$

The equations in this thesis would still work without calculating the grid temperatures and the net-flows. However, there is a reason behind this step. Since we are only interested in the energy losses and heat dissipation from the pipes, everything that happens inside of a sub-station is irrelevant to what happens on the grid. To illustrate this, imagine a grid with consisting of one almost perfectly balanced building, with a large demand for both heating and cooling, and one active balancing unit placed in a different part of the grid. If the energy losses on the grid are calculated as a percentage of the total produced energy, the energy losses would appear much smaller than the actual energy losses in the pipes affecting only water transported between the active balancing unit and the building. That is why, although introducing additional bias, this method was used.

Although the constant k for small flows was used, some suspiciously small or large temperatures were calculated. These were not filtered out, with the rationale being that these outlier temperatures would equal out over time and that they mostly occurred when the flow was small and would not impact the data in any substantial way.

4.2 Temperature Changes in ectogrid^{TM}

The temperatures for each pipe are calculated as a weighted average, based on volume of water. The inlet temperatures are calculated separately from the outlet temperatures. A building or balancing unit with a positive net-flow to the grid $Q^{outlet} > 0$ will contribute to the outlet temperature T^{outlet}_{mean} in proportion to total flow to the grid $\sum_i Q^{outlet}_i$, and similarly for the inlet temperatures, see equation (4.5).

Since the energy in ectogrid^{TM} is directly proportional to the temperatures in the pipes, the grid energy losses at any given time can be estimated using the difference in input and output temperatures from the grid. A temperature difference of -1 ^{o}C between production and consumption on the warm pipe, in a grid where the temperature difference ΔT between the warm and the cold is 10 ^{o}C would signify a 10% energy loss on the warm pipe. Similarly a -1 ^{o}C difference on the cold pipe using the same grid parameters results in a 10% energy gain for cooling.

$$
\begin{aligned}
T^{inlet}_{mean} &= \frac{\sum_i \left(T^{inlet}_i \cdot Q^{inlet}_i\right)}{\sum_i Q^{input}_i} \\
T^{outlet}_{mean} &= \frac{\sum_i \left(T^{outlet}_i \cdot Q^{outlet}_i\right)}{\sum_i Q^{outlet}_i}
\end{aligned}
\tag{4.5}
$$

These calculations are not including the flow in to or out of the accumulator tank, since there are no temperature sensors for the inlet and outlets. As the temperatures are assumed to not mix and stay the same upon exit as upon entry to the tank, the impact of the accumulator tank on the temperatures to the grid should over time cancel out. Hence, excluding the temperatures to and from the accumulator tank should not impact the temperatures significantly.

In buildings with both heating and cooling, the grid temperatures and net-flows calculated in section 4.1 are the ones used. The reason as to why this is done is because little to no temperature difference is likely to be registered when the water does not leave the substation, which might skew the calculated in- and outlet temperatures and not reflect the state of the pipes.

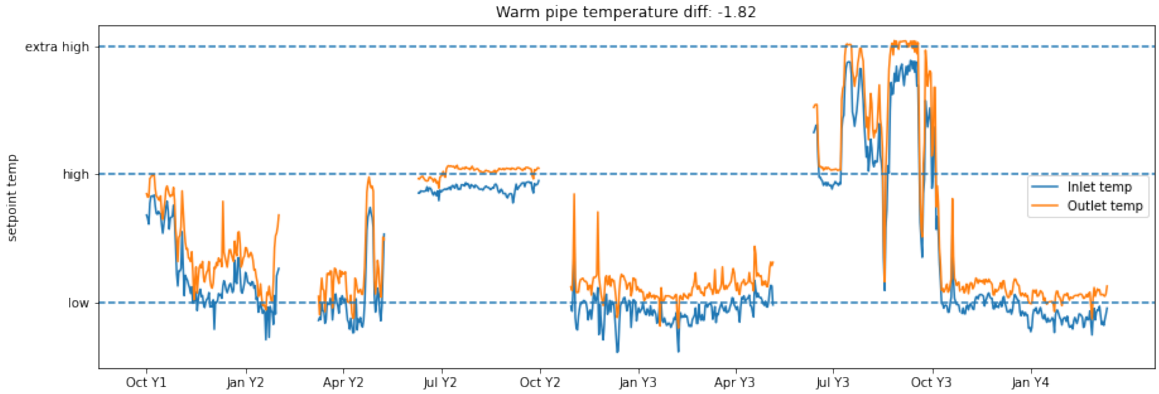


Figure 4.2: Temperature change on the warm pipe.

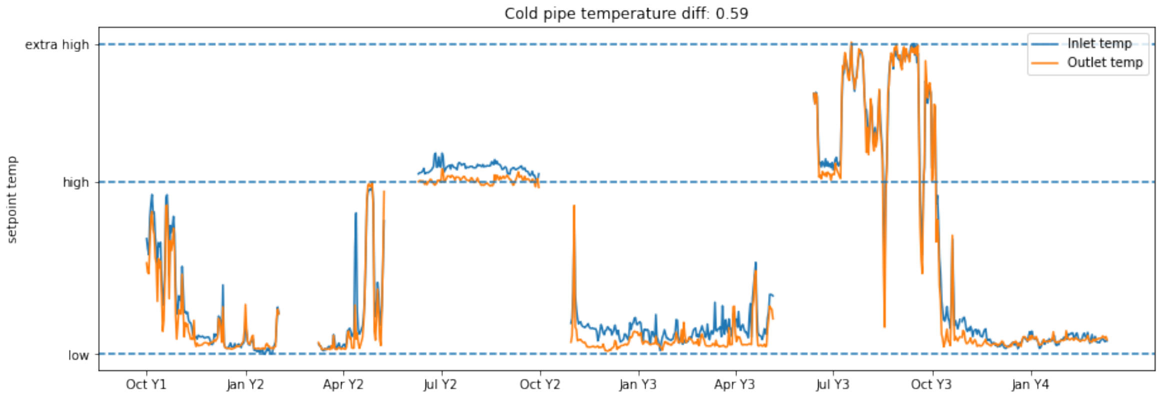


Figure 4.3: Temperature change on the cold pipe.

4.2.1 The Calculated Temperature Change

The temperature difference between outlet and inlet temperatures for the warm pipe can be seen in figure 4.2, and for the cold pipe in figure 4.3. The average temperature change on the warm pipe is -1.82 ^{o}C, meaning that on average the temperature decreases 1.82 ^{o}C in temperature during transportation in the pipes, which would be a loss of roughly 18% of the produced heating energy. On the cold pipe the average change is 0.58 ^{o}C, indicating an increase in temperature when the cold water is in the pipes. This is also undesirable, since the cold pipe should maintain as low temperatures as possible. Combined, the contribution from the two pipes temperature change is 2.40 ^{o}C from the ΔT, or a 24% reduction in total energy in the system.

It should be noted that the contribution of the accumulator tank to the pipe temperatures is not included. In figure 3.10 the temperatures on the top and on the bottom of the accumulator tank can be seen, showing how the temperatures that will be entering and exiting the tank are both likely far from the setpoint temperatures. Figure 3.9 shows how the accumulator is one of the main contributing entities to the flow to the grid. The contribution is usually somewhere between 10 to 40 % of the total flow, indicating just how much of an impact the tank has on the grid. However, if the accumulator tank is viewed as a part of the pipes in ectogrid, the impact it has on the temperature change should not be excluded.

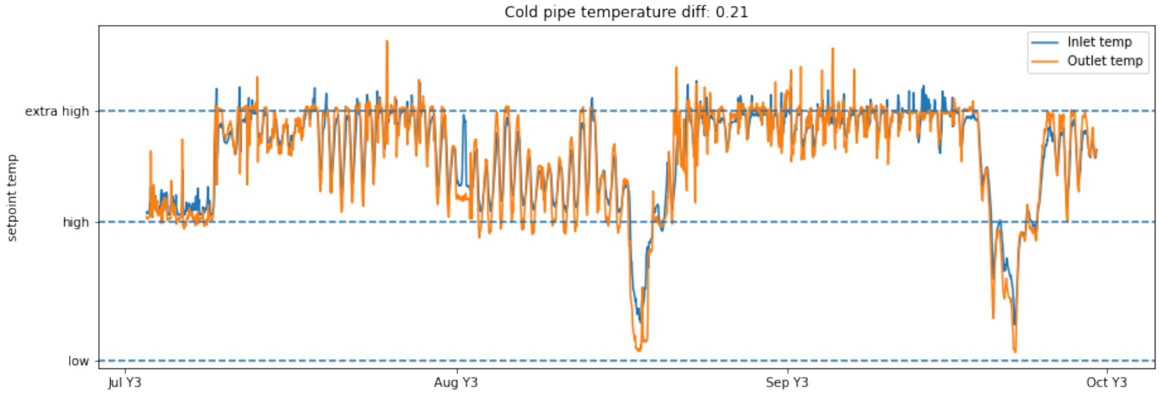


Figure 4.4: The temperature change on the cold pipe during a time period with high but unstable setpoints

The temperature change on the warm pipe is not necessarily a bad thing during the summer months, since the excess heating energy would still have to be removed through active balancing when the cooling demand is higher than the heating demand. It is during the periods when the demand for heating is stronger, especially the winter months, that this temperature loss to the surroundings is especially troublesome, since this dissipation of heat will have to be made up for. The outside temperatures throughout the period are presented in figure C.1 in appendix.

The temperature change can be divided into categories based on which setpoint was used at the time. The results are shown in table 4.1. For the cold pipe the problematic period is the summer, when the cooling demand is large. As the temperature in the pipe rises, cooling energy is lost. The expectation of the grid was that the cold pipe would potentially lose temperature to its surroundings, as the temperature in the pipe would be higher than the outside temperature. This is one of the main assumptions which the decision of not insulation the pipes is based on.

Table 4.1: The temperature change between outlet and inlet temperatures at different setpoints.

		Temperature	**Change**	
	mean	setpoint low	setpoint high	setpoint extra high
warm pipe	-1.82	-1.82	-1.52	-2.51
cold pipe	0.58	0.50	0.86	0.20

During the summer of year 3 there was a period when the setpoint temperatures were increased further, although these setpoints were not kept stable during an extended period of time. The temperatures in the cold pipe can be seen in figure 4.4, where the average temperature change between inlet and outlet was 0.2 ^{o}C. The shakiness of the setpoints does not allow for any real conclusions as the surroundings never reaches a steady state. Due to the periodicity in the changing setpoints, the soil surrounding the pipe will alternately be heating up and cooling down the pipe, due to the thermal inertia. However, it is possible to speculate that the cold pipe would be cooled down, gaining cooling energy, if the setpoints were fixed at the higher temperature.

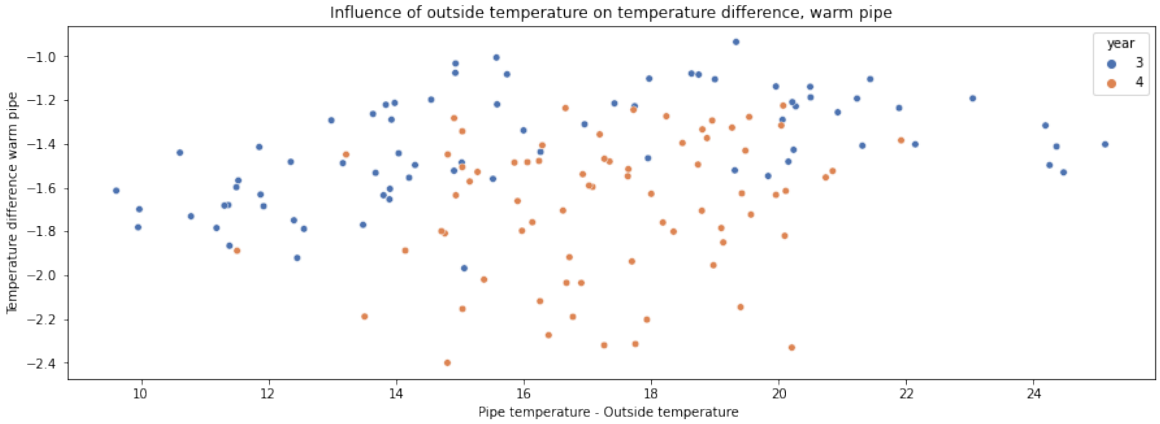


Figure 4.5: Scatter-plot of how the outside temperature affects the temperature change of the warm pipe.

As mentioned in section 2.6 the influence of the difference between pipe temperature and the surrounding temperature $(T - T^a)$ is in traditional district heating and cooling deemed to be one of the most significant factors when modeling energy losses. Since the temperature change in the pipes is proportional to the energy losses, the pipe temperature change should in turn also be proportional to the difference to the outside temperature $(T - T^a)$. This was tested by running multiple regression models on the data on both the larger dataset including all seasons, as well as the most stable season during winter year 3-4 when the topology of the grid and the setpoint were consistent. None of the models were able to produce a coefficient with a significant impact of regressors containing the outside temperature. Figure 4.5 shows the relationship between the temperature difference and $(T - T^a)$ for the data during the winter of year 3-4. No clear correlation is shown. It is more likely that there are other factors playing a larger part in causing the temperature change.

Another take away is that there is a likely case of "cross-contamination" between the pipes, as the warm pipe could be heating up the cold pipe, and vice versa. During the winter months when the outside temperature is significantly lower than the cold pipe, it can be seen from figure 4.3 that the cold pipe is still not cooled down by the surrounding soil. In the summer months the cold inlet temperatures are higher than the outlet temperatures, although the outside temperature is colder than the cold pipe. That would also indicate that the warm pipe is being cooled down by the cold pipe. This kind of cross-contamination means the ΔT of the grid as a whole decreases, which in turn means that less energy can be extracted from the system as a whole. These findings would indicate that some additional separation or insulation of one or both of the pipes could be beneficial.

It also ought to be noted that the impact the accumulator tank most likely has on the grid temperature change cannot be determined from this model, as it is not verifiable. The accumulator tank could be in part or solely the cause for the temperature change. However, it does not affect the results if losses in the tank are to be included in the losses on the grid as a whole.

4.3 Calculating and Predicting Energy Gains and Losses on ectogrid^{TM}

In this section a data-driven approach to estimating and predicting the energy gains and losses is described. The models take the entire grid into account using the available and quantifiable data. The results are later compared to some expected values from a white-box theoretical model in section 5.

