Heat recovery from district cooling

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Thesis for the degree of Master of Science in Engineering
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Abstract

District cooling is increasing in the society and in many areas two separate infrastructural systems are used for heating and cooling. It's an expensive and inefficient solution, by utilizing the heat in the return pipe of a district cooling system, one system could be used to supply customers with both heat and cold. By conducting a case study, this master thesis intends to investigate the potential system utilities with connecting heat clients to the district cooling return pipe through heat pumps. Based on customer data from an area with both district heating and cooling systems, simulations are made in MATLAB in order to answer how factors such as electricity consumption, cold and heat production will change when two large heat clients are connected to the district cooling system instead of the district heating system. These factors are dependent on the *Seasonal Performance Factor* of the heat pump, wherein a few different values are studied. The results show that both customers could be connected and that the cold production in the heat pumps could replace the central production plant for roughly 140 days of the year. At the same time the produced heat will have an efficiency that's higher than the efficiency of the heat pump itself. The reason for this being the amount of saved electricity in the central production plant. A cost comparison was conducted between heat pumps and conventional district heating and showed that conventional district heating is much more expensive in the investigated area, mainly due to the high costs of building the infrastructure. Overall, the study has indicated that there are many advantages and that a combined district heating and cooling system would be efficient in the investigated area and other areas whit similar heat and cold demand. It could be efficient in areas with different heat and cold demand as well, the important factor being that the heat demand isn't much higher than the cold demand during too long periods over the year.

Content

1. Introduction

District cooling systems are increasing in the world and with new technology it might be possible to get a better cooperation between district cooling and its corresponding system for heating, district heating systems. Both work in a similar way, distributing an energy carrier, hot or cold, to buildings through large distribution pipes. Today, these systems are often separated without any interaction between each other but there would be benefits with combining them into one system. As heat pumps becomes more efficient, a solution might be to use these heat pumps to produce both heat and cold and thereby make the two systems work together.

This report aims to investigate the possibility to add heat clients to existing district cooling systems and determine what the advantages and disadvantages of this would be for the energy company. The idea is based on the fact that the temperature in the return pipe of a district cooling system is around 16 ˚C. By using heat pumps, the temperature of the water in the return pipe could be raised in order to supply buildings with space heating and domestic hot water. Today, it's common to have two separate systems for district heating and cooling. For each system, two pipes are needed, for an area with both district heating and cooling the number of pipes is therefore four. This is a problem because it's very expensive to install these pipes and there isn't a lot of space left in our cities to build all these pipes. It would be very beneficial to find a solution where only two pipes are needed.

Another great advantage with using heat pumps is that they also produce cold-water. In theory the central production of cold-water could be decreased at the same time as more customers are connected to the district cooling system. Figure 1 shows the fundamental ideas of how the system that will be investigated in this report looks. The dotted line is representing the demarcation of the clients, which means that the heat pumps are located at the clients, even though they're in this report are owned by the energy company.

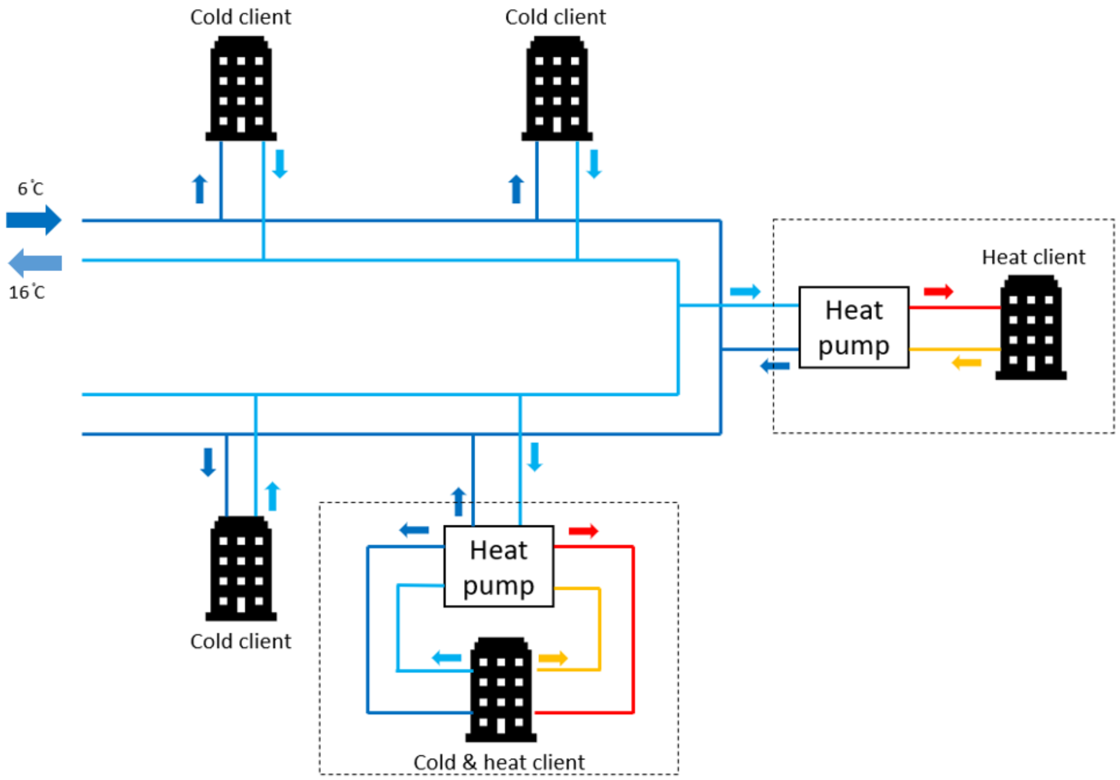

Figure 1: Sketch of a district cooling system with heat clients connected through heat pumps.

As can be seen in Figure 1, customers that are using both heating and cooling could use the heat pump to produce both hot and cold-water and thereby utilize the full potential of the heat pump.

To make this idea more tangible, an area which is supplied with both district heating and cooling is chosen as an example area where calculations are made by using the data from both heating and cooling clients in the area. The purpose of this is to show the results in an actual district.

This Master's Thesis is written in collaboration with E.ON, an energy company which is providing both district heating and cooling and the data is taken from their customers.

1.1 Background

There could be many benefits with combining district heating and cooling, the energy consumption is a global issue and if a combined system could prove more energy efficient than two separate systems it would be beneficial from both an environmental as well as a financial perspective. The fact that the heat pumps convert electricity to extract heat from the fluid which results in both hot and cold water is the reason for the potentially more energy efficient system. Less electricity emits less green-house gases and cost less money.

The most common contradiction to combining district heating and cooling in Sweden is the fact that the need for heating and cooling differs over the year. The demand for cooling is high in the summer while the demand for heating is high in the winter. Even though this is the case, there is still lot of opportunities to combine these systems since they are overlapping in many applications.

Even though Sweden might not be the most suitable area due to the varying climate over the year, another interesting opportunity is in more southern countries, where the demand for cooing is much higher and where district heating isn't as established. It's common to use natural gas as an energy source for heating in southern Europe because the demand for a district heating system is small. Natural gas emits a lot of greenhouse gases when it's combusted, therefor a solution where a heat pump is connected to the return pipe of the district cooling system could be much more environmentally friendly. Of course, this depends on how the electricity is produced, but renewable electricity is increasing, and, in the future, it will probably be sustainable to use electricity as the energy source.

The main reason why this is particularly interesting for E.ON is that there are huge savings to be done if one infrastructure could be used instead of two. It costs around 8 000 SEK per meter to install district heating pipes and as cities are getting more and more complex it's getting harder to find the space for two infrastructures. [4]

1.1.1 District heating and cooling

The idea with district heating and cooling is to move energy in form of a fluid in large distribution systems. By doing so, you're able to deliver heat or cold to a consumer from one of multiple central production plants. Heat is produced by combustion of different materials, for example biomass, gas or waste and the heat that occurs are transferred to the water fluid and delivered to the buildings. It's also common to produce heat by using so called heat pumps, which uses electricity to raise the temperature of heat extracted from air/ground/water.

There are a few different ways to produce cold water for district cooling, free cooling is one of them, where cold is extracted from the natural environment. The source can be ambient air, seawater, lake water or river water. Another possibility is to use cooling machines which uses the same process as a heat pump, but instead it's the cold water that is utilized.

The energy carrier (hot or cold) is then transported in underground pipes from the production plant to the consumers, there is one supply pipe and one return pipe. The return pipe transports the energy carrier back to the production plant so it once again can be heated/cooled.

At the consumers there are so called substations where the pressure is lowered and distributed into the building. [1]

1.1.2 Decentralized heat production – an example

The concept of utilizing the heat in the return pipe of a district cooling system is not an entirely new idea. E.ON does already have a system with heat clients connected to the district cooling system up and running, in this report called *The pilot system*. In this system (Figure 2) there is a hospital who acts as a cooling client and the return pipe is connected to two apartment buildings. This arrangement is suitable because the hospital has a constant need for cooling over the year and therefore the return pipe will always be able to deliver residual heat to the apartment buildings. The reason why it's not heated with conventional district heating is because the nearest connection point to the district heating grid was too far away and it would have been too expensive to install those pipes. Instead, the builder wanted to use geothermal heat pumps, though this seemed to be a problem as well since there wasn't enough room for the boreholes. The solution then became to connect the building with the district cooling system, as it was already passing close by.

The apartment buildings are supplied with heat from two vapour compression heat pumps with a nominal output of 100 kW each, which should be able to cover the whole heat demand for domestic hot water and space heating over a year. There is one accumulator for space heating, storing domestic hot water for the radiators, and two water heaters for domestic hot water.

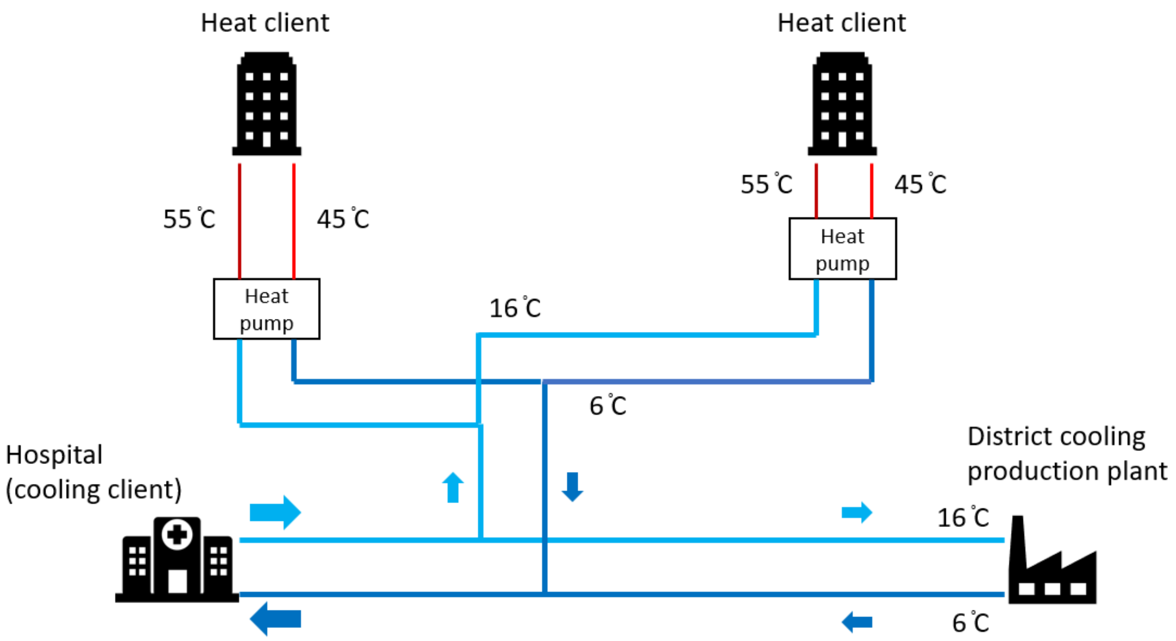

Figure 2: Sketch of The pilot system.

1.2 Purpose

The purpose of this master thesis is to investigate the possibilities and advantages and disadvantages with adding district heating clients on the return pipe of the district cooling system. The demand of comfort cooling is increasing in the society and it would be valuable to use one system for both heating and cooling mainly from a financial perspective but also as it could be more energy efficient for the customers not to buy heat and cold at the same time from two different systems.

A solution like this hasn't been realizable earlier, due to the fact that district cooling hasn't been as established as it is now. More and more buildings are being connected to district cooling systems which means that the potential for a combined district heating and cooling system is increasing in the society.

In order to determine the advantages, factors such as electricity consumption, cold and heat production will be calculated and compared to the same factors for an area where there's two separate systems for heating and cooling. Additionally, a cost comparison between heat pumps and conventional district heating is to be conducted.

Research questions

1. Which values of *Seasonal Performance Factor (SPF)* should be used for the heat pumps?
2. How will the electricity consumption change when heat clients are connected to a district cooling system?
3. How much cold-water will be produced by heat clients and how much of the central production can it replace?
4. What's the cost of the produced domestic hot water and space heating in terms of electricity?
5. What's the cost of the produced domestic hot water and space heating for the energy company in comparison to conventional district heating?

These questions are meant to be answered trough a case study in *The research system*. The case study includes specific clients in an area operated by E.ON and the questions are concretized to suit the case study.

1.3 Limitations

This master thesis is based on sensitive information about E.ON's business and clients. In order to not reveal any of this information, some parts of this report will be anonymized. There are two specific areas located in Sweden that will feature frequently and onward will be called *The pilot system* and *The research system.* There will be more information about these areas later on in the report. There will also be data used from specific E.ON clients, since it's classified, these clients will be named *Customer A* and *Customer B.*

2. Theory

2.1 System overview

The different components in the system will be explained separately, this section will explain how they work together and how the system as a whole is intended to work.

The central part of this concept are the heat pumps/cooling machines (chapter 2.1.1) which are extracting heat of the water in the return pipe of the district cooling system. A result of this will be both hot and cold water, the amount of produced hot water depends on the heat demand and the resulting cold water will either be consumed by the building itself or distributed back to the district cooling system, dependent on what the cold demand for that specific building is at the moment. The heat pumps are located at the customer but are owned and operated by E.ON in this case.

The COP-value (chapter 2.1.2) of the heat pumps decides how efficient the heat pumps are and is the ratio between produced heat and provided electricity. It's a momentaneous value, compared to SPF-value (chapter 2.1.3) which indicates the efficiency over time. The calculations are based on SPF rather than COP because it's easier to compare different operation cases and also because there's limited hourly values in one of the investigated heat pumps.

