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Investigation of system effects of return flow temperature in a district heating system containing waste heat sources

An investigation for possibilities of introducing heat pumps in the district heating system of Göteborg in order to reduce the temperature of return flow of district heating

Master’s thesis in Sustainable Energy Systems

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Abstract

In order to meet the climate change mitigation in Göteborg city, the district heating (DH) company is aiming to increase the share of recycled energy sources in the DH-system. This goal can be reached by maximizing the usage of currently available waste heat, both in the nearby industries in the city and internal waste heat at company.

This master thesis is trying to investigate a concept to recycle the available low temperature heat in the return flow of the DH in order to use it in an industrial heat pump to lift the temperature in the supply flow of the DH. The effect of the heat pump on achieving a maximum temperature reduction of the DH return flow was studied in detail. Since the waste heat delivery in city of Göteborg to the DH-network occurs from different companies, the study tried to cover the entire waste heat provider conditions, mass-flow and temperature, The project comprises also an analysis of the effect of potential lower DH return temperature on the energy generation units of the DH-system. An economic analysis has been implemented, including the variability of electricity prices throughout the year, to analyze the impact of the various investigated concepts to waste heat prices.

In one investigated scenario, the project introduces a new concept of heat exchanging between the waste heat supplier and DH-company in order to achieve a better usage of waste heat at lower temperature. In this context, it is discussed that the introduced concept can lead to better utilization of higher temperature waste heat for other purposes like carbon capture for e.g. refineries in Göteborg.

The modeling results indicate that a temperature reduction of about 7,5 degrees can be achieved with a coefficient of performance (COP) of 3,87 for the current system of one refinery and the DH-company and this results in about 11 MW more extracted heat from the heat exchanger(HEX). Furthermore, a temperature reduction of 8,7 degrees can be achieved with a heat pump COP of 3,31 and additional mass-flow of DH-water of 82 kg/s (i.e., considering 15% more available heat at 10°C lower temperature) this would result in around 25 MW more extracted heat from the HEX.

The result of economic analysis indicates that the concept of installing heat pump by DH-company will become cost-efficient for a cheaper waste-heat price. The introduced price calculation approach showed that for a waste heat price about 30% lower than current prices, the heat pump installation would be cost beneficial for the DH-company. However, the results show that this will not be highly motivated by waste heat providers for the cooling savings related with the reduced return temperature. Further, it is discussed in this paper that by deeper analysis of the economic aspects with a higher resolution (e.g. hourly variation of electricity prices, real waste heat and cooling prices) and by considering the environmental issues, the motivation for this project for both the DH-company and the waste heat providers can be adjusted in between the business parts.

Table of contents

1 INTRODUCTION 7

1.1 BACKGROUND TO THE PROJECT 8
1.2 GOAL AND SCOPE 9

2 METHODOLOGY 10

2.1 CONCEPT 10
2.1.1 Waste heat delivery to the DH-company 11
2.1.2 Heat pump 12
2.1.3 Excel - Solver 14
2.1.4 Cost estimation for the Heat Pump 19
2.2 CONCEPT FOR PREEM 22
2.2.1 Sensitivity analysis 23
2.2.2 Investigation for waste heat at lower temperature 24
2.3 CONCEPT FOR ST1 27
2.4 CONCEPT FOR RENOVA 28
2.4.1 Applying heat pump solver to Renova 31
2.5 EFFECT OF TEMPERATURE REDUCTION OF THE RETURN FLOW OF DH ON DH-PRODUCTION PLANTS OF GE 31

3 RESULT AND DISCUSSION 32

3.1 OPTIMIZATION AND DIFFERENT SCENARIOS OF INSTALLATION FOR PREEM 32
3.2 OPTIMIZATION OF INSTALLATION FOR ST1 36
3.3 OPTIMIZATION OF INSTALLATION FOR RENOVA 38
3.4 EFFECT OF TEMPERATURE REDUCTION OF THE RETURN FLOW OF DH ON DH-PRODUCTION PLANTS OF GE 40
3.5 ECONOMIC ESTIMATION 41
3.5.1 Economic calculation for Preem 41
3.5.2 Economical calculation for ST1 and Renova 45
3.6 FURTHER DISCUSSION 46

4 CONCLUSION 47

5 BIBLIOGRAPHY 48

6 APPENDIX 52

1 Introduction

Space heating in Sweden accounts for about 40% of the total energy use in Sweden, and district heating (DH) satisfies about 55% of the heat demand in Swedish buildings and multi-family residential buildings [1]. DH is a technique which is used to distribute heat to parts of or a whole city by having a common heat distribution system [2]. Some benefits of using DH as a heat source for domestic and industrial heat supply are: high fuel conversion efficiency, ability to convert variety of fuels and high level flexibility in operation [3]. However, the most important benefit of using DH is that there is a possibility of utilizing energy from sources which are hard to use like waste heat from industries, waste heat at low temperature and domestic waste [1]. Thus, heat sources in a DH system can vary. DH production can be based on fossil fuels like natural gas and burning oil, renewable fuels like biomass and biofuels, waste as fuel, waste-heat from other nearby industries and heat pumps (electricity to heat). In Swedish DH system more than 90% of produced DH is based on biofuels and waste incineration, however the remaining 10%, which stands mostly for peak production, is based on fossil-fuel fired heat-only-boilers [4].

A very common heat carrier in the distribution system for a district heating is water. District heating is a well-known heating system in countries with cold winters like Scandinavian countries, north America, Russia, western Europe, China, Japan and Korea [2]. In a production plant for district heating, raw energy source like biomass or natural gas, converts to heat by burning in a boiler. The produced heat in the boiler is then transmitted to the heat carrier and sent to consumers. The water in the distribution system leaves the production plant with a temperature of 65-120°C and the return flow from consumers to the plant has a temperature in the range of 35-65°C [2] [5].

DH system in Göteborg city is distributed and operated by Göteborg Energi AB (GE). By employing three large power production plants, Sävenäs, Rya CHP and Rya Hot Water Center (HVC HOB), and several small heat production units, GE supplies more than 90% of multi-family building and 12000 villas with a length of the DH-network more than 1350 km [6]. Also, more than 89% of the produced DH in the company is from recycled or renewable sources [6].

The goal of reduction of greenhouse gas (GHG) emissions by 80-95% until 2050 in Europe [7] has made all countries in Europe to take their plans and actions. One part of the plan for this according to Energy roadmap 2050 is that all European cities and municipalities need to intensify their effort past 2020 with a policy framework and it should include milestones for 2030 [7]. Therefore, as a plan and action in order to a sustainable city, GE has as goal to produce DH of renewable sources, waste-burning and industrial waste heat in year 2030 [6]. More DH in the European energy system would help to decrease primary energy supply and reduce the GHG emission [8]. In additional to this, DH should be subjected to significant changes to be more competitive compared to other heat supply solutions. Therefore, the fourth generation DH (4GDH) concept identifies the range of the DH transition [9] [10].These articles investigate and discuss the future changes in the DH-system from the structural and infrastructural perspectives. To implement such a system with low thermodynamic losses and economic worth, it is stated that by DH and heat pump, electricity to heat devices, a cheap cost alternative for heating can be achieved in year 2050 [11].

GE has already a heat pump plant which can produce DH with a maximum capacity of 160 MW [6]. Since the company has a great cooperation with industries in city of Göteborg, there is good enough access to waste heat from industries. By utilizing more waste heat in the DH-system the need for burning can reduce. This utilization can be maximized when low temperature heat can be used. Heat pumps can then be used for waste heat recovery and also as a link between electricity and DH sector [12]. Heat pumps usage in the DH system are advantageous since they provide flexibility to the DH-systems based on a cooperation with the electricity prices [13]. Moreover, using of heat pumps for heat production while electricity prices are low increase the possibility to store the low cost heat to satisfy the peak need of the heat demand [4].

1.1 Background to the project

GE's main responsibility is to supply district heat and electricity to the whole Göteborg city [14]. During last year GE delivered more than 3300 GWh DH to the consumers in Göteborg and the nearby areas [6]. The company has different large and small production units which includes different types of production like heat only boiler and CHP.

Main production units are: Sävenäs with 4 different boiler and heat production more than 440 GWh during 2019 [15], Rya heat water center with two hot water boilers and production more than 75 GWh during 2019 [16], Rya heat pumps with a capacity of 160 MW [6], Rya natural gas CHP- plant with a heat and electricity production of 462 respective 394 GWh during 2019 [17], Rosenlund with 23 GWh heat in 2019 [18] and Högsbo CHP with 17 GWh heat and 12 GWh electricity in year 2019 [19].

In addition to the company's production units, waste heat from nearby industries is main share of the DH of GE. Preem refinery with a current capacity of almost 60 MW [20], Renova waste-to-energy plant with more than 155 MW [21] and ST1 refinery in Göteborg with heat delivery capacity of about 90 MW [22] are the three major waste heat providers to GE. The delivered waste heat to GE plays the role of base load in the company's heat load duration curve and by decreasing the outdoor temperature and increasing the heat demand, the production units work in order of increasing cost. Figure 1 representing the company's heat load curve based on effect of entire plant and waste heat provider from year 2015 [23].

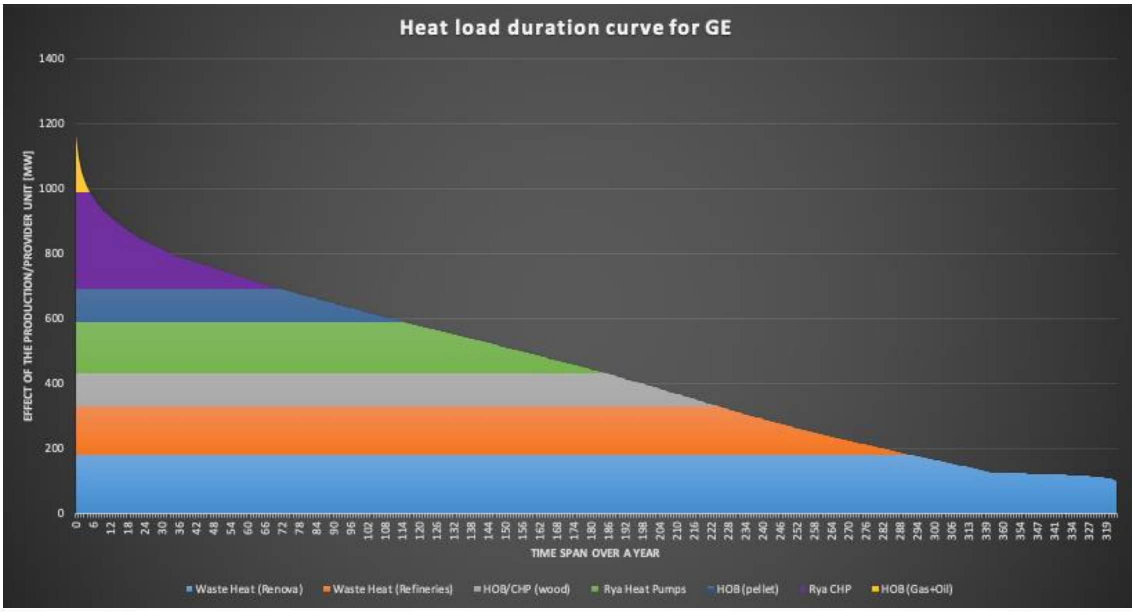


Figure 1 Heat load duration curve for company GE and data from 2015, figure by [23].

When extracting waste heat from an industrial process, the temperature of the cold stream (the return flow of DH to the waste heat provider) is a critical parameter. There is excess heat in low temperatures, in this return flow, but to access that heat a technology like a heat pump should be employed [24].

According to the collected information, Preem applies further cooling to the flow returned from the heat exchanger (HEX) between Preem and GE or further cooling directly on the process stream. This is done since the return flow is not cold enough to be able to cool the internal process [20] [23] [25] [26] [27] [28]. This cooling of the heat carrier by e.g. air coolers or other types of cooling system means wasting of a certain amount of heat. Cooling requires anyway some form of investment and additional energy in form of electricity for pumps or fans which can partially counterbalance the investment and operating costs of heat pumping. By installing heat pump, the heat available at low temperature of the return flow between GE and the waste heat provider can be recirculated to the heat supply process and the temperature of the return flow can be further reduced. This can help GE to take out more heat from the waste heat supplier, and also helps the waste heat provider to reduce the amount of work invested for cooling of the flow [23]. The concept of heat pump installation on the return flow of DH is not a new concept and exists already in some places such as in the DH system in Vienna, Austria [29].

This project, will investigate if installing a heat pump in order to use the return line of DH as heat source and add the heat to the supply flow, is beneficial both for the DH-company and the waste heat providers.

1.2 Goal and Scope

The aim of this Master thesis is to study and investigate some alternatives which facilitate a better usage of the heat at low temperature in the return flow of DH that in the current system either cools down by e.g. air coolers or remain unused. Using heat pump in order to reduce the temperature in the return flow and increase the temperature in the supply flow will be studied as main hypothesis.

Since the project is an investigation on a system between the DH-company, GE, and its waste heat provider companies there are some difficulties for collection of data. Access to detailed data, like hourly mass and temperature of flows is not possible, neither from GE nor from waste heat providers. This is because of many reasons like sensibility of the data and confidentiality issues. Further, since the project is motivated by GE, and waste heat suppliers have not been directly involved from the beginning of the project, getting access to high resolution data from waste heat suppliers could further delay the project.

Another issue in this project is that Preem is planning to rebuild their processes and the refinery plant. This means that the heat exchanging system between GE and Preem could differ in the future, without however knowing in what extent.

The project will focus on the modeling of introducing a heat pump for the current system between GE and Preem, GE and ST1, and GE and Renova. A base-case solution of installing a heat pump in the current system and some other heat pumps integration design alternatives will be studied to assess the sensibility of various design parameters to the thermodynamic efficiency of the system. Further, the impact of the temperature reduction of the DH return flow on the production units of GE is discussed. At the end of the project, some basic economic calculation is implemented to analyze if the solution is economic efficient.

2 Methodology

At the beginning of the project a literature study was conducted for DH-system and heat pump, such as [2] and [30], followed by discussions with the main stakeholders, and model development to illustrate the concept of reducing temperature of the return flow. Then, the concept of installation of heat pump between GE's flows and waste heat suppliers has been formulated.

2.1 Concept

The return temperature in a DH-system depends on different factors. The outdoor temperature and heat demand are two main factors [2], which however cannot be affected by the heat producer [23]. However, taking up heat from the DH return flow as a low temperature source effectively means that a certain amount of energy which would be released in the environment, like the work of a cooler, can be caught and used in for example a heat pump [31]. A heat pump installation, which can take up the heat from return flow of DH and uses it to lift the temperature in the supply side, is thus the main concept for the project.

Waste heat delivery for a DH-company can occur in different ways. One way is, when industry A needs to cool down their process and the cooling medium (mostly water) heats up. The cooling medium can then exchange heat with the DH-water in one or several heat exchangers. The second way is that Industry A uses directly the DH-water as the cooling medium, in this way there is not a certain amount of heat exchangers used to deliver the heat, but the DH-water can go through different parts of the process inside the industry plant. By knowing these, the temperature reduction will have different effects on different plants and the effects depend completely on the processes and the design of the industry plant, as will be discussed laterin this thesis.

To estimate the effect of a heat pump in the system, without considering a specific heat pump device but rather a closed cycle compression heat pump concept, a model based on energy and mass balance equations was developed in Microsoft Excel and was thereby used to optimize the usage of heat pump in order minimize the return temperature; for this purpose the Solver-function Add-in in Excel was used.

The calculations during the project include some general assumptions which are listed in the table below [32] [33]:

Table 1 General assumptions in the project.

Specific heat capacity Cp of water for all temperatures $[\frac{kW}{kg°C}]$	4,19
ΔT_{min} for heat pump condenser and evaporator	5 K
Heat pump Compressor electricity efficiency η_{comp}	90%

Energy and mass balance have been the base of the calculations in this project. For a HEX, the energy balance is depicted as shown in figure 2 [34]:

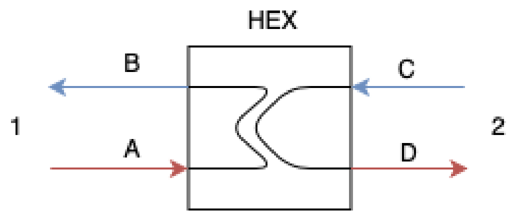


Figure 2 HEX energy balance.

The following relations, eq. 1, represents the set-up of the HEX [35]:

$$m_A = m_B \; and \; m_C = m_D$$

$$Q_{HX_1} = m_1 * Cp * (T_A - T_B) \qquad Eq. \; 1$$

Where Q_{HX_1} is the heat load of the HEX for side 1, m_1 is the mass-flow of side 1, and T_A and T_B is the temperatures for flow A and B respective.
Assuming that heat is supplied from side 1 (side 1 is the hot side), and that the HEX has some losses L_{HEX}, then the following equation can be stated:

$$Q_{HX_1} = \frac{Q_{HX_2}}{(1 - L_{HEX})} \qquad Eq. \; 2$$

Figure 3 shows a set-up of different flows which gather into one flow. For this set-up an enthalpy-balance equation, which is including the assumption of constant Cp for all flows, can be used as in eq. 3 [34]:

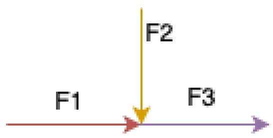


Figure 3 Applying mass-balance on three flows.

$$(m_{F3} * T_{F3}) = (m_{F1} * T_{F1}) + (m_{F2} * T_{F2}) \qquad Eq. \; 3$$

2.1.1 Waste heat delivery to the DH-company

As mentioned earlier, one common set up is that the waste heat is delivered to the DH-company by one or several heat exchangers. To explain this concept, it can be assumed that there is a system like showed in figure 4.