4.3.1 Calculating Energy Losses

The simplest way of calculating the losses is to subtract the energy that is put into the pipes by the energy taken out of them, as described by equation (4.6).

$$E_{loss} = E_{to\ grid} - E_{from\ grid} \tag{4.6}$$

Because the warm and cold pipe are separate, they can be viewed as independent systems as seen in equation (4.7). By studying the warm pipe and cold pipe independently, the energy dissipation from each of the pipes can be calculated, resulting in the possibility of a more accurate model.

$$\begin{aligned} E^w_{loss} &= E^w_{input} - E^w_{output} \\ E^c_{loss} &= E^c_{input} - E^c_{output} \end{aligned} \tag{4.7}$$

All components of the grid were studied, with the contributions of each of the buildings and balancing units taken into account. Figure 4.6 illustrates how a small ectogrid^{TM} can work, containing buildings with different demands as well as active and passive balances. At each inlet and outlet, the energy consumed or provided to ectogrid^{TM} is calculated. The data is sampled at minute frequency, in order to get a sufficiently good resolution.

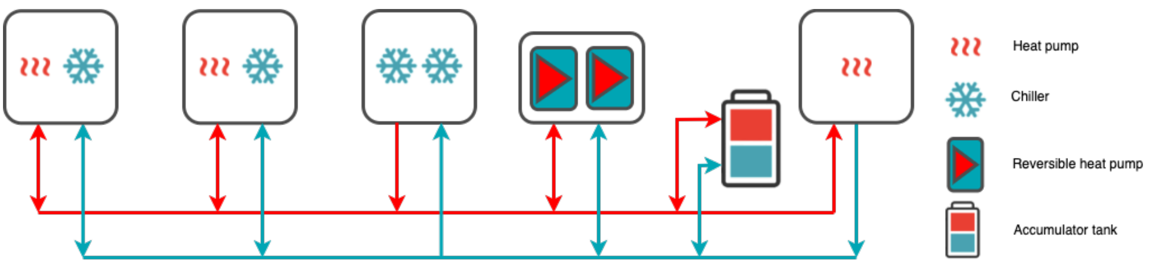


Figure 4.6: A representation of a small theoretical ectogrid^{TM}.

The energy of a mass of water consumed or produced by a building or balancing unit on the grid can with the help of equation (2.2) be calculated in accordance with equation (4.8). Using this equation, the energy from the warm pipe and energy from the cold pipe can be calculated separately. This is dissimilar to the method used by the energy-meters, that calculate energy based on the difference between incoming and outgoing temperatures. Since the energies of the pipes are calculated separately in this thesis, the choice is made to assume that the water on the pipe that is not of interest will have the setpoint temperatures of T^w_{sp} or T^c_{sp}. Note that the cooling energy E^c grows larger when $T^c_{measured}$ is lowered, due to the fact that lower temperatures means that the ΔT gets larger leading to a higher potential thermal energy exchange.

$$
\begin{aligned}
E^w &= (T^w_{measured} - T^c_{sp}) \cdot c_p \cdot m(Q_{from\ warm\ pipe}) \\
E^c &= (T^w_{sp} - T^c_{measured}) \cdot c_p \cdot m(Q_{from\ cold\ pipe})
\end{aligned}
\tag{4.8}
$$

Combining equation (4.7) and equation (4.8) provides the formula for calculating heating and cooling energy losses that is seen in equation (4.9). It should be noted that the energy to and from the accumulator tank is calculated differently, as seen in section 3.5.1.

$$
\begin{aligned}
E^w_{loss} &= E^w_{input} - E^w_{output} \\
&= \sum_{i}^{producers} (T^w_i - T^c_{sp}) \cdot c_p \cdot m(Q_i) - \sum_{j}^{consumers} (T^w_j - T^c_{sp}) \cdot c_p \cdot m(Q_j) \\
E^c_{loss} &= E^c_{input} - E^c_{output} \\
&= sum_i^{producers} (T^w_{sp} - T^c_i) \cdot c_p \cdot m(Q_i) - \sum_{j}^{consumers} (T^w_j - T^c_{sp}) \cdot c_p \cdot m(Q_j)
\end{aligned}
\tag{4.9}
$$

The choice of T^w_{sp} and T^c_{sp} to be the setpoint temperatures would be entirely arbitrary if the flow is balanced between producers and consumers, making $m(Q_i)$ equal to $m(Q_j)$ and cancelling out the impact of the setpoint temperatures. But as seen in section 3.6 this is not necessarily the case. In reality the choice of T^w_{sp} and T^c_{sp} will be significant due to differences in flow, which is why the setpoint temperatures were used.

The calculated energy losses can then be presented in both absolute or re-scaled values. The proportion of energy lost to energy produced as seen in equation (4.10) is interesting to analyse as it to some extent compensates for larger grids and different demand profiles. The loss ratio is also easier to scale to other theoretical grids.

$$
loss^i = E^i_{loss} / E^i_{input} \tag{4.10}
$$

4.3.2 Calculated Energy Losses

Since the energies might not be consumed during the same time period as they are produced, it is of interest to use a larger time scale. That is why the energy loss ratios are calculated as the mean loss during a longer period, and the results are shown in figure 4.7. The heating losses are consistently positive, indicating how there is a net positive heating energy dissipation from the pipes during all modes of operation, whilst the results from the cold pipe show how the losses are both positive and negative.

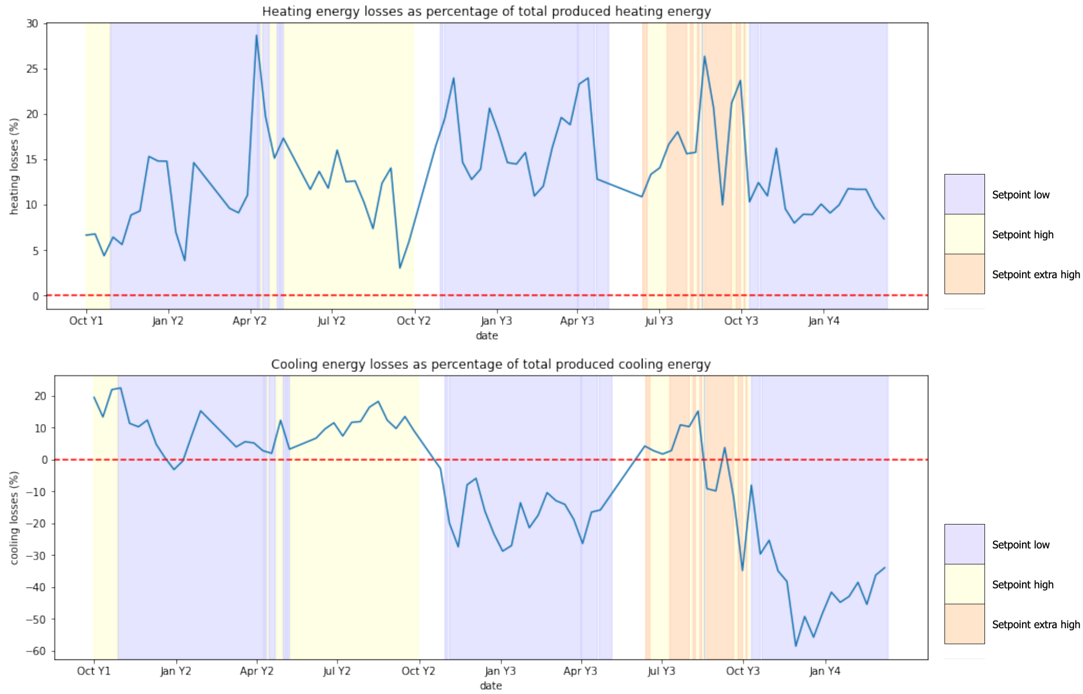


Figure 4.7: Calculated energy losses on each pipe as percentage of produced energy.

The positive energy losses on the warm pipe are undesirable during the periods of dominant heating demand, as these are pure losses on the grid. However during the summer periods where there is a dominant cooling demand, these energy losses on the warm pipe are in fact desired, since this means that less active balances have to be used to get rid of the excess heat. One less desired outcome is that the energy losses on the cold pipe are also positive during these periods with a dominant cooling demand. Since the temperature in the cold pipe is still warmer than the outside temperature, one desired and in part expected consequence is that the cold pipe would be chilled by its surroundings during this period. Part of the reason why the cold pipe is not insulated is for it to be able to gain cooling energy from its surroundings, and it does not appear to do so during the summer of year 2, and even though the data for the summer of year 3 would suggest that the cold pipe in part gained cooling energy, the data for this period is unreliable due to the unstable setpoints. During the winter periods with a dominant heating demand the cold pipe however gains cooling energy, but during these periods it is not as desired. The average energy losses on the pipes at different setpoints are presented in table 4.2.

Table 4.2: Energy losses on the pipes for different setpoints

		Energy	**Difference**	
	mean	setpoint low	setpoint high	setpoint extra high
warm pipe	14%	13%	14%	21%
cold pipe	-10%	-18%	8%	-2%

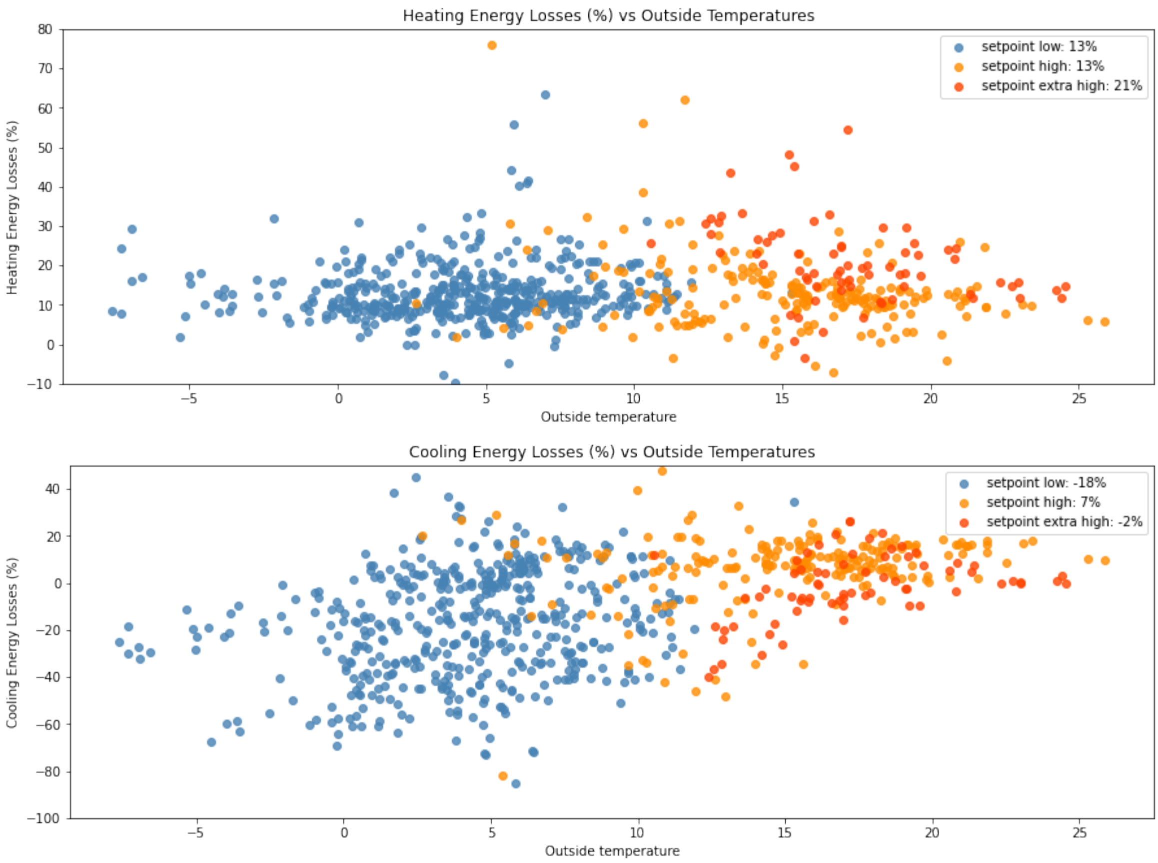


Figure 4.8: Heating and cooling losses against the outside temperatures

Another way of looking at the energy losses is to plot them against the outside temperatures, done in figure 4.8, which showcases the daily averages of both energy losses and outside temperatures. The expected trends in line with conventional methods as described in section 2.6 are for the energy losses on the warm pipe to decrease with higher outside temperatures, and for the energy losses on the cold pipe to increase. On the cold pipe this behaviour seems to be somewhat supported, but it is not as clear on the warm pipe. From these plots it is clear that other factors are influential when it comes to determining the energy losses.

4.3.3 Predicting Energy Losses

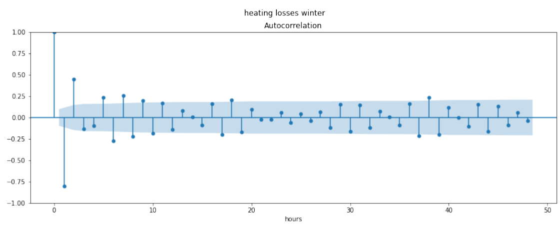
Time series analysis: At any given moment, the energy in the pipes of the grid will be the same as the energy in the system during the previous point in time plus any energy added to the system minus the energy removed from the system. For a point in time i, the equation for the energy in the system can be formulated as (4.11).

$$E^i_{grid} = E^{i-1}_{grid} + E^i_{to} - E^i_{from} \tag{4.11}$$

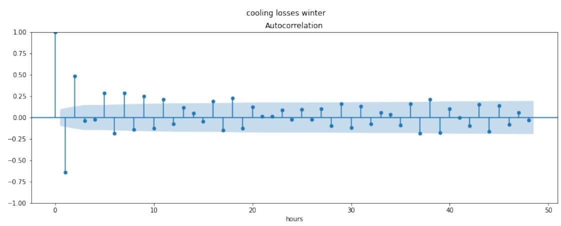
The smaller the time intervals, the more influential the previous time step is likely to be. A period where the volume of the flow to and from the grid is many times larger than the total volume of the pipes, it can be assumed that the impact of the previous time step is insignificant.

The auto-correlation of the heating and cooling losses were studied in order to find to what extent the previous time step was influencing the current one. Using the energy loss-data was sampled at hour-intervals, the auto-correlations and partial auto-correlations (ACF and PACF) were plotted for both the heating and the cooling losses. For this, the python library statsmodels [28] function plot_acf and plot_pacf were used, and the resulting auto-correlations can be seen in figure 4.9. The auto-correlations show a negative correlation between the time steps, as the value shifts between positive and negative signs. This behaviour is to be expected, as an excess production in energy during one hour can be compensated by the system consuming more and producing less energy the following hour, thus causing the negatively correlated pattern seen in figure 4.9. In addition, the partial auto-correlation functions (PACF) were plotted, which showed significant correlations until lag = 6 hours. For more information on auto-correlation functions, the literature by Jakobsson is referred to [29].