An immersion heater (chapter 2.1.4) is used at the heat clients in order to minimize the cost and operates when the heat demand is high. It's cheaper compared to a heat pump, which is why it's used instead of dimensioning a heat pump that could cover the whole heat demand over a year.

There's also a pressure pump (chapter 2.1.5) at the client, its purpose to raise the pressure of the produced cold water in order for it to be able to enter the supply pipe of the district cooling system.

2.1.1 Heat pumps/cooling machines

The purpose of heat pumps is to upgrade heat extracted from various heat sources to a higher temperature level. As a result of this, there will also be cold water since the source where the heat is extracted from will get a lower temperature. That's why they're both called heat pumps and chillers. There are different kinds of heat pumps, in this report the focus is on vapour compression heat pumps as they are used in *The pilot system.*

The heat pump/chiller works as following (Figure 3). A compressor (1) compresses the low temperature (T_2) and pressure gas into a high pressure, which causes it to raise its temperature (T_2). This enables phase change at different, more favourable temperatures. Then the gas moves on to the condenser (2) which also acts as a heat exchanger where the gas gives up its heat and turns into liquid. This heat is transferred into the heating system of the building. The pressure is then lowered in an expansion valve (3) and the liquid decrease in temperature. The last step of the cycle is an evaporator (4), which also act as a heat exchanger. In the evaporator, heat is taken from the source (in this case the water in the return pipe of a district cooling system) and transferred to the refrigerant (the substance circulating in the heat pump/chiller). In the evaporator there is once again a phase change (liquid to gas), this happens because of an expansion valve and the suction effect of the compressor. [1] [2]

This loop goes on and on, producing both heat and cold at the cost of electricity to run the compressor.

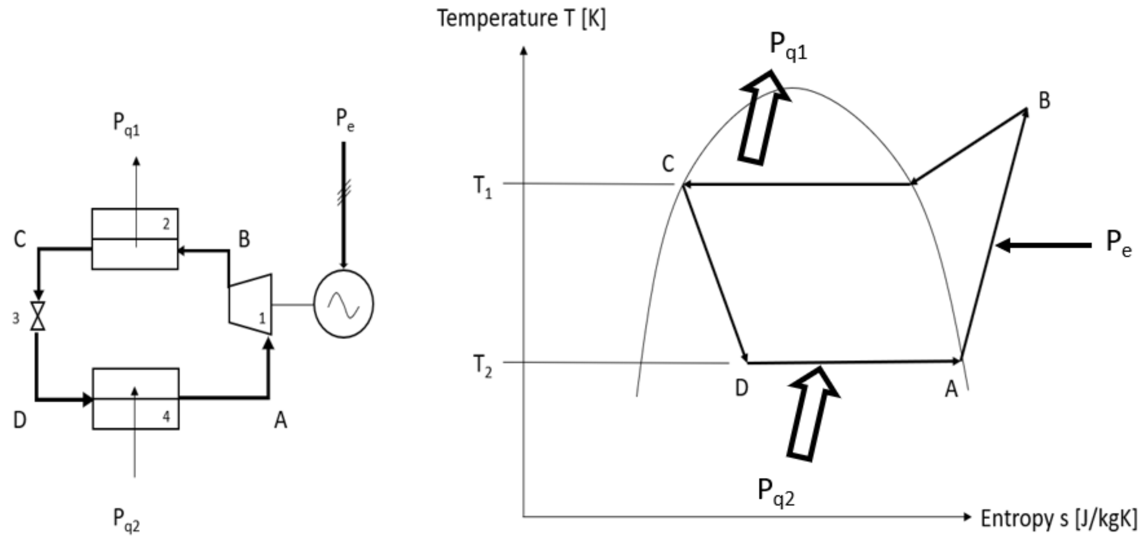

Figure 3: Simple practical vapour compression heat pump/chiller and its corresponding T-s diagram.

2.1.2 Coefficient of Performance (COP)

The *Coefficient of performance (COP)* is a value that represents the effectiveness of a heat pump. It's a ratio between heat output and provided electricity.

$$COP_{heat} = \frac{P_{q1}}{P_e} \quad (1)$$

Where P_{q1} is heat supplied to the building and P_e is work required (electricity). A heat pump works as both a heating and cooling producer since cold is a by-product when extracting heat. The equation looks like following:

$$P_{q2} + P_e = P_{q1} \quad (2)$$

So, for example, a heat pump with a COP-value of 3, results in three units of heat and two units of cold by using one unit of electricity.

As it's producing both heat and cold there are two different COP-values, one for heat and one for cold. Combining equation 1 and 2 gives:

$$P_e * COP_{cold} + P_e = P_e * COP_{heat} \quad (3)$$

Divide by P_e and you finally get:

$$COP_{cold} = COP_{heat} - 1 \quad (4)$$

The COP-value is interesting in two regards, partly because it determines the electricity usage for the heat pump but also since it affects the cold energy produced. Since one of the biggest advantages with connecting heat clients to the district cooling system is the possibility to replace the central cold production, a higher COP-value would be more efficient in that aspect as well.

The relation between electricity usage and the COP-value is linear, for example if the COP-value is doubled then the electricity usage will be halved. However, this is not the case with the cold production. The relation between heat consumption and cold production:

$$E_{electricity} = \frac{E_{heat}}{COP_{heat}} = \frac{E_{cold}}{COP_{cold}} \tag{5}$$

$$<=>$$

$$E_{cold} = E_{heat} * \frac{COP_{cold}}{COP_{heat}} \tag{6}$$

Which according to equation 4 can be written as:

$$E_{cold} = E_{heat} * \frac{COP_{cold}}{COP_{cold} + 1} \tag{7}$$

Figure 4 shows how cold production changes with different COP_{cold}-values. The Y-axis shows the percentage of the corresponding heat power output.

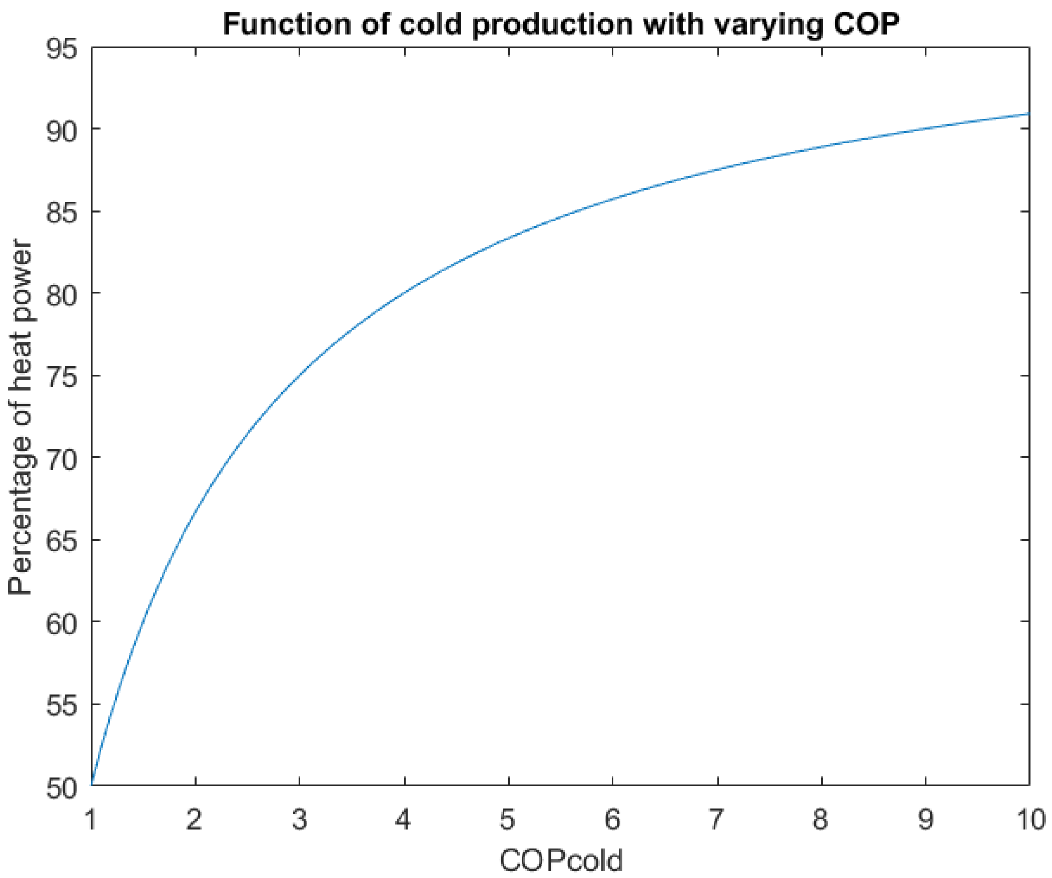

Figure 4: Cold production as a function of the COP_{cold}-value.

2.1.3 Seasonal Performance Factor (SPF)

The Seasonal Performance Factor (SPF) is the weighted COP-value over a whole year. The COP-value is a non-time variable which only tells the effectiveness for a heat pump during a specific moment. The SPF-value is however taking time into consideration. A heat pump can operate at different COP during a year since there is different temperature levels for space heating and domestic hot water. It is mainly the SPF-value that will be used in the report and is calculated like following:

$$SPF_{heat} = \frac{\sum E_{heat}}{\sum E_{electricity}} \tag{8}$$

$$SPF_{cold} = \frac{\sum E_{cold}}{\sum E_{electricity}} \tag{9}$$

2.1.4 Immersion heater

An immersion heater is a device that’s used for heating a liquid with electricity. It works by electricity running through metal loops that’s heating the liquid. It’s often used as a back-up in storage tanks when the heat from heat pumps isn’t enough to cover the energy demand. The COP-value for an immersion heater is maximum 1, even though there probably some losses in the heat transfer which makes the COP less than 1. This will however be neglected in this report and calculations will be made with a COP-value of 1. [3]

2.1.5 Pressure pumps

In district heating and cooling systems, the water flow is managed by a pressure drop along the flow direction. In other words, the pressure in the pipes gets lower and lower the further away from the production plant it gets. [1] Therefore the pressure is higher in the supply pipe than in the return pipe which is displayed in the pressure cone (Figure 5). In order to raise the pressure along the way, it’s possible to use pressure pumps.

In a regular district cooling system, the cold-water from the supply pipe enters the customers heat exchanger where it collects heat from the building and then moves on to the return pipe. Since the pressure is lower in the return pipe than at the heat exchanger, as can be seen in Figure 5, the water flows into the return pipe.

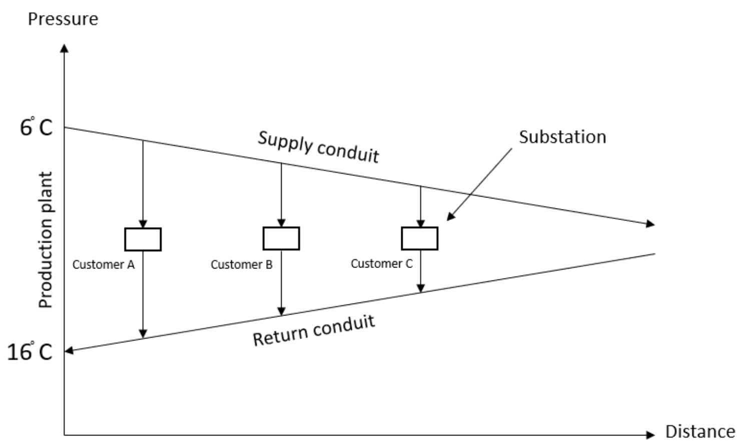

Figure 5: A pressure cone showing the pressure drop in a regular district cooling system.

However, when the district cooling system should be used for heating as well, there is a problem because the cold-water that’s produced in the heat pump has a lower pressure than the cold-water in the supply pipe. By using a pressure pump at the customer, the pressure can be raised and thereby be able to enter the supply pipe. This is shown in Figure 6.

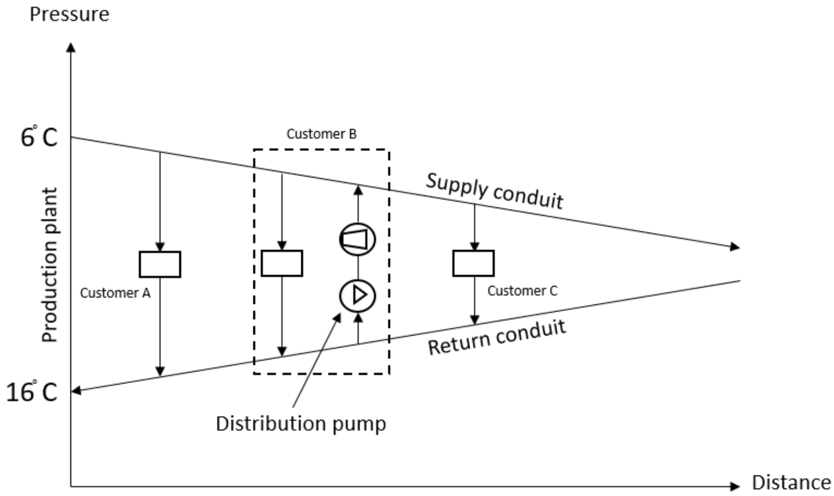

Figure 6: Pressure cone for a district cooling system with both cooling and heating clients. Includes a distribution pump at the customer in order to raise to pressure of the warm water.

In a conventional district heating system, the pressure cone looks the same, except that the hot water has the higher pressure. For that reason, there's no need for pressure pumps. When comparing conventional district heating with heating from district cooling, the operation of the pressure pumps must be included in the COP-value as well as the heat pumps. Both are driven by electricity.

2.2 Space heating and domestic hot water

A building's heat consumption can be divided into two parts: *Space heating* and *Domestic hot water*. The difference in application area is clear but there's also a difference for the operating heat pump because the temperature of the water may differ. For domestic hot water it's important that the water is heated to at least 60 ̊C in order to prevent eventual legionella bacteria growth.

The temperature level of space heating on the other hand can vary dependent on the building and its heating means. For instance, if the building is using underfloor the temperature could be around 40 ̊C but with radiators around 50 ̊C. The insulation of the building is also of importance. With a better insulation, the space heating temperature can be lower. [4] [5]

The temperature level is important because it affect the electricity consumption of the heat pump. The COP-value gets lower with increased temperature output.

As the calculations are based on annual SPF-values, a distribution of the domestic hot water and space heating must be estimated. The weighted SPF-value depends on the allocation of space heating and domestic hot water for a building since the SPF will be a combination of both space heating and domestic hot water.