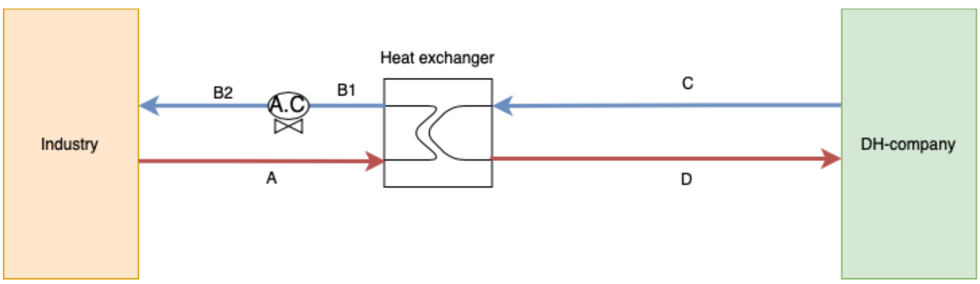


Figure 4 A heat exchanger between a DH-company and an industry which deliver waste heat.

By applying eq. 1 the energy balance would seem as eq. 4:

$$Q_{HX_{ind}} = m_{ind}Cp * (T_A - T_{B1}) \qquad \textit{Eq. 4}$$

According to the DH-company GE [36] the HEX is well-isolated so the losses can be neglected, then eq. 2 can be written as:

$$Q_{HX_{ind}} = Q_{HX_{DH}}$$

There Q_{HX} is the amount heat that the DH-company can take from the HEX, therefore, the heat load of the HEX will be noted by using only Q_{HX}.

where:

$$Q_{HX} = m_{DH}Cp * (T_D - T_C)$$

There m_{DH} is the mass flow of DH and T_D and T_C are the temperatures of flows D and C. From this set up the temperature reduction in flow C would result in temperature reduction in flow B and thereby a lower Air Cooler work.

Another way for delivering waste heat is that the DH-company sends its DH-water inside the industry, which needs cooling, and then the DH-water can work like a cooling medium for the process. The water flows through different devices, e.g. turbine condenser, flue gas condenser, absorption heat pumps etc. Then the flows can be gathered again in one point and sent back to the DH-network. This set up is simply showed in figure 5.

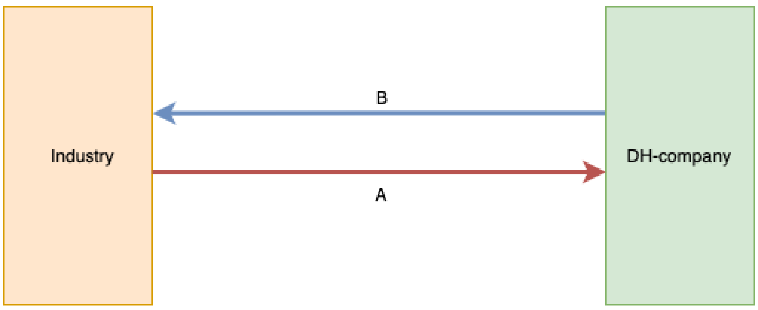


Figure 5 Waste heat delivery to a DH-company without any specific heat exchanger in between.

From Figure 5, it can be understood that the whole industry plant can be seen as a big heat exchanger.

2.1.2 Heat pump

The installation of heat pump in order to reduce the return temperature (flow C in figure 4 and B in figure 5) can occur in different ways. One way is to install the heat pump between the waste heat supplier and the HEX. In this way the temperature of flow B can directly be reduced and then the heat can be added to the supply flow (flow D). This feature has not been studied in this project, but a schematic of the idea is shown in Appendix 1.

The second way is to install the heat pump between the DH-company and the HEX. This feature is the studied set-up in this project because the heat pump is working with heat sources and

sinks from the same company (i.e., GE in this case) which makes its implementation more practical.
The schematic of heat pump is visualized in figure 6.

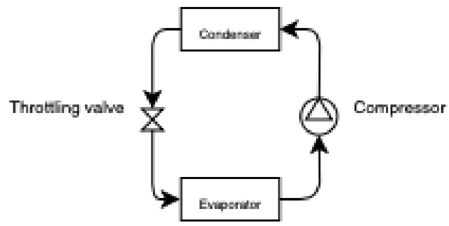


Figure 6 Heat pump schematic.

This industrial heat pump can have different sizes and different temperature lift. The size of the heat pump can be decided based on the compressor, condenser and evaporator loads. The working fluid can be chosen according to the desired temperature lift. The pressure of the working fluid, toxicity and such issues related to the working fluid are the issues which should be thought and studied to be able to choose a correct system. However, these issues are not part of this initial study as the working fluid conditions are within typical ranges of heat pumps and an easy selection should be possible after the optimal heat pump configuration in terms of temperatures and loads is defined.

As mentioned earlier, the concept of heat pump installation in this project is done on the flows between the DH-company and the heat exchanger. The return flow goes through the evaporator and cools down, this energy is then used to evaporate the working fluid of the heat pump which is then compressed to be used in the condenser. In the condenser, the working fluid leaves its energy to heat up the supply flow of DH-water. The temperature reduction of the return flow, the compressor work and temperature lift of the heat pump and the increased heat delivered to DH (i.e., in the form of higher supply temperature) are formulated in equations and visually shown in the schematic in figure 7.

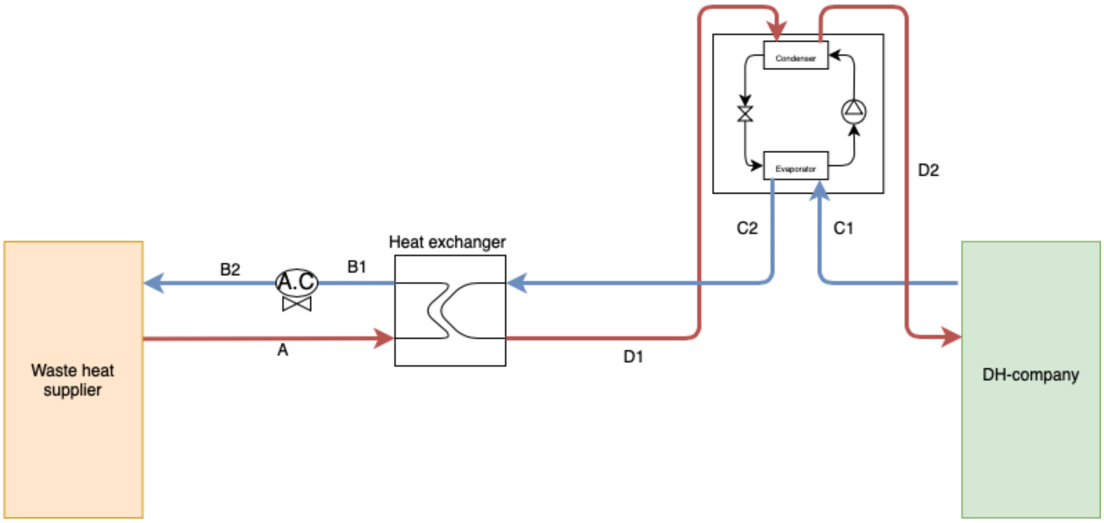


Figure 7 Heat- pump set-up between waste heat supplier heat-exchanger and a DH-company in this project.

The load of the heat pump condenser and evaporator can be calculated using equation 1 on the DH side, as presented in eq. 5:

$$Q_{cond} = m_{DH}Cp * (T_{D2} - T_{D1}) \qquad Eq.\ 5$$

Then for the evaporator it is presented in eq. 6:

$$Q_{eva} = m_{DH}Cp * (T_{C1} - T_{C2}) \qquad Eq.\ 6$$

In these equations, Q_{cond} and Q_{eva} are the condenser load and evaporator load respectively, and T is representing the temperatures for different flows.
The compressor work, W_{comp}, and the electricity consumption of the compressor $W_{El,comp}$, can then be calculated based on the condenser and the evaporator load [34] [37] [38] as presented in equations 7 and 8:

$$W_{comp} = Q_{cond} - Q_{eva} \qquad Eq.\ 7$$

$$W_{El,comp} = \frac{W_{comp}}{\eta_{comp}} \qquad Eq.\ 8$$

The Carnot coefficient of performance (COP_{Carnot}) and the real COP of the heat pump can be estimated as in equations 9 and 10 [34] [37] [38]:

$$COP_{carnot} = \frac{(T_{D2}+\Delta T_{min})}{(T_{D2}+\Delta T_{min})-(T_{C2}-\Delta T_{min})} \qquad Eq.\ 9$$

where the temperatures in eq. 9 are in Kelvin. Further it is assumed that the working fluid of the heat pump condenses and evaporates at constant temperature, which means that $(T_{D2} + \Delta T_{min})$ and $(T_{C2} - \Delta T_{min})$ in eq. 9 are the smallest temperature difference in the condenser respective evaporator.

$$COP_{real} = \frac{Q_{cond}}{W_{comp}} \qquad Eq.\ 10$$

And finally, the heat pump efficiency is calculated as presented in eq. 11 [37] [38]:

$$\eta_{HP} = \frac{COP_{real}}{COP_{carnot}} \qquad Eq.\ 11$$

2.1.3 Excel - Solver

Optimization of a function can be done in many different software but in this project, it has been chosen to implement it in Excel-solver. To optimize a function in solver it needs an objective function, one or several variables and optionally a number of constraints. Excel-solver comprises None-linear GRG, Simple LP and Evolutionary optimization algorithms.

For the waste heat supplier using a HEX to deliver the heat, two main scenarios on the design were implemented. For the waste heat suppliers which use directly the DH-water only one design option was implemented. Sensitivity analyses on different parameters (flow rates through the condenser and the evaporator of the heat pump), have been done in all cases a will be explained later in detail. During the project two different objective functions have been tried. The first objective function was maximizing the ratio of the air cooler's work divided by the heat pump compressor work:

$$Maximize \quad \left(\frac{\Delta Q_{AC}}{W_{comp}}\right)$$

This was decided and applied to analyze how much cooling work can the concept win in relation with the electricity work that the heat pump consumes. The alternative objective function was to directly minimize the temperature of the return flow of DH (flow C2 in figure 7 and flow C5 in figure 8). Since the goal of this project was to reduce the temperature of the return flow, in the middle of project it became discussed and decided to set the temperature reduction as the objective function. In other words, minimizing the temperature of the flow to the main HEX became the new objective function. The result of both this objective function will be presented in the result chapter.

2.1.3.1 Scenario 1

The schematic of scenario one is visualized in figure 8:

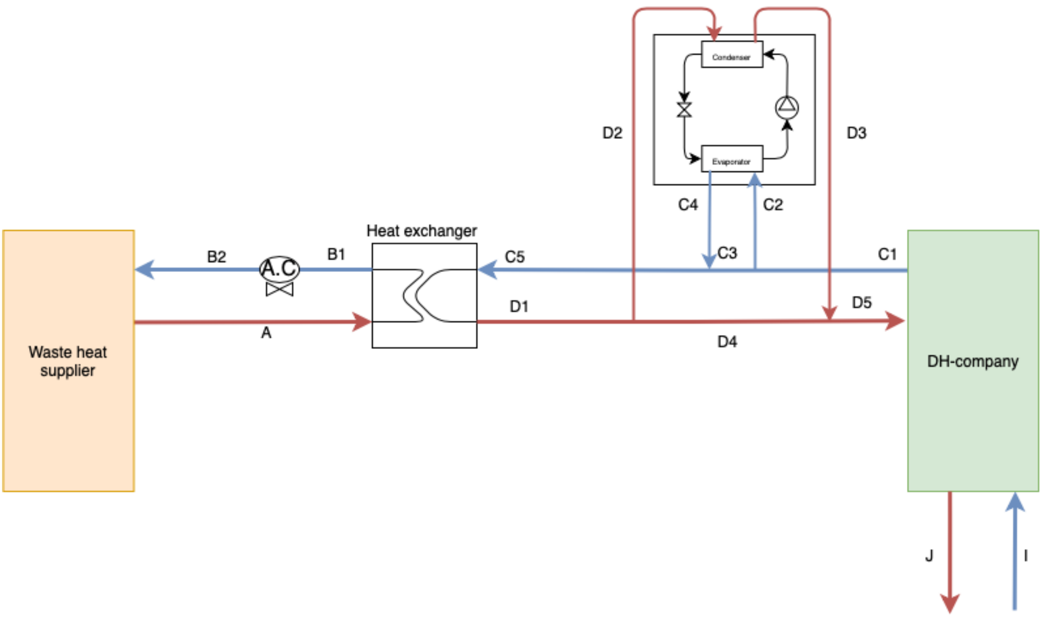


Figure 8 Overview of scenario 1, a heat pump between the HEX and DH-company.

Assumptions and given data (given as a system specification):

- $T_A = given$: This temperature is set based on a mean value of historic data.
- $T_{B2} = given$
- $T_{B1} = calculated$
- $Q_{HX} = given$
- $T_{C1} = given$
- $T_{D1} = given$: This temperature is set based on a mean value of historic data.

- $T_{D5} = given$: This temperature is set to a specific value higher than the temperature of flow D1. Without higher temperature than D1 the energy balance of the system including heat pump is impossible.

- $C_p = constant\ for\ all\ flows$
- $m_{DH} = given$
- $m_{ind} = calculated\ based\ on\ the\ current\ system\ for\ the\ given\ Q_{HEX_{ind}}$.

Variables:
- T_{C4}
- $X\ (fraction\ of\ mass - flow\ to\ evaporator)$
- $Y\ (fraction\ of\ mass - flow\ to\ condenser)$

Equations:
In addition to the equations described above, the following equations have been formulated in order to define the model in Solver:

$T_{B1_{after-HP}}$ → *Eq. 1* → $T_{B1} = T_A - \frac{Q_{HX}}{m_{ind}Cp}$ *Eq. 12*

$$T_{C1} = T_{C2} = T_{C3}$$

$$T_{D1} = T_{D2} = T_{D4}$$

$$m_{C2} = X * m_{C1} \qquad \text{Eq. 13}$$

From eq. 3:

$$m_{C3} = m_{C1} - m_{C2}$$

$$\mathrm{m_{C4}} = \mathrm{m_{C2}}$$

$$m_{C5} = m_{C1}$$

By using eq. 3 the temperature of flow C5 is calculated as eq. 14:

$$T_{C5} = \frac{(m_{C3} * T_{C3}) + (m_{C4} * T_{C4})}{m_{C5}} \qquad \text{Eq. 14}$$

Flows D1, D2, D3 and D4 are calculated based on Y as presented in eq. 15:

$$m_{D2} = Y * m_{D1} \qquad \text{Eq. 15}$$

$$m_{D4} = m_{D1} - m_{D2}$$

$$m_{D3} = m_{D2}$$

And the temperature of flow D3 is calculated as shown in eq. 16:

$$T_{D3} = \frac{(m_{D5} * T_{D5}) - (m_{D4} * T_{D4})}{m_{D3}} \qquad \text{Eq. 16}$$

The load of the air cooler (A.C in the schematic) before and after implementing heat pump in the system are signed with $Q_{AC_{before-HP}}$ and $Q_{AC_{after-HP}}$ respectively, and are calculated as presented in equations 17 and 18:

$$Q_{AC_{before-HP}} = m_{ind} Cp \left(T_{B1_{before-HP}} - T_{B2}\right) \qquad \textit{Eq. 17}$$

$$Q_{AC_{after-HP}} = m_{ind} Cp \left(T_{B1_{after-HP}} - T_{B2}\right) \qquad \textit{Eq. 18}$$

In equations 17 and 18, $T_{B1_{before-HP}}$ is the temperature of flow B1 before implementing heat pump in the system, and $T_{B1_{after-HP}}$ is the temperature of flow B1 after implementing heat pump in the system.

Then the difference between the air cooler work before and after implementing heat pump is signed as ΔQ_{AC} and is calculated as shown in eq. 19:

$$\Delta Q_{AC} = Q_{AC_{before-HP}} - Q_{AC_{after-HP}} \qquad \textit{Eq. 19}$$

Objective function:

$$Maximize \quad \left(\frac{\Delta Q_{AC}}{W_{comp}}\right)$$

Alternative Objective function:

$$Minimize \left\{ \quad T_{C5} = \frac{(m_{C3} * T_{C3}) + (m_{C4} * T_{C4})}{m_{C5}} \right\}$$

For the heat pump installation different scenarios were considered. These different scenarios refer to the connection of the DH-flows to the condenser and evaporator. This can also be an indirect sensitivity analysis on the connection. Depending on the studied case, the variables, objective function and some of the equations are changed in some of the scenarios, as will be explained later in this thesis.

Constraints:
The variables should have an upper and lower limit. In this case:

1- $30\ oC < T_{C4} < 40$ oC
2- $0 < X < 1$
3- $0 < Y < 1$
4- $30\ oC < T_{C5} < 40$ oC
5- $T_{C5} < T_{B1}$
6- $Q_{cond} > 0$
7- $Q_{eva} > 0$
8- $Q_{cond} > Q_{eva}\ (or\ W_{comp} > 0)$
9- $\Delta Q_{AC} > 0$
10- The heat pump efficiency should have limits. In this case:

$$0{,}2 < \eta_{HP} < 0{,}6$$

The limits of the heat pump efficiency is set after a discussion with examiner of the thesis and the supervisor at company [23] and also a literature review [39].

2.1.3.2 Scenario 2

The set-up of this scenario was suggested by the supervisor of the project at company GE. The background for this set-up is that this is one of the connection ways of such heat pumps in reality, to install it on the costumer's side specially at a bottleneck area of DH-network and regulate the flow and the temperature of the DH [23]. The schematic of scenario 2 is figure 9.