Additionally it can be seen in figure 4.9 how the auto-correlations between the heating and cooling losses are very similar. That is to be expected, since the volume of water consumed on one pipe should equal the volume on the other pipe, as discussed in section 3.6. The replacement of the water should then be equally significant on both pipes, and the auto-correlations will thereby be very similar.



(a) Auto-correlation of heating losses



(b) Auto-correlation of cooling losses

Figure 4.9: Auto-correlations of energy losses on an hourly basis, using statsmodels [28]

Due to the uncertainty in the data, larger time periods were preferred to shorter ones. Using larger periods of time is more likely to be smoothing out any inconsistencies in the data, causing less spikes and more reliable data. An additional reason as to why the larger time scales were preferred is due to the calculated energy from the accumulator tank. Because of the size of the tank and the inability of measuring the energy from and to the tank, longer time frames where the temperatures have been able to stabilize more is preferred.

Working with these larger time series meant that the data samples could be viewed as being more independent from each other, and that the variations in data would be due to outside circumstances. The data was aggregated to daily means, thus allowing for the approximation of the data as independent samples.

Regression model: Different linear regression models were tested on the energy loss data, for both the data on the warm and the cold pipe. Based on the conventional methods for calculating energy losses on district heating described in section 2.6, there is support for linear relationships between energy losses in district heating and cooling, and variables such as outside temperature times length of the grid. These and other relationships were explored using linear models. As the dependent variable for the model to predict, both energy losses as absolute values and as ratios were tested. Though both are of interest to investigate, energy losses as a ratio of produced energy will be used henceforth.

The data was aggregated to daily means and the samples were divided using a 80/20 split, with 80% training data and 20% testing data. The split was random, and even though the ACF showed some time-dependencies as no time-series analysis was performed. The reason for this was attributed to the data inconsistencies and the many gaps in the time series, and the large time aggregations were expected to minimise the time-lag. The behaviour was expected to be dependent mostly on outside variables. A variety of regression variables were tested, and these include:

1. Mean hourly energy produced
2. Setpoint temperatures
3. Outside temperature
4. Setpoint temperature - Outside temperature
5. Setpoint temperature - Mean weekly outside temperature
6. Linear or Circular grid, "Topology"
7. Amount of rain in the last 24 hours
8. Setpoint temperature - Soil temperature
9. Total surface area of the pipes
10. Length of the pipes
11. Setpoint temperature - mean tank temperature
12. Recent change in setpoint with exponential decline

Where the "Recent change in setpoint with exponential decline" was calculated to be the temperature difference in setpoint multiplied with a function exponentially decreasing with time. The "Topology" categorical variable was chosen to be 0 when the grid was linear and 1 when circular.

The python libraries scikit-learn and statmodels was used in this analysis, and specifically the method Linear.Regression() and OLS. Both of these methods produces a coefficient for each variable based on the ordinary least squares method [30] and [28]. For more information on ordinary least squares I refer to Craven, B. D., and Islam, S. M. [31]. Ideally all variables should be independent when fitting a model, which is the assumption of a linear regression model. But as expected, several of these variables were highly correlated or showing multicollinearity tendencies, which becomes a problem when two or more dependent variables are used in the same model and causing large standard errors and unreliable coefficients for prediction [32]. Correlation matrices for both the heating and cooling data can be seen in section C.3.

In order to find the significant variables and reduce the risk of dependent variables causing large variance in the models, the AIC- and BIC-values where investigated. The feature selection was largely based on backwards elimination using the BIC-criterion, although models using step-wise, forward and the AIC-criteria were also tested. This was performed using the step-functions in **R** which returns the best model based on the criteria [33]. In addition the p-values of the coefficients were investigated to ensure the significance of including each variable in the model. To avoid overfitting, smaller models were preferred.

In figure 4.10 and 4.11 the models found using the linear regression are tested using the test-data. The real and predicted values are shown in the upper plot, and the absolute errors of these predictions are shown in the lower. These models had the r^2 values of 0.33 for the heating model and 0.74 for the cooling model, where the higher r^2 of the cooling model is likely due to its ability to follow the higher variability of the cooling data. When it comes to the mean absolute errors on the test data, these were found to be 0.05 or 5% on the heating data and 0.09 or 9% on the cooling data, again likely to be due to the higher variability of the cooling data.

Figure 4.10: Heating model, predictions on the test-data

The chosen variables and their coefficients can be seen in table 4.3 and 4.4, as they relate to the energy loss ratios. In both of the models the produced energy, setpoint temperature, outside temperature, length of the grid and recent change in setpoint temperatures are significant to the model, and in the case of the heating energy model the topology is also used.

Figure 4.11: Cooling model, predictions on the test-data

Table 4.3: Heating model coefficients, the number corresponds with the description in the list of variables

Nbr	Coefficient		interpretation
	intercept	0.1107	
1	energy heating produced	-0.0001	Losses decrease when energy production is high
2	setpoint	0.0045	Losses increase with higher temperatures in the pipes
3	outTemp	-0.0016	Losses decrease as outside temperature rises
6	topology	0.0972	The circular grid has increased losses
10	length	-0.0001	Losses decrease with longer pipes
12	setpoint change	0.0333	Changing setpoints affect the losses

In figures 4.10 and 4.11 some clear trends can be seen in the relation between the actual data and the predictions. For example, the real heating energy losses during the fall and winter of year 1 shown in figure 4.10 are visibly following a trend that the linear model is not fitted to handle. This suggests that there are some parameters that the linear models does not include that are significant. The ACF and PACF for both of the models were tested, all of which proved that the residuals from the data were far from white noise, and that there are still improvements that could be made.

Machine Learning: Some machine learning methods were considered for the prediction of the energy losses on the pipes. Both explainable boosting machines and random forest regression was considered and to some extent tested, but ultimately ruled out due to the quality of the data being unsatisfactory and the results from these models not significantly outperforming the linear models on the test-data. As one of the disadvantages of many machine learning methods, the limited explainability could cause the models to make inaccurate predictions that are more difficult to gain insight to.

Table 4.4: Cooling model coefficients

Nbr	Coefficient		interpretation
	intercept	0.2533	
1	energy cooling produced	0.0001	Losses increase when energy production is high
2	setpoint	0.0077	Losses increase with higher temperatures in the pipes
3	outTemp	0.0129	Losses increase with higher outside temperature
10	length	-0.0004	Losses decrease with longer pipes
12	setpoint change	-0.0543	Changing setpoints affect the losses

Establish flow and losses on specific pipes: In addition to this full-grid model, a separate method for finding how temperatures change in specific pipes based on flow to and from the pipes was developed and in part tested on a section of the grid during a limited period. The specifications and results from this model was can be found in section B in the appendix. The model showed how the longer the time the warm water spent in the pipes, the more the temperatures differed between production and consumption. It also showed the influence of outside temperature and pipe temperature. Due to the lack of more reliable data and time constraints, this model was not developed further, but more exploration using this model could be interesting for future research.

4.4 White-box Model of Energy Losses

One way of modeling the energy losses of the system is to create a white box model that is entirely based on thermodynamics and physics. The theoretical model is based on the assumptions of a steady state scenario where all temperatures are constant and a thermal balance has been reached. The assumption of steady state is supported by the fact that the temperatures that all buildings and balancing units are outputting to ectogrid^{TM} are supposed to be the setpoint temperatures that are consistent over longer periods of time. However that is not the case for the outside temperature which fluctuates over the day. However these initial simplifications are used in the model presented below.

The proposed model is based on the work by Wallensten [8], and describes the heat dissipation a two-pipe system and calculates the heat loss of the steady state scenario where the temperatures are assumed static (not changing over time) and the system having achieved thermal balanceThe heat dissipation q_w and q_c (W/m) from the respective pipes is calculated using a superposition formulation of a symmetric and an anti-symmetric sub-problem. The symmetrical describes a system of two pipes with same internal temperature, as the mean of the actual temperatures, and an outside air temperature. In the anti-symmetrical sub-problem the temperatures in the pipes are $\pm$ half of the temperature difference between the pipes, and the air temperature is set to zero [8]. An illustration of the system can be seen in figure 4.12, and all relevant equations are available in section D. According to the source the relative errors are typically less than 0.5% [8].

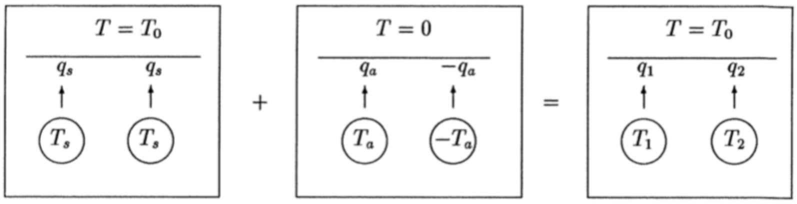


Figure 4.12: Illustration of the superposition principle from [8]. The symmetrical and anti-symmetrical formulations are combined to create a steady state formulation for energy losses of two pipes with separate internal temperatures. The image is from the book by Wallensten [8].

4.4.1 Results from the White-box Model

The two pipe steady state model from section 4.4 was implemented using python and javascript, and was tested using conditions meant to resemble the pipes of an ectogrid^{TM} under different specifications.

Since the thermal conductivity of the ground and the material used for the pipes was unknown, the impact of these variables were tested for under different outside temperatures. According to a study from the Swedish Geotechnical Institute [34], the thermal conductivity in different places in Sweden is typically around 1 - 1.5 (W/mK). The thermal conductivity of the material of the pipes was unknown.

The theoretical energy losses in a system that assumes pipe temperatures 20 and 30 ^{o}C for the cold and the warm pipe respectively can be seen in figure 4.13. In chapter D more plots of the energy losses under different grid parameters can be seen. In the scenario shown in figure 4.13 the thermal conductivity of the soil is set to 1.25 (W/mK) and for the pipes 0.3 (W/mK). The distance between the pipes, the pipe diameters, the thickness of the pipes, and the depth of the pipes is set to values similar to those of the studied grid. More plots where the constants are varied can be seen in chapter D of the appendix. According to the model, the warm pipe loses energy even when the outside temperature is equally high to the pipe temperature, which is likely caused by the cold pipe lowering its temperature. The cold pipe has energy gains until a specific point, which in the test case is 15 ^{o}C, before the impact of the warm pipe becomes larger than the impact of the outside temperature and the cold pipe experiences energy losses.

The drawbacks of this model is that it is a very simplified model of the grid, and most probably the reality is that there will not be a steady state perfectly balanced grid. However the energy losses found in the data should be proportional to the real losses, unless some other unexpected variable has a big influence.

Some of the parameters were varied in order to understand their impact on the losses. By lowering the thermal conductivity the material becomes more insulating. If this is done for the soil, the outside temperature becomes less influential. By lowering the thermal conductivity for the pipes, more energy losses between the pipes are likely

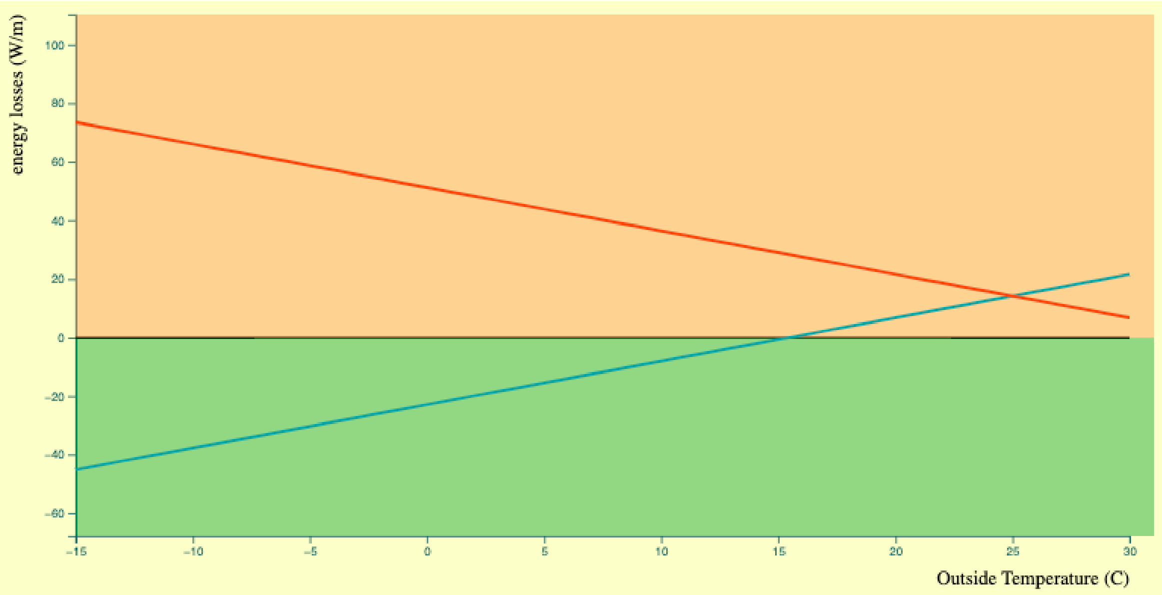


Figure 4.13: Energy losses per meter for the warm and the cold pipe under a steady state scenario.

to occur. Thicker material of the pipes means that the pipes are less impacted by their surroundings, and distancing the pipes further from each other meant that the impact from the outside temperature became more prominent, and the pipes will experience less "cross-contamination". The diameter of the pipes also influenced how big the energy losses were due to the additional surface area where heat can dissipate from. However it should be noted that more energy is able to be stored in a larger pipe, and the dissipation relative to stored energy therefore becomes smaller. Smaller temperature difference between the pipes lead to smaller energy losses between the pipes, which should also be taken into consideration.

This model was chosen, even though it does not include many of the parameters usually used when modeling energy loss from district heating pipes. For example, it does not take into consideration that the temperature of the water will change temperatures as heat dissipates. But as it is assumed that the water temperature at all outlets from buildings and balancing units to the grid will hold the setpoint temperatures, and how this water then moves in the pipes is unknown, these parameters cannot be estimated and are deemed to be of lesser importance. In more conventional district heating with one producer and many consumers spread along a grid, these parameters would be easier to estimate, and the energy difference between producer and consumer becomes more straightforward.

5 Temperature Changes and Energy Losses on ectogrid^{TM}

In sections 4.2, 4.3 and 4.4 three different methods for estimating thermal losses on ectogrid^{TM} are presented. Some of the findings are supported by all three methods, while some findings are contradictory. In this chapter, the results will be analysed per pipe and in regards to demands and setpoint temperatures, and then the grid as a whole is analysed.