To get a weighted SPF for a specific heat pump, assumption is made that during the summer there's no need for space heating and therefore only domestic hot water is produced in the heat pump. It's also assumed that the consumption of domestic hot water each day is constant all around the year. Then it's easy to see how much domestic hot water is consumed per day and year, the remaining energy must be space heating. Equations 10-12 shows an approximate method to calculate the weighed SPF_{heat} based on these assumptions.

$$X = \frac{E_{hot\ water}}{E_{total}} \quad (10)$$

$$Y = \frac{E_{comfort\ heat}}{E_{total}} \quad (11)$$

$$SPF_{heat} = COP_{hot\ water} * X + COP_{comfort\ heat} * Y \quad (12)$$

3. Case Study – *The research system*

In order to answer the research questions, a case study is conducted. The case study is based on an actual area where there is both a district heating and cooling system in place. Both are being operated and supplied by E.ON. The reason why this area is investigated in this report is because it's a modern district with a lot of recently built residential buildings and offices with good insulation and therefore it's possible to supply the buildings with a lower temperature, which would be the case with the return pipe in a district cooling system. E.ON have customer data for both heat and cold customers in the area which makes this area easy to examine.

A demarcation with the number of clients included in the case study is made in order to make this an area where a combined district heating and cooling system could be effective. In reality there is a lot more heat customers than cold customers in the area and therefore it wouldn't be possible to replace the district heating system. The investigated area will onward be called *The research system* and includes the two heat customers in the area with the highest heat consumption. It also includes all the cold clients in the area that is currently connected to the district cooling system. The two heat customers are called *Customer A* and *Customer B.* Thus, *The research system* is a demarcated area within the actual area operated and supplied by E.ON.

Customer A is connected to both the district heating and cooling system and is a building with apartments, office space and restaurant while *Customer B* is only connected to the district heating system.

3.1 Current production

E.ON uses two cooling machines in *The research system* to produce cold-water for their district cooling system. Attached to the cooling machines is a storage tank for the cold-water. One of the cooling machines is used more frequently since it's more efficient. The combined SPF_{cold} for the cooling machines is estimated to approximately 4,5 [6]. *The research system* is located closely to the ocean; it gives the opportunity to use free cooling during the winter. Free cooling is using pumps to transport cold-water from the ocean to the production plant. At the production plant, heat is extracted from the return pipe in the district cooling system to the cold ocean water [1]. The SPF for free cooling is much higher than for the cooling machines since electricity is only needed for the pumps. The SPF_{cold} is approximately 9,0 for free cooling in *The research system* [6].

The heat clients in *The research system* are at present connected to a district heating system. The heat in this system is produced from a few different heat plants. Most of the heat is from waste combustion, around 60-70 %. The second largest is natural gas combustion, around 20 % of the total heat produced. 10 % of the heat comes from an industry nearby, where E.ON is using the waste heat from their production processes. There are also a few percentages of heat produced from biomass. In theory the cooling machines in *The research system* could also supply heat to the district heating system, though this is not the case since it not efficient enough. [5]

3.2 Costs for heat pumps and conventional district heating

The cost for the energy company to supply district heating to their customers will in this report be divided into two parts. Firstly, the fixed cost for the infrastructure which is estimated to 8 000 SEK/m. Secondly, the variable cost of combustion fuel, pumps and energy losses which is estimated to 350 SEK/MWh. In reality the costs are more complex than this, not included is for example staff and CAPEX. Also, for this report it's assumed that there isn't a capacity problem, which means that there isn't a problem for the energy company to increase their produced heat power.

For the heat pumps and immersion heaters, the cost for installation, piping and operation is estimated to 1 500 SEK/kW. The power in this case is the maximum heat power output. The cost of producing cold water for the district cooling system is estimated to 200 SEK/MWh. [4]

To run the heat pumps, electricity is needed. The annual average electricity spot price for 2018 was 0,4521 SEK/kWh [12].

4. Method

The method is divided into two parts, the first explaining how data and information is collected. The second part explains how this data and information is used to answer the research questions separately.

4.1 Data collection

As described in the case study, an essential part of this investigation is the customer data. To get hold of this data, E.ON's database *DISA* is used. *DISA* contains hourly data from all of E.ON's customers and other non-customer specific parameters. Examples of this is energy consumption, ambient temperatures and temperatures in the distribution pipes. In this report, all data is taken from 2018 and the data points used are energy consumption (heat and cold), ambient temperature and temperatures in supply and return pipes.

The data for all customers in *The research system* is included in *DISA* but for *The pilot system* a lot of hourly data is missing. As a result of this, the data used in this report for *The pilot system* is a summarized value over the whole year. That meaning, the total electricity consumption, cold production and heat production in the heat pumps for 2018. The customers in *The pilot system* aren't a part of *The research system* but the data is used to the calculations which will be explained later.

The production data from the cooling machines currently operating in *The research system* isn't available in *DISA*, instead it's obtained from an employee at E.ON, responsible for the operation of the district cooling system.

Other information besides customer data has been collected throughout the project by conducting interviews with employees at E.ON. E.ON is a large company with many employees and much knowledge, therefore a lot of information could be obtained through personal contact.

Apart from internal interviews, contact was made with a heat pump supplier, Carrier. The purpose was to gather information about how their heat pumps works as well as product specifications to help answer the research questions if their heat pumps were to be used in the case study.

A part of the research were also to visit the E.ON office responsible for *The pilot system* that's already up and running with heating clients connected to the district cooling system. Peter Johansson who's responsible for district cooling in the area had a presentation about the district cooling system in general as well as a more in-depth presentation about *The pilot system.* The reason for this visit was to further understand the heat pumps and get more data from *The pilot system.*

4.2 Calculations

All calculations and graphs in this report are made in the software program MATLAB. The code is designed so it's easy to change fundamental variables such as SPF, P_{max} for heat pumps, and dates for winter and summer.

4.2.1 Dimensioning of heat pumps

There are two common ways of dimensioning heat pumps, either by installing a heat pump large enough to supply heat during peak loads or by installing an immersion heater combined with a smaller heat pump. Figure 7 shows an example of a power signature for one of E.ON's heat clients corresponding to the ambient temperature. As can be seen, the power rapidly increases for a few hours over the year when the ambient temperature drops low.

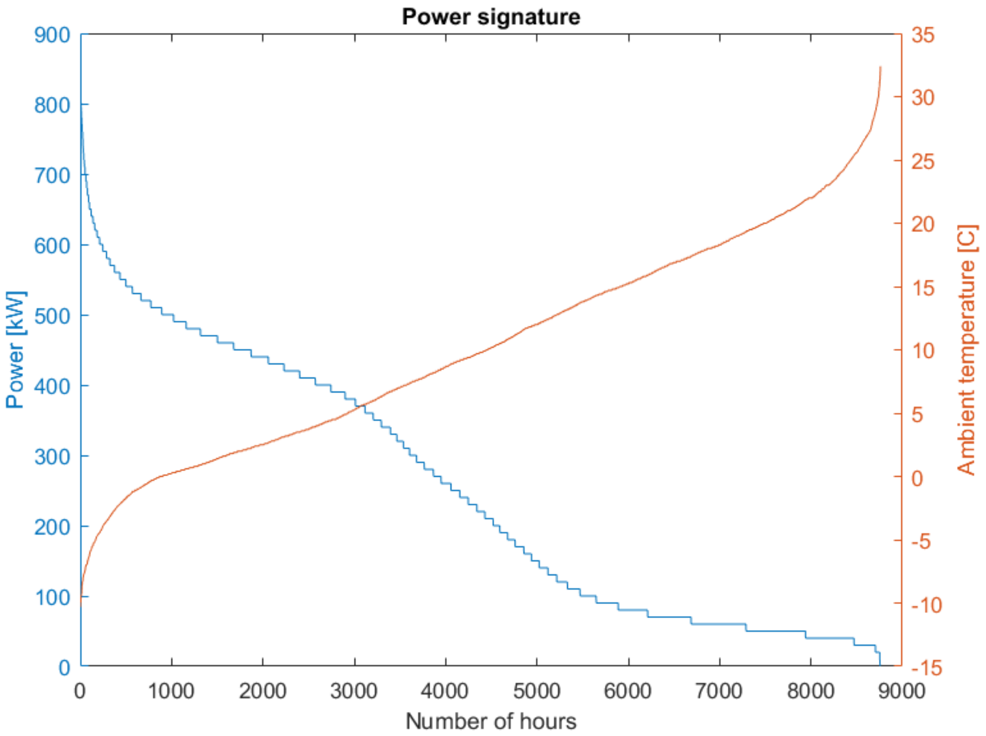

Figure 7: Example of a power signature from one of E.ON's heat customers.

Instead of only using a heat pump that covers the maximum heating demand (880 kW), a heat pump with an output of 475 kW could be used in combination with an immersion heater. In this example the heat pump would cover 54 % of the peak load but 96 % of the total energy demand over the year. As heat pumps gets more expensive the more power they have, an immersion heater would be more cost efficient in this case.

In *The pilot system* the heat pumps are dimensioned to manage the peak load. E.ON suggested the use of immersion heaters but there was a request from the builder to only use heat pumps since they didn't want another extra electricity source installed.

The downside with using an immersion heater is that the COP-value is lower and therefore the electricity consumption gets higher as well as it's not producing any cold-water for the district cooling system. A higher electricity consumption results in a less efficient system and more expensive operation costs. Not producing any cold-water isn't really a problem since the immersion heater will only run when there's a high heat demand (in the winter) and the cold production is only useful when there's a high cold demand (in the summer).

In the forthcoming calculations, the investigated clients will be dimensioned with an immersion heater. The power output of the heat pumps will be determined based on the clients' power signature, where the curve start to rapidly increase. An example is shown in Figure 8.

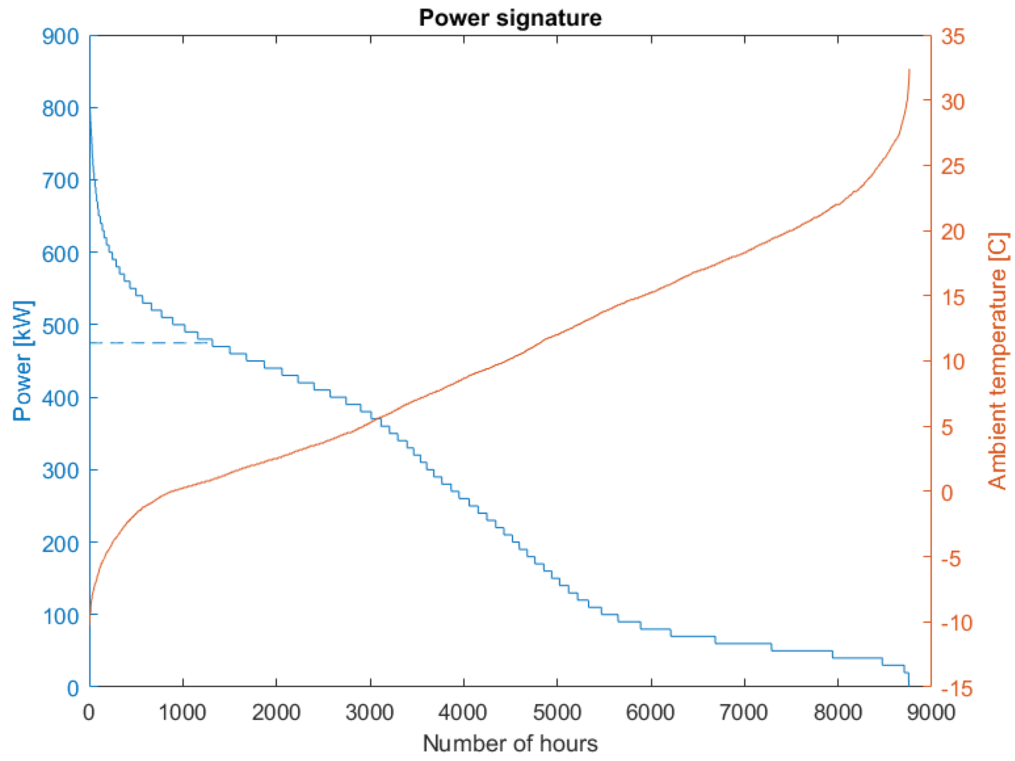

Figure 8: A power signature for a heat client where the dotted line represents the maximum power output from the heat pump. The additional power is produced by an immersion heater.

4.2.2 Seasonal performance factor (SPF)

As this is a theoretical report, there's no possibility to test how high the SPF-value would be in reality for *The research system*. In order to get a reliable value of the SPF for the heat pumps, two different methods to calculate an approximate SPF was identified. The first method is to use data from *The pilot system* and assume that the SPF would be similar in *The research system*. The other method would be to contact a heat pump supplier and let them make simulations for specific temperature levels and from that get momentary COP-values. Since there was no clear alternative that was better than the other, it was decided to use both ways and calculate the results for both options separately.

4.2.2.1 The pilot system

The SPF-value based on *The pilot system* was calculated by using the summarized data of heat production, cold production and electricity consumption in the active heat pumps. Data was taken from between 22nd February 2018 to 22nd February 2019. By using equation 5, SPF_{heat} and SPF_{cold} could be obtained.

4.2.2.2 Heat pump supplier

The second method to determine a reasonable SPF-value were to contact a heat pump supplier, in this case *Carrier*. Carrier made simulations for two different operation cases, one representing domestic hot water production and one representing space heating production. Inputs in the simulations were power of the heat pump as well as desired temperatures before and after the heat pump. The output of the simulations was a COP-value.

The weighted SPF-value is a combination of the two operation cases, equation 12 is used to get a final SPF_{heat}. However, the electricity to run the pressure pump is not included in these simulations. The get a more reliable value, the SPF is slightly decreased.

4.2.2.3 Varying SPF

As a compliment to the previous described methods to calculate a reasonable SPF-value, this report will also investigate what happens when the SPF is varying. It can be viewed as a sensitivity analysis where all research questions are answered with SPF_{heat} varying between 3-8.

4.2.3 Electricity consumption, heat and cold production

First off, hourly data of *Customer A's* and *Customer B's* heat consumption in 2018 is collected. The heat consumption in 2018 is from district heating and the objective is to calculate how much the electricity consumption and cold production would be if the whole heat demand would be produced by a heat pump and immersion heater instead.

The SPF used for the heat pump is described in previous chapter (4.2.2), while the SPF for the immersion heater is 1. Based on the dimensioning of the heat pump, the distribution between heat produced in the heat pump and the immersion heater is calculated. Based on equation 5, the electricity consumption is calculated as following:

$$E_{electricity,heat\ pump} = \frac{E_{heat,heat\ pump}}{SPF_{heat,heat\ pump}}$$

$$E_{electricity,immersion\ heater} = E_{heat,immersion\ heater}$$

$$E_{electricity,total} = E_{electricity,heat\ pump} + E_{electricity,immersion\ heater}$$

Since cold-water isn't produced in the immersion heater, only electricity consumption in the heat pump is used to calculate the cold-water production.

$$E_{cold} = E_{electricity,heat\ pump} * SPF_{cold}$$

These calculations are made in MATLAB and results in hourly values of both electricity consumption and cold production for each customer.