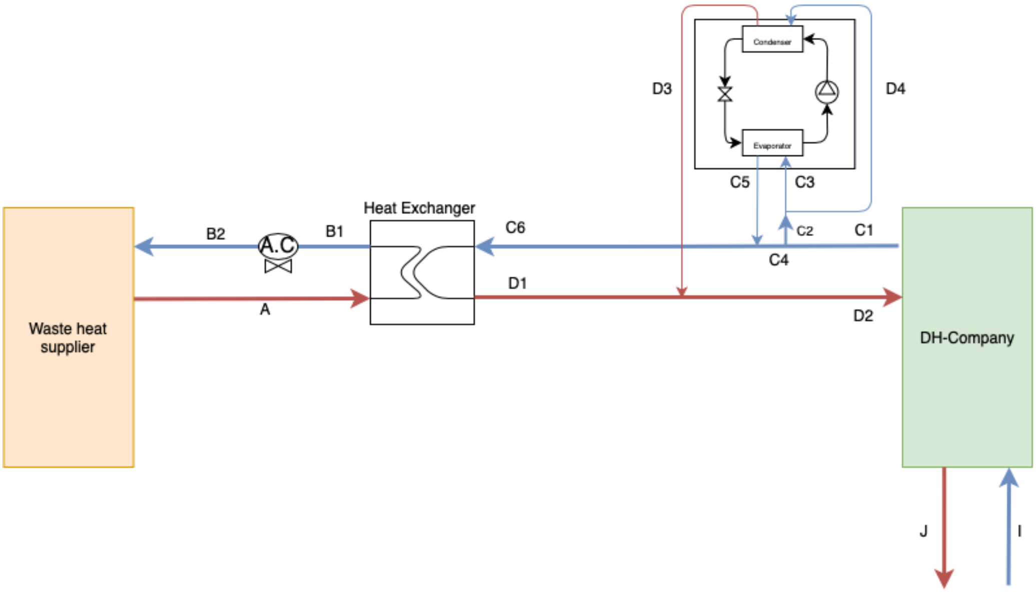


Figure 9 Schematic overview of scenario 2.

The input data and the objective function were the same as in previous scenario, but some equations are changed because of the different process layout.

Assumptions and given data:

- $T_{C1} = T_{C2} = T_{C3} = T_{C4} = T_{D4} = given$
- $T_{D1} = given$: This temperature is set based on a mean value of historic data.

- $T_{D2} = given$: This temperature is set to a specific value higher than the temperature of flow D1. Without higher temperature than D1 the energy balance of the system including heat pump is impossible.

- $T_{C6} = Calculated\ by\ help\ of\ eq. 3$
- $Other\ assmptions\ are\ same\ as\ in\ Scenario\ 1.$

Variables:

- T_{C5}
- T_{D3}
- *X (fraction of C1 for C2)*
- *Y (fraction of C2 for C3)*

Equations:

Applying the equations 3 and 9 for flows C1 to C5 and D1 to D4:

$$m_{C2} = X * m_{C1} \qquad \textit{Eq. 20}$$

$$m_{C3} = Y * m_{C2} \qquad \textit{Eq. 21}$$

$$m_{D4} = (1 - Y) * m_{C2} \qquad \textit{Eq. 22}$$

$$m_{C5} = m_{C3}$$

$$m_{C4} = m_{C1} - m_{C2}$$

$$m_{C6} = m_{C5} + m_{C4}$$

$$\{m_{D1} = m_{C6} \quad \& \quad m_{D3} = m_{D4}\} \rightarrow \quad m_{D2} = m_{D1} + m_{D3}$$

And by using equation 3 the temperatures for flows C6 and D3 can be calculated as presented in equations 23 and 24:

$$T_{C6} = \frac{(m_{C5}*T_{C5})+(m_{C4}*T_{C4})}{m_{C6}} \qquad \textit{Eq. 23}$$

$$T_{D3} = \frac{(m_{D2}*T_{D2})-(m_{D1}*T_{D1})}{m_{D3}} \qquad \textit{Eq. 24}$$

Constraints:
Most the constraints are the same as in Scenario 1, but since the structure is different one of the limits were in need of changes.

- $90 < T_{D3} < 150$

Objective function:

$$Maximize \quad \left(\frac{\Delta Q_{AC}}{W_{comp}}\right)$$

Alternative Objective function:

$$Minimize \left\{ \quad T_{C6} = \frac{(m_{C5} * T_{C5}) + (m_{C4} * T_{C4})}{m_{C6}} \right\}$$

2.1.4 Cost estimation for the Heat Pump

The project does not include investment costs in the cost calculation. The following calculations are only to show approximately the benefit of the temperature reduction for the DH-company and the Waste heat supplier by installation of one (or a set of) heat pump(s).

The time resolution during this project is set to weekly resolution, in other words, the electricity prices and heat prices are weekly mean values for a “winter half year”, which is approximately from the middle of September to the end of April.

The electricity price has been downloaded from Nordpool [40] which is a reliable source for electricity price in north part of Europe. The electricity tax in Sweden is taken from Skatteverket [41] and the other fees are provided by Göteborg Energi AB [23]. The waste heat prices used in this thesis are approximate prices based on the currently used fuels and fuel prices [36]. Thus, the waste heat prices are not real and this because of secretes issues between companies. Since by decreasing the outdoor temperature more production units in a DH-company will be running, the price of heat would increase by decreasing the outdoor temperature. The outdoor temperatures for each week have been estimated as mean values based on hourly temperature for each day. Then, the weeks have been ordered from coldest to warmest and thereby the coldest week got the most expensive heat price. The weekly heat prices then decreased by increasing outdoor temperature.

The installed heat pump will not be working during all the winter [23], and by increasing outdoor temperature and decreasing heat demand the usage of the heat pump in the DH-system will reduce. Therefore, a running-rate has been decided for the heat pump based on the outdoor temperature. By running rate here it means that for the weeks with mean outdoor temperature below 7,5°C the heat pump would work with 100% of its capacity, for the outdoor temperature between 7,5°C and 8°C the heat pump will be running at 70% of its capacity, and for the outdoor temperatures between 8°C and 8,5°C it will run at 50% of its capacity. This is set after a discussion with the supervisor of the thesis and according to an already existed heat pump in the company GE [23].

Finally, based on these assumptions and data the heat cost, the heat load of the main HEX can be calculated and by calculating the electricity cost of the heat pump, a break-even price for the waste heat can also be calculated.

Break-even price in this thesis is referring to the price which DH-company would pay, after implementing and running the heat pump, in a given amount of time the same money as they are paying now for only the waste heat. The break-even price can be translated as the original waste heat price subtracting the cost of cooling which the waste heat supplier should pay to cool down the return flow to the desired temperature [42]. The assumptions and the equations for the cost calculation is shown below:

Assumption:

- Index i represent the number during the winter period
- Electricity Price, $P_{el,i}$: Mean weekly electricity price for each week $[\frac{SEK}{MWh_{el}}]$
- Waste heat Price, $P_{WH,i}$: Given $[\frac{SEK}{MWh_{heat}}]$
- Outdoor temperature, $T_{od,i}$: Mean weekly temperature calculated based on hourly temperature $[°C]$
- Electricity tax, Tax_{el}: Given $[\frac{SEK}{MWh_{el}}]$
- Other electricity fee, F_{el}: Given $[\frac{SEK}{MWh_{el}}]$
- Maintenance price, P_{Main}: Given $[\frac{SEK}{MWh_{heat}}]$
- Break-even price of waste heat, BEP_{WH} $[\frac{SEK}{MWh_{heat}}]$
- Price of fuel, $P_{fuel}[\frac{SEK}{MWh}]$
- Weeks: From middle of September to the end of April (33 weeks)
- Heat pump running rate, $R_{HP,i}$: Given $[rate\ in\ \%]$

- Hour to week factor, H: 168 $[\frac{hour}{week}]$

Waste heat cost for one week, C_{WH_i}:

$$C_{WH_i} = P_{WH} * H * Q_{HX} \quad [\frac{SEK}{Week}] \qquad Eq.\ 25$$

While the heat pump is installed and running the return flow is cooler than before, this means that the load of the main HEX is now more, so the amount heat bought by the DH-company is now more. This new cost for the waste heat is shown by an index *new* which represent the heat cost with the new load of the HEX eq. 26:

$$C_{WH_{i,new}} = P_{WH} * H * Q_{HX_{new}} \quad [\frac{SEK}{Week}] \qquad Eq.\ 26$$

The electricity cost of the heat pump compressor is calculated as following in equations 26 and 27:

$$P_{el,tot,i} = P_{el,i} + Tax_{el} + F_{el} \quad [\frac{SEK}{MWh_{el}}] \qquad Eq.\ 27$$

$$C_{el,HP,i} = P_{el,tot,i} * H * R_{HP,i} * W_{El,comp} \ [\frac{SEK}{Week}] \qquad Eq.\ 28$$

And the maintenance cost of the heat pump is calculating by using eq. 25 as presented in eq. 28:

$$C_{Main,i} = P_{Main,i} * H * R_{HP,i} * Q_{Cond} \quad [\frac{SEK}{Week}] \qquad Eq.\ 29$$

Then, to estimate the break-even price of waste heat eq. 30 is used:

$$BEP_{WH,i} = \frac{\left(C_{WH_i} - C_{el,HP,i} - C_{Main,i}\right) + \left(\left(Q_{HX,new} - Q_{HX} + W_{el,comp}\right) * P_{fuel} * H * R_{HP_i}\right)}{H * Q_{HX_{new}}} \quad [\frac{SEK}{MWh_{WH}}] \qquad Eq.\ 30$$

The idea of calculating a BEP in eq. 30 is to see which price for waste heat would be cost beneficial for GE including a heat pump in the system. The existence of heat pump means more extracted heat from the HEX, and also additional energy in form of electricity to the system. This additional energy in the system is then resulted in form of higher temperature in the supply flow (90°C compared to the current 80°C). This is therefore included in form of a benefit for the DH-company in eq. 30. The benefit is that if the company would increase the supply temperature from 80°C to 90°C by e.g. a HOB, they would need to pay a fuel cost. This fuel cost here is assumed to be equal to the highest price of the waste heat during the winter period. By assuming this fuel price in eq. 30 the BEP for DH-company includes most of factors that can affect the heating prices.

The new weekly waste heat cost can then be calculated based on the break-even prices for every week, as presented in eq. 31:

$$C_{WH,BEP_i} = BEP_{WH,i} * H * Q_{HX_{new}} \quad [\frac{SEK}{Week}] \qquad Eq.\ 31$$

This waste heat price reduction can be assumed as a compensation for the savings in the cooling cost. The cooling price and cost, based on the above calculation approach, can be shown as in equations 32 and 33:

$$C_{cooling_i} = \quad C_{WH_i} - C_{WH,BEP_i} \quad [\frac{SEK}{Week}] \qquad Eq.\ 32$$

$$P_{Cooling_i} = \frac{C_{cooling_i}}{Q_{eva} * H} \quad [\frac{SEK}{MWh_{cool}}] \qquad Eq.\ 33$$

The weekly costs of the above parameters are summarized for the whole winter period of 33 weeks:

$$C_{WH_{Winter}} = \sum_{i=1}^{33} C_{WH_i} \quad [\frac{SEK}{Winter}] \qquad Eq.\ 34$$

Electricity cost, maintenance cost, waste heat cost based on the BEP and the cooling cost are also summarized for a winter period of 33 weeks. This has been done to be able to analyze a weekly resolution but also the cumulative costs per year.

To compare the calculated cooling cost for the waste heat provider with a reference cooling cost, the paper of [43] was used. The paper shows a typical cooling price in country Switzerland. Based on the paper [43] a cooling price of 100 $[\frac{\text{SEK}}{\text{MWh}_{\text{cooling}}}]$ is assumed just to be able to compare the calculated price with a reference price. However, this price seems to a little high for the situation in Sweden.

2.2 Concept for Preem

Preem refinery in Göteborg is one of the waste heat suppliers to GE. Refinery processes and products (directly after production) are in need of cooling [20]. This means that there will be a good access to waste heat in a refinery plant [28].

Earlier studies and an interview with GE provided initial information for the connection between Preem and GE. According to the information from GE, Preem delivers waste heat by two HEX to GE and Volvo [20] [23]. The heat exchanger which delivers to GE has a capacity of around 60 MW and the heat exchanger which delivers to Volvo has a capacity about 40 MW [20].

Although a detailed description of Preem’s plant and utility system is outside the scope of this project, it can only be pointed out that Preem has internal cooling system which exchanges heat by an external system, flows A and B in figure 11, and this external system exchanges heat with DH-system, flow D and C [20]. Since in this project the focus has been on the DH-system and the delivered waste heat from the suppliers, the connection between Volvo and DH-network is neglected. Thereby, the studied system is summarized in figure 10.

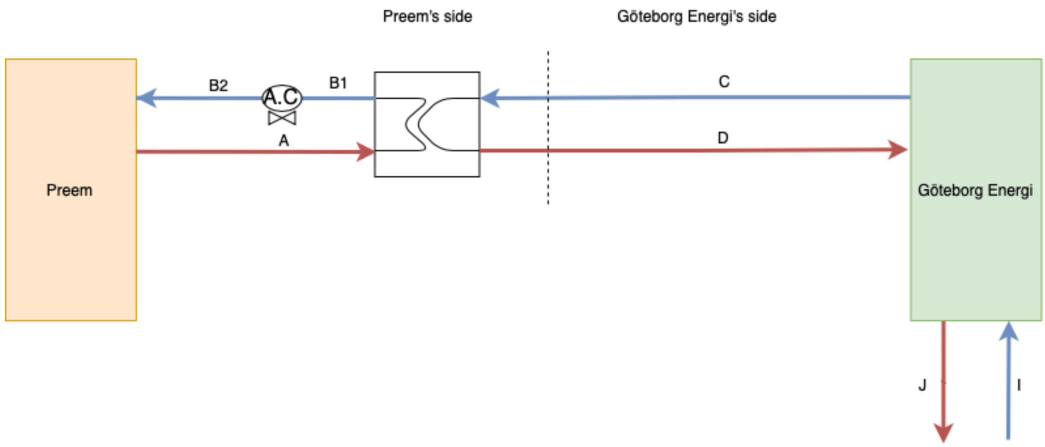


Figure 10 The studied system between Preem and GE.

In the figure 10 the flow C and D, represent the DH-pipes of GE and flows I and J represent the network of DH. According to Preem, the temperature of the return flow should not be lower than 30°C. Lower temperature than this might cause salt precipitation, fouling or unwanted condensation in their internal system [20]. Table 2 shows the input data used in this study [23] [36]:

Table 2 New data for the main HEX after the interview with Preem.

Minimum temperature difference in the HEX (ΔT_{min})	5
Temperature of flow D [°C]	80
Temperature of flow C [°C]	41,9
Mass flow GE-side (m_{DH}) [kg/s]	350
Temperature of flow A [°C]	90
Temperature of flow B1 [°C]	49

Then the mass-flow in Preem's side was calculated as:

$$From\ eq.1:\quad Q_{HX} = m_{pr}C_{p_{Ind}} * (T_A - T_{B1}) \rightarrow m_{pr} = \frac{Q_{HX}}{Cp_{pr} * (T_A - T_{B1})}$$

$$Q_{HX} = 55{,}8\ MW \quad and \quad m_{pr} = 325{,}2\ [\frac{kg}{s}]$$

Both scenarios presented in Figure 8 and Figure 9 are applied to Preem along with sensitivity analysis described next.

2.2.1 Sensitivity analysis

The first sensitivity analysis was the change of the objective function in both scenarios. Further, since the result of optimization showed always $X = Y = 1$ for Scenario 1 and $X = 1$ for

Scenario 2, the sensitivity analysis has been done to study for each case by setting different values for X and Y.

2.2.2 Investigation for waste heat at lower temperature

One important point that Preem has stated during the interview was that if GE wants heat at a lower temperature than what it is now, then Preem can send more waste heat to the heat exchanger [20]. This low temperature heat can be exemplified as heat at 80°C instead of today's 90°C from Preem. This was then a ground for an extra investigation for heat at lower temperature and at a lower price.

The first assumption for this idea was that Preem could provide an additional 15% of the current heat load at 80 oC (based on a cooling curve in [45]). The idea was then to have a two-stage heat exchanger. The first stage exchanges the heat at 90°C from Preem and the return flow will be at 80°C. Then this return flow becomes mixed with the extra available heat at 80°C and goes in to the second stage HEX which exchanges heat and become 49°C, as in current system (note that this return temperature will reduce after applying heat pump in the system). The schematic of the system is illustrated in figure 11.

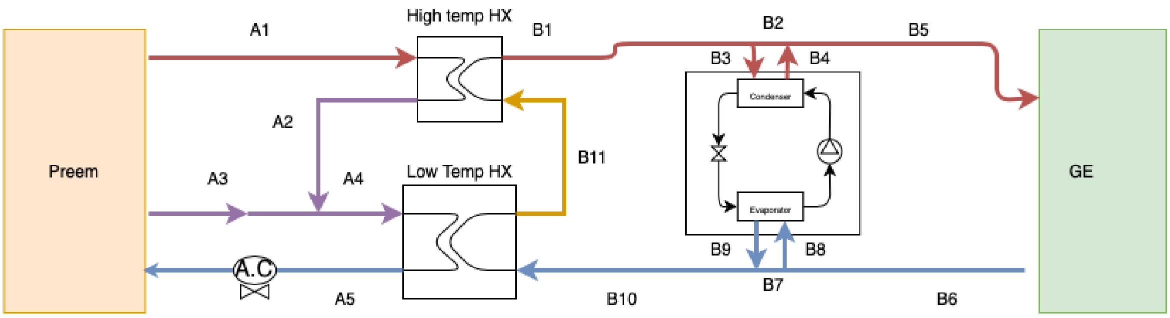


Figure 11 Illustration of the system with 15% more available heat at 80°C and its double HEX.(Note that in the figure below, the colors are indicating the temperature levels in the flows and same colors do not mean that they are the same flow).

