CHALMERS

Investigation of the opportunity for heat integration at Preemraff Göteborg

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

ROBIN GOTTFRIDSSON & ISABELLE JOHANSSON

Department of Energy and Environment
Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

MASTER'S THESIS

Investigation of the opportunity for heat integration at Preemraff Göteborg

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

ROBIN GOTTFRIDSSON & ISABELLE JOHANSSON

SUPERVISORS:

Viktor Andersson

Cecilia Hellman

Sofia Ohlsson

EXAMINER

Thore Berntsson

Investigation of the opportunity for heat integration at Preemraff Göteborg

Master's Thesis within the *Innovative and Sustainable Chemical Engineering* programme
ROBIN GOTTFRIDSSON & ISABELLE JOHANSSON

Cover:
Picture showing air-cooled exchangers in the crude distillation unit. To the right are four heat exchangers connected to the district heating system.

Investigation of the opportunity for heat integration at Preemraff Göteborg

Master's Thesis in the *Innovative and Sustainable Chemical Engineering* programme
ROBIN GOTTFRIDSSON & ISABELLE JOHANSSON
Department of Energy and Environment
Division of Heat and Power Technology
Chalmers University of Technology

ABSTRACT

The industrial society is a large contributor to the anthropogenic climate change. It is therefore crucial to decrease the use of fossil fuels and to find better and more sustainable alternatives that are economically feasible. When price of energy and carbon credits increases due to limited reserves and environmental issues, the significance for improving energy efficiency becomes more important. For an energy demanding industry like oil refining, the incentives to decrease energy consumption is large in order to keep down the running costs. Pinch analysis is than a helpful tool for identifying potential energy savings at an existing plant.

In this master thesis, a pinch analysis has been performed at Preemraff Göteborg with the objective to investigate the option for increased internal heat recovery, thereby decreasing the utility demand. The potential for energy savings has been evaluated using information and stream-data collected at the refinery.

The pinch analysis shows that Preemraff Göteborg has a theoretical potential to save 40,2 MW of hot and 47,8 MW of cold utility. A retrofit replacing 12,9 MW of hot and 10,9 MW of cold utility, out of which 3,1 MW is reduction of deliveries to the district heating system, has been identified. The proposed heat exchanger network consists of 10 heat exchangers, and the cost was estimated to 28,5 MSEK with a payback time of 0,48 year. The retrofit also corresponds to approximately 25 kton of decreasing CO_2 emissions annually.

Key words: Pinch analysis, retrofit, energy savings, oil refinery

En utredning över möjligheten för ökad värmeintegrering på Preemraff Göteborg

Examensarbete inom masterprogrammet *Innovative and Sustainable Chemical Engineering*
ROBIN GOTTFRIDSSON & ISABELLE JOHANSSON
Institutionen för Energi och Miljö
Avdelningen för Värmeteknik och maskinlära
Chalmers Tekniska Högskola

SAMMANFATTNING

Industrisektorn är en stor källa till de antropogena utsläpp som orsakar global klimatförändring. Det är därför viktigt att minska användandet av fossila bränslen och finna bättre och mer miljövänliga alternativ som är ekonomiskt hållbara. Med ökande priser på bränsle och utsläppsrätter på grund av begränsade energitillgångar blir energieffektiviseringar allt viktigare. Detta blir extra viktigt för energiintensiva industrier som oljeraffinaderier där bränslekostnader är en stor utgift. Pinchanalys är då ett kraftfullt och hjälpfullt verktyg för att identifiera potentiella energibesparingar inom en befintlig anläggning.

I detta examensarbete har en pinchanalys utförts vid Preemraff Göteborg med målet att undersöka möjligheten för en ökad intern värmeåtervinning, och därmed minska behovet av befintliga hjälpsystem. Med hjälp av tillgänglig information och insamlad data från Preemraff Göteborg har potentialen för en ökad energibesparing undersökts.

Pinchanalysen visar att det är teoretiskt möjligt att minska värmetillförseln med 40,2 MW och kylbehovet med 47,8 MW. Ett förslag till ombyggnad som ersätter 12,9 MW varma och 10,9 MW kalla hjälpsystem, varav 3,1 MW består av minskade fjärrvärmeleveranser, har presenterats. Det föreslagna värmeväxlarnätverket består av 10 värmeväxlare och kostnaden för detta uppgår till 28,5 MSEK med en återbetalningsperiod på 0,48 år. Förslaget motsvarar också en årlig minskning av CO_2-utsläpp med cirka 25 kton.

Nyckelord: Pinchanalys, ombyggnation, energieffektivisering, oljeraffinaderi

Contents

Preface

In this master's thesis Preemraff Göteborg has been studied using pinch analysis. The objective has been to investigate the opportunity to decrease the energy consumption