4.2.4 Production savings

Based on the cold production in the heat pump, the central cold production that could be replaced could be investigated. For those hours during the year when the cold production in the heat pumps are higher than the total cold demand in the area, the overproduction is viewed as useless and thereby not included in the saved energy. Thus, saved energy from central production plant is calculated as following:

$$\begin{cases} E_{cold,saved} = E_{central\ production} & E_{heat\ pump} \geq E_{central\ production} \\ E_{cold,saved} = E_{cold,heat\ pump} & E_{cold,heat\ pump} < E_{central\ production} \end{cases}$$

There are two central cooling machines producing the cold-water for the district cooling system today. One of them is more efficient and is used as much as possible, but when the outdoor temperature is increasing, both are being used to handle the cold demand. The combined SPF_{cold}-value for the central cooling machines is in this report estimated to 4,5. Though, E.ON has the possibility to use free cooling from the ocean during the winter. It gives a much higher efficiency since they don't have to use the cooling machines but only the distribution pumps to get cold-water from the ocean. The estimated SPF_{cold} is 9,0 during this period. [6] To get a reasonable overall SPF, free cold is estimated to be used from 1st November to 31st March and the cooling machines between 1st April to 31st October.

1st November – 31st March	Free cooling: $SPF_{cold} = 9{,}0$
1st April – 31st October	Cooling machines: $SPF_{cold} = 4{,}5$

The total saved electricity from the central production plant is calculated based on the time of the year:

$$\begin{cases} E_{electricity,saved} = \dfrac{E_{cold,saved}}{SPF_{free\ cooling}} & 1^{st}November \leq x \leq 31^{st}March \\ E_{electricity,saved} = \dfrac{E_{cold,saved}}{SPF_{cooling\ machine}} & 1^{st}April \leq x \leq 31^{st}October \end{cases}$$

$$x = date\ of\ the\ year$$

4.2.5 Efficiency of produced heat

So far, the method of calculating electricity consumption and cold production has been explained, but the purpose of this system is to also produce heat to the heat clients. Even though the electricity consumption may increase with the introduction of heat pumps there is an obvious benefit that there are now both heat and cold clients in one system. The following method was used in order to quantify the efficiency of the heat delivered to the heat clients through heat pumps instead of conventional district heating.

The cost of the produced heat can be viewed as the difference between the electricity to operate the heat pumps plus immersion heaters and the saved electricity in the central production plant. The district cooling system delivers the same amount of cold-water as before but a by-product of this is hot water at the cost of the extra electricity. The efficiency of this system can then be viewed as the heat delivered divided by the extra electricity.

$$\Delta E_{electricity} = E_{electricity} - E_{electricity,saved}$$

$$SPF_{heat,system} = \frac{E_{heat}}{\Delta E_{electricity}}$$

4.2.6 Cost comparison

From the perspective of the heat customer, there's no difference between how the heat is produced. If heat pumps are used, they will be owned by the energy company. The energy company pays for the electricity to run the heat pumps and immersion heater and sells the produced heat and cold to the customer for the same price as for conventional district heating and cooling. Thus, the income for the energy company is the same for the two alternatives.

4.2.6.1 Conventional district heating

The cost for district heating consists of a fixed price for the infrastructure and a variable cost for production of hot water. Since there is a lot of other heat customers in the area that is not included in *The research system*, it is in reality not possible to remove the current infrastructure since it still needs to be there to supply the other customers. Therefore, it might be incorrectly to include the cost of the infrastructure in *The research system.* But on the other hand, it's interesting to investigate what the cost would be if *The research system* would be a completely new area and the alternatives were to build or not to build a district heating system parallel to the district cooling system. For this reason, there will be two calculations, one including costs for the infrastructure and one without. The length of the district heating system is calculated by using *Google Maps* and measure the distance between *Customer A* and *Customer B* as well as the distance to a reasonable location for the production plant.

The variable cost is a yearly cost, dependent on the heat consumption for *Customer A* and *Customer B* during 2018. The cost is 350 SEK/MWh.

4.2.6.2 Heat pumps and immersion heaters

The cost for heat pumps and immersion heaters depends on the maximum power output. As mentioned in the theory chapter, the estimated cost is 1 500 SEK/kW and includes installation, piping and operation. By using the highest power demand for 2018 for each heat customer separately, a total cost can be calculated. This cost is seen as a fixed one-time cost for the energy company.

It's also dependent on the customers electricity consumption since there will also be a variable yearly cost because of the electricity need to run the heat pumps and immersion heaters.

5 Results

5.1 Heat and cold demand in *The research system*

The total heat and cold demand in *The research area* during 2018 is displayed in the duration diagram in Figure 9. The Y-axis shows the average power output per day which means that the actual power output could be higher during single hours.

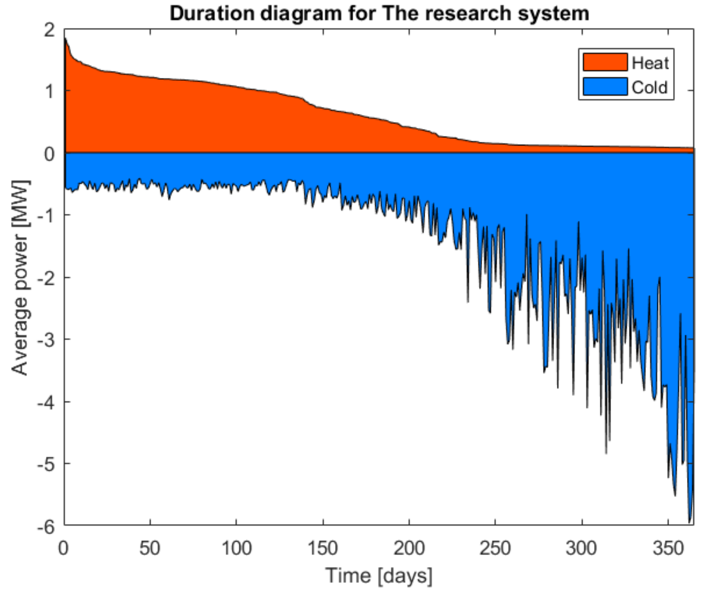

Figure 9: Duration diagram of the power demand in 2018 for both heat and cold clients in The research area

Since the cold demand is corresponding to the heat demand at a specific day it can easily be seen that the heat demand is high when the cold demand is low and vice versa. The period of time where the heat and cold demand are similar is relatively short. Figure 10 shows the difference between heat and cold demand over the year. On the X-axis, day 1 represents 1st January and day 365 represents 31st December. It can be seen that the cold demand is higher than the heat demand between day 94 – 299 which represents between 4th April to 26th October.

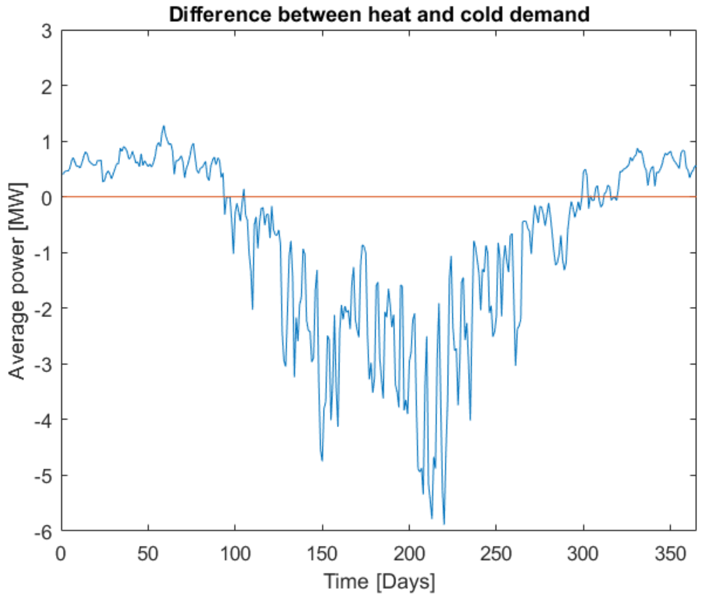

Figure 10: The difference between heat and cold power demand over the year. A negative value mean that the cold demand is higher than the heat demand.

5.1.1 Customer A

The power signature for *Customer A* is displayed in Figure 11, it shows the number of hours during 2018 on which it operates on a certain power level. It's not a linear curve and as can be seen in the graph the heat demand is very high during a small number of hours. It's not efficient to install a heat pump that's able to deliver heat during the peak loads, therefore a maximal power of the heat pump is set at 450 kW. The rest of the heat will be provided by an immersion heater. Since the maximal power demand in 2018 for customer A is 880 kW, only 51 % of the peak load is covered by a 450 kW heat pump. On the other hand, the heat pump covers 94 % of the energy need over the year.

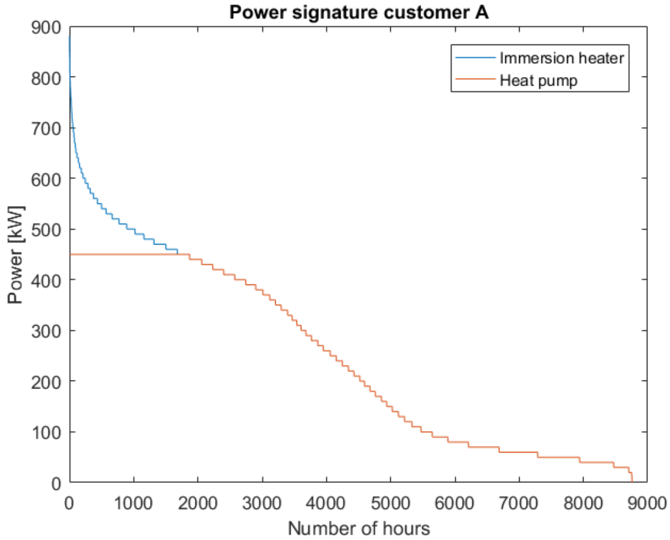

Figure 11: Power signature for customer A. The orange line represents the heat demand covered by a heat pump (450 kW) and the blue line represents the heat demand covered by the immersion heater.

Since *Customer A* is both a heat and cold customer, a duration diagram for both the heat and cold demand is displayed in Figure 12. Once again it shows the average power per day, which is why it's not as high as in the power signature. The heat demand is much higher than the cold demand for most of the year.

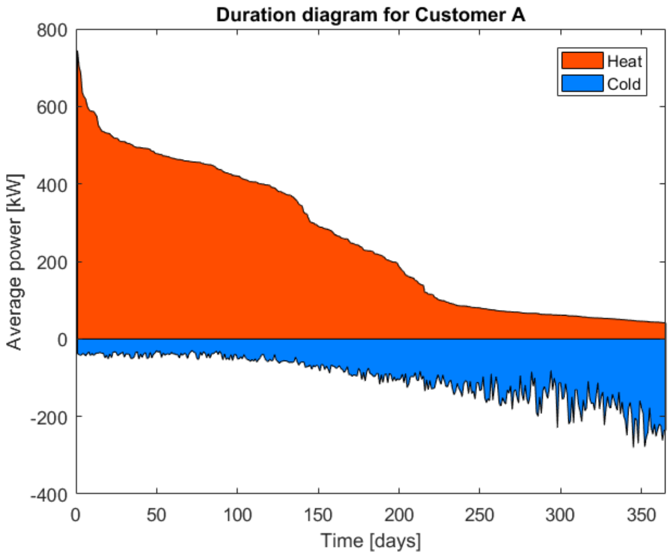

Figure 12: Heat and cold demand for Customer A in 2018. The graph displays the averaged power per day.

5.1.2 Customer B

The power signature for *Customer B* is displayed in Figure 13, where the maximal power of the heat pump is set to 700 kW. The peak load goes as high as to 1370 kW which means that the heat pump can cover 51 % of the peak load but 94 % of the total energy demand. Just like for *Customer A.*

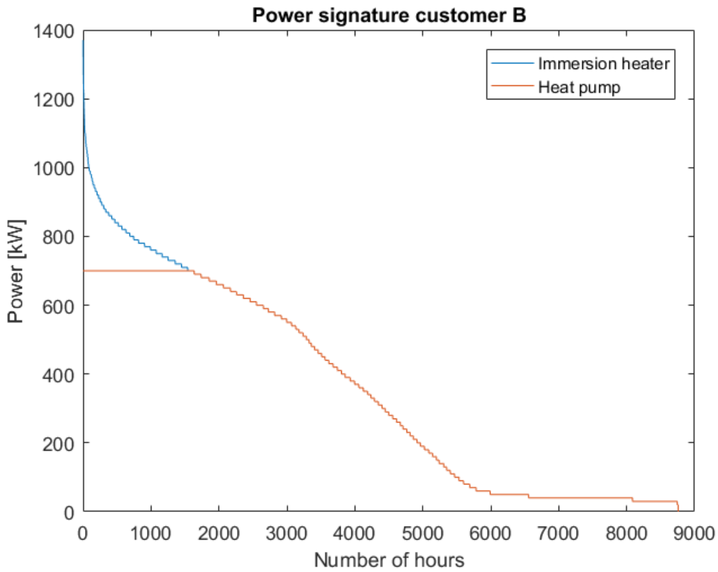

Figure 13: Power signature for customer B. The orange line represents the heat demand covered by a heat pump (700 kW) and the blue line represents the heat demand covered by the immersion heater.

5.2 Heat pump operation

As described in the theory chapter, a heat pump uses electricity in order to raise a temperature of a fluid and a result of this is also that cold is produced as well. Easily explained, $Electricity + Cold = Heat$. This chapter will present the results of electricity consumption as well as heat and cold production for the heat pumps at the customers described in the case study. First part will use the SPF-value taken from *The pilot system*, and the second part will use the SPF-value taken from the heat pump supplier. Since the both parts contain similar results and much of the information will be repeated, the first part (4.2.1) will explain the result in detail while the second part (4.2.2) just focus on the differences.

These results will be compared with current energy consumptions in *The research system.*

5.2.1 SPF – *The pilot system*

For the period between 22 February 2018 – 22 February 2019 the heat production, cold production and electricity consumption are displayed in Table 1.

Table 1: Energy consumption and production in The pilot system between 22 February 2018 – 22 February 2019.

E_{heat} $[MWh]$	**492,4**
E_{cold} $[MWh]$	349,2
$E_{electricity}$ $[MWh]$	146,6

The heat pumps in *The pilot system* operates at following SPF-values:

Table 2: SPF-values for The pilot system.