Assuming that Preem sends a heat load $Q_{HX_{pr}}$ to the main HEX, then the heat load of 15% more available heat at low temperature is showed as Q_{LT} and is presented in eq. 35:

$$Q_{LT} = Q_{HX_{pr}} * 0{,}15 = 8{,}3\ MW \qquad Eq.\ 35$$

The temperatures are assumed to be:

$$T_{supply_{LT}} = 80°C \text{ and } T_{return} = T_{B1} \text{ in current model} = 49\ °C$$

So, the mass-flow is presented in eq 36:

$$m_{LT} = \frac{Q_{LT}}{Cp*(T_{supply} - T_{return})} = 64{,}5\ [\frac{kg}{s}] \qquad Eq.\ 36$$

Now this mass-flow can be used to construct the model with a double HEX. According to figure 11, flow A1 has a temperature at 90°C and the mass-flow is same as before, 325 [kg/s]. This flow goes into the high temperature heat exchanger (HTHX) and cools down to 80°C. Flow A2 mixes with flow A3 which is also at 80°C and the total mass-flow, m_{A4}, becomes as presented in eq. 37:

$$m_{tot,pr} = m_{LT} + m_{pr} = 389{,}5\ [\frac{kg}{s}] \qquad Eq.\ 37$$

This flow then cools down in the low temperature heat exchanger (LTHX) to 49°C. In the other side the return flow of GE enters to the LTHX at 41,9°C and heats up to 70°C. This temperature is chosen based on the data from the company, where a typical temperature difference between entering and leaving flows was 10°C. If then this temperature is chosen, to be able to have a complete heat transfer and cool Preem's flow the flow of GE should increase. This increase in the flow is presented as in equations 38 and 39:

$$Q_{LTHX_{pr}} = Q_{LTHX_{GE}} = Q_{LTHX}$$

$$m_{GE,new} = \frac{Q_{LTHX}}{Cp*\left(T_{out}-T_{return_{GE}}\right)} = 428,8 \left[\frac{kg}{s}\right] \quad \text{Eq. 38}$$

$$m_{add\_GE} = m_{GE,new} - m_{GE} = 78,8 \left[\frac{kg}{s}\right] \quad \text{Eq. 39}$$

After the LTHX all the flow of GE flows into the HTHX and heats up to a temperature which has been calculated, by using energy balance equation like equation 1, to 77,5°C. The values of the calculation before applying heat pump are shown in table 3.

Table 3 Values for the concept of Double HEX, before applying heat pump in the system.

Temperature after LTHX	70
Temperature after HTHX	77,5
Total mass flow of DH-water [kg/s]	428,8
Heat load LTHX [MW]	50,5
Heat load HTHX [MW]	13,6

2.2.2.1 Appliance in Solver

The variables in this approach are:

- T_{B1} temperature after the HTHX
- T_{B4} temperature after the heat pump condenser
- T_{B9} temperature after the heat pump evaporator
- X fraction of B6 for B8
- Y fraction of B1 for B3
- $m_{add_{GE}}$ the additional mass-flow of DH to satisfy the heat transfer in the HEX.

After deciding variables, equations 40-42 are applied:

$$Q_{HTHX} = m_{current_{pr}} * Cp * (T_{A1} - T_{A2}) \quad \text{Eq. 40}$$

$$T_{A5} = T_{A4} - \frac{m_{new,GE}*Cp*(T_{B11}-T_{B10})}{(1-loss\ share)*(Cp*m_{tot,pr})} \quad \text{Eq. 41}$$

$$Q_{new,15\%} = m_{LT} * Cp * (T_{A3} - T_{A5}) \quad \text{Eq. 42}$$

Other unknown parameters have been found by energy- and mass-balance equations which are already explained. The heat pump parameters have also the same equations as previously presented.

Constraints:
The constraints for this case were the same as in the previous cases, upper and lower limit for the variables, constraints for the temperatures in and out to and from the HEXs, constraints for the condenser and evaporator load, the compressor work and the limits for the efficiency of the heat pump.

Objective function:
The objective function in this case is to minimize the temperature back to the LTHX (flow B10).

Cost calculation for the Double HEX
The double HEX is fed with a high temperature stream at 90°C and a low temperature stream at 80°C. The heat load of these streams is calculated by using eq. 1 and rewriting it as in eq. 43:

$$Q_{90°C,pr} = m_{current,pr}Cp(T_{A1} - T_{A5}) \qquad \text{Eq. 43}$$

$$Q_{80°C,pr} = m_{LT}Cp(T_{A4} - T_{A5})$$

Since the heat exchangers are assumed to be without losses the heat loads give then:

$$Q_{90°C,GE} = Q_{90°C,pr}$$

$$Q_{80°C,GE} = Q_{80°C,pr}$$

The main assumption for the cost calculation in this case is that the price of the low temperature heat is zero, $P_{WH,LT} = 0$ and the only cost for the DH-company is the cost of the heat at 90°C. The weekly waste heat cost, C_{WH_i} , is the same as before (eq. 25) and the new cost of weekly waste heat has been rewritten as presented in eq. 44:

$$C_{WH_{i,new}} = (P_{WH_i} * H * Q_{Q_{90°C,GE}}) + 0 \quad [\frac{SEK}{Week}] \qquad \text{Eq. 44}$$

The electricity cost, maintenance cost, the break-even prices and the new weekly heat costs based on the break-even prices (C_{WH,BEP_i}), and the cooling cost are calculated with the same approach and formulas as already explained. The additional calculation in this case was the calculation of the revenue of the additional DH-flow. By calculating the load of the additional DH-water and assuming a DH-price [46], the revenue is calculated as showed in Table 4:

Table 4 Price and Revenue of selling DH for GE, based on assumed heat price.

Price of DH, P_{DH} $[\frac{SEK}{MWh}]$	84,8
Heat load of the additional DH-water after applying HP, $Q_{add_{new}}$ $[MW]$	16,6
Revenue of the additional mass-flow, Rv_{DH} $\left[\frac{MSEK}{Week}\right]$	0,24

$$Rv_{DH} = P_{DH} * Q_{add_{new}} * H \quad [\frac{SEK}{Week}] \qquad \text{Eq. 45}$$

By having this, the weekly net cost has been calculated as eq. 46:

$$C_{net,GE_i} = C_{WH,BEP_i} - Rv_{DH} \qquad \text{Eq. 46}$$

2.3 Concept for ST1

ST1 is another refinery company in Göteborg. As well as Preem, ST1 is also in need of cooling and thereby is able to deliver waste heat [36]. The difference between ST1 and Preem is that ST1 use GE's water as coolant and it means that there is no specific HEX between ST1 and GE to supply the waste heat [36].

Information about ST1 was in form of a set of data for around three years [36]. The data contents the outdoor temperature, the supply and return temperature of the DH-water and the delivered effect. By Studying the data and removing the extreme hours and days, a new set was constructed. This new data set gave then a mean value for the supply and return temperature and also the mass-flow, which were different from the data for Preem.
These differences in the structure of connection and the data, was the reason that the ST1 case was studied separately from the Preem's case. Further, since Scenario 2 in Preem's case did not show good results, only Scenario 1 was studied for ST1. Table 5 summarize the information about the refinery ST1.

Table 5 Collected and calculated data for ST1 refinery.

Supply temperature to GE [°C]	85
Return temperature from GE to ST1 [°C]	45
Heat load [MW]	90
Mass flow [kg/s]	535

The connection between GE and ST1 seems more or less like in the figure 2. The idea of applying heat pump would then look like in figure 12.

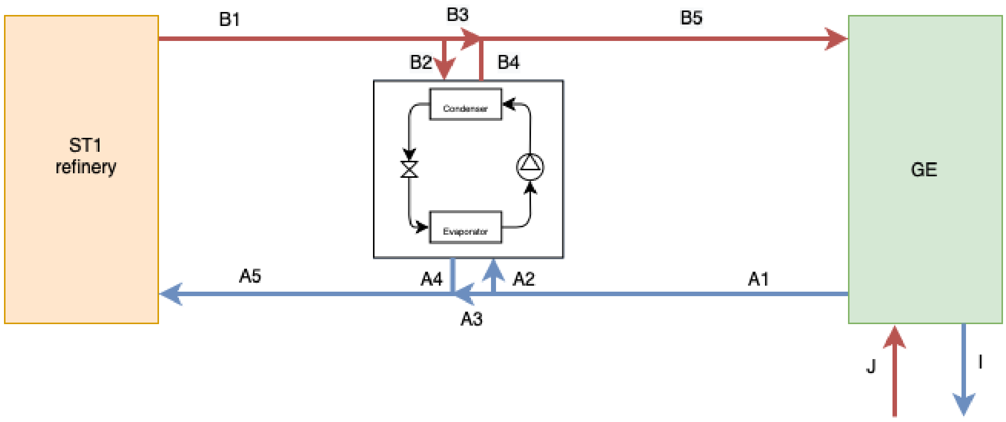


Figure 12 Heat Pump configuration between GE and ST1.

After a discussion with the supervisor at GE and looking at an old document between GE and ST1, it has been established that temperature reduction would also be desired from ST1 side. Lower return temperature would help the refinery to have a more effective cooling and save a certain amount of cooling cost.

Applying the concept of heat pump installation for ST1 was a little different from the Preem's case. Since there is no specific HEX in this connection there is no need to include any equation about the main HEX. The current supply and return temperature are different, based on historical data. The principal of the approach of appliance in Solver is the same as in case of Preem, the only main difference is that the temperature of B5 is not set in this model, but it is calculated based on the temperature of B4, which is a variable. Other assumptions and used equations are the same as previously presented.

Assumptions and input data:
The assumptions are mostly same as for scenario 1 of Preem, except the differences in the supply and return temperature.

Variables:
The variables are the same as for Scenario 1 in Preem case.

Equations:
The equations used here follows the same approach as in scenario 1 for Preem.

Constraints
Major of constraints are the same as Scenario 1 for Preem. In this case there is no calculation for the air coolers so thereby no constraint for it. The limits for the temperatures of flows A4 and B4 are presented as:

- $30°C < T_{A4} < 44°C$
- $86°C < T_{B4} < 90°C$

The upper limit of the temperature for flow B4 is set to values 90°C,95°C, 100°C and 105°C to see how it affects the temperature reduction.

2.4 Concept for Renova

Renova is a waste-burning CHP plant in Göteborg. The idea is to get heat and power by using waste as fuel in the boiler. Renova's process consists of many devices like condensers, pre-heaters, absorption heat pumps etc. GE's DH-water flows in to the Renova process plant and circulates as cooling medium [21]. Since the plant is a CHP plant and not like Preem and ST1 a refinery, there was a need of pre-study about the temperature reduction. Therefore, an interview has been done with a process engineer at Renova [21]. According to the retrieved information, the return DH-water from GE goes directly to flue-gas condenser to cool down the flue-gases. Then it continues to other absorption heat pumps and other devices. A screen shot of the process depicting this concept is available, in Appendix 2. Figure 13 shows the configuration of the direct condenser.

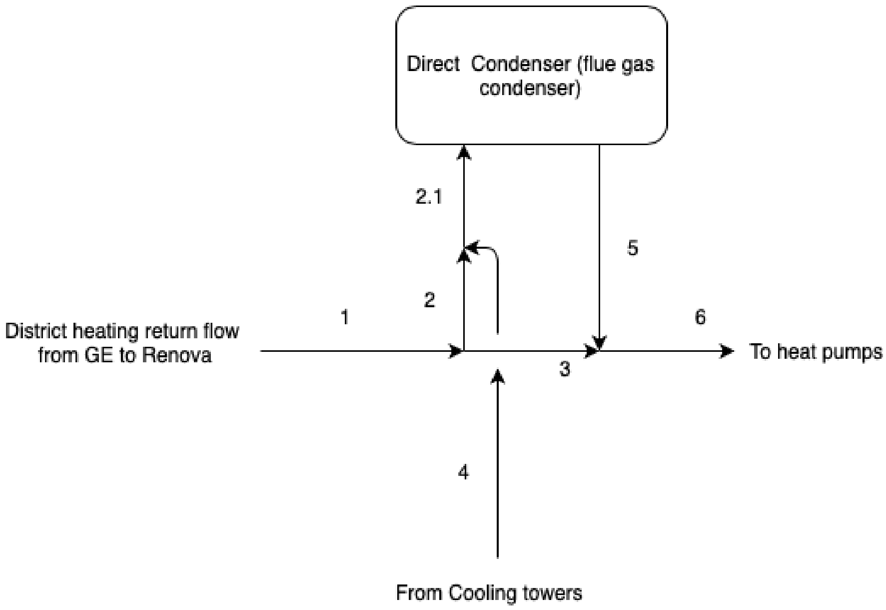


Figure 13 Schematic of the flows around the direct condenser (flue-gas condenser) at Renova.

Based on the information in the screen shot (Appendix 2), a mass- and energy balance was applied for the flue-gas condenser. Table 6 shows the available information for the illustration in figure 13.

Table 6 Data and information for Direct Condenser at Renova plant, Screenshot in Appendix 1.

Volume flow of DH $[m^3/h]$	1775
Volume flow of 2.1 $[m^3/h]$	1764
Volume flow of 4$[m^3/h]$	1110
T1 [°C]	38,7
T4 [°C]	47
T6 [°C]	47,2

Further relations and calculations will be as following [34]:
Density of water [32]

Table 7 Water density.

$\rho(40°C)\left[\frac{kg}{m^3}\right]$	992,2
$\rho(95°C)\left[\frac{kg}{m^3}\right]$	965,1
$\rho_{Renova} = \frac{\rho(40°C) + \rho(95°C)}{2}$	978,7

$$m = v * \rho_{Renova} \qquad \text{Eq. 47}$$

By using this equation, the mass flows of streams 1, 2.1 and 4 will be found.
Then:

$$m_2 = m_4 - m_{2.1}$$
$$m_3 = m_1 - m_2$$
$$m_5 = m_{2.1}$$
$$m_6 = m_5 + m_3$$

So, all the mass flows are summarized in table 8.

Table 8 Mass-flows for the flows around the Direct Condenser at Renova.

$m_1\left[\frac{kg}{s}\right]$	482,5
$m_2\left[\frac{kg}{s}\right]$	177,8
$m_{2.1}\left[\frac{kg}{s}\right]$	479
$m_3\left[\frac{kg}{s}\right]$	304,7
$m_4\left[\frac{kg}{s}\right]$	301,7
$m_6\left[\frac{kg}{s}\right]$	784,3

The temperatures were then calculated as eq. 48:

$$T_1 = T_2 = T_3 \qquad \textit{Eq. 48}$$

$$T_{2.1} = \frac{(m_2 * T_2) + (m_4 * T_4)}{m_{2.1}}$$

$$T_5 = \frac{(m_6 * T_6) + (m_3 * T_3)}{m_5}$$

By knowing all the temperatures, the heat load of the direct condenser has been calculated by using the eq.1 as presented in eq. 49.

$$Q_{DC} = m_{2.1} * Cp * (T_5 - T_{2.1}) \qquad \textit{Eq. 49}$$

When this heat load became known, the temperature of the flow 1 was changed to a lower value, 30°C, and it was obvious that the load of the direct condenser increased with a factor of two. This increase in the load of direct condenser is indicator for taking more heat from the flue gases, in other words, the reduced temperature in the return flow will cause better cooling in the direct condenser.

2.4.1 Applying heat pump solver to Renova

In Renova case, like the ST1, there is not a single HEX to transfer waste heat to the DH-network. Therefore, the connection between Renova and GE is illustrated same as ST1 and the heat pump configuration is same as ST1. The equation, variables and constraints are the same as the case of ST1. The big difference between ST1 and Renova is the supply temperature of the DH-water. After studying the data of Renova the following values were established:

Table 9 Input data for the case of Renova based on information from [21].

Supply temperature (leaving Renova) [°C]	100
Return temperature [°C]	45
Mass flow of DH [kg/s]	680
Heat load [MW]	156,7

This would therefore mean that if a heat pump is installed between Renova and GE which reduces the return temperature, it should be thought that the temperature lift should be at a temperature above 100°C. This was followed by investigation of potential need of temperature lift to a higher temperature than 100°C in the network. Information provided by GE made clear that since the Renova plant is near the city centrum and because that area is a bottleneck of the DH-network this temperature lift is needed.

Therefore, the approach of temperature reduction by heat pump has been analyzed with different condenser temperatures to see how factors like temperature reduction, compressor work, condenser load and etc. changes by different condenser temperatures.

2.5 Effect of temperature reduction of the return flow of DH on DH-production plants of GE

Information about the distribution network of DH was not accessible for this thesis; therefore a what-if case of this study has been that if the return flow of district heating which will be cooled down by the heat pump goes to production plant of GE how would then the production plant be affected. Or if something happens between GE and its waste heat providers and the flows leads directly to the production plant, then the temperature reduction of return flow of DH by the heat pump would have some impacts.

The production of DH can be based on different fuels and different boilers. The main method for analyzing the effect of temperature reduction on the production plants has been literature study. Further, a simple calculation was done to show the relation of temperature reduction in the return flow and fuel consumption in the boiler. By implementing equations 50 and 51 [35]:

$$Q_{boiler} = m_{DH} * Cp * (T_{Out} - T_{In}) \qquad \text{Eq. 50}$$

$$Q_{boiler} = \frac{m_{fuel} * LHV_{fuel}}{\eta_{boiler}} \qquad Eq.\ 51$$

3 Result and Discussion

The optimization models are dependent on many factors, in this project a simple model based on thermodynamic and economic approaches have been studied to analyze how beneficial would the implementation of heat pump be for the DH-company GE, in order to decrease the temperature of the return flow of the DH and increase the share of recycled heat in the system. The temperature reduction followed by installation of heat pump results in more extracted heat from the waste heat suppliers. This more extracted heat is approximately same as the heat load of the heat pump evaporator. Table 10 is showing the amount of more extracted heat for each scenario against its temperature reduction.