5.1 Findings Relating to the Warm pipe

The data for the warm pipe consistently shows how energy dissipates from the pipe to its surroundings, as shown in figure 5.1. This is supported by the theoretical model showing how there can only be energy losses, if the warm pipe is on average warmer than its surroundings. The energy losses from the warm pipe are usually between 5 and 25% of produced energy. The calculated energy losses can be compared to the calculated temperature difference that is mostly centered around a 1.8 ^{o}C when the setpoints are low, and 1.5 and 2.5 ^{o}C when the setpoints are high and extra high respectively, indicating energy drops of 15% and 25% between production and consumption. A 15% - 25% drop in heating energy could be beneficial during periods with high cooling demand, which is usually the case when the setpoints are high. In these cases the energy leaving the pipes would otherwise most likely have to be removed by active balances to produced more cold water to use for cooling, which requires additional electricity. However in periods when the heating demand is higher, which is largely the case for the data during the studied period, a 13% decrease in heating energy is undesirable. The energy loss has to be compensated for through

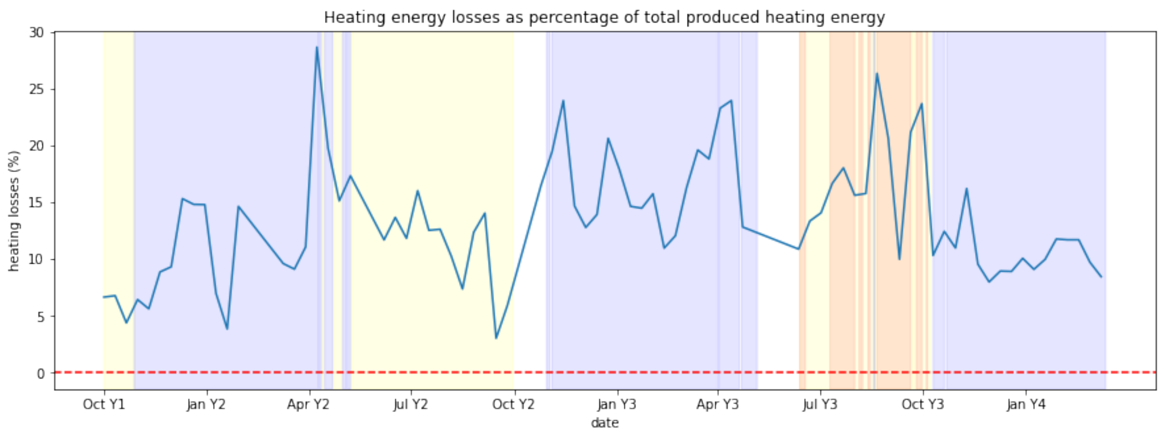


Figure 5.1: The energy heating losses on the warm pipe

active balancing which requires supplementary electricity.

Although the temperature model and the energy model mostly rely on the same data, the major difference is how the accumulator tank is included in the model. As discussed in section 3.5, the limitations in the data from the accumulator tank leaves the impact from it completely excluded from the temperature calculations, whereas an estimate of the energy to and from the tank is included in the energy model. It is highly possible that the temperatures in the tank are mixing to some degree, and that there are losses in the tank due to mixing of the water. Based on figure 3.10 it can be seen how the temperatures at the sensors in the tank closest to the in- and outlets do not follow the setpoints as desired, but are instead slightly shifted towards the opposite setpoint. If the energies, temperatures and flow from the accumulator tank could be estimated more accurately, it is likely that the prediction model for losses could be more exact, especially on smaller time-scales.

The overall losses on the warm pipe and their significance depends on a variety of factors, and their impact on ectogrid^{TM} are multifaceted. Since ectogrid^{TM} has expanded continuously throughout the studied period, there does not exist a period with dominant heating demand and a period with dominant cooling demand that have the same grid topology and layout, due to new buildings being added continuously. Conclusions have to be made and reassessed with varying demand profiles. On ectogrid^{TM} the expected demand for heating is larger than the demand for cooling over a year, which indicates that the energy losses from the warm pipe during a whole year are overall not beneficial with the current demand profile. It should also be noted that since the warm pipe is typically warmer than the outside temperature, excess heating can be exchanged with the outside temperature for cheap, with very little supplied energy in the form of electricity. As opposed to actively heating cold water, a much more costly operation that has to be done to excess cooling.

When it comes to predicting energy losses on the warm pipe the data-driven model suggests that the energy produced is one of the most significant variables. The absolute losses are larger the more energy is put into the system, but the ratio of losses to produced energy gets smaller. If compared to the theoretical model, the heat loss as an absolute value is not influenced by the produced energy, but is instead stable, and the relative loss to produced energy naturally decreases with higher energy production. The question is if the energy produced is in fact significant to the absolute energy losses, or if the energy produced should be seen as an indicator for other influential factors such as grid-size. Another of the variables deemed significant by the data-driven model was if the grid is linear or circular. The coefficient would indicate that a circular grid has much larger energy losses compared to a linear one, but this could be due to multicollinearity and that the topology of the grid changes when the grid expands and starts to include more buildings and balancing units.

The uncertainty of the model is high, and the findings correspond badly to the theoretical steady state model, indicating that either the assumption of a steady state is inaccurate, that the specifics of the grid are inaccurately estimated, or that the data from the grid is inherently faulty like in the case of the accumulator tank. Most likely it is a mixture of all three aspects. There are still benefits to the theoretical model however, since the overall trends are in line with the findings from the data, and it

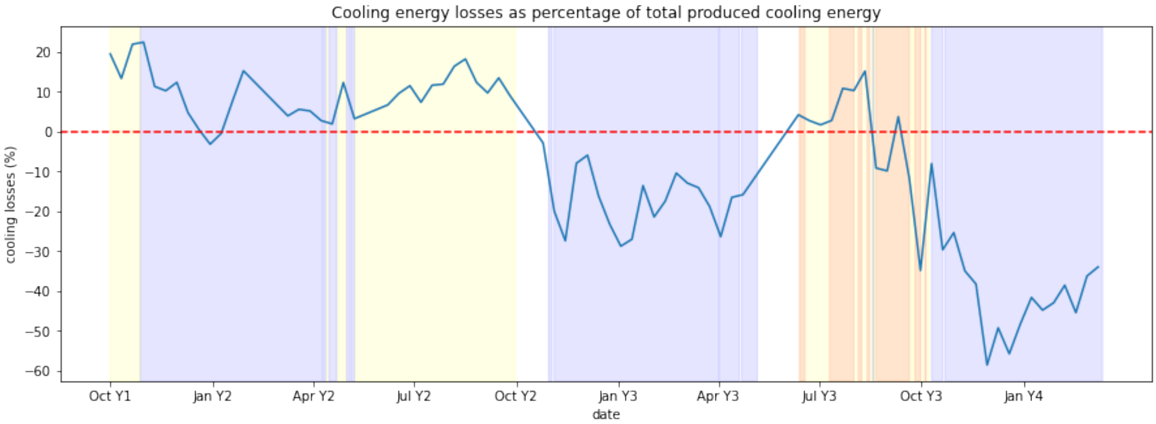


Figure 5.2: The energy cooling losses on the cold pipe

sheds insight into how a perfectly steady system would act.

5.2 Findings Relating to the Cold pipe

The energy gains and losses on the cold pipe have higher variance than those of the warm pipe, and the losses shift between positive and negative, as seen in figure 5.2. The gains primarily appear when the setpoint is low and there is a dominant heating demand. Ideally the gains would appear during periods when the demand for cooling was dominant, as the cooling energy gains in the winter period are not desired. However, this is not the case, and in the summer there are limited recordings of cooling energy gains. It is possible that more cooling energy gains would be possible during periods with the setpoint being extra high, but due to this scenario not being tested for any stable extended period of time, it cannot be validated, although the data suggest there gains are possible with these setpoints. This is corroborated by the findings from the steady state model.

Like the warm pipe, the energy losses on the cold pipe are in proportion to the energy produced, although the outside temperature seem to be a far more influential variable in the cooling model than in the heating model. The energy gains on the cold pipe are greater when the outside temperatures are low, which is in line with the theoretical model. And just as the case for the theoretical model, the cooling energy difference alternates between gains and losses. The topology of the grid is deemed insignificant in the cooling model, and a longer grid corresponds to more cooling energy gains.

The data-driven models for the cold pipe shares the problem of high uncertainty and large errors. Although the R^2 value of the cooling model is significantly larger than that of the heating model, the residuals of this model is larger. That is due to the fact that the data for the cold pipe has a lot higher overall variance than the data for the warm pipe, but might be indicative of the data not being sufficiently reliable.

One interesting finding is that the data for the period of October year 2 to May of year 3 seem to indicate that the temperatures in the cold pipe increase, which indicates losses in cooling energy, however the energy data suggests otherwise. As mentioned in relation to the warm pipe, the impact of the accumulator tank is not included in the temperature calculations, but is included when calculating the energies. The impact of the accumulator tank might be part of the reason as to why this period seems to contradict itself. A similar behaviour is seen the following winter, as the temperatures in the cold pipe seem to remain stable, but more cooling energy can be extracted than is put in. However there may also be other factors impacting this, such as the difference in flow to and from the pipe.

5.3 Findings Relating to Both pipes

The total energy in the grid is proportional to the temperature difference on the pipes ΔT. If the warm pipe loses 1^{o}C, but the cold pipe does so as well, the total thermal energy of the grid is unchanged. During both winter seasons of years 2-3 and years 3-4, the warm pipe experienced heating energy losses and the cold pipe experienced cooling energy gains according to the calculated energy. The implication of this is that the impact on thermal energy of the system due to energy losses is small. But the findings from this thesis make us able to separate these gains and losses, which provides a more insightful analysis of the grid as a whole. If instead the cold pipe is heated by 1 ^{o}C and the warm pipe is cooled by 1 ^{o}C, there are total losses on both sides of the grid. But the grid as a whole is not negatively impacted, as the negative effects from the cooling losses are made up for by the positive effects of the heating losses. This is the actual scenario where the grid as a whole does not lose cooling energy.

Although the pipes are being kept separate in both data-driven models, there is likely interaction between them. As described in section 4.2.1 the temperatures in the pipes are most likely influencing causing a degree of "cross-contamination", which is why the temperature in the cold pipe does not decrease in some of the situations where it is warmer than its surroundings.

The theoretical model is cleaner to work with and is far more specific in its predictions than the data-driven model, however the results stemming from this model is not accurately depicting the data from the ectogrid^{TM}. It can therefore in its current form not be used to predict energy losses on the grid. It can however shed light on some key concepts about how the pipes interact and with each other and their surroundings. As an example, if the temperature difference between the pipes decreases, their "cross-contamination" is much less prevalent. This can be used when considering how to build other grids and how different aspects can affect the energy losses.

6 Analysis and Discussion

In the previous Chapter 5, the energy distribution losses and temperature changes in the pipes, that were calculated in Chapter 4, are described. The model for predicting the energy losses is also discussed. The findings presented suggest that there are potential improvements that could be made, and some of these will be discussed in terms of the implications they could have on ectogrid^{TM}. In this section the results are discussed in terms of how they relate to insulation, grid temperatures and grid layout. Some of the assumptions made are evaluated, as well as sources of error, and potentially improvements for data quality.

6.1 The assumption of steady state

In the white-box model, the assumption is that the pipes operate in a steady state environment. A steady state refers a to time period when the system has reached an equilibrium. This will never be the case for a real grid, since the outside temperature changes over the course of a day, and the daily mean temperatures change over the course of the year. The internal temperatures of the pipes are also inconsistent, as can be seen in section 4.2.1. The most significant changes, in the sense of how drastically the system is changed, occur when the setpoint temperatures are changed. The system can be thought of as an impulse response that reacts to the new conditions, and there will be a longer period of time before it reaches a state resembling a steady state. Due to the losses according to the theoretical model not being consistent with the findings in the data, this indicates that the system is not well represented by an equilibrium state.

6.2 Insulation of the pipes

One major characteristic of ectogrid^{TM} is that it does not have insulation on the pipes, which is possible due to the low temperatures. During design the benefits of this setup were estimated to outweigh the disadvantageous energy losses.

One of the most straightforward reasons for not insulating the pipes is that it is cheaper and easier to build and expand the grid, since the capital cost is ultimately one of the main factors determining how to invest in and build projects.

One of the most important reasons for not insulating the grid is the assumption that the energy losses will be outweighed by the energy gains, or at the very least not exceed the insulation cost. The idea as previously described is that excess heating, especially during warm summer periods when the demand for heating is low, will diffuse out of the warm pipe in proportion to how much warmer the pipe is than the outside temperature. This is supported by the findings of this thesis. Heat diffusion out of the cold pipe is also expected, due to the fact that the temperature in the cold pipe is on average warmer than the outside and the soil temperatures. This is however not readily supported by the findings of this thesis, as it appears that the cold pipe loses cooling energy in periods with dominant cooling demand. The probable reason for this is that the heat diffusing out of the warm pipe is transmitted to the cold pipe in larger quantities than expected, effectively heating up the cold pipe. Based on this finding of the cold pipe being heated, it can be assumed that the system with two pipes work in some ways like a heat exchanger, and that the impact of the outside temperature is relatively smaller in comparison to their interference with each other. It is unfortunate that the interference between the pipes affect the energy in the grid in this way, causing cooling energy losses of 8% during a period where the demand for is high.

Another more expected disadvantage of not insulating the pipes is that the warm pipe will lose heating energy in the winters when outside temperature is low and the heating demand is high. The losses on the warm pipe during seasons with dominant heating demand are around 13%, which is comparable to the 12% average losses on district heating systems in Sweden, but not unreasonable. It should be noted that the losses in conventional district heating would be substantially larger if the pipes were uninsulated, but it should also be considered that the typical length of a heating or cooling grid is longer than the distance of the pipes in an ectogrid™.

Since the expected demand-profile over the course of a year for ectogrid™ is that there will be a larger heating demand than there is cooling demand, these losses on the warm pipe are more significant. Additionally, it is more important to keep the warm pipe warm in winter than to keep the cold pipe cold in summer. This is due to the cost of heating water to temperatures higher than the surroundings being much larger than the cost of cooling water, if the water being cooled is also warmer than its surroundings.

Adding insulation to the pipes could be considered for one or both of the pipes, and an analysis of the potential effects follows in the next paragraphs.

Insulating the warm pipe would reduce the heating energy losses throughout the year. This would be very beneficial during the winter months when the heating demand is large and the active balancing is used to supply the non-balanced demand. However the cold pipe would likely gain more cooling energy during the winter period with dominant heating demand due to less interference with the warm pipe, and the effects would be costly as the water would have to be heated up more. During the summer seasons with dominant cooling demand, the cold pipe would probably be cooled, which is beneficial. The downside is that the warm pipe would not lose energy during the summer periods with dominant cooling demand, however this could potentially be compensated for in a relatively cheap heat exchange with the outside air.