$\boldsymbol{SPF_{heat}}$	3,36
$\boldsymbol{SPF_{cold}}$	2,38

5.2.1.1 *Electricity consumption, heat production and cold production*

The resulting electricity consumption and heat/cold production based on the heat demand for *Customer A* and *Customer B* are displayed in Figure 14 and Figure 15. Cold energy is displayed as negative in the graph. Since both customers are using immersion heaters for the peak loads, the production of cold-water will stay constant during these hours. The immersion heater is also operating at a lower efficiency ($SPF_{heat} = 1$) which makes the electricity consumption rapidly increase for peak loads.

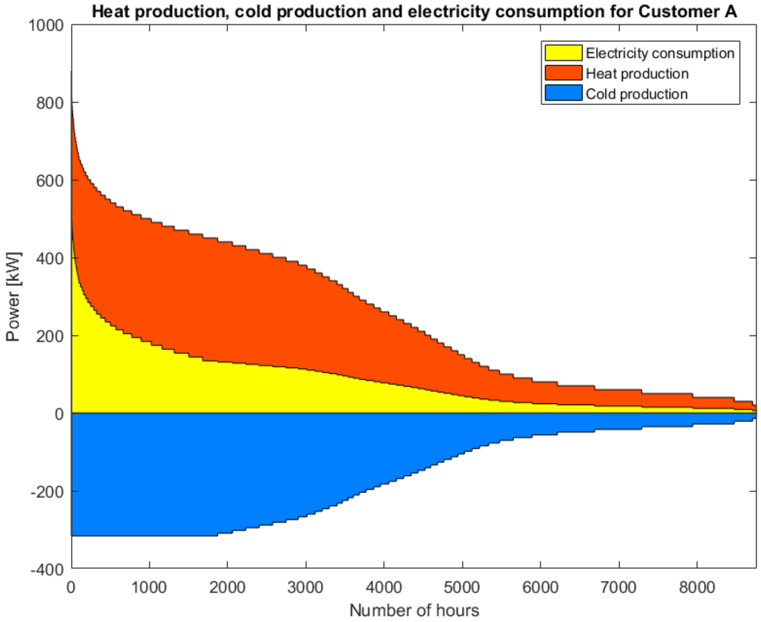

Figure 14: Shows the heat production, cold production and electricity consumption for Customer A over a year with a SPF_{heat} equal to 3,36. Cold energy are displayed as negative.

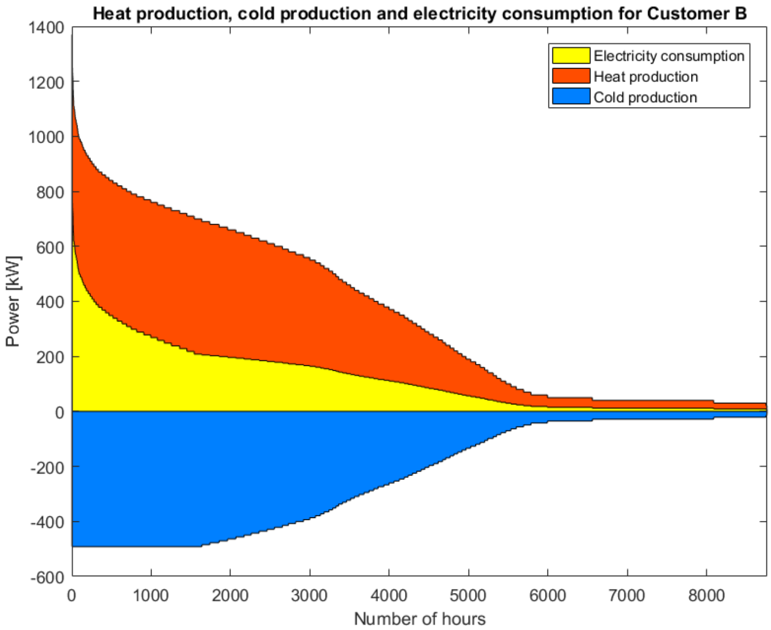

Figure 15: Shows the heat production, cold production and electricity consumption for Customer B over a year with a SPF_{heat} equal to 3,36. Cold energy are displayed as negative.

The resulting yearly energy values for both the customers is shown in Table 3. A new value for SPF_{heat} and SPF_{cold} is calculated based on the resulting energy levels. As expected, these values are lower with the introduction of an immersion heater. The $SPF_{heat + cold}$ is the value of the total energy production (heat and cold) divided by the electricity consumption.

Table 3: Shows the total energy consumption/production for a whole year as well as the actual SPF-values for a heat pump with SPF_{heat} = 3,36

$SPF_{heat} = 3,36$	Customer A	Customer B
Heat consumption	2 220 MWh	3 148 MWh
Cold production	1 466 MWh	2 083 MWh
Electricity consumption	754 MWh	1 066 MWh
Actual SPF_{heat}	2,95	2,95
Actual SPF_{cold}	1,95	1,95
$SPF_{heat+cold}$	4,89	4,91

5.2.1.2 *Potential production savings*

One of the biggest benefits with connecting heat clients to the district cooling system is the possibility to also produce cold-water for the cooling clients. By doing so, the production in the central cooling machines can be decreased or maybe even replaced. As shown previously in Figure 9, the demand of heat and cold occur at different points during the year and the big problem is that the heating clients will produce the most cold-water when the demand of cold-water is low. Figure 16 is an updated version of Figure 9, now including the production of cold-water in the heat pumps at *Customer A* and *Customer B.* The green area represents the cold demand in *The research system* which could be covered by these heat pumps. As can be seen, the central production could be replaced for approximately 140 days in 2018. For the rest of the year, the cold demand is much higher (blue area) than the potential cold production so it’s not possible to replace the central production plant during the whole year, at least not with only *Customer A* and *Customer B.*

The turquoise area represents the overproduction of cold-water, in order to not disrupt the temperatures in the district cooling system this energy will need to be led away and can be regarded as useless energy. However, it could also be regarded as a buffer. Since E.ON can’t control the operation of the heat pumps at the clients, they can’t be sure how much energy that will be produced. Therefore, a system that’s designed to also produce some extra cold-water could be a good idea just in case of a lower production than estimated.

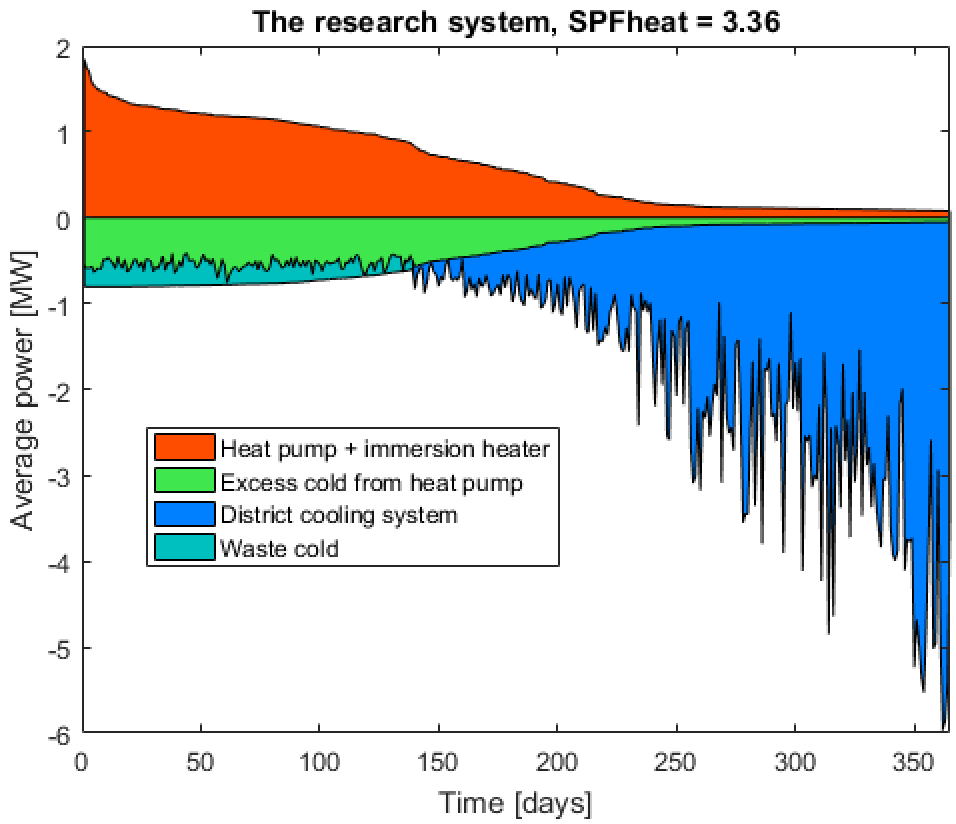

Figure 16: Duration diagram of the heat demand for Customer A and B, cold demand for all cooling clients in The research system and cold production by heat pumps at Customer A and B.

Table 4 contains the yearly values of saved energy and electricity compared with the electricity needed to operate the heat pump and immersion heater. It's clear that the electricity to operate the heat pump and immersion heater is much higher than the potential savings in central production. This result is expected since the SPF-value for the central production plant is much higher than in the heat pumps. The central production plant operates at an average of $SPF_{cold} = 6{,}65$ compared to 1,95 in the heat pump and immersion heater. Another reason for this result is that the heat pumps are overproducing cold-water which leads to worse efficiency. However, even though the electricity consumption gets higher, there are now heat clients that are supplied with heat included in this electricity consumption. This will be more investigated in the next chapter.

Table 4: Yearly values of savings and consumptions for Customer A and B compared to the central production plant.

	Customer A + B
Cold production in heat pumps	3 549 MWh
$E_{cold,\ saved}$	2 512 MWh
Percentage of central production	20 %
$E_{electricity,\_saved}$	378 MWh
Electricity consumption in heat pumps	1 820 MWh
Result	-1 442 MWh

5.2.1.3 *Efficiency of produced heat*

Table 5 shows the efficiency of the heat delivered to *Customer A* and *Customer B* by adding extra electricity to the system. The $SPF_{heat, system}$ means that 1 MWh extra electricity is needed to supply 3,72 MWh. It can also be viewed as 1 MWh of heat are supplied to a cost of $\frac{1}{3{,}72} = 0{,}27$ MWh electricity.

Table 5: The resulting efficiency of the heat delivered to Customer A and B when the electricity consumption for the cold supply stays the same as in the current system.

	Customer A + B
Heat production	5 369 MWh
Electricity consumption	1 820 MWh
$\mathbf{E_{electricity, saved}}$	378 MWh
$\mathbf{\Delta E_{electricity}}$	1 442 MWh
$\mathbf{SPF_{heat, system}}$	3,72

5.2.1.4 *Self-sustaining cooling clients*

Customer A is an example of a customer that's connected to both the district heating and cooling system which means that's it's buying hot and cold-water at the same time. A customer like this would benefit by using a heat pump to produce heat and utilize the by-product that is cold-water to cover its cooling need. Figure 17 shows the heat and cold demand for *Customer A* during 2018.

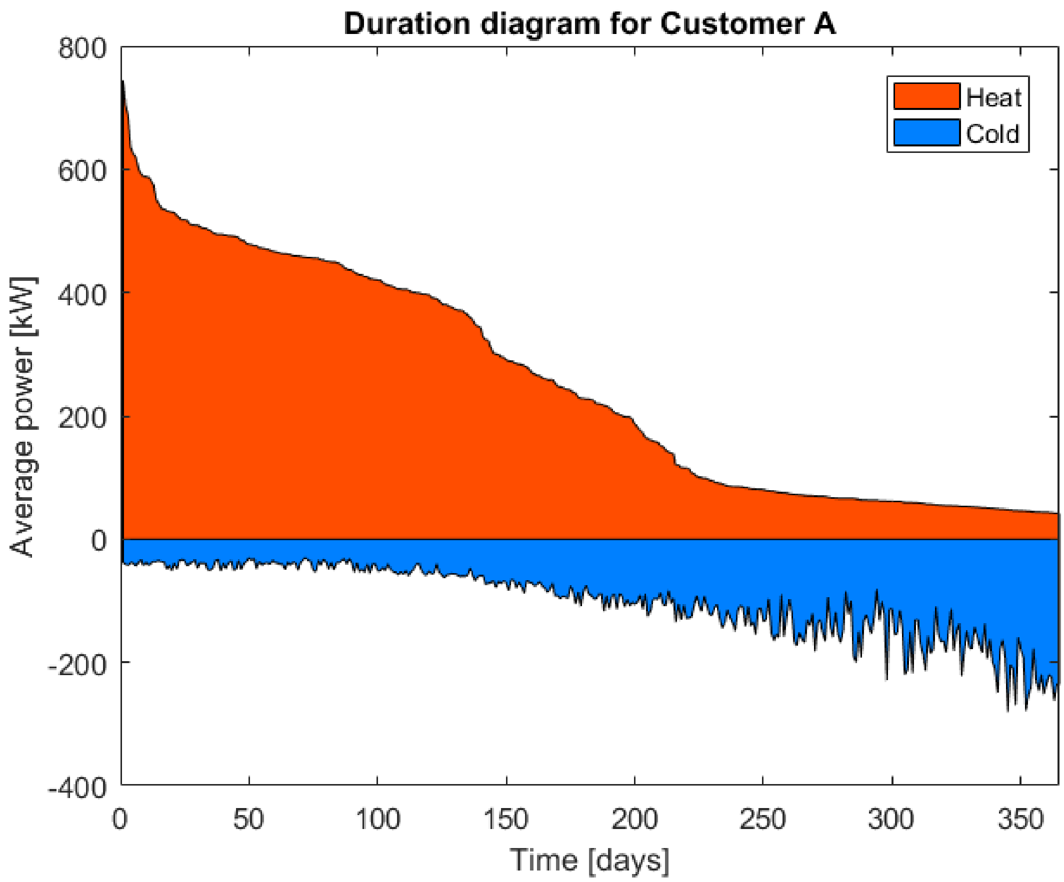

Figure 17: Average heat and cold power demand per day for Customer A during 2018.

Since the heat demand is higher than the cold demand, *Customer A* could cover more of its cold demand compared to the previous example for *The research system*, where there's only two heat clients and much more cold clients.

Figure 18 shows the cold production in the heat pump and how big share of the cold demand that could be covered. 55 % of *Customer A's* cooling need could be covered by the heat pump. The turquoise area could be sold back to the district cooling system if there's a demand of cold-water at other customers connected to the district cooling system.