Table 10 Results of temperature reduction and more extracted heat for each case.

	Temperature reduction GE side	**Heat win by temperature reduction [MW]**	**Temperature reduction on Preem's side**	**Amount of waste heat saved in the waste heat supplier's side [MW]**
Preem Scenario 1	7,42	10,87	8,02	10,87
Preem Scenario 2	11,9	14,1	2,6	14,1
Preem Double HEX and 15% more available heat at lower temperature	8,72	15,8	9,96	15,8
ST1, with supply temperature 90 C	3,67	8,2	-	(8,2 ?)
ST1, with supply temperature 100 C	10,04	22,5	-	(22,5 ?)
Renova, with supply temperature 105 C	3,4	9,7	-	3,6
Renova with Supply temperature 110	6,5	18,5	-	6,8

The column *Amount of waste heat saved in the waste heat supplier's side* explains that how much heat can be saved for each waste heat supplier. In the case of Preem it is somehow known that the temperature reduction of the return DH-flow would directly affect the heat which would release to the environment by the air coolers. But in the case of ST1 it is not clear since there has been lack of information. Therefore, the values are shown within brackets and with a question mark. However, the calculation by the company GE shows that the values for ST1 are around 0,3-0,4 of the heat win by the temperature reduction [36]. For the case of Renova, the values are calculated based on the moment of the flow-schematic shown in Appendix 2 and the mass-flow relations around the direct condenser at Renova plant. This may vary in each time based on the flows and the operation, but this is only to understand the concept.

3.1 Optimization and Different Scenarios of installation for Preem

Figure 14 shows the behavior of compressor work and the temperature reduction in relation to heat pump efficiency. By changing the constraint of upper limit for the heat pump efficiency in the main scenario, the following graph has been made. It is clear that by having a heat pump with a higher efficiency a better temperature reduction can be achieved with a low compressor work and therefore lower operating costs for the heat pump [37]. Since flows D1 and D2 has fixed temperatures, degrading in temperature of flow B1 means less work in the heat pump, which in turn means COP can increase. This means that, the temperature reduction in flow B1 can continue to the point that the heat pump reaches its maximum limit of efficiency.

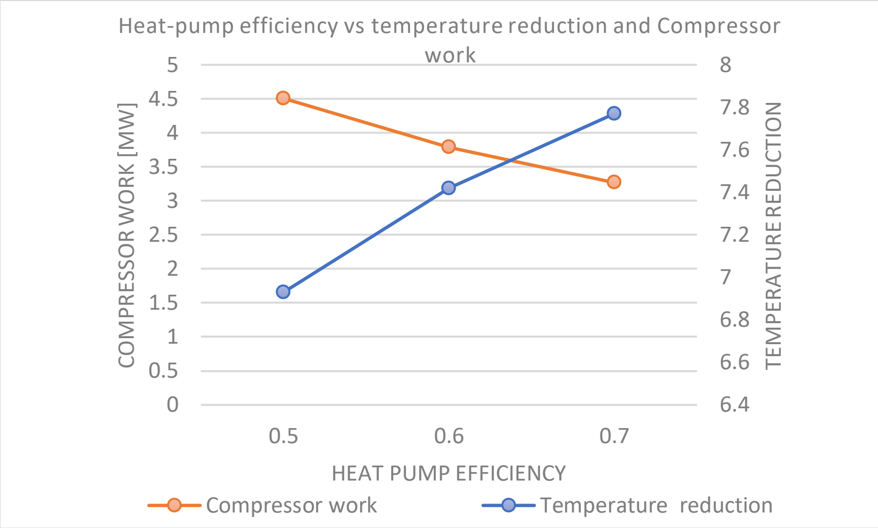


Figure 14 Impact of heat pump Carnot efficiency on compressor work and temperature reduction.

Changing X and Y - Sensitivity analysis

In the optimization analysis, it was observed that using either of the objective functions, the same result was obtained. In both cases the minimized temperature was 34,48°C and the first objective function had a value of 2,87. As explained before, the upper limit of the heat pump efficiency is the binding constraint. By setting a higher temperature for the supply flow, the temperature reduction can be further reduced. The upper limit of the heat pump efficiency is set according to the already heat pump set at GE, Rya Heap Pump Plant. They have a Carnot-efficiency of about 0.6 [23]. However, the new technologies and new heat pumps could reach higher values than this, so the values presented in this study may be characterized as conservative. Kosmadakis in [12] consider a COP-value of 4 for an industrial heat pump and further states that it can vary from 2 to 5. In this thesis, the COP-values range between 2,5 and 3,5.

Moreover, some sensitivity analysis was done to study what happens if the system is forced to run the heat pump in part load. Figure 16 shows that while X=1 and Y is reducing, (i.e., the flow through the condenser decreases), the COP-value of the heat pump does not change. The temperature after the condenser, flow D3, increases by reducing Y, but this increase because of decreasing of the mass flow through condenser and the condenser load does not change. Therefore, by decreasing the flow fraction Y the temperature reduction does not affect.

The second graph in figure 15, is for a case when the flow through the evaporator changes, X, and Y is constant at 1. This case has a little more impact on the different factors. The temperature of the condenser is constant in this case and thereby the load of the condenser is constant as well. But the COP value decreases by reducing Y since the evaporator load decreases. The decrease in the evaporator load forces the compressor to compensate the decrease in the evaporator to keep the outcome of condenser constant, thereby COP decreases.

By changing the temperature of flow C4, COP_{Carnot} will be changed, and by decrease in the value of COP_{Carnot}(because of decrease of X), and since the models always try to reach the maximum available heat pump efficiency, 0,6, the value of real COP will reduces.

The increase of the compressor work results also in decreasing the first objective function. Since the return flow separates and part of it flows through the evaporator, the other part has still the same temperature as the return flow from the network, 41,9°C, this causes that the temperature of flow C5 is not decreases as much as in the case of X=Y=1.

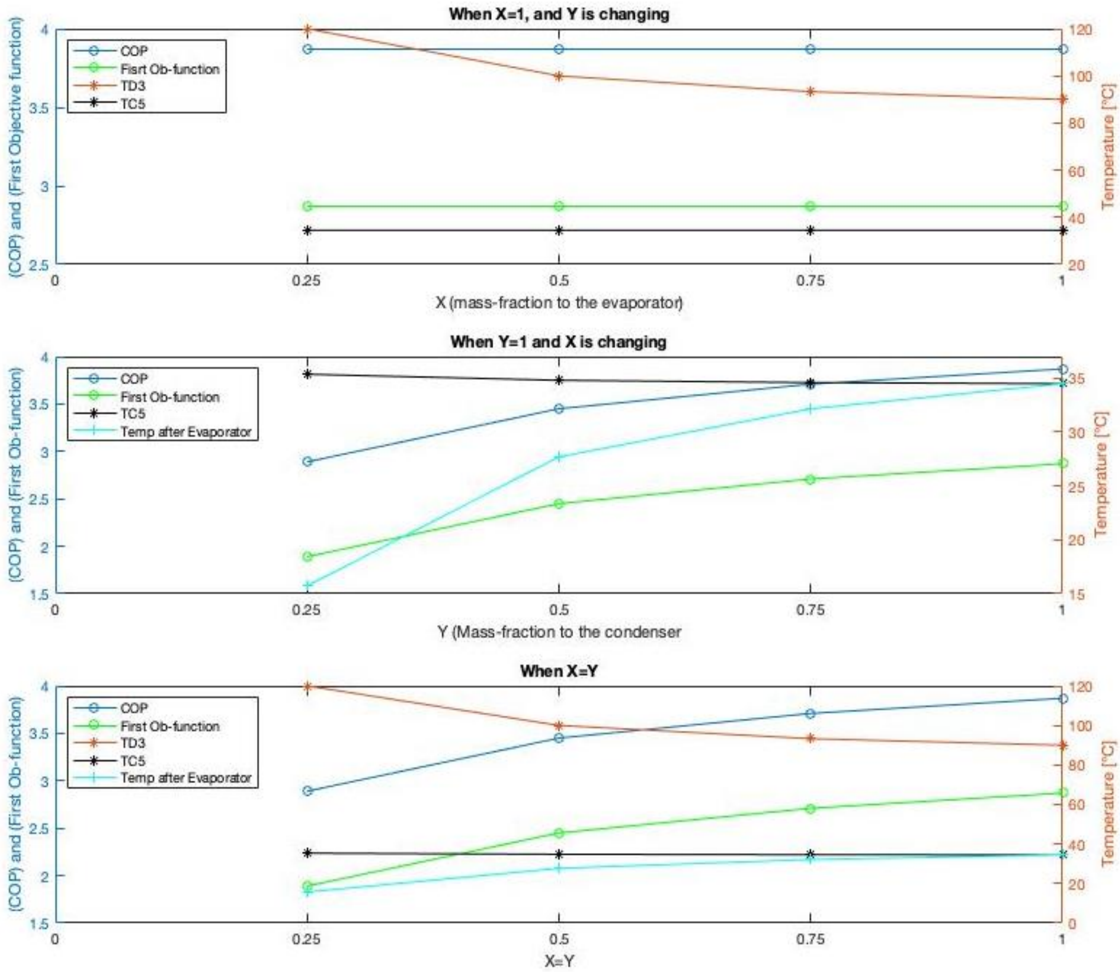


Figure 15 Result of different mass-fraction analysis through the condenser and the evaporator for scenario 1.

By changing both variables at the same time, a combined result of first and second analyses can be achieved.

Scenario 2

Scenario 2 showed very extreme values in the results. The set-up and the structure of scenario 2 requires a significantly bigger temperature lift (>60). The water flows into the condenser at 40°C and since the mass-flow is not high the temperature after the condenser should be much higher than 90°C to reach temperature 90°C for the flow D2. This large temperature lift gives therefore very low COP-values. However, there could be heat pump technologies which can compensate this with acceptable COP like the high temperature heat pumps introduced in [47], however the evaporation temperature in [47] is higher than 80°C but for a high condensation temperature more than 120℃ a COP value of around 4 is reached. But since the project had limited time investigation for the heat pump design which suits the system was out of scope.

Scenario 2 as well as scenario 1 has been tried with two different objective functions. The first run of the scenario with objective function maximize $\frac{\Delta Q_{AC}}{W_{comp}}$ gives a result of 0,41 for the objective with a temperature reduction in GE-side at 1,9. The second objective function which was the temperature reduction had better result. The temperature reduction in GE-side reached a value of 11,9 and the first objective reached a value of 0,29. But, even though the temperature to the HEX became 30°C the temperature reduction at Preem side was very low 2,6. This was because of the low flow which goes into the HEX.

A sensitivity analysis was conducted on the basis of the second objective function (Figure 16). By setting two lower values for X, 0,75 and 0,5, and letting Y be still as variable, it shows clear that the COP decreases further to lower than 2. The condenser load and the compressor work both decrease with decreasing X, and the ration of these two factors (i.e., the COP value) also decreases. Also, the temperature back to the HEX increases in by decreasing X, and this results in higher return temperature to Preem side.

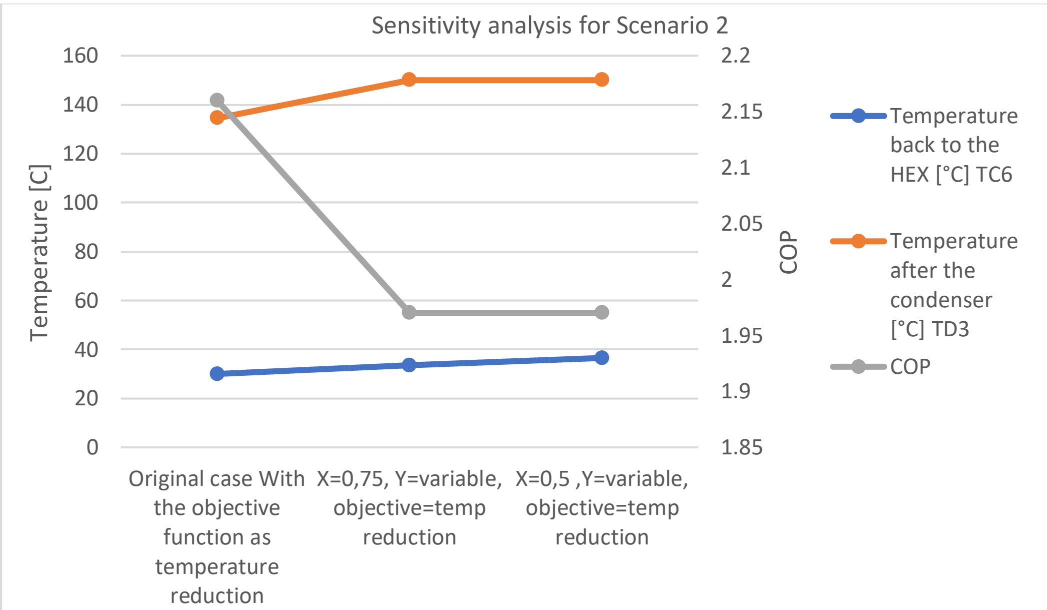


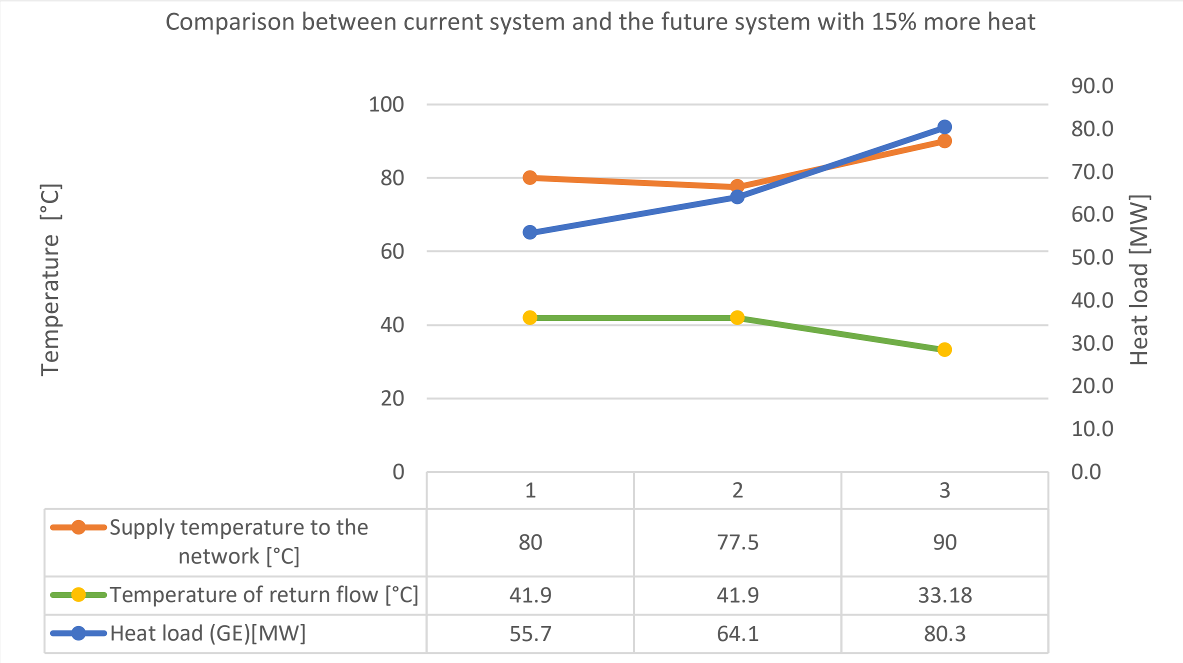
Figure 16 Result of sensitivity analysis on mass-fraction through the evaporator for Scenario 2.

Because of these results for scenario 2, this scenario was not further investigated in terms of economic analysis.

Double HEX and 15% more temperature Waste Heat

The analysis of the mass-fractions X and Y showed that the best theoretically result reaches by X=Y=1. Therefore, for the case of 15% more available heat at lower temperature with double HEX, the sensitivity analysis for X and Y has not been done.

One important thing, as mentioned earlier, is that by decreasing the return temperature in each case the amount heat taken from the HEX increases. This is shown for the idea of double HEX with 15% more heat, figure 17. In case of having heat pump in the system and by having this double HEX the amount of heat taken from the waste heat of Preem increases further to 80,3 MW. This gives also a supply temperature of 90℃ in the network. But, if during the times when the outdoor temperature is enough high to not to use heat pump, the double HEX can give a supply temperature of 77,5 ℃ which is enough near the mean value of current supply temperature. One other thing from this figure is that the mass-flow of DH-water increases in order to be able to cool down the waste-heat flow. An increase of almost 79 kg/s with no heat pump and 82,5 kg/s while the heat pump is working, is an extra revenue for GE.



	1	2	3
Supply temperature to the network [°C]	80	77.5	90
Temperature of return flow [°C]	41.9	41.9	33.18
Heat load (GE)[MW]	55.7	64.1	80.3

Figure 17 Result of the concept of a double HEX for accessing to waste heat at low temperature, 80°C. Point 1: represents the current system with its HEX. Ponit 2: represent the existence of the Double HEX but without heat pump. Point 3: Represents the case of the Double HEX with implementing heat pump.

3.2 Optimization of installation for ST1

The analysis of heat pump installation for ST1 started by studying different heat pump condenser temperatures. The supply temperature after the heat pump to the network (B5 in figure 12) has been set as a variable in case of ST1 and Renova (despite the temperature of this flow has been set in the case of Preem). This was done firstly because of different temperature from ST1 and Renova (85℃ and 100℃ respectively, compared to 80℃ from Preem); secondly because according to the DH-company higher temperatures in the network can be needed in the areas that are as bottlenecks in the city. Since the temperature of the current supply flow is 85℃, the condenser of heat pump should have a minimum temperature lift of 5℃. This analysis is shown in figure 19 and is in condition X=Y=1.