Insulating the cold pipe would mean that the cold pipe would not lose nor gain much energy from its surroundings. But seeing how the gains on the cold pipe currently outweigh the losses, this is not necessarily good. The warm pipe would be less influenced by the cold pipe, but energy losses on it would still be prevalent as the temperature of the warm pipe is significantly warmer than the outside temperature. Insulating the cold pipe would probably not be as beneficial as insulating the warm pipe.

Insulating both pipes would mean that the ectogrid^{TM} does not have the same thermal interactivity with the outside temperatures, limiting the impact of one of its more prominent features. The expense of building the grids would also increase. Energy losses and energy gains would be minimized, which is not necessarily beneficial.

The data suggests that the best course of action for similar grids is to insulate the warm pipe.

Separating the pipes, or adding a barrier between them. If the overall energy demand of the grid was to change in favor of a dominant cooling demand, insulation of the warm pipe might not be the best course of action. If the pipes were to be separated, either by moving them further away from each other or by inserting a barricade between the two, the positive effects of energy heating losses would still be possible, while the cold pipe would not be as prone to cooling losses. This could be considered for ectogrids^{TM} built in areas with other demand profiles.

6.3 Lowering the temperature difference between the pipes

One potential solution for having lower energy losses on the grid is to lower the temperature difference ΔT between the warm and the cold pipe. The reasoning behind this is that a lower ΔT would lead to less interference between the pipes. Since the energy dissipation from a pipe is proportional to the temperature difference between the pipe and its surroundings, lowering the temperature difference to another nearby pipe will likely lower the energy dissipation between the pipes. Hence, energy losses will decrease.

The second reason to do so is that the water will be transported at a faster rate, since the smaller ΔT will have to be made up for by the flow. The flow would have to be doubled if ΔT were halved, to be able to deliver the same amount of energy. The findings from the energy models were that the relative energy losses decrease when there is a higher energy production, indicating more flow in the pipes. More flow means that water will spend less time in the pipes before being consumed, which also decreases the losses, which is discussed in section B of the appendix.

However, some other problems may emerge from such a scenario. We have seen that the temperatures in the grid are sometimes volatile, and a small temperature difference may be reduced to no temperature difference, hence removing all of the thermal energy in the grid. A larger flow in order to uphold the energy demand is needed as mentioned, which can be strenuous for the equipment and not compatible with the current pipes. And in the case of there being little to no temperature difference between the pipes, an infinite flow to a heat pump or chiller could be needed in order to meet the demand, which is obviously not deliverable.

6.4 Sources of error

Some of the sources of error have been discussed at length in other parts of this report, mainly in terms of data cleaning in section 3. A large portion of the potential errors relate to the unreliable signals from the accumulator tank, the active balancing unit and the recreated data from heat pumps and chillers.

When it comes to the data-driven models, one important factor to address for both of the pipes is the imbalanced flow to the pipes. This flow-difference is indicative of the energy and temperature calculations being incorrect, since water is being unaccounted for in the grid. All flow-data from October year 2 and forward should be more or less perfectly balanced, however it can be seen in figure 3.11 that it is not. This is not compensated for in the energy model, as it is unknown what causes the discrepancies. But a large difference in water to a pipe and water from a pipe will cause an energy difference, even if the temperatures in the system are the same. Especially the winter of years 2-3 is affected by this problem, where for extended periods of time the difference between the flows to and from the warm pipe make up 10% of the total flow to the warm pipe. This makes all the data from this period more unreliable, and could be due to faulty meters or that there are buildings on the grid that are not in the data-set. The energy losses on the warm pipe during this period are also larger than the losses the following winter season. Although other factors seem to influence this, such as the outside temperature being colder during the winter, the significance of this flow difference should be considered. Even in the period with the most balanced flow, during the winter of years 3-4 there is still a discrepancy, with more registered flow to the warm pipe than is accounted for leaving it.

Another unstable period in the data is the summer of year 3 when the setpoint temperatures were not kept stable for longer periods of time, meaning that the thermal inertia of the system and the soil probably influenced the energies to some degree. The energy models include a variable for recent setpoint changes, but the models are probably not accurately depicting the expected behaviour if the pipes were stable at the extra high setpoints.

Then there is the question of whether the substations should be modeled as described in section 4.1, or if it is better to include data from all of the heat pumps and chillers on the grid. The reason to only include the net consumption of a substation was to accurately depict the energy losses and gains in the pipes, and not include the building-side. It is probable that the energy loss ratio would be smaller if this decision was not made, but the data would not be depicting what happens in the pipes. The downside to calculating the net consumption is that the temperatures to and from the grid from which the energies are also calculated are estimates. These estimates could be inaccurate and introduce erroneous temperature estimates, causing the calculated energy losses and temperature changes to not reflect the actual grid. However the likelihood of these effects having a significant impact on the grid overall are estimated to be small.

The quality of the data was not sufficient to perform an accurate in-depth analysis of when energy losses occur on the grid. Questions about how the setpoint temperatures really affect the losses and gains remain, and so does the influence of the grid topology and the surface area of the pipes. The accumulator tank and unbalanced flow seem to be the two largest contributing factors to the data not being reliable. While new sensors can be installed on the accumulator tank, it is not as simple to address the other issue. It is unclear where the imbalance in the flow data stems from, and it could likely be due to the buildings where the flow is calculated manually for some of the affected data, and from "hidden" buildings on the grid for other parts of the data. But in order to find the cause, several new meters would have to be installed, which still may not be able to determine the source of the imbalance.

There is a high variance to the model, meaning that the accuracy is low. In the case of heating, the model cannot explain more than half of the variance with the current input variables, and in the case of the cooling model the mean absolute error is still large compared to the value it estimates.

One of the sources of error that have not yet been mentioned is the sampling frequency, and if the intervals for which the data is collected provide an image that is not reflective of the data. If the data is sampled incorrectly, the effects might emerge as outliers, distorting the data in smaller time-scales. Over a longer period of time this is usually not a problem, but Nyquist's theorem should be taken into consideration [35]. The sampling is done at too low frequencies, the system might be changing to quickly to gain an accurate depiction. When sampling at minute intervals the assumed behaviour of the buildings is that drastic changes do not occur at frequencies higher than every 2 minutes. Due to compressor cycles and inertia in the machines, it is likely that the data is not changing at rates significantly faster than the sampling frequency. This is likely not a big issue.

6.5 Suggested improvements for data quality

Many of the findings in this report are made with a degree of uncertainty that can be attributed to the quality of the data. As data science and the engineering workflow are iterative processes, much of the analysis performed in this thesis could be reevaluated in the light of new and improved data.

As one of the already mentioned suggestions to improve data quality, installing a functioning energy meter and temperature sensors on the inlets of the accumulator tank would provide a much clearer image of one of the potentially most influential actors on the grid. The accumulator tank holds approximately twice the total volume of the grid, and is a major component. It is the main reasons as to why energy production does not have to be simultaneous to the energy usage, because of its properties as a thermal battery and capacity to be charged with heating and cooling energy. Installing these sensors would make it easier to determine how big the energy losses are at any moment, and could improve the energy model.

It would also make it possible to asses energy losses on the accumulator tank to its surroundings, as well as to internal mixing of the temperatures in the tank. If working temperature sensors are not put into place, there are still studies that could be performed. One example would be to disconnect the tank from the grid, and not allow any flow into or out of it for several hours. If doing so, the energy difference of the tank would be pure losses and a model of the insulation properties of the tank could be determined. We would also see the effects of mixing temperatures, and see whether the water is layered as assumed, or if there is mixing. A smaller version of this experiment was conducted and is presented in section A.

Another suggestion is to install energy and flow meters on the buildings where these are absent. The result of which would show if the flow to the grid is balanced when these are in place, or if there are other factors that are causing the imbalance. In case of the latter, the reliability of all of the data from the grid would improve, and if not it would be clear that one or more of the data sources are inaccurate.

Additionally, if the flow in the grid was established, more in-depth studies could be performed on where losses occur in relation to pipe specifications. This could potentially be done by looking into data from pressure cones on the grid combined with reliable flow-data. An analysis similar to the one made in section B in the appendix could be performed.

7 Conclusion

This thesis in collaboration with E.ON had the objective of calculating the energy losses in a low temperature bi-directional grid, and find out what influenced them. The studied ectogrid$^{\text{TM}}$ shows potential as an efficient and adaptable solution for heating and cooling, and insights from this thesis could be used for further development of these grids. The approach taken was data-driven, and included calculating the temperature changes in the pipes, calculating the energy losses and gains for both the warm and the cold pipe, and finding the influential factors which was achieved through a linear regression model fitted to the energy data, as described in Chapter 4. The conclusions are as follows:

Temperature changes: The findings indicate that the temperature of the water will change during its time in the pipes. On average the water in the warm pipe is cooled down around 1.5 - 2.5 ^{o}C, while the temperature of water on the cold pipe stayed consistent or was heated up, usually less than 1 ^{o}C, as seen in Section 4.2.1. The results indicate that the uninsulated nature of the pipes and the currently used temperatures will cause interference between the pipes, i.e. that they "cross-contaminate" each other. A white-box simulation of the pipes also indicate that this behaviour is to be expected.

Energies: The difference in energy produced and energy consumed on the warm pipe is consistently above zero, showing that there are consistent energy losses on the warm pipe of the grid. Although volatile, these losses were usually centered between 10-20% of produced heating energy, as seen in Section 4.3.2. On the cold pipe both energy gains and energy losses can be observed. The cooling energy gains mainly appear during the colder winter months the gains were large, which is when they are not as desirable. One of the more unexpected findings was that the cold pipe showed cooling energy losses of around 8% during the summer periods, even though the setpoint temperature of the cold pipe was on average warmer than the outside temperature. It was however consistent with the findings that the temperature in the warm pipe on average decreased during this period. The positive effects from losing heating energy during summers did however not outweigh the negative effects from losing heating energy during winters. This is described in detain in Chapter 5.

Predictions: Based on the models created in Section 4.3.3, the energy losses are dependent on factors like the amount of energy produced, outside temperature, setpoint temperature and the length of the grid. The model however was not able to explain the variance in the energy-loss data with, and the heating loss model reached a R^2 of 0.33 and the cooling model having a R^2 of 0.74. Based on solely the R^2-values this would indicate that the heating model is worse, although the mean error for this model is smaller with 0.05 compared to 0.09 of the cooling model. Further studies are needed if a more accurate model is to be found, as the models would likely benefit from studying more variables and interaction between variables. Better R^2 values and smaller residuals are possible, but will likely sufferer from over-fitting if a similar approach is taken. But in order to reach significantly better results it is likely that data that is more reliable will be needed. With the current data, studying the losses at a smaller time frame is estimated to be too influenced by inconsistencies, and therefore not possible for a stable model.

Some recommendations based on the findings include that in order to lower energy losses on both pipes, some insulation on the warm pipe could be considered, as described in Section 6.2. If however the demand profile of the grid was to change in favor of a dominant cooling demand, insulation could be replaced by some sort of separating barrier between the pipes instead. This way the cold pipe would not be as affected by the warm pipe, but the warm pipe could still lose energy to its surroundings which in that case would be positive.

Another method to optimize the system that is discussed in Section 6.3, is to lower the temperature difference between the pipes, which could lead to less stagnant water in the pipes and overall lower losses.

It was also shown how some aspects of the data were unreliable, and that some of the results could not fully be trusted in their current form, as described in Section 6.4. The two main components of this were missing sensors on the accumulator tank, and the volumes of water that were unaccounted for in the grid. By replacing the temperature sensors by the inlets to the tank, a more accurate study and understanding of the grid could be conducted. And by adding flow-sensors to the buildings where these are missing, the discrepancy in flow could potentially disappear, creating a better account for the total energy in the pipes. And if not, it would be clear that one or more of the meters are faulty.

7.1 Suggestions for further studies

Since some of the question marks still remain in relation to the research questions, the following suggestions would be interesting to investigate.

Different setpoints: By testing different setpoint scenarios on ectogrid™, the interaction between the pipes could be investigated further, to see how much of the energy leaves the system altogether, and how much finds its way to the other pipe.

Insulating or separating: To find out how the overall energy and temperature losses would behave if one or both of the pipes were insulated or if they were further separated, both white-box models and black-box models could be tested. Similar grids could be investigated, or if the grid is expanded with these design specifications taken into consideration, more analysis could be done. Especially if temperature sensors are placed in the soil surrounding the new pipe, or if the flow in that part of the grid is easier to establish.

Pipe specification: The models could not determine how the pipe specifications related to the energy losses. It would be interesting to know how pipe material, diameters and specific lengths of pipe factor in to the energy gains and losses.

Disconnecting the accumulator tank: To find out more about the losses on the accumulator tank and whether the water stays separated, the accumulator tank could be disconnected from the grid for an extended period.

Time in the pipes: The time the water spends in the pipes could also be investigated, if the flow in the pipes was established further. A small implementation of this was tested, and the theory and findings from this can be seen in section B in the appendix.

Establishing the flow: One method for estimating the flow is based on looking into the pressure cones that are placed on the grid. As the pressure difference moves the water, this could shed more light into how the grid as a whole works.

7.2 Reflections on the Thesis Task and the Approach Used

The scope of this thesis was deceivingly straight forward and easy to understand. Upon an initial glance my personal belief was that the predictions and estimations would be more in-depth and precise, and that more time would be spent on predicting energy losses. I did not think that the data gathering and cleaning would take the amount of time it did, and that the results would still not be to my satisfaction. I do not believe that the analysis I had envisioned in the beginning of the thesis is possible with the current data.

Throughout the process of writing this thesis I have personally developed an understanding for district heating and cooling that I did not have before, and the ability to think in terms of thermal energy. Through conversations with the data science team, and hearing about projects ongoing parallel to the thesis, I gained more insight into the data, the grid and possible approaches. My understanding of how to value different aspects of the grid was deepened and my work was put into a larger context.

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Appendix A

Losses from the Accumulator Tank

During the time periods when the tank was disconnected from the grid there was a slight decrease in the tank temperature. Period 1 lasted 18 hours and period 2 lasted 12 hours, and occurred during two consecutive dates but with slightly different outside temperatures, spanning 0-9 ^{o}C on the first day and 2-5.5 ^{o}C on the second day.

If going by the mean temperature of the entire accumulator tank, the temperature drop during period 1 was 1.4 ^{o}C, compared to 0.3 ^{o}C during period 2. Although different circumstances in outside temperature, time and a slight difference in initial mean temperature, the relative difference of 1.4 compared to 0.3 ^{o}C could not be explained easily. The temperature sensors in the tank were examined individually, which showed how the sensors placed lower in the tank behaved uniformly, whilst the ones above a certain height in the tank behaved vastly different. It was determined that the tank was not filled during the period, and to instead only account for the lower sensors that were presumed to be submerged under water.