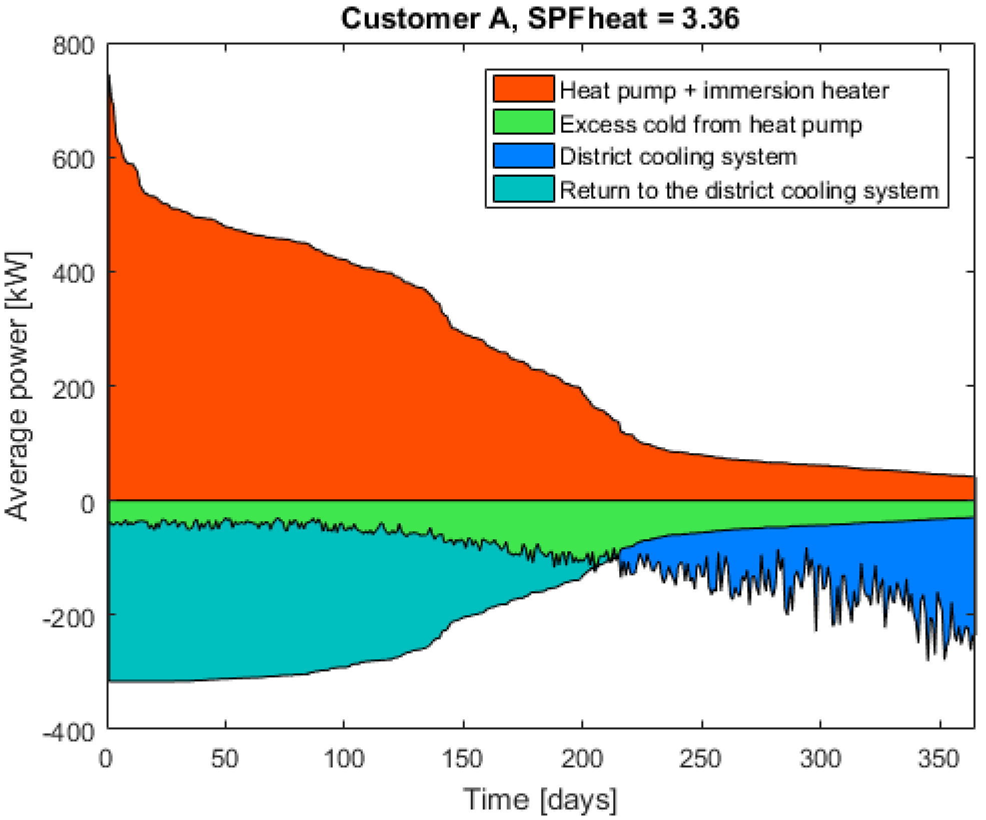

Figure 18: Displays the heat and cold production compared with the cold demand for Customer A.

5.2.2 SPF – Heat pump supplier

This chapter includes the same results as in the previous chapter (4.2.1) with the difference that now heat pumps with a SPF-value based on the data from a heat pump supplier is used. Therefore, the results will not be explained unless there is a difference from previous results.

Carrier's simulations for a 501,4 kW heat pump resulted in the following COP_{heat}-values:

Table 6: Temperature and COP-values for the two operation cases using a 501,4 kW heat pump from Carrier.

	$T_{c,in}$	$T_{c,out}$	$T_{h,in}$	$T_{h,out}$	COP_h
Case 1	12 ℃	6 ℃	30 ℃	40 ℃	5,63
Case 2	14 ℃	9 ℃	50 ℃	60 ℃	3,84

The weighted SPF-value (explained in chapter 4.2.2.2) based on these simulations are:

Table 7: SPF-values for a heat pump from the heat pump supplier Carrier.

SPF_{heat}	5,10
SPF_{cold}	4,10

5.2.2.1 *Electricity consumption, heat production and cold production*

The production of heat and cold as well as the electricity consumption for *Customer A* and *Customer B* when a heat pump with $SPF_{heat} = 5{,}10$ is used can be viewed in Figure 19 and Figure 20.

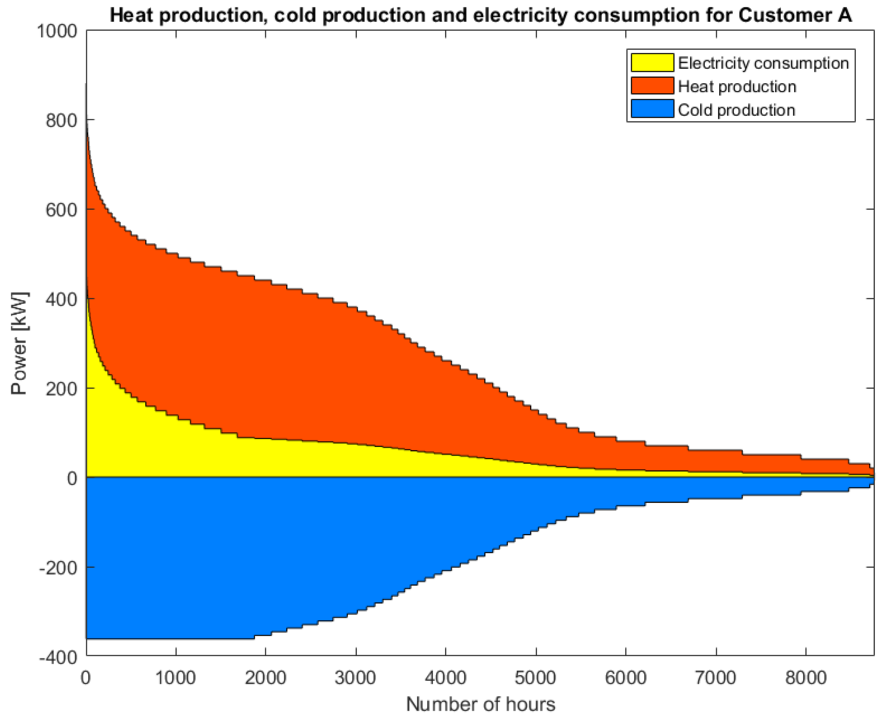

Figure 19: Shows the heat production, cold production and electricity consumption for Customer A over a year with a SPF_{heat} equal to 5,10. Cold energy are displayed as negative.

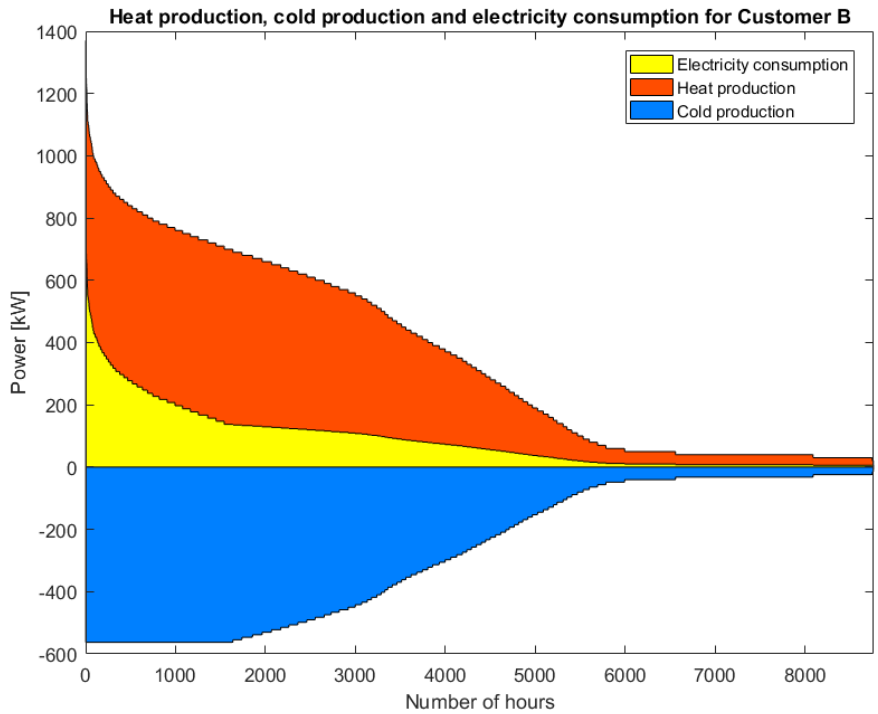

Figure 20: Shows the heat production, cold production and electricity consumption for Customer B over a year with a SPF_{heat} equal to 5,10. Cold energy are displayed as negative.

The yearly energy values are displayed in Table 8. As the heat pump is more efficient, the cold production is increased, and the electricity consumption is decreased compared to the heat pump used in *The pilot system.*

Table 8: Shows the total energy consumption/production for a whole year as well as the actual SPF-values for a heat pump with $SPF_{heat} = 5{,}10$

$SPF_{heat} = 5{,}10$	Customer A	Customer B
Heat consumption	2 220 MWh	3 148 MWh
Cold production	1 678 MWh	2 384 MWh
Electricity consumption	542 MWh	765 MWh
Actual SPF_{heat}	4,10	4,12
Actual SPF_{cold}	3,10	3,12
$SPF_{heat+cold}$	7,19	7,23

5.2.2.2 *Potential production savings*

When it comes to potential production savings there are some differences by using a more efficient heat pump. In Figure 21 it can be seen that there is no big difference in the number of days that the cold production in the heat pumps could replace the central production plant. For this case it's also approximately 140 days. On the other hand, the production of cold-water is slightly higher during the summer and could therefore replace a bigger share of the district cooling even though is a small share of the total cold demand. During the winter, the overproduction of cold-water (turquoise area) is higher with this heat pump. As described earlier, this is unwanted since this waste cold needs to be led away to avoid disruptions in the temperatures. Thus, a more efficient heat pump isn't as efficient for the whole system during the winter.

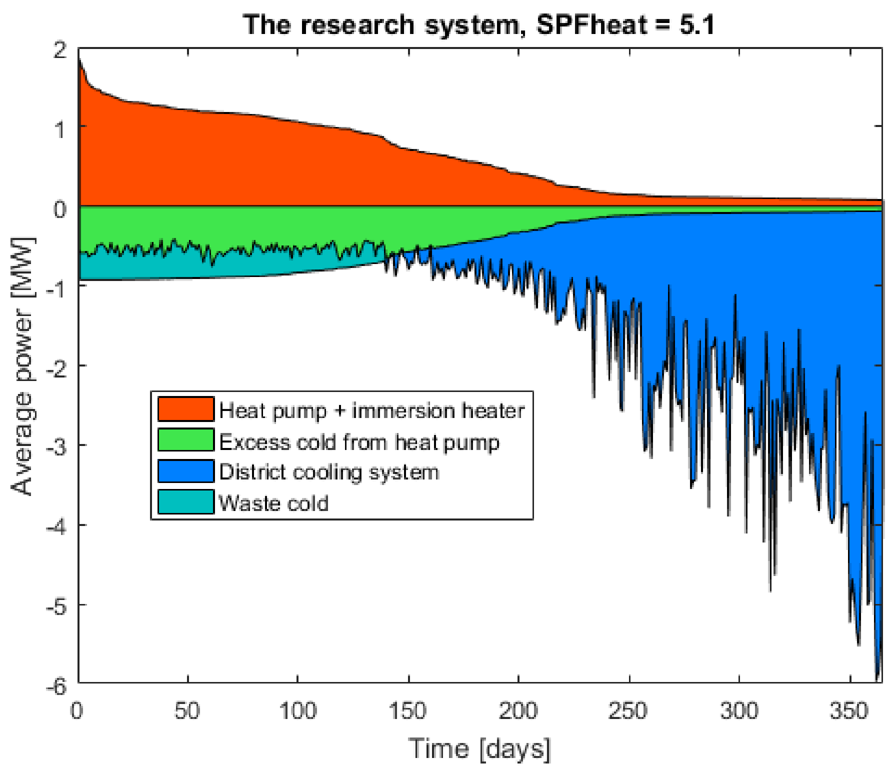

Figure 21: Duration diagram of the heat demand for Customer A and B, cold demand for all cooling clients in The research system and cold production by heat pumps at Customer A and B.

Even though there is more overproduction of cold-water, the resulting extra electricity is lower with a more efficient heat pump, mainly because the electricity consumption for the heat pump is lower. This is displayed in Table 9.

Table 9: Yearly values of savings and consumptions for Customer A and B compared to the central production plant.

	Customer A + B
Cold production in heat pumps	4 062 MWh
$E_{cold, saved}$	2 655 MWh
Percentage of central production	21 %
$E_{electricity,\_saved}$	406 MWh
Electricity consumption in heat pumps	1 307 MWh
Result	-901 MWh

5.2.2.3 *Efficiency of produced heat*

For a heat pump with $SPF_{heat} = 5{,}10$ the resulting cost of the produced is obviously even lower than for the first case with heat pumps as in *The pilot system*. The efficiency of the heat delivered is displayed in Table 10. The $SPF_{heat,\ system}$ is increased to 5,96 compared to 3,72 which means that 1 MWh electricity is needed to deliver 5,96 MWh heat.

Table 10: The resulting efficiency of the heat delivered to Customer A and B when the electricity consumption for the cold supply stays the same as in the current system.

	Customer A + B
Heat production	5 369 MWh
Electricity consumption	1 307 MWh
$E_{electricity, saved}$	406 MWh
$\Delta E_{electricity}$	901 MWh
$SPF_{heat, system}$	5,96

5.2.2.4 *Self-sustaining cooling clients*

The difference when the SPF_{heat} is increased is that the cold production is increased as well. Therefore, a bigger share of the cold demand could be covered, which is shown in Figure 22. However, the difference is very small, the heat pump covers 58 % of the cold demand compared with 55 % when $SPF_{heat} = 3{,}36$. That's because the production of cold-water is mainly increased during the winter when the cold demand is low.

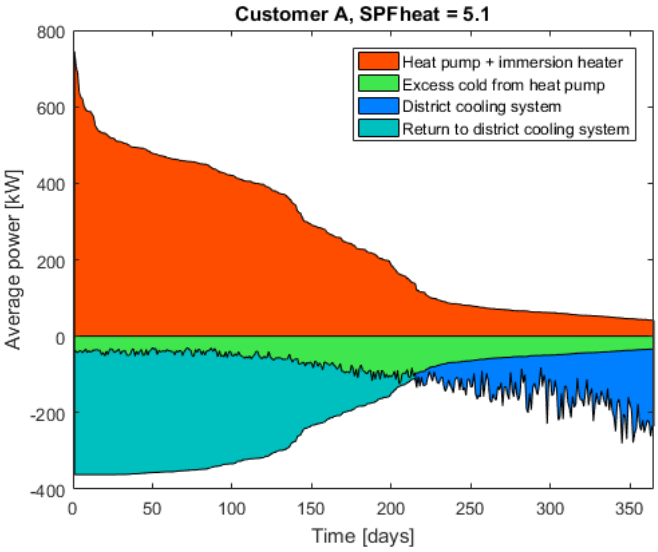

Figure 22: Displays the heat and cold production compared with the cold demand for Customer A.

5.3 Varying SPF-values

It's not possible to calculate the SPF-value precisely. Previous calculations are made with the SPF-values from *The pilot system* and a heat pump supplier. This section is a sensitivity analysis and will investigate what happens when the SPF-value of the heat pump is changed based on previous results.