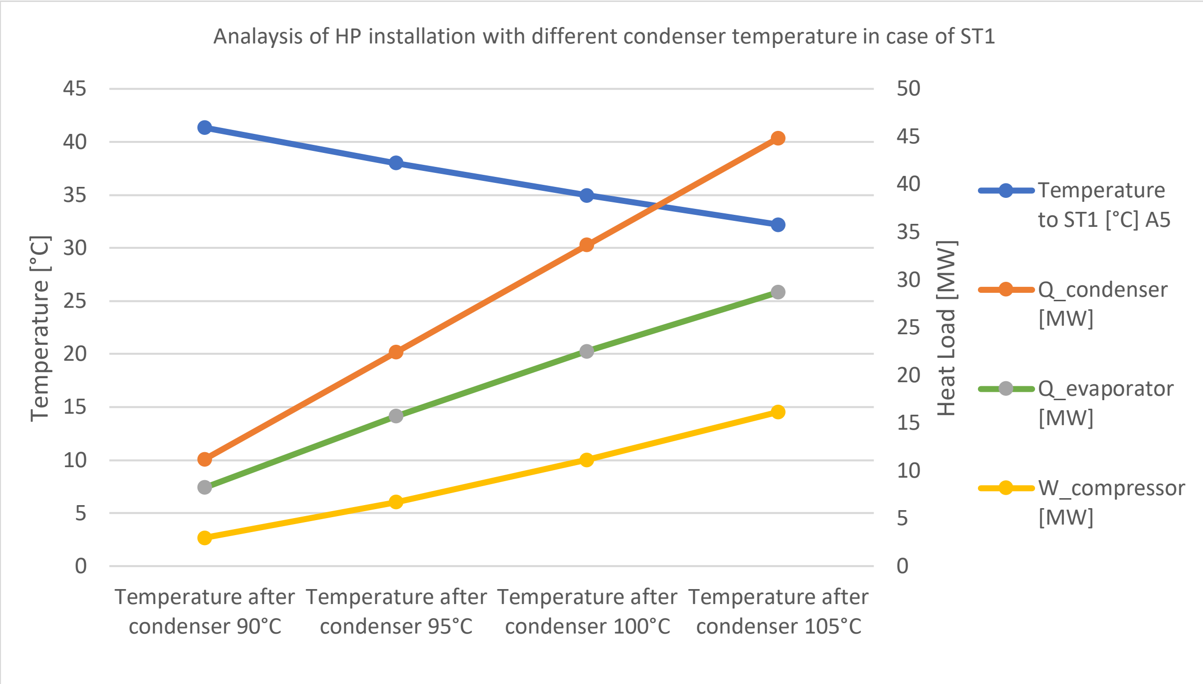


Figure 18 Sensitivity analysis on heat pump installation on the ST1 flow with different condenser temperatures.

According to figure 18, by increasing the heat pump condenser temperature (flow B5, which is the X-axis in the figure) the COP-value decreases but in the other hand this gives a better temperature reduction in the return flow. The problem structure and constraints of this case was different from case of Preem since the temperatures were different and there was no consideration of air coolers in this case (however they probably exist in reality). In this case, the constraint of having a certain supply temperature was removed by setting it to be calculated based on the condenser temperature which was a variable. The reason for this can be explained as a back-calculation. Since the temperature of flow B1 is set to be at 85°C, and by installing heat pump, the temperature of A5 will decrease the total heat extracted from the waste heat provider will increase, this means that if the temperature of B5 is set to be constant at 85°C, as it was before heat pump, the work of the compressor would be negative. By this, higher temperature than 85°C is a crucial parameter for the model.

In the heat duration load curve of the company that the heat pump will be used for outdoor temperatures <7°C. For these outdoor temperatures the approximately supply temperature is 85°C in the network. This means that if the supply temperature after the heat pump is higher than 90°C, the company can mix it with other flows in the network with lower temperatures. This would then replace a peak production unit which would increase the temperature of the flow to satisfy the demand during low outdoor temperatures.

One common issue between Preem and ST1 scenarios was that in the optimization both would give minimized temperature by passing all the flow through the condenser and evaporator, X=Y=1. To further analyze the result of the heat pump installation on ST1 a sensitivity analysis has been done on the X and Y variables. The chosen condenser temperature for the analysis is 100°C since it showed an acceptable temperature reduction against an enough high COP, around 10°C of reduction and COP-value of 3,02.

Figure 19 shows how the changing of X and Y affects the heat pump set-up. By reducing the mass-flow through the condenser, the load of the condenser decreases, and the condenser temperature follows this reduction. When the condenser load decreases the evaporator cannot give all the heat taken from the return flow to the condenser and thereby reduces the load of the evaporator to somehow balance the system. This result in higher temperature after the evaporator compared to when Y=1.

Changing of X in the opposite does not affect the condenser load nor the condenser temperature. Moreover, the load reduction of evaporator has not the same gradient as it had by changing Y. The lowest value of evaporator load by changing X is for X=0,5 which is 21,1 MW, while for Y=0,5 the evaporator load is 11,6 MW. What is noticeable here is the increasing of COP in case of reducing Y and decreasing of COP for X reduction. Both the condenser and evaporator load decrease with reducing Y, the COP increases. On the other hand, decreasing X does not affect the condenser load and as the evaporator load decreases COP decreases too.

With changing both X and Y at the same time it is shown that by decreasing X and Y the COP-value and the evaporator outlet temperature (flow A4) will be constant. However, the evaporator load decreases because of decreasing mass-flow through it. But the total temperature reduction (temperature of flow A5) increases because of mixing flows. The temperature of the condenser decreases like when only Y is changing but since the load of evaporator decreases too, the COP-value stays constant when fractions X and Y are the same.

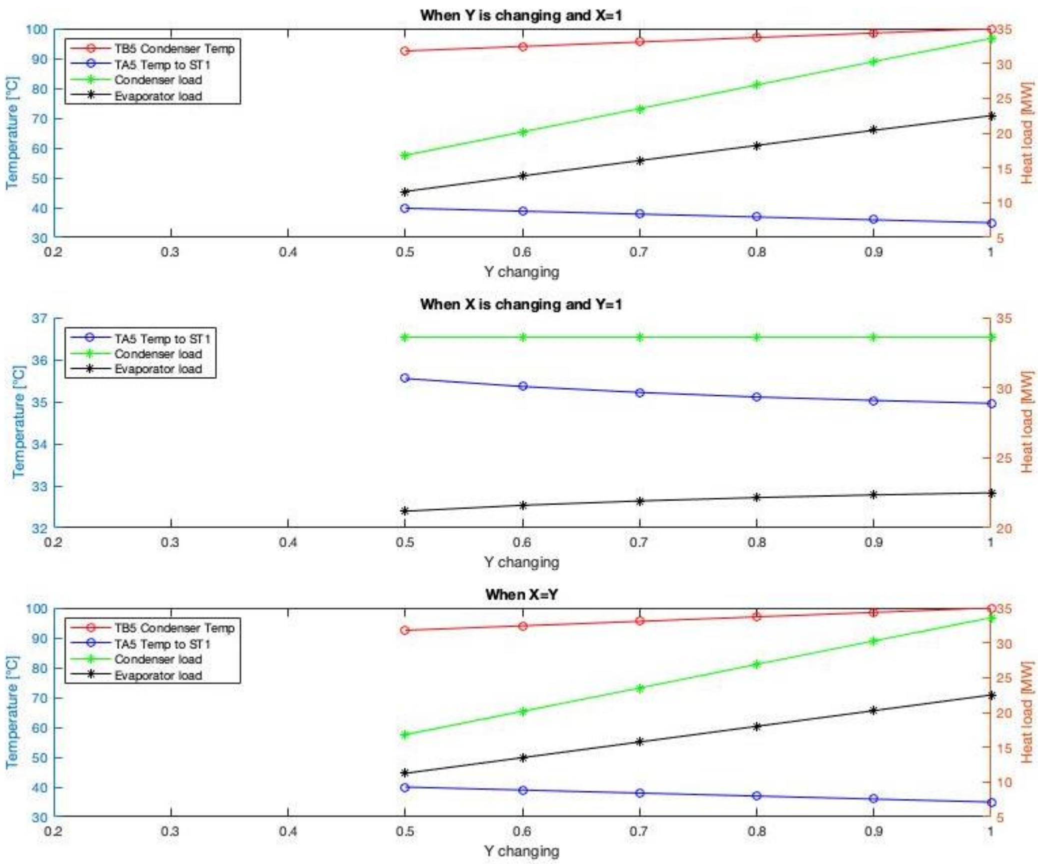


Figure 19 Sensitivity analysis on different mass-flows through the condenser and evaporator of the installed heat pump in case of ST1.

3.3 Optimization of installation for Renova

The investigation and energy balance over the DC of Renova showed that by reducing in the return temperature more heat can be taken out from the flue gases at Renova plant. Figure 20 shows how DC-load increases by reduction in the return temperature from 42,7 °C to 32,7°C.

This simple calculation could show that the concept of temperature reduction of DH-network will result in a positive way for one of the waste heat providers of GE.

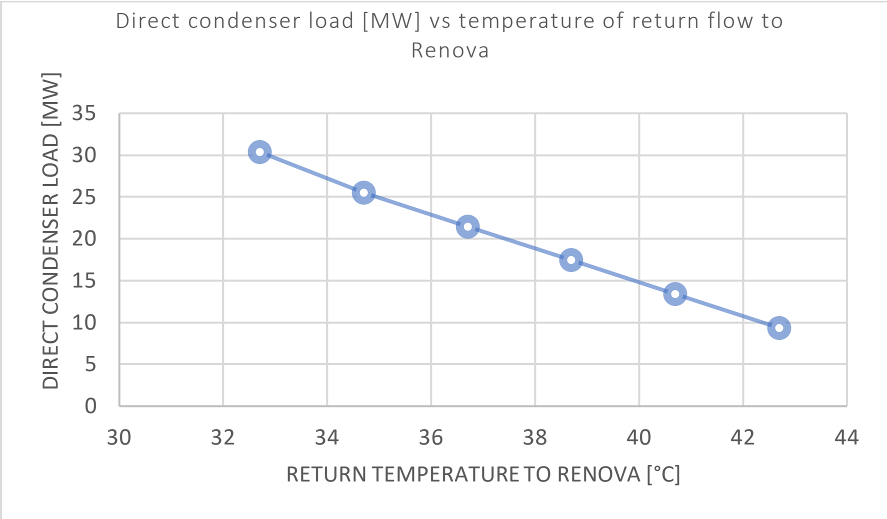


Figure 20 Effect of temperature reduction on the direct condenser (flue gas condenser) of Renova.

The results of installation of a heat pump between GE and Renova shows same trends as for ST1. The main difference is that the supply temperature from Renova to the DH is usually higher than 95°C, which in this study is assumed to be 100°C. The installation of heat pump in order to reduce the return temperature means that the taken heat from the return flow by the evaporator should be added to the supply flow which is already at 100°C. To do this the condenser of the chosen heat pump should have the possibility to operate in higher temperatures than 100◦C. In this project,, temperatures of 105◦C, 110°C, 115°C and 120°C were investigated as supply temperatures to GE.

The result is similar to ST1 case; by having higher condenser temperature in the heat pump, better temperature reduction can be achieved but the COP value degrades. For heat pump condenser temperature of 105℃ a COP value of 3,13 is calculated and a temperature reduction of 3,4◦C. For condenser temperature 120°C then the temperature reduction is 11,89◦C while the COP is 2,46. It is obvious that these low COP-values are because of the maximum limit of the Carnot-efficiency of the heat pump in this study.

Bamigbetan et. al. in [48] [49] investigate a hydrocarbon-based cooling medium high temperature heat pump that can recover heat at 25°C-30°C and provide heat at above 110°C with COP-value above 3. Wu et. al. [47] also investigated the performance of high temperature heat pumps based on water vapor and use a water injection twin-screw compressor. But the evaporation temperature is 83°C-87°C and the condensation temperature is 120°C-128°C, giving COP-values in the range of 3,64 - 4,87. This issue can be further investigated if high temperature lift would be required for GE in some connections as to Renova or ST1.

The X and Y reduction analysis for Renova showed also the same trend as the case of ST1. Figure 21 shows how the COP value and the temperature reduction varies by changing mass-flow fractions X and Y.

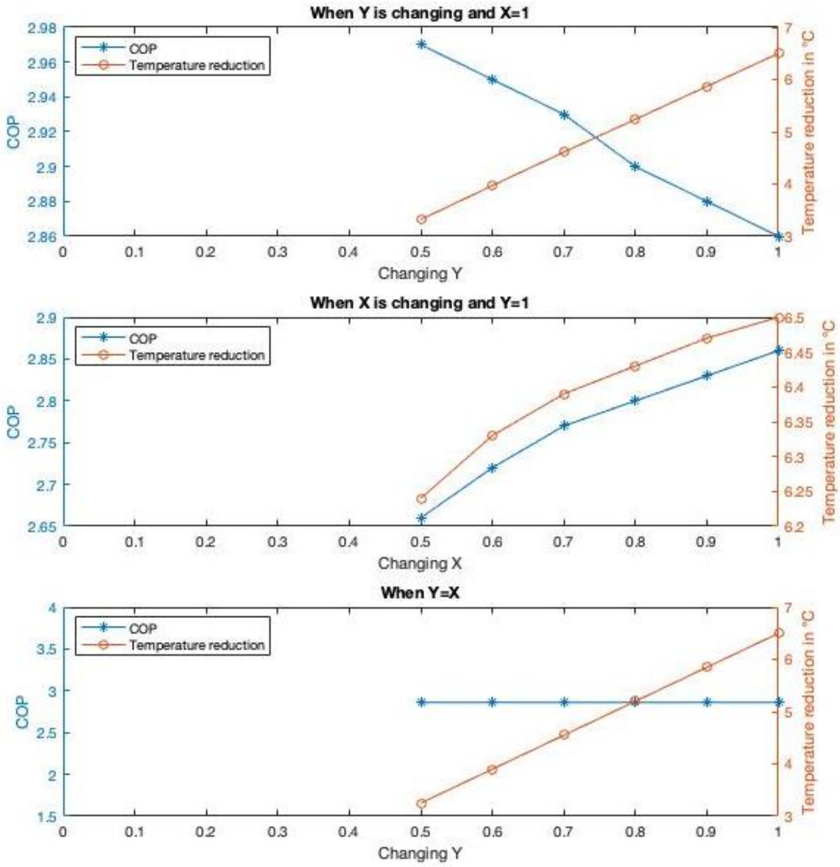


Figure 21 Impact of different mass-fractions through the condenser and evaporator of heat pump in case of Renova on the COP-value and the temperature reduction.

3.4 Effect of temperature reduction of the return flow of DH on DH-production plants of GE

When the return temperature of the DH reduces, a simple heat only boiler which has no other features or sub-systems, like feedwater preheating or flue-gas condensation, will be in need of more fuel flow in order to keep the supply temperature constant. This is simply showed in figure 22. It is obvious that by reducing the temperature of return flow in DH from 41°C to 30°C the fuel consumption increases by approximately 1 [kg/s]. This effect will be different for a plant like CHP or a boiler with flue gas condensation.

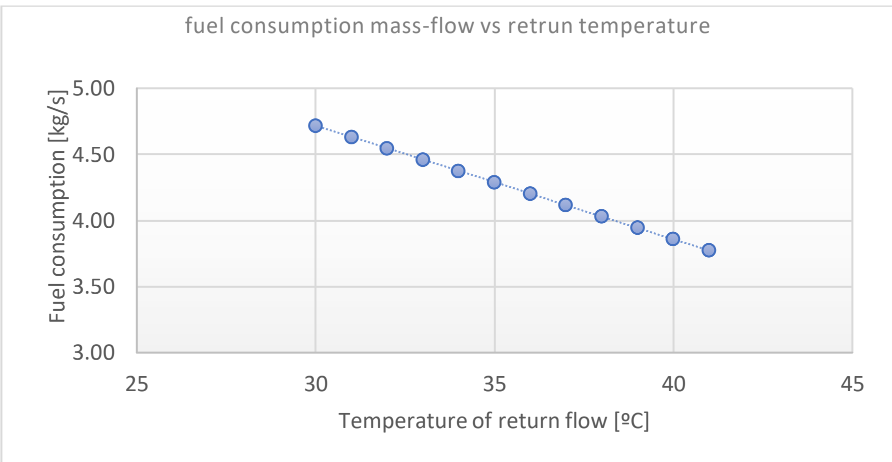


Figure 22 Varying of fuel consumption in a simple HOB with changing in the return temperature.

Rya CHP is one of GE's big production plant with 600 MW fuel effect [17]. One issue about such a CHP plant can be corrosion in the economizers due to low temperature feedwater [50]. But by ensuring an intern recirculation in the inlet of the economizer this issue can be prevented [50]. Since the recirculation in inlet of the economizer increase the inlet temperature of the feedwater the fuel consumption would not be affected that much. Rya Hot-water center (HVC) has a total maximum capacity of 110 MW and a boiler-efficiency of about 90% [16]. According to [36], the plant is coupled in series with Rya Heat Pumps plant. The idea is to increase the temperature of the DH-water after passing the heat pumps. During wintertime the Rya HVC is more acting like a base load plant [16] and according to figure 1 HVC runs while Rya heat pumps are running. This means that the reduction in temperature of return flow if it happens in the way to these plants would not affect the outlet temperature and the fuel consumption.

Chen et. al in [51] claim that in CHP plant, mostly coal-fired, the low pressure feedwater in the heat regeneration system can be used for DH instead of extracting steam from turbine. This concept is even discussed in [52]. Although it is maybe not relevant for the GE's production plant, it is showed is that reduction in return temperature in a CHP-plant, that has pre-heating of feedwater by e.g. heat regeneration or flue gas condensation systems, does not affect the fuel consumption [51]. This can be true for Sävenäs HP3 boiler which produces both DH and electricity [15]; [53] the amount of energy needed for preheating the feedwater is taken from the flue gases which means that if the feed water temperature is reduced by 5-10°C, more energy would be taken from the flue gases, as in the case of direct condenser at Renova.