The temperature differences for the submerged sensors were 0.175 ^{o}C and 0.15 ^{o}C for period 1 and 2 respectively. Using Newton's law of cooling (A.1) and the adjusted temperatures, the constant k (heat transfer coefficient) was calculated to 0.0016 and 0.0012 for the periods.

$$\frac{dT}{dt} = -k(T - T_{outside}) \tag{A.1}$$

This is probably a slightly high value for the constant, since heat convection from the water to the air inside the tank is not accounted for.

Appendix B

Establishing Flow

Due to the many uncertainties in the data, another model using fewer variables and a smaller subset of the grid was tested. The grid was broken down into smaller components with the model targeting one part, or subgrid, where the signal providers were deemed reliable and the behaviour from all components were mostly consistent. The benefits of a subgrid-model is that it is possible to extract more information relating to how the water moves in the pipes, compared to the energy loss model for the entire grid. An estimation of the heat loss in a specific pipe can be made, if the flow is fairly consistent and the production sources are known.

One such location is in the far end of a linear grid, during a limited time period where the outer-most, or anchoring, building has a primary heating demand. The warm water flowing into that building will be supplied by buildings along the grid with a primary cooling demand, see figure B.1. The figure shows how building A located at the end of the grid has a primary heating demand, taking more warm water from the grid than it is putting back into the warm pipe. The water in the warm pipe comes primarily from building B with a primary cooling demand and building C that only has a cooling demand.

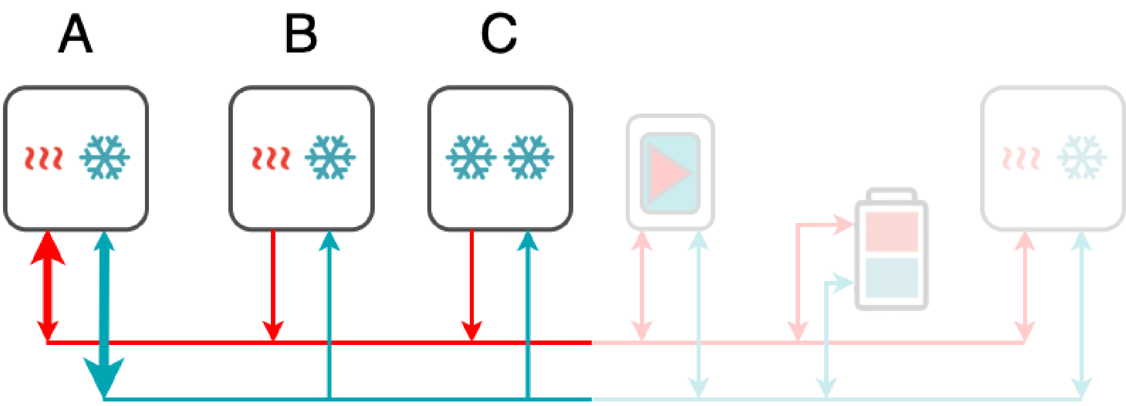


Figure B.1: Illustration of a sub-grid. The buildings used in the calculations, from left to right are A, B and C. A has a net positive heating demand, building B has a net cooling demand and building C has only a cooling demand.

The chosen building, building A, has a stronger heating demand during the chosen time period. The net heating demand during the period is positive in almost 88% of the time-steps, meaning that 88% of the time warm water flows to the building, and a 89% heating demand in terms of volume of water flowing into the building. The final data-set ended up consisting of one months worth of data.

The aim is to calculate the temperature difference between the outgoing warm water T_{out} from buildings A,B and C, and the incoming warm water T_{in}^{A} to building A. The difference will be represented by T_{out} - $T_{in}^{A} = T_{diff}$ and is likely due to transmission losses, as there are no additional buildings or balancing units in this part of the subgrid. With this information, it is possible to make predictions about how the time spent in the grid is likely to affect energy losses during transmission.

The incoming temperature to building A from the warm pipe T_{in}^{A} is calculated using the same formula as in section 4.1, by assuming that the measured temperature is the weighted average of the outgoing temperature from the chiller and the grid temp T_{in}^{A}. The same assumption is made for the incoming and outgoing temperatures on building B. The outgoing temperature T_{out} has to be matched in time to when the water is consumed, in order to find the real temperature difference of the water during transmission.

The constructed model looks at the pipes from a queue-perspective. There is a certain volume for each of the pipes, and any water that goes into the pipes is placed in order. An illustration can be seen in figure B.2. Building A takes the water that is in the front of the queue, and any water that goes back to the pipe also ends up in the front of the queue. This queue is a representation of the warm pipe between A and B; pA-B. Building B with a primary cooling demand will mostly output warm water to the grid. If the volume of water in pA-B is less than the volume capacity of pA-B, the output from building B goes in the last position of the queue that is pA-B. Otherwise it goes first into the pipe between B and C, pB-C. The output from building C can go into the last position of pB-C, or first in pipe C, pC. After each time step the water balance in the pipes is readjusted to make sure there are no vacuums.

The sampling frequency is 1 minute, and the data saved from each building is the volume of water that is taken from or put into the grid, and the temperature of that water with a timestamp. Using this data it is then possible to track the path that the water has taken in the pipes, how long it has been there and at what temperature it was when produced. That is how the temperature T_{out} is calculated; the temperature that would be measured at the inlet to building A if there were no losses during transmission.

The pipes were initially assumed to be filled with an arbitrary temperature, and in order to separate this data from the real data, the timestamp of this volume was set to a value that would stand out in comparison to the other, and the affected data could then easily be filtered out.

The data was resampled to hourly means, and the temperature difference was plotted as a function of time spent in grid, which can be seen in figure B.3. The result show that the water spend on average between 2 and 7 hours in the pipes. The heat losses are somewhere between 0 and 12 degrees, with the majority of the data-points being in the interval 4 to 8 degrees. One of the observations that could be made from the data is that the time the water spends in the grid is somewhat proportional to the outside temperatures. This would be explained by a larger demand for heating in

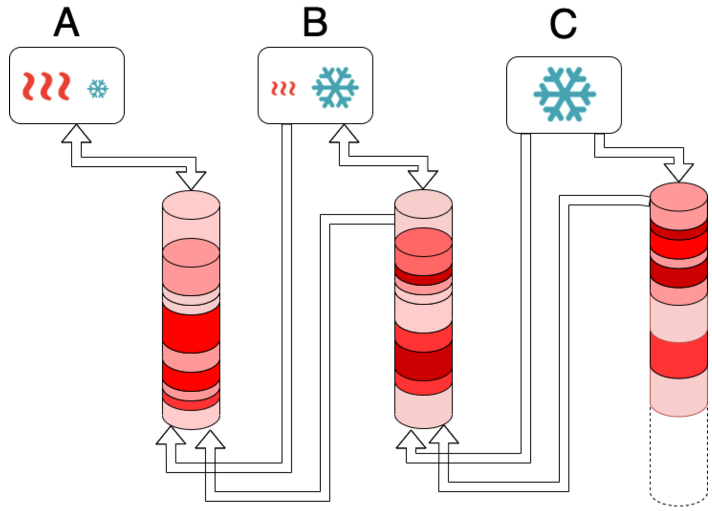


Figure B.2: Illustration of the queue-implementation of a subgrid. The pipes are shown as filled with different packages of water, with different volumes showcased by varying heights and different temperatures as the color hue.

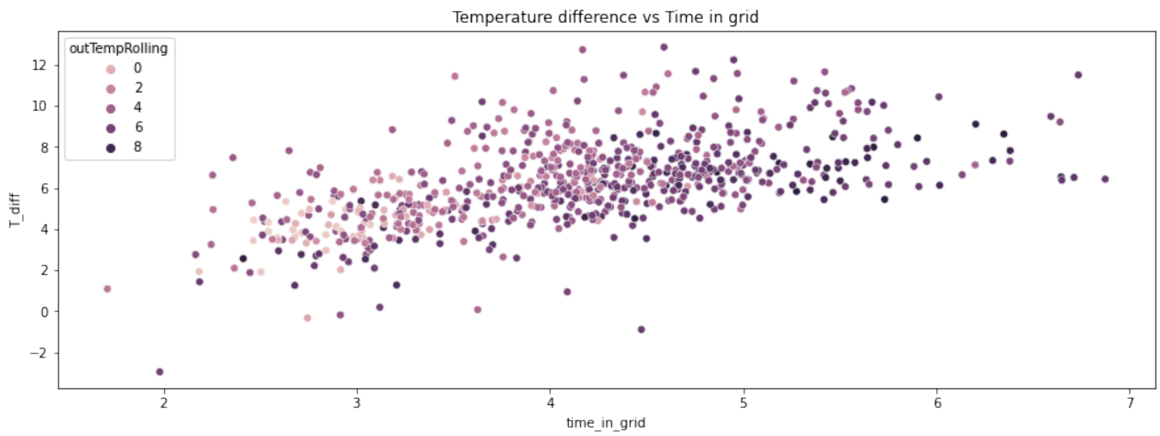


Figure B.3: Scatter plot representation of the temperature difference between the outgoing temperatures to building A and the measured temperatures. The hue of the dots showcases the mean outside temperature of the last 4 hours.

building A when the temperatures are low, and a lower heating demand when outside temperatures are high.

A relationship between the time spent in the pipes and the temperature difference was attempted to be recreated, based in Newton's law of cooling, which can be read about in Appendix A. A value for the constant k for the warm pipe was found to be around 0.11. The predicted temperatures at the inlet of building A based on this k was plotted together with the measured temperatures, and the result can be seen in figure B.4. If this is correct, the energy losses on the pipes could be predicted more accurately and at a far wider variety of temperatures and modes of operation. However the model has only been tried on a small sample of the data, and no validation has been performed. It could be an interesting approach for further studies, but it involves establishing the flow of the pipes which has been proved to be difficult on the current ectogrid™.

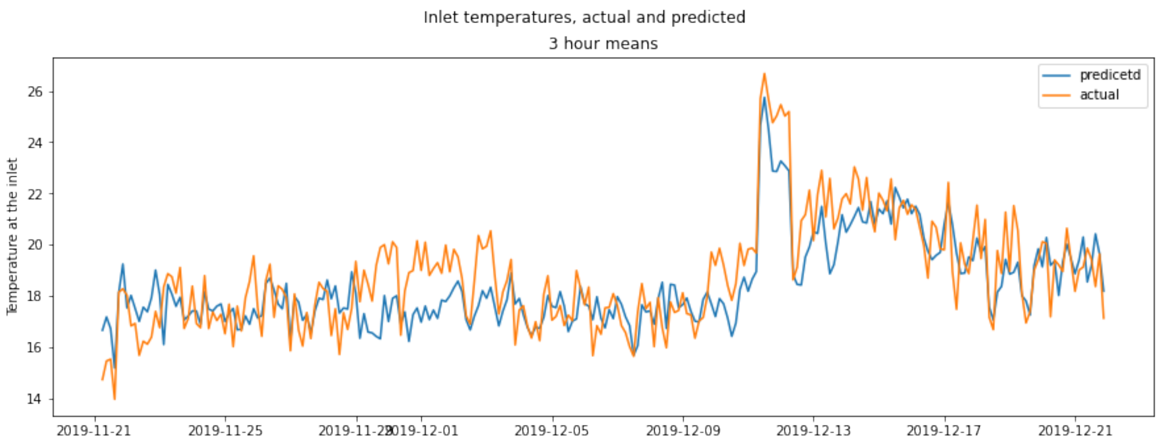


Figure B.4: Predicted and Actual temperatures at the inlet of building A

Appendix C

Plots

C.1 Outside temperatures during the time period

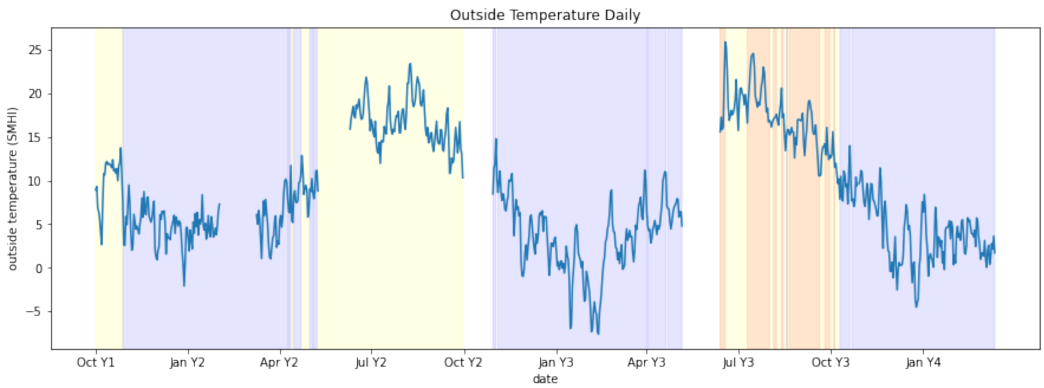


Figure C.1: Outside temperature

C.2 PACF

Partial auto-correlation functions for the heating and cooling losses respectively.

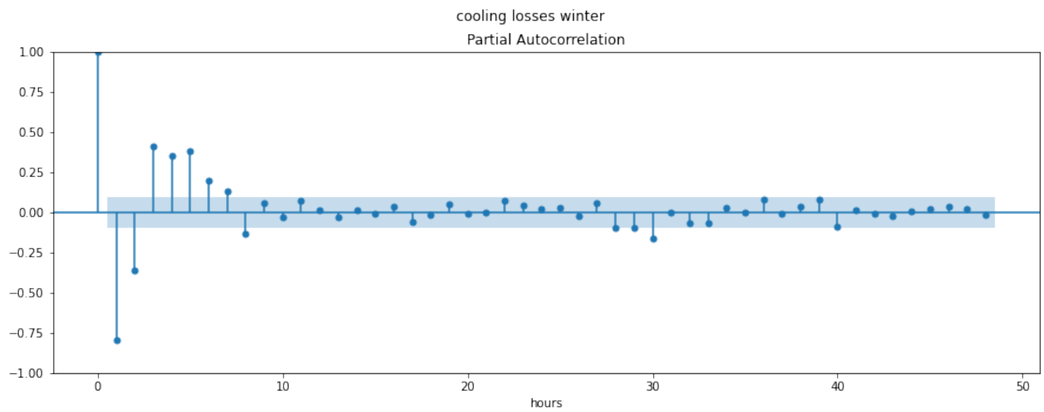


Figure C.2: PACF cooling

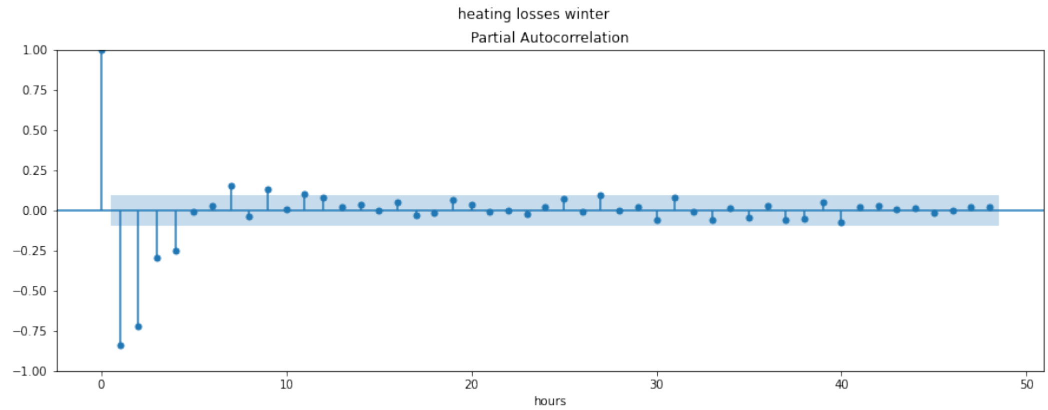


Figure C.3: PACF heating

C.3 Correlation Matrices

Correlation matrices for the variables tested in the linear regression models from section 4.3.