5.3.1 Electricity consumption, heat production and cold production

As shown in theory-chapter regarding COP (2.1.2) the production of cold-water isn't linear with COP_{cold}. In reality it means that when the SPF_{heat} is increased, the production of cold-water will increase but the increase of production will subside with higher SPF_{heat}. Figure 23 shows how the cold production and electricity consumption for the heat pump varies with different values of SPF_{heat}. The heat consumption is the summarized value over the year for *Customer A* and *Customer B*. The graph displays that electricity plus cold energy equals hot energy.

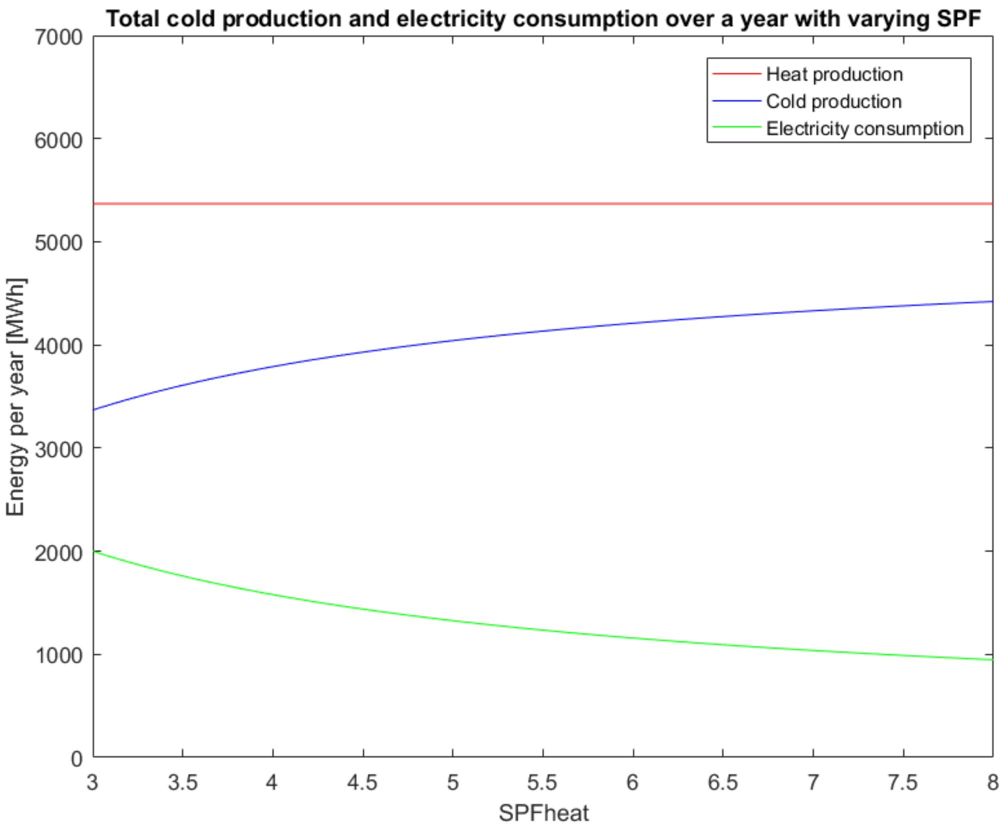

Figure 23: Shows the total electricity consumption, heat and cold production over a year for Customer A and B with SPF_{heat} for the heat pump varying between 3-8.

5.3.2 Potential production savings

As previous figure showed (Figure 23) the increase of cold production isn't linear to the increase in SPF_{cold}. Once again, the heat and cold demand for *The research system* is illustrated in Figure 24. Included is also the cold production for four different values of SPF_{heat} in the heat pump, as well as the black line which represents the cold demand for the whole system. As can be seen, there isn't much difference in cold production. The most significant difference occurs when the cold demand is low and during that period there isn't any need for more cold production since even the heat pump with $SPF_{heat} = 3$ could cover that demand. When the cold demand is high, the difference in average power is so small it could be neglected. This result indicates that even if more efficient heat pumps were introduced, the cold production from these heat pump would still not come close to cover the whole cold demand for *The research system.*

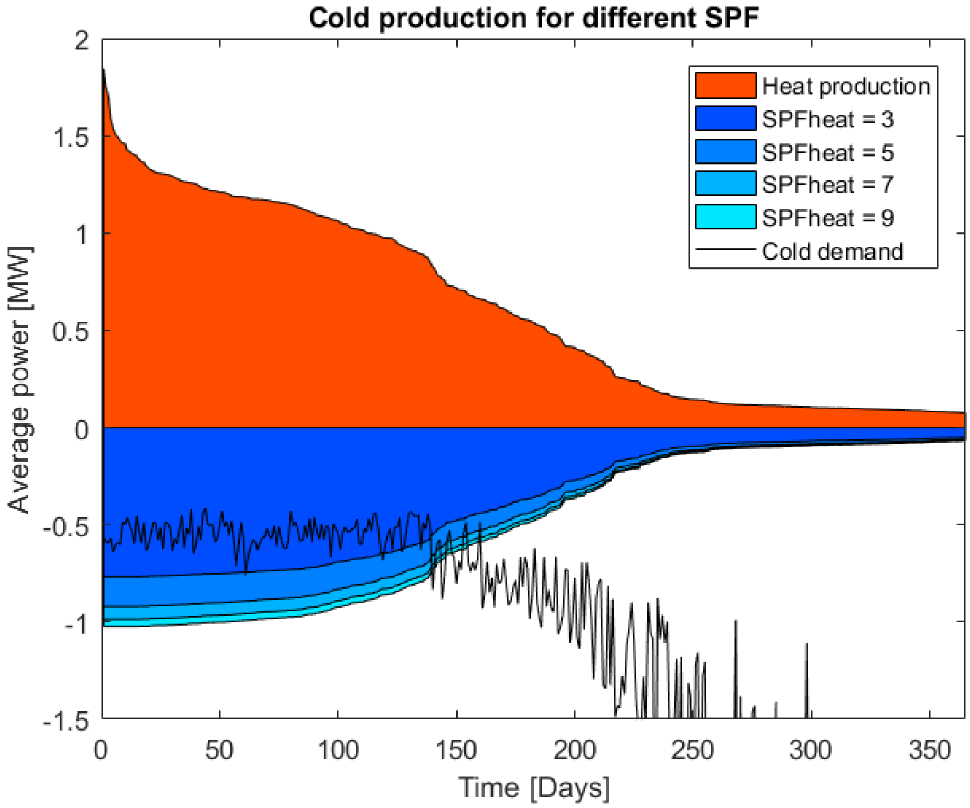

Figure 24: Illustrates cold production from heat pumps with different SPF_{heat}. The black line represents the current cold demand in The research system.

5.3.3 Efficiency of produced heat

The efficiency of the produced heat can be viewed as the difference between electricity needed to run the heat pump plus the immersion heater and the savings of electricity in the central production.

$$\Delta E_{electricity} = E_{electricity} - E_{electricity,saved} \quad (16)$$

$$SPF_{heat,system} = \frac{E_{heat}}{\Delta E_{electricity}} \quad (17)$$

The change in electricity consumption for the heat pump and immersion heater for different SPF_{heat} is illustrated in Figure 25. The orange line represents the savings of electricity in the central production with the introduction of the heat pumps. Both *Customer A* and *Customer B* are included in the graph. It's mainly the electricity consumption that's decreasing rather than electricity savings increasing for higher SPF_{heat}. The lines are never crossing, which imply that the electricity in the system will never be lower than it was for just the regular district cooling system. It depends on three things, first the SPF_{cold} for the central cooling machines is 9,0 between November and March, and 4,5 during the rest of the year. Depending on how the cooling need is distributed over the year it gives a total SPF_{cold} at approximately 6,5 – 7,5. The graph includes SPF_{cold} for the heat pumps up to 7, which means that for the most of the time the central cooling machines will be more efficient then the heat pumps. Second, as the SPF_{heat} for the heat pump is increasing, so is also the overproduction of cold-water but there isn't much useful cold-water produced (displayed in previous chapter in Figure 24). Hence the small increase in electricity savings. Third, the immersion heater will operate at a COP equal to 1 regardless of the SPF_{cold} in the heat pump. Therefore, the total SPF_{cold} for the heat pump and immersion heater is lower than the SPF_{cold} for the heat pump.

The $\Delta E_{electricity}$ is also displayed in Figure 25 as the difference between the two lines, the extra electricity input in the system that is.

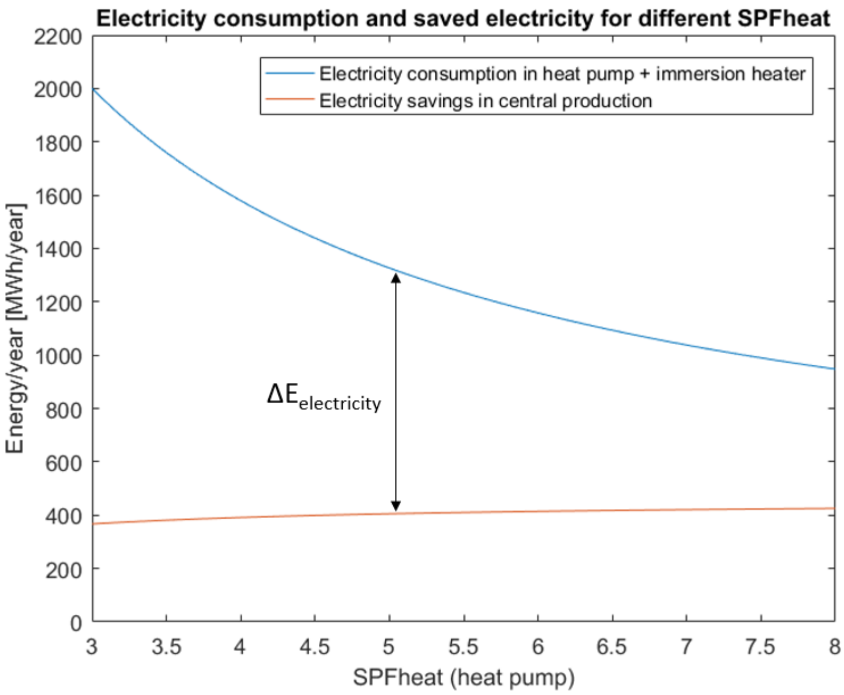

Figure 25: Shows the electricity consumption for the heat pumps and immersion heaters at Customer A and Customer B, as well as the savings of electricity in the central cooling machines when the heat pumps are producing cold-water. The difference between them is defined as $\Delta E_{electricity}$.

Since $\Delta E_{electricity}$ is decreasing with higher SPF_{heat} for the heat pumps, the efficiency of the produced heat will increase. Figure 26 displays how the $SPF_{heat, system}$ changes with different values of SPF_{heat} in the heat pump. $SPF_{heat, system}$ is the heat production in the heat pumps divided by the extra electricity needed to run the system, it describes how efficient the system is to produce heat if the cold production is regarded as the same as before.

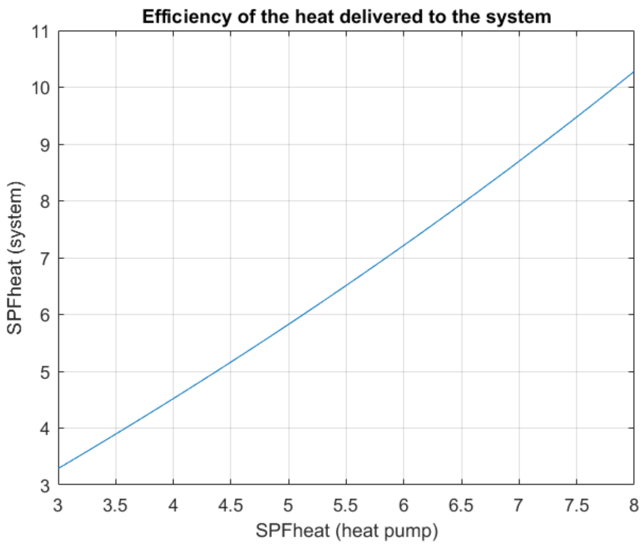

Figure 26: Shows how the $SPF_{heat, system}$ changes with different SPF_{heat} for the heat pump.

5.4 Cost comparison

The cost for E.ON to install the heat pumps and immersion heaters at *Customer A* and *Customer B* would be 3 375 000 SEK. This includes hardware, installation, piping and maintenance. It's regarded as a fixed one-time cost.

The total electricity cost for running the heat pumps and immersion heaters at *Customer A* and *Customer B* would be 590 800 SEK for 2018.

By using heat pumps there are also savings in the production of cold-water for the district cooling system. Roughly 2 500 MWh cold-water could be saved each year which would result in 500 000 SEK per year.

For conventional district heating the cost to deliver heat to *Customer A* and *Customer B* is 1 879 000 SEK per year. This includes, combustion fuel, pumps and losses in the distribution.

For the case where the construction of the infrastructure is included, the fixed cost of a 5 km long system would be 40 000 000 SEK.

	Heat pumps and immersion heaters	Conventional district heating
Investment cost	3 375 000 SEK	40 000 000 SEK
Electricity/combustion fuel	590 800 SEK/year	1 879 000 SEK/year
Savings in cold production	-500 000 SEK/year	0
Total variable cost	90 800 SEK/year	1 879 000 SEK/year

If the cost for infrastructure is disregarded, the option with heat pumps and immersion heaters would pay back after 1.9 years. If infrastructure is included though, conventional district heating is much more expensive because the fixed cost is much higher and heat pumps would pay back instantly.

6. Discussion

6.1 SPF

The results in this report and the outcome of this investigation is highly dependent on the SPF-value of the heat pumps. Two main cases has been explored, one with $SPF_{heat} = 3{,}6$ and one with $SPF_{heat} = 5{,}1$, as well as the sensitivity analysis where the SPF_{heat} vary between 3-8. The SPF isn't of great importance when it comes to cold production for this system, but it certainly affects the electricity consumption and thereby the efficiency of the heat produced. So which SPF is reasonable to use? The 3,36 value makes a strong case since it's proven in reality in *The pilot system*. However, there are some differences between *The pilot system* and *The research system*. Mainly, the buildings in *The pilot system* aren't well insulated and the heat pumps are dimensioned to supply the buildings with at least 55 ̊C. The buildings in *The research system* on the other hand is more modern and better insulated which would lead to a lower supply temperature and therefore a higher SPF. The second case where SPF_{heat} is just over 5, also seems reasonable since it's calculated through simulations by *Carrier*. The simulations are based on the heat demand and temperatures in *The research system* which would make this case more accurate. The value 5,1 is a weighted average of the different simulations which could mean that the SPF-value would be higher or lower in reality. There's also an uncertainty since *Carrier* themselves made the simulations and that the SPF-value is an optimal value in purpose of selling heat pumps to E.ON. To summarize, a reasonable assumption is that the SPF_{heat} for the heat pumps in *The research system* would be between 3,36 and 5,1.