One other issue is the amount of electricity produced in such boilers, Rya CHP and Sävenäs HP3. According to the above argument and the definition of the electricity efficiency and the α −value of the plant ($\alpha = \frac{\eta_{el_{CHP}}}{\eta_{tot} - \eta_{el_{CHP}}}$ $where\ \eta_{el_{CHP}} = \frac{Produced\ El}{total\ fuel\ consumpton}$) [53], if the fuel consumption stays unchanged the electricity production does not become affected and the α −value remains unchanged. This question can be further investigated based on the entire plant and what is the main focus of production in the plant.

3.5 Economic Estimation

The result of heat pump analyses has been complemented by an economic investigation. It is showed and discussed how the waste heat price variation can affect the installation and operation of the heat pump. The results of the price and cost calculations are shown in form of a share of the original price with unit [%].

3.5.1 Economic calculation for Preem

By comparing the weekly cost of waste heat for GE, which is calculated based on amount heat exchanged between GE and Preem, and the weekly cost based on the BEP it is obvious that GE can have economic benefit of the set-up. By reducing the temperature of return flow, more heat can be recovered by the waste heat provider, and this is the benefit for both for GE and the waste heat provider. The BEP prices as a proportion of currents prices are plotted in figure 23. The lowest level is for the coldest week around 64% and it reaches around 83% as maximum (for warm weeks). One other issue is the effect of the electricity prices on the BEP-based heat cost. If we look at two different weeks which have the same heat price and same heat usage and electricity usage for the compressor (e.g. weeks 16 and 18), the week which has higher electricity price has lower BEP. This is because of the electricity consumption of the heat pump in the BEP-calculation. The other issue in figure 23 is the approximately prices of the cooling.

As expected, they follow the same trend with electricity prices. However, compared to cooling prices in industry (e.g., approx. 50-100 SEK/MWh, see for instance [43]), these cooling prices are significantly higher. Since the heat prices and waste heat prices are not easy to access, a price level and proportions are showed in this section.

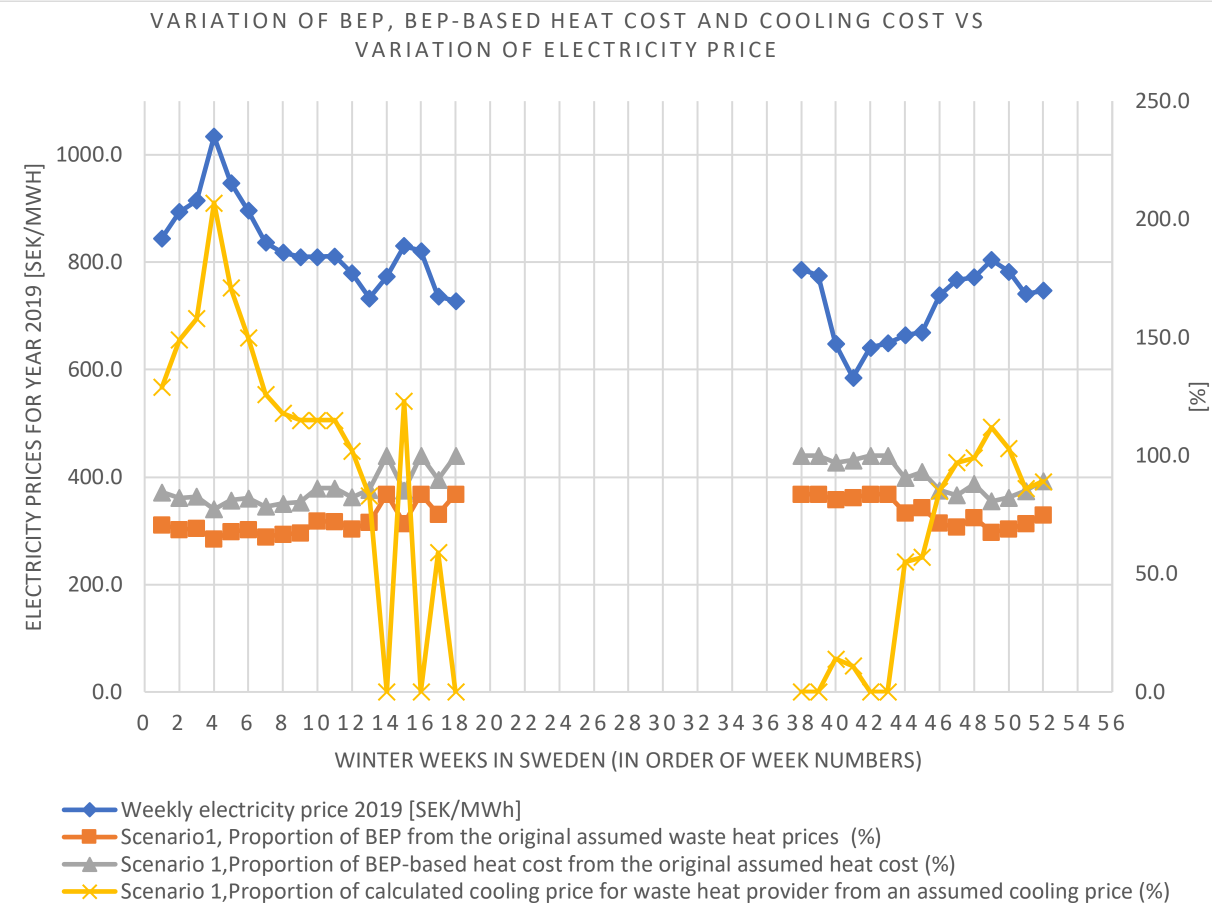


Figure 23 Comparing of current heat cost and the cost of heat based on a BEP.

A standard cooling price is presented in [43] which is between 50-100 [SEK/MWh] (however the paper is explaining about a plant in Switzerland). By assuming this price as a base for cooling prices, the cooling prices has been calculated for the waste heat providers in this thesis. The result is shown in figure 24 as a proportion of the assumed cooling price. It seems that the cooling price calculated is higher than the standard cooling price in [43]. This issue is taken up as cost related question to see if there is a motivation also for Preem or other waste heat providers, since the motivation for GE is strong already. But, if the point of BEP and the BEP-based waste is also seen from environmental or industrial symbiosis perspective, then it can be a motivation for both sides. Preem is interested in a project that could give DH based on more renewable and recycled sources instead of releasing the energy by air coolers. A more detailed cost analysis is outside the scope of this thesis and could be perhaps conducted in the future including capital costs and flexibility of the plant operation.

Figure 25 shows the result in order of increasing weekly outdoor temperature. Here it is confirmed that the BEP-based cost of heat follows the reduction of waste heat prices but has more fluctuations than the original price setting, which is because of the electricity price. The variations of electricity prices in form of increasing outdoor temperature is shown in figure 26.

If these two figures compare at the same time it is obvious that BEP increases by decreasing electricity price and the cooling price decreases by decreasing electricity price.

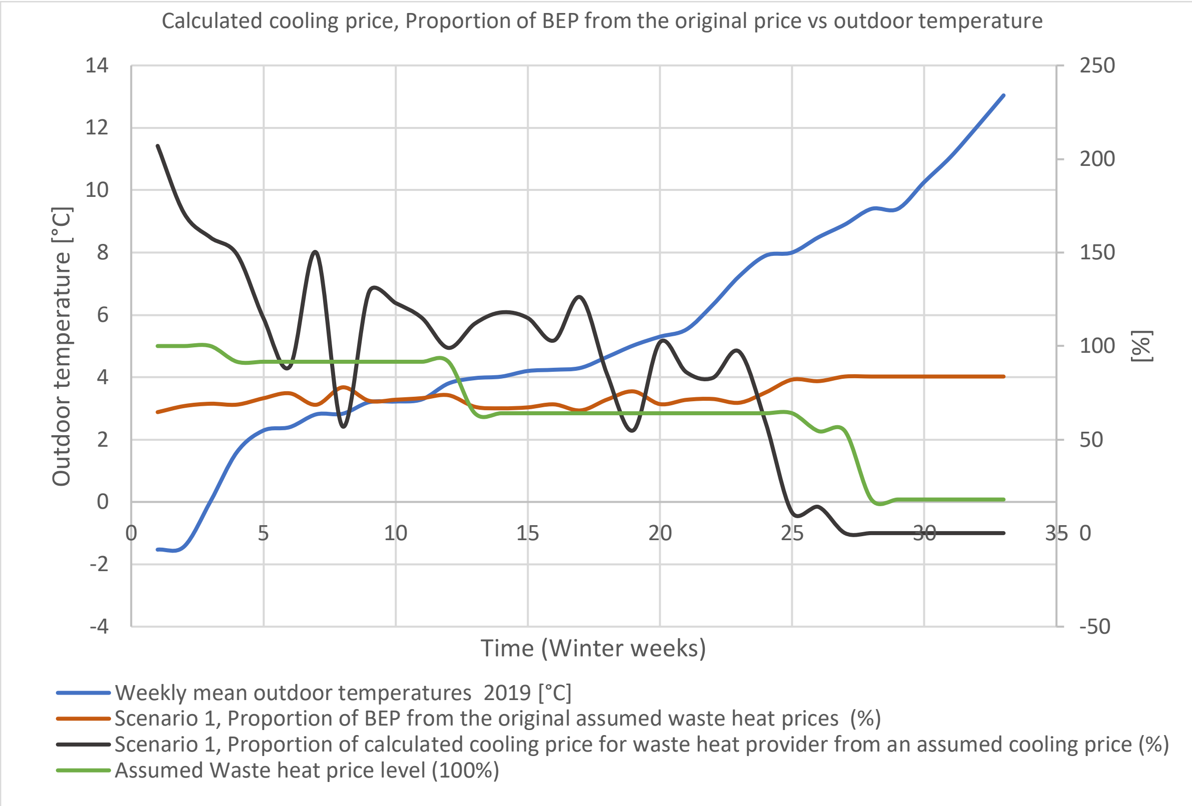


Figure 24 Heat and cooling price comparison plotted in order of increasing outdoor temperature.

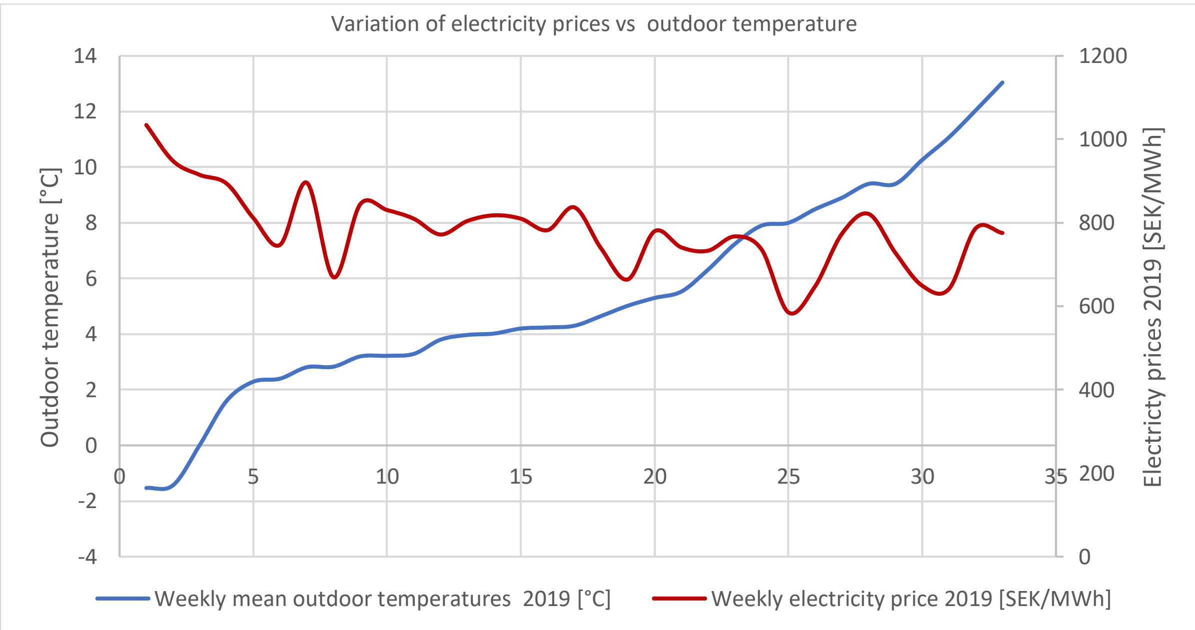


Figure 25 Weekly variation of electricity prices in order of increasing weekly mean outdoor temperature.

Available heat at lower temperature
The concept of heat at lower temperature resulted in more mass-flow of the DH, which means a weekly constant revenue of 0,24 [MSEK/Week] can be added to the cost calculation. But this revenue is not affecting the BEP that is between GE and it waste heat provider, Preem in this case. Figure 26 shows a comparison between the installation of HP as Scenario 1 and the case with double HEX and its heat pump installation.

According to figure 26, the BEP is lower in case of Double HEX compared to Scenario 1. The level of cooling prices for the waste heat provider shows also lower values than in case of scenario. This means that, even though this new introduced concept seems very expensive and needs a lot of changes in the system [20] but by considering its cost efficient operation it can be beneficial for both sides of the business.

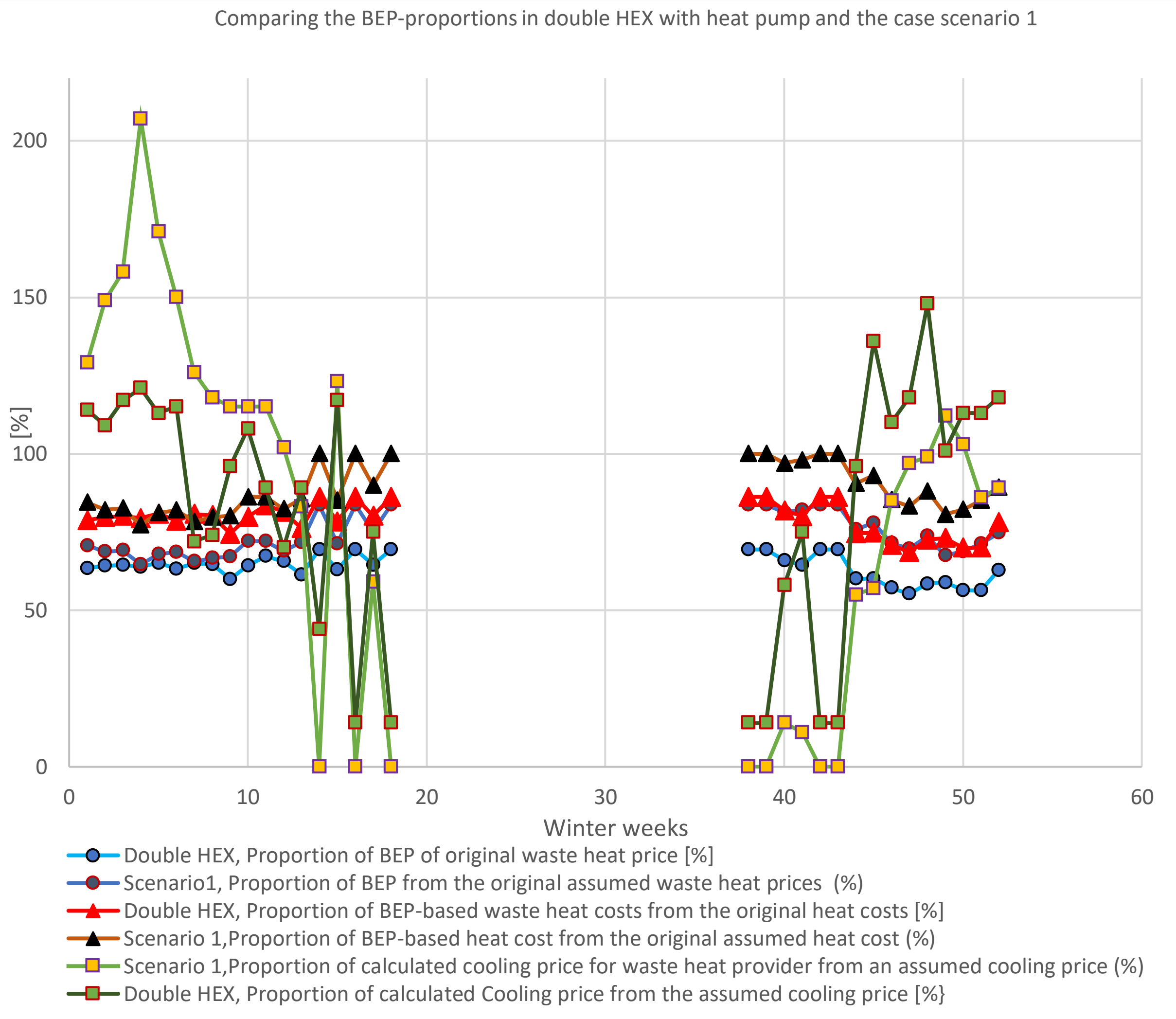


Figure 26 Heat and cooling prices compared with the scenario of double HEX and its low temperature waste heat.

3.5.2 Economical calculation for ST1 and Renova

Figure 27 compares the different BEP for the two different supply temperature (flow B5) for in case of both Renova and ST1. As discussed earlier the BEP can differ for each case according to varying of the compressor electricity consumption and the heat load exchanged between GE and each plant. Therefore, the BEP-based costs of the heat for each case is different.