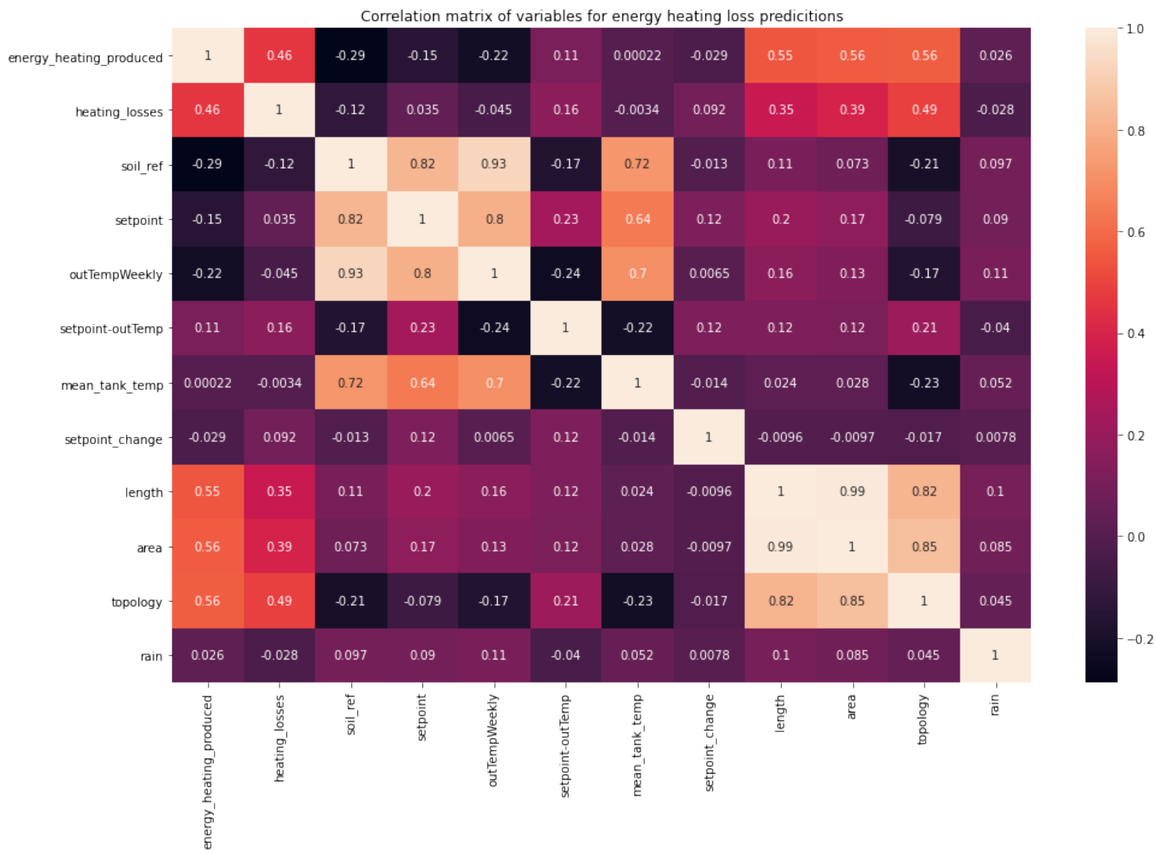


Figure C.4: Correlation matrix heating

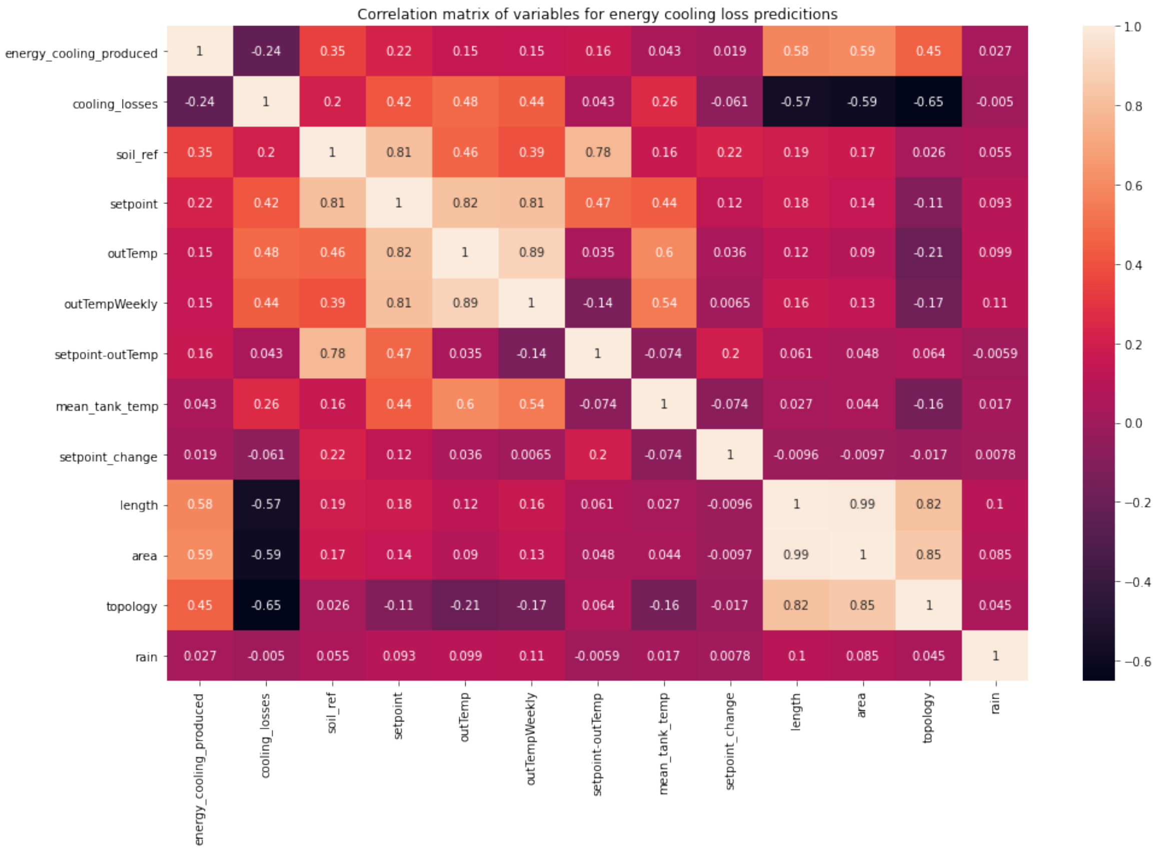


Figure C.5: Correlation matrix cooling

Appendix D

Theoretical model

D.1 Equations for energy losses in the steady state scenario

The following equations are used to calculate the theoretical energy losses from a steady state system [8].

Table D.1: Constants explanation, [8]

Symbol	Explanation	Unit
H	Depth from the ground surface to the center of the pipes	m
D	Half of the distance between the center of the pipes	m
r_o	Outer radius of the pipe	m
r_i	Inner radius of the pipe	m
T_g	Temperature on the ground surface	degrees
T_c, T_w	Temperature in cold pipe and warm pipe	C
λ_g	Thermal conductivity of the ground	W/mK
λ_i	Thermal conductivity of the insulation	W/mK
q_w	Heat dissipation from the warm pipe	W/m
q_c	Heat dissipation from the cold pipe	W/m

The heat dissipation q_w (W/m) from the warm pipe and q_c (W/m) from the cold pipe are calculated using equation (D.2) - (D.5), where all constants are described in table D.1. The heat dissipations are the combination of the two sub-problems:

$$\begin{aligned} q_w &= q_s + q_a \\ q_c &= q_s - q_a \end{aligned} \tag{D.1}$$

and the temperatures for each case are given by:

$$\begin{aligned} T_s &= \frac{T_1 + T_2}{2} \\ T_a &= \frac{T_1 - T_2}{2}. \end{aligned} \tag{D.2}$$

The heat dissipations (W/m) from the sub-problems are calculated as:

$$
\begin{aligned}
q_s &= \frac{T_s - T_0}{R_s} \\
q_a &= \frac{T_a}{R_a}
\end{aligned}
\tag{D.3}
$$

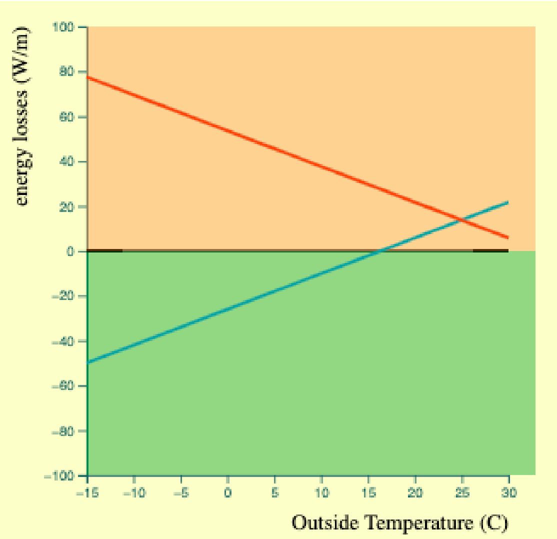
where the thermal resistances R_s and R_a (mK/W) are calculated as follows:

$$
\beta = \frac{\lambda_g}{\lambda_i} ln \left(\frac{r_o}{r_i} \right) \tag{D.4}
$$

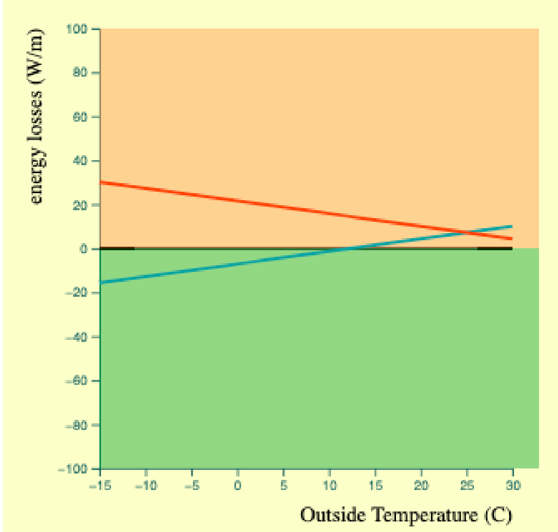
$$
\begin{aligned}
R_s &= \left(ln \left(\frac{2H}{r_o} \right) + \beta + ln \left(\sqrt{1 + \left(\frac{H}{D} \right)^2} \right) - \frac{\left(\frac{r_o}{2D}\right)^2 + \left(\frac{r_o}{2H}\right)^2 + \frac{r_o^2}{4(D^2+H^2)}}{\frac{1+\beta}{1-\beta} + \left(\frac{r_o}{2D}\right)^2} \right) \cdot \frac{1}{2\pi\lambda_g} \\
R_a &= \left(ln \left(\frac{2H}{r_o} \right) + \beta - ln \left(\sqrt{1 + \left(\frac{H}{D} \right)^2} \right) - \frac{\left(\frac{r_o}{2D}\right)^2 + \left(\frac{r_o}{2H}\right)^2 - \frac{3r_o^2}{4(D^2+H^2)}}{\frac{1+\beta}{1-\beta} - \left(\frac{r_o}{2D}\right)^2} \right) \cdot \frac{1}{2\pi\lambda_g}
\end{aligned}
\tag{D.5}
$$

D.2 Plots

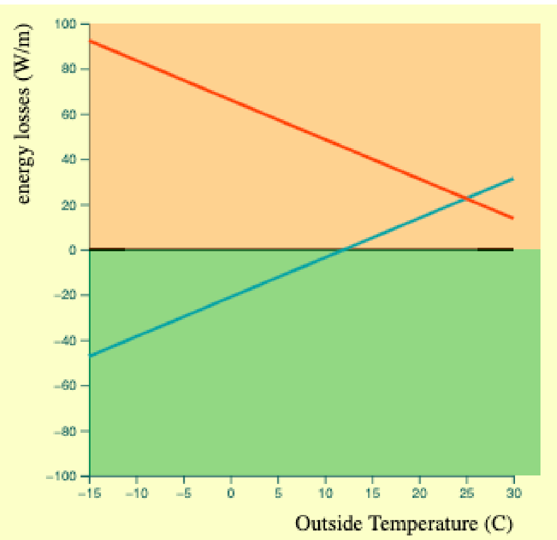
Figure D.1 show how the thermal conductivity of the soil and the material of the pipes affect the energy losses (W/m) for different outside temperatures, according to a steady state scenario [8]. Pipe diameter is 150 mm, pipe thickness is 20 mm, and distance between the pipes is 200 mm. The temperature of the warm pipe is 30 ^{o}C, and 20 ^{o}C of the cold pipe.