Calculations are also made with SPF_{heat}-values varying between 3-8 in order to see what happens with the results if the performance of the heat pumps would change. It is primarily three reasons why the SPF would change in the future, one being improvements of the heat pump itself to make the cycle closer to the Carnot-cycle, which is the theoretical ideal thermodynamic cycle. It's however unlikely that this will happen since the efficiency is already close to the Carnot-efficiency. [5] The other two reasons have to do with the temperatures in the system or in the buildings. E.ON have ideas about raising the temperatures in the district cooling system to make it more suitable for both heating and cooling. Today, the desired temperatures are 6 °C in the supply pipe and 16 °C in the return pipe. If the temperatures were to be raised to 10/20 °C, the SPF-value of the heat pump could be higher. It would of course depend on if the cold clients could cope with 10 °C. The third reason is that buildings in the future may require lower supply temperatures. That would mean that the heat pumps don't need to raise the temperature as much and thus, the SPF would be higher.

6.2 Electricity consumption and cold production

A clear result of this study is that the total consumption of electricity is increased in *The research system* no matter the SPF of the heat pumps. Even though there would be less electricity used in the central production plant, it would be outweighed by the electricity consumption in the heat pumps, immersion heaters and distribution pumps. The reason for this is that the central production plant operates at a higher SPF than the combination of heat pumps and immersion heaters, also because of the overproduction of cold-water during the winter which is regarded as useless energy. The cold-water in the central production plant is produced by cooling machines during most of the year but in the winter free cooling is used, leading to a much higher SPF in the central production plant in the winter. If a solution with combined district heating and cooling system like this would be used in another area where free cooling isn't available, the saved electricity in production would be higher and the total electricity consumption in the system lower.

Early in this process it was decided that the heat clients should use an immersion heater for peak loads. Mainly because heat pumps are expensive, and it would be cheaper to combine a heat pump and immersion heater. The downside is that the immersion heater doesn't produce any cold-water and consume more electricity. It could be a possibility to dimension the heat pump to cover peak loads in order to produce more cold-water and decrease the electricity consumption.

The cold demand in *The research system* can be covered by the heat pumps at *Customer A* and *Customer B* for approximately 140 days of the year, regardless of the SPF-value in the heat pump. The difference is that there is more overproduction during these days with the 5,1 heat pump as well as a negligible higher production during the rest of the year. The overproduction is in this report regarded as useless, but it serves a point if it's looked upon as a buffer. Since the production of cold-water is dependent on the customers, there might be a convenience to ensure that there always will be enough cold production to supply the whole cold demand. For the rest of the year, overproduction isn't a problem, rather the lack of it. As the cold demand is increasing, the cold production is decreasing and only a small portion of the cold demand can be covered by the heat pumps. Even an increase in SPF will not have a big effect on the cold production.

Since the cold demand could be fully covered for around 140 days of the year, there's a possibility for E.ON to shut down the central production plant during this period and save more resources. This would occur during the winter and the advantage with that is that free cooling could be used as backup and the cooling machines could thereby be shut down for a period. However, since the central production plant must be operating during most of the year, there would still have to be maintenance.

6.3 Efficiency of produced heat

The production of heat could be quite efficient for *The research system.* Since there is production of cold-water, the $SPF_{heat, system}$ will be higher than the SPF_{heat} in the heat pump. It depends on how the electricity consumption is viewed. In this report, the efficiency of the produced heat has been viewed as the extra electricity input in the system, the difference between electricity consumption and electricity savings that is. Another way of looking at it is that the production of extra cold-water is the positive by-product of this system, leading to lower production costs. But since the purpose of this master thesis is to add heating clients to the district cooling system, it's reasonable to make the efficiency of heat production higher. This will give greater incentives for heat clients.

The efficiency of the heat pump is also higher in this arrangement compared to other heat pumps since the temperature of the water in the return pipe of the district cooling system is higher than regular sources (up to 16 °C).

A consequence of moving the heat supply from a district heating system to a district cooling system is the source of the energy. For district heating, the source in *The research system* is combustion of wastes, natural gas, a small portion of bio mass as well as waste heat for a nearby industry. For the district cooling system, the source is electricity to run the heat pumps and immersion heaters. Since they're two completely different sources the comparison between the alternatives becomes more complex. For the case with the $SPF_{heat} = 3{,}36$ the energy needed is 1 442 MWh electricity or 5 369 MWh district heating. From an environmental perspective, electricity probably would be better, at least in Sweden where the electricity mix is good and often produced from renewable sources, compared to the emissions in combustion of natural gas and wastes. Even though wastes emit greenhouse gases, there is a problem in the society with landfill of wastes, and district heating is a good solution to this problem. Since this report haven't investigated what's best between district heating and electricity, this is only speculations.

6.4 Cost comparison

The cost of building an infrastructure for *Customer A* and *Customer B* was calculated to 40 MSEK, which is very high in comparison with the cost of installing heat pumps and immersion heaters (3,375 MSEK). Obviously, it's not a viable option for *The research system.* But there are only two heat customers in the area so for conventional district heating there has to be a much higher heat demand to get competitive. In *The research system* there are two customers along a 5 km district heating system, it's possible for heat clients to be located much tighter than that. If the heat demand was 12 times higher, the cost of heat pumps and immersion heaters would be similar to the fixed and variable costs of a conventional district heating system. However, for an area with that high heat demand, a solution with heat pumps would be very inefficient because of the high overproduction of cold-water. Thus, it would be more viable with a separate district heating system.

Since *The research system* is a restricted area within an area with many more heat customers, it's misleading to include the cost of the infrastructure in the cost comparison since it's still necessary for supplying other customers with heat. But the results have shown that it would be beneficial to connect *Customer A* and *Customer B* to the district cooling system instead of the district heating system since the payback is only 1.9 year.

For the cost comparison calculations in this report there has been assumed that the district heating system doesn't have a capacity problem. If capacity is a problem and for example a new heat customer wants to connect to the district heating system, there might be even higher costs in order to ensure that the production plant can deliver enough heat. *Customer A* and *Customer B* are in reality connected to the district heating system, for this reason capacity isn't a problem in this case.

6.5 General discussion

The results have shown that the heat customers in *The research system* could be connected to the district cooling system without overproducing too much cold-water and thereby make the system efficient. Thus, it's fair to say that for this specific area, two separate infrastructures could be avoided. The estimated cost of building the district heating system is 40 MSEK which is very high in comparison with the 3,375 MSEK for heat pumps and immersion heaters.

The key to using only one system is to find an area where the heat and cold demand suits this type of system. The area where *The research system* is located is in reality not a suitable area since the heat demand is much higher than the cold demand, in this report there are only two heat customers connected to the district cooling system. Even though they are the largest heat clients in the area, they represent only 11 % of the total heat demand in the area over a year. So, there would still need to be two systems in the area. If all heat clients in the area would be connected the overproduction of cold-water would be huge and it would be a problem to manage this in order to not disrupt the temperatures. It would also decrease the efficiency of the system, since the electricity saving in production would be smaller compared to the electricity consumptions in the heat pumps, leading to higher cost of produced heat.

What's the optimal distribution of heat and cold demand then? Well, firstly it's favourably to have an even heat and cold demand over the year, not a fluctuating demand that is. That's the reason why *The pilot system* is such a great area, the hospital provides a constant stream of warm water since it's cold demand is high over the whole year. The heat demand is however much higher in the winter but that's a general problem by nature in Sweden. Secondly, in order for the efficiency of the system to be as high as possible it great to have a heat demand that's slightly higher than the cold demand for as long time of the year as possible. This leads to a system where the heat pump can cover much of the cold demand but still don't overproduce to much cold-water and lower the efficiency. The biggest obstacle for *The research system* is that the heat demand is so low in the summer, it doesn't affect the efficiency, but it would decrease the central production and more of the heat in the return pipe could be recovered. It would be beneficial to find heat clients that's not only using heat for space heating, for example swimming pools.

Areas where there's a warmer climate, like southern Europe, seem especially interesting for a combined heating and cooling system. The cold demand is higher, and the heat demand is lower. It's more likely to find a suitable area in these countries than in Sweden. This study is conducted in a Swedish climate and the customer data used are dependent on the outdoor temperature, but as long as data about heat and cold consumption in the area can be accessed, an evaluation could be made. Since free cooling probably isn't a possibility in warmer climates, the production of cold-water at heat clients would be even more valuable.

There's also an environmental advantage for a combined district heating and cooling system in southern Europe. In Sweden, the use of natural gas and other fossil fuels for heating are much less common compared to the average in Europe. [10][11] By using heat pumps instead of natural gas burners the heat production could generate less greenhouse gases. Though it should be said that the electricity mix in Europe includes a lot of fossil fuels, so it doesn't solve the whole problem.

For areas where the heat demand is higher than the cold demand in such a way that the overproduction of cold-water would make the system inefficient, there is still a possibility to avoid two infrastructures. Heat could be produced from other sources to cover the peak loads of heat in order to not need a whole district heating system. For example, specific buildings in the area that doesn't have a cold demand could be disconnected from the system and use geothermal heat pumps or any other heat source instead. By doing so, there won't be a need for the infrastructures, even though the combined district heating and cooling system couldn't supply heat to all customers in the area.

6.6 Method discussion

There are some assumptions made in this study which potentially could be provide an inaccurate result. The MATLAB-code has been designed in a way that these parameters easily could be changed. The first assumption relates to the SPF-value of the *Carrier* heat pump. It's based on two simulations, one for space heating and one for domestic hot water. The resulting SPF is weighted dependent on how much of the total heat demand which is domestic hot water. It's possible that domestic hot water has a bigger part of the total heat demand which would lower the SPF.

The second assumption is regarding the SPF at the central production plant in *The research system.* Free cooling is assumed to operate between 1st November and 31st March, and the cooling machines for the rest of the year. These dates aren't based on any data, just discussions with E.ON employees. The SPF of the free cooling and cooling machines are based on data for specific operation cases and an average value has been estimated. These values may not be correct, and further investigations are recommended in this area.

Calculations in this report are made with yearly SPF-values rather than COP-values. The COP is the instantaneous efficiency of the heat pump, while the SPF is the weighted value over the year. The reason for using SPF is that there weren't any hourly data available for *The pilot system.* By using SPF, it's assumed that the COP is constant over the year, which it isn't in reality. The COP is probably higher in the winter and lower in the summer since there is more space heating in the winter which require lower temperatures than domestic hot water. In practice, this would increase the cold production during the winter and lower the same during the summer. The cost of produced heat would thereby be lower in the winter and higher in the summer.

The overproduction of cold-water, the cold-water produced in the heat pumps that there isn't a demand of that is, is assumed to be led away in order to not disrupt the temperatures in the system. How this would be done and what it might cost haven't been investigated in this report and may thereby affect the results of this report.

The cost comparison calculations are based on estimations and simplifications. The electricity price is set as constant over the year and is the mean value of the price per month. But the consumption isn't constant over the year. In reality the cost of electricity would be lower since the consumption is higher in the winter when the prices are lower. The other costs for heat pumps and district heating is values taken from E.ON and are used to make fast and simple calculations and isn't exact values. The reason why these simplifications were made was that the cost comparison wasn't the main objective with the report and in order to have time to investigate the other research questions thoroughly, compromises hade to be done.

7. Conclusions

A reasonable efficiency of heat pumps in a combined district heating and cooling system would be around SPF_{heat} = 4. The electricity consumption will increase compared to conventional district heating and cooling due to the fact that the efficiency of the central production plant of the district cooling system is much higher than the heat pumps. If heat pumps with SPF_{heat} = 4 were to be used in *The research system* the electricity consumption for the heat customers would be 1 576 MWh/year and the saved electricity in central production would be 391 MWh/year.

Customer A and *Customer B* will yearly produce roughly 3 800 MWh cold-water, even though some of this is regarded as useless since it's overproduction, producing more than the demand that is. If the overproduction is removed, the heat clients can replace 20 % of the central production. The central production can be replaced 140 days per year, during the winter.

The efficiency of the system, $SPF_{heat, system}$, would be 4,53 when using a heat pump with SPF_{heat} = 4 and an immersion heater with SPF_{heat} = 1. The efficiency of the system is higher than the actual heat pump since there's also production of cold-water. This means that for the cost of 1 MWh electricity, 4,53 MWh heat is produced.

By adding heat customers on the district cooling system there is also an economic advantage, the cost of installing heat pumps will pay back after only 1.9 years since it's much lower variable costs.

The result of this study has shown that there's definitely benefits of connecting heat clients to the district cooling system. The heat that will be produced in the heat pumps will be cheap in terms of electricity and the production of cold-water could decrease the production in the central production plant and even fully replace it for 4 to 5 months of the year.

In this report, the heat production in the heat pump has been regarded as the by-product of the cold-water. In other words, the extra electricity needed to supply the same amount of cold-water compared to regular district cooling results in heat. But the cold-water production in the heat pumps could also be viewed as the by-product and thus would be the advantageous factor. For *The research system*, it's probably more favorably to see the heat production as the advantageous factor since it would replace the district heating system and thereby require one less infrastructure. However, it might be better to see the cold production as the advantageous factor if it would be applied in an area where heat clients use other sources than district heating.

To reach the full potential of a system like this, it should be applied in an area where there won't be a need for a district heating system. If the heat demand is much higher than the cold demand during parts of the year, the efficiency would be low, and a district heating system or other heat sources would be needed to supply heat to some of the customers. The best case is for an area where the heat demand is slightly higher than the cold demand. But it's also viable for an area where the cold demand is higher, it would still be as efficient even though it wouldn't replace as much of the central production.

The electricity consumption will increase with the introduction of heat pumps and immersion heaters, but the benefit is heat clients that weren't connected before now are included in the electricity consumption. Assuming the electrification of the society to be positive thing, a combine district heating and cooling system is definitely a viable option for the future.

The most common contradiction for this system would be that the heat and cold demand is so different over the year. The results clearly showed that the cold production in the heat pumps weren't close to cover the cold demand in the summer, but in the winter it wasn't a problem. To get more cold production in the summer, more heat clients would be needed. Though this isn't a solution since there would be huge overproduction of cold-water if these clients were connected in the winter. It can be determined that a central production plant is needed in order to supply cold-water to the district cooling system, at least for *The research system*. It might be possible to find an area where the heat and cold demand is of such character that the central production could be fully replaced, but that require a nearly equal demand of heat and cold over the whole year.

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