Renova's heat has big amount of heat delivering to GE, approximately 156 MW heat(however this is taken from the historical data as a mean value, according to GE the company Renova deliver near 180 MW of heat to GE).This means that by considering a BEP which is lower than the current heat price, large amount of money can be saved which is economic beneficial for GE. If this analysis become done with real prices then an economic model with capital expenditure and operation expenditure can be made for the heat pump installation, which probably show a short payback time and economic benefits for GE. On the other sides the waste heat delivery company Renova, get a cooling medium at lower temperature which will help them to cool down the flue gases furthermore. One other thing which is understood from the graphs in figure 27 is that the BEP is lower for higher supply temperature for each plant. This is because of the bigger amount of electricity consumption in the compressor. This can be studied from another perspective as well, by increasing the supply temperature after the heat pump, an area which is a bottleneck of the DH-distribution network, the demand would be well satisfied with more recycled heat share, at the same time a lower BEP would mean that the installation of the heat pump is also economic beneficial.

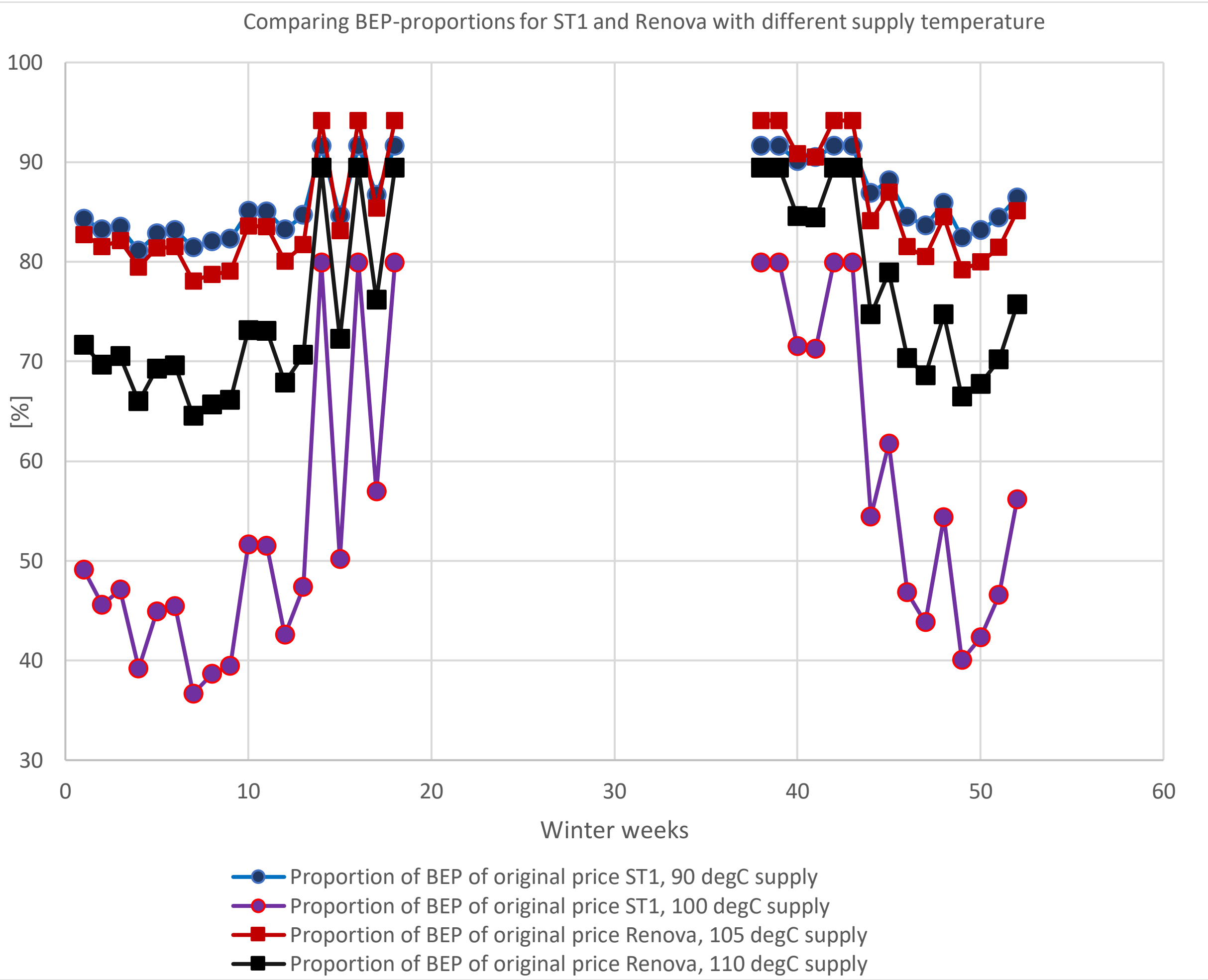


Figure 27 Heat cost comparison between 4 different cases, Scenario 1, Double HEX with Preem, ST1 and Renova.

3.6 Further discussion

The energy system of a region (or country) depends on the national energy policies and the climatic situation [54]. With the defined goals for year 2030 and 2050, the development of energy system in Sweden, specially the DH-system, is an important factor for a future with smart and sustainable energy systems in Göteborg [54].

At low electricity price and high biomass price using electricity-to-heat solution like heat pumps instead of CHP, reduce both the fuel consumption and usage of primary energy [55]. Since the goal of the company GE is to move forward to fossil-free DH in future, it will be good investment for using heat pump in order to strengthen the DH production network of the city. Moreover, this project did not include the investment cost in the calculations, but Kosmadakis [12] shows that by comparing a heat pump in the study and a gas-burner boiler, the annual saving is around 810 k€/year (considering natural gas as fuel, fuel saving of 27 GWh/year, a boiler efficiency of 86%, gas price 0,03€/kWh and excluding taxes), this is just an example to claim the cost efficiency of such an installation.

If the idea of taking low temperature heat from the waste heat providers realizes that the efficiency of the fuel used in the waste heat supplier's plant increases. Recycling of the waste heat does not mean that the heat is green (has zero emission) but it means that consumption of further fossil fuels or biofuels can decrease. Further, Averfalk et. al. [13] list a set of advantages of large scale power-to-heat solutions in the DH system; flexibility in fuel usage in the DH system, greater capability of acceptance of large heat storages, possibilities to combine higher fraction of renewable sources, absorption of surplus electricity while it is at low price, and heat pumps potential to use of strategically advantageous heat sources. These are the system benefits which can be known as general benefits for a whole society like Göteborg city. These can help significantly the companies in the city, Preem, ST1, Renova and GE, to move forward the goal of year 2030.

Even though Sweden has been one the world's leader in usage of large-scale heat pumps in 1980s, the capacity utilization has been decreased during las decades because of the higher electricity prices and taxes [13]. In a future system the capacity utilization of heat pumps will be a factor which is dependent on the availability of surplus electricity and low electricity price [13]. However, Romanchenko et. al. [3] indicate that in a future electricity system with high average electricity prices and price fluctuations the heat produced by heat pumps will be 20% lower than current while the CHP production will increase by a factor of 25%. The cost calculation in this project has been based on a weekly resolution, while the electricity prices in the market of Nordpool vary hourly [40], this entails that to analyze based on a real world the calculations can be redone with an hourly electricity price and perhaps another optimization program. Another perspective on this weekly calculated heat prices is that large heat pump plants cannot turn on and off hourly, this is a factor which is dependent on the mechanical performance of the heat pump, therefore, this weekly-based calculation can give a picture that can be enough close to the reality.

Another interesting point during this project was heat available at low temperature from Preem to GE. This concept can be generalized, by reducing the supply temperature on waste heat provider's side the amount of mass-flow can increase as it is showed in the results of Preem case. If consumers decrease further the desired temperature to e.g., 70 then there will be access to enough high temperature on the waste heat provider's side which can be used for other issues like carbon capture.

Carbon capture and storage (CCS) is one the new and under investigation processes to meet the climate change goal for the future [56]. According to [57] there are three commonly considered technologies for carbon capture; pre-combustion, post-combustion and oxy-fuel combustion. The appliance of technology for different chemical industries is depending on the industry processes and it is a process which requires a lot of energy. Liu et. al. in [58] investigate carbon dioxide capture in a Coal-to-Methanol process plant. The study deals with improving the efficiency of the plant with CCS based on waste heat recovery.

In the case of refineries and other waste heat providers, by reducing the supply temperature to the HEX for the customers, the heat at higher temperature can be directed to carbon capture purposes. Since, for instance, post-combustion methods require large amount of energy [57], if this energy demand is satisfied by cheap waste heat, the carbon capture process would be price-beneficial in the way to meet the climate change goals as described in [56].

4 Conclusion

The project investigated a method of reducing the temperature of return flow DH in the city of Göteborg in Sweden. Since the DH-network of Göteborg is operated and distributed by company GE, the analysis tried to include the main plants which can be affected by reduction in the return temperature. These plants were three waste heat providers to GE: Preem refinery Göteborg, ST1 refinery Göteborg and Renova waste-fuel CHP plant; and also, production units of GE, as a what-if situation.

The optimization done in the project showed that temperature reduction in the return flow of DH by installing a heat pump is a concept which have many aspects to be considered. Since the COP-value of a heat pump is an indication of operation expenditure, reaching an enough high COP-value is an important point. The calculations and the optimization models showed that a high COP cannot always promise a high enough temperature reduction, but the system can always balance to find an enough high temperature reduction with an acceptable COP.

Another factor which could limit temperature reduction of the return flow, was the supply temperature of DH. The supply temperature is a characteristic of the DH which becomes decided by the DH-company and based on the outdoor temperature. For higher supply temperature the temperature reduction was high enough, and it was reduced by reducing the supply temperature.

Mixing the flows after the heat pump condenser and the supply DH flow have also been analyzed which indicated that for larger flow passing the heat pump condenser a better temperature reduction can be achieved.

For a waste heat purchaser company, installing of the such heat pump in order to extract more heat would be cost benefit if the waste heat prices reduce. The analyses of economic issues of the heat pump installation showed that installing heat pump by the purchaser company with the hope of cheaper waste heat prices brings low economic motivations for the waste heat seller. But if the environmental issues are considered, this issue can be further discussed to make both sides motivated.

The installation of large industrial heat pump has uncertainties which are mostly because of the high average electricity prices and high electricity price fluctuations in the coming years. But in the other side, heat pump, as a power-to-heat idea, can be a good complement for electricity surpluses and the times with lower electricity prices. The heat produced by the heat pump with cheap electricity price can also be a motivation for more heat storages in the future to reduce the usage of heat only boilers in the DH-system during peak hours.

The project introduced a concept of changing the structure of the heat exchanging between Preem and GE in order to have more waste heat available but at lower temperature. According to the information from both companies this is desired by both of the business part. The calculation showed that the concept is more cost- and environmental beneficial than the installation of heat pump on the current system, however this change in the structure can bring high investment cost. Further, this concept brings the idea of saving the residual waste heat at high temperature in order to direct it to a future carbon capture and storage at similar waste heat provider's plant.

The main questions for further investigations and studies are discussed, the most important are:
- Investigation for large high temperature heat pumps which can fit the DH-system of Göteborg.
- Investigation and analysis of the hourly price fluctuations and its impact on the DH prices for the installation of large industrial heat pumps in Göteborg.

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6 Appendix

Appendix 1

The schematic of heat pump installation between a waste heat supplier, and the HEX between the waste heat supplier and DH-company.

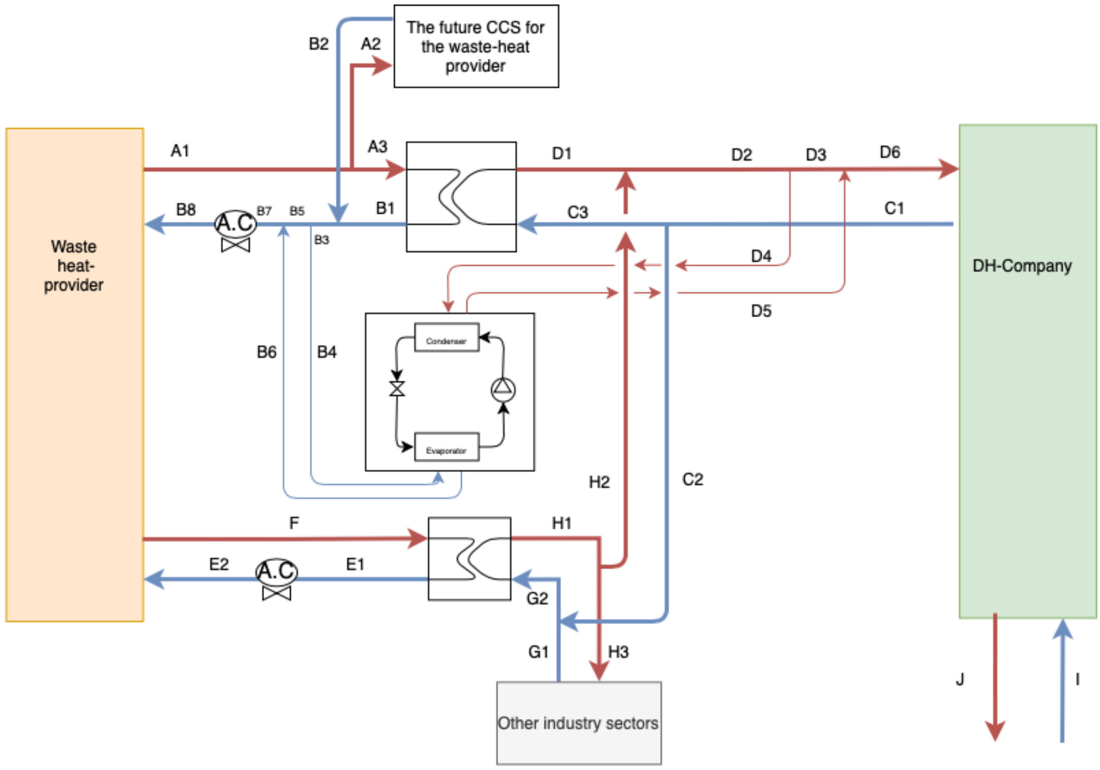

Figure 28 Schematic of heat pump installation between Waste heat provider and the HEX in order to save energy for CCS.

Appendix 2

Screenshot over the DH process of Renova's plant, taken from available material for course Industrial Energy system KVM013, with permission of [21] [42].

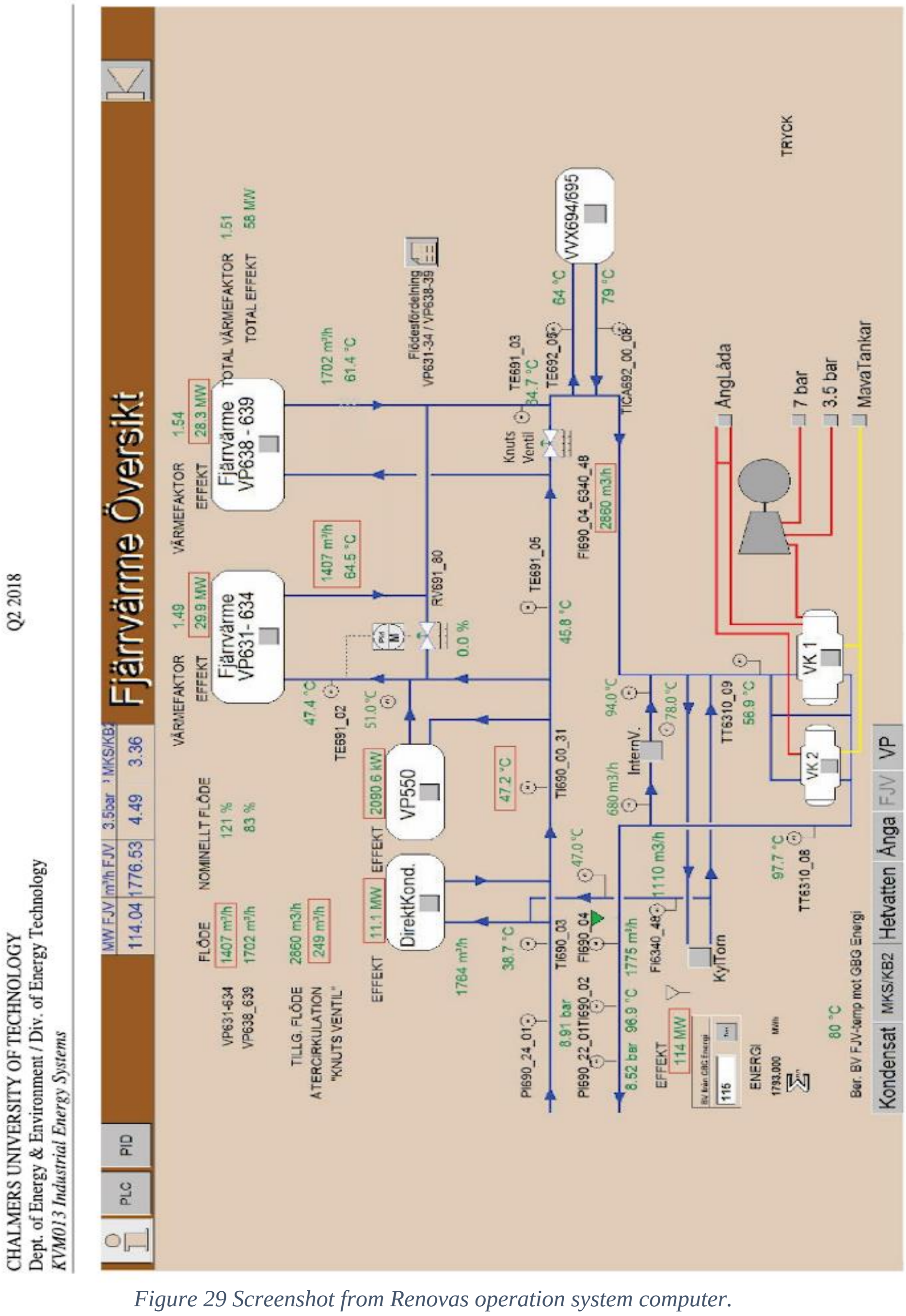

Figure 29 Screenshot from Renovas operation system computer.