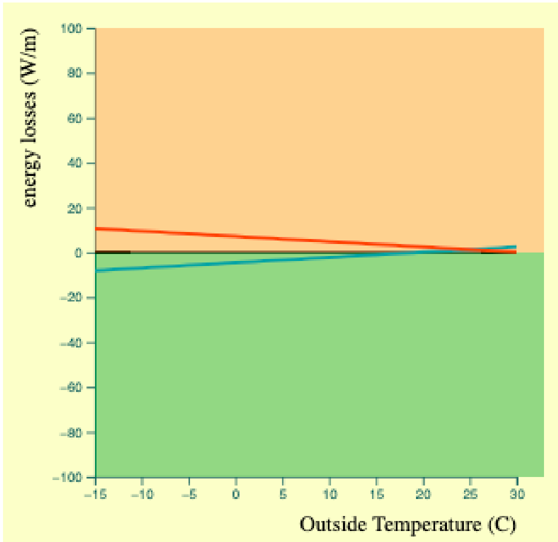
(a) High thermal conductivity (2) of the soil



(b) Low thermal conductivity (0.5) of the soil



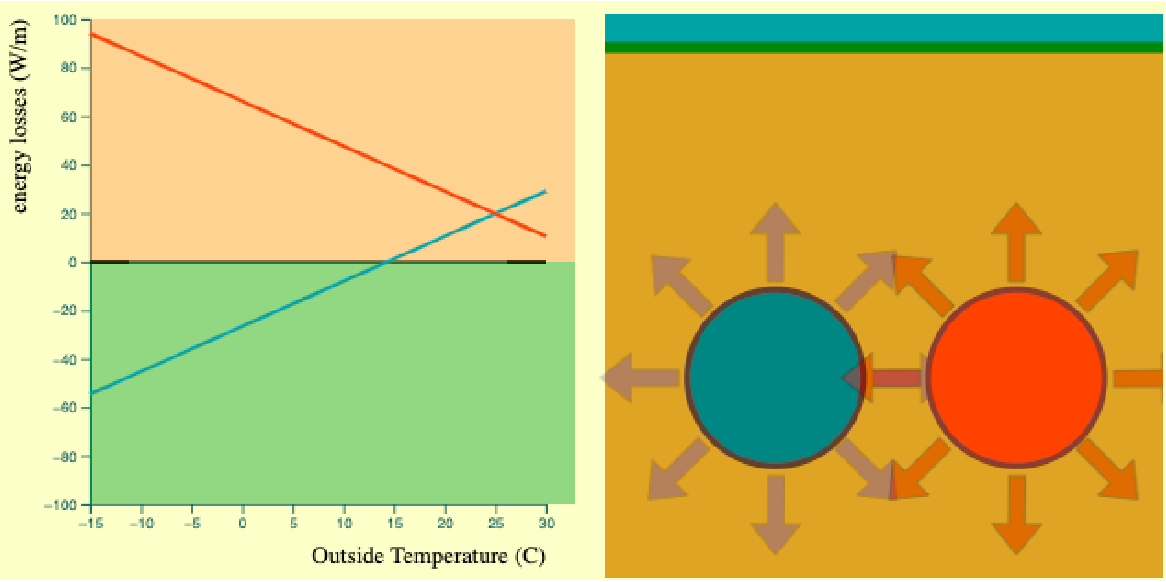
(c) High thermal conductivity (0.5) of the material of the pipes



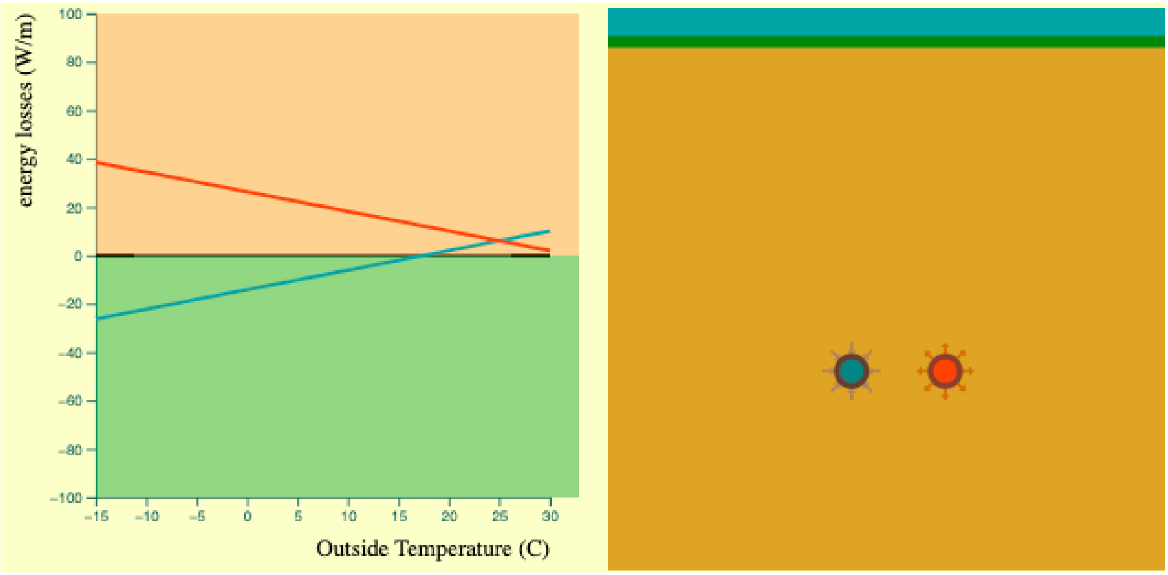
(d) Low thermal conductivity (0.01) of the material of the pipes

Figure D.1: How the thermal conductivity of the soil and the pipes affect the energy losses in relation to outside temperatures.
Red line = energy heating losses (W/m)
Blue line = energy cooling losses (W/m)

In figures D.2, D.3 and D.4 the energy losses from different pipe specifications can be seen. The thermal conductivity of the soil is set to 1.5 (W/mK) and the conductivity for the pipes is set to 0.15 (W/mK). The figures show both how the energy losses vary with

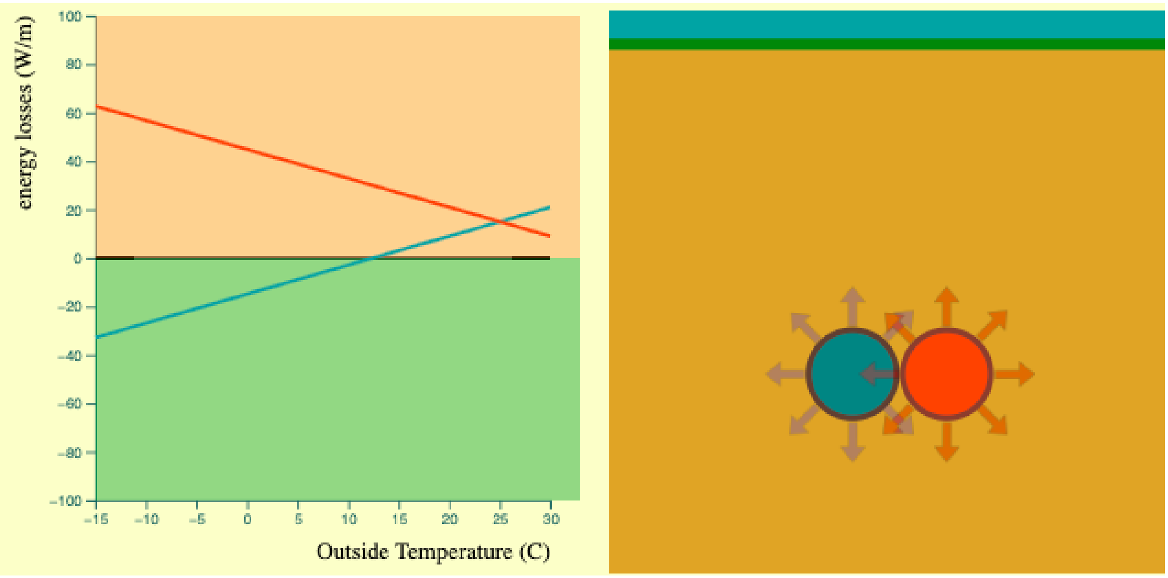


(a) Pipe diameter = 300 mm

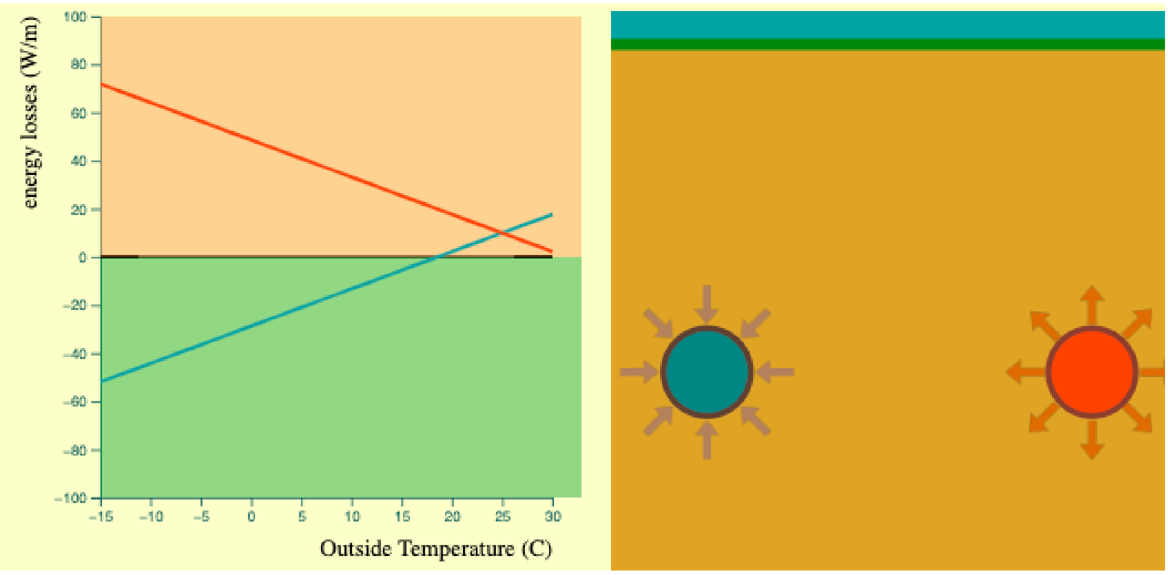


(b) Pipe diameter = 50 mm

Figure D.2: How the pipe diameter affect the energy losses.
Red line = energy heating losses (W/m)
Blue line = energy cooling losses (W/m)

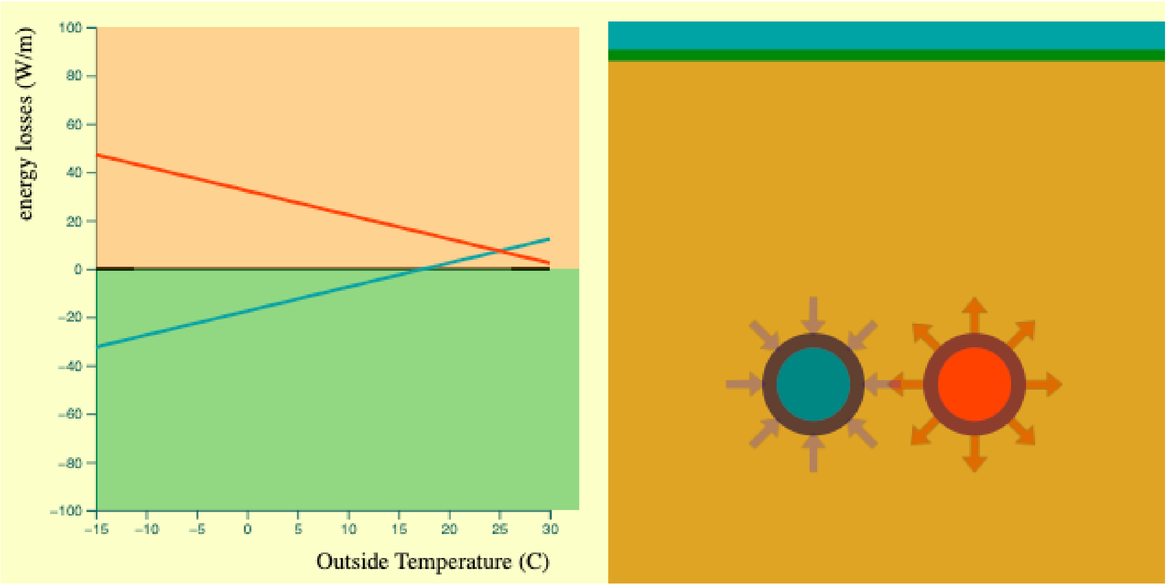


(a) Distance between the pipes = 0 mm

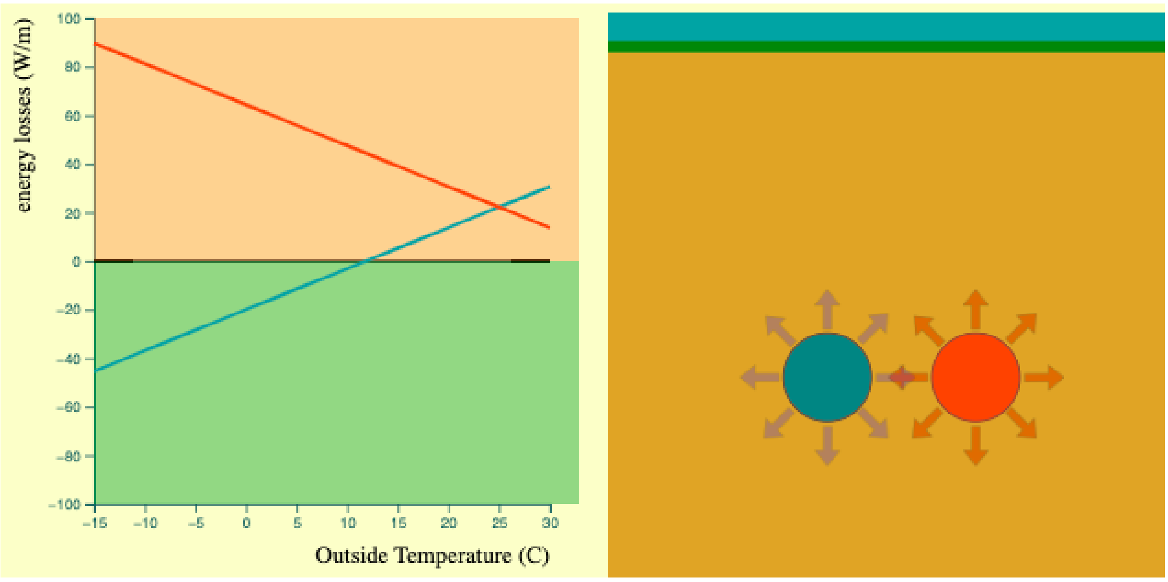


(b) Distance between the pipes = 1 m

Figure D.3: How the distance between the pipes affect the energy losses.
Red line = energy heating losses (W/m)
Blue line = energy cooling losses (W/m)



(a) Thickness of the pipes = 0 mm



(b) Thickness of the pipes = 1 m

Figure D.4: How the distance between the pipes affect the energy losses.
Red line = energy heating losses (W/m)
Blue line = energy cooling losses (W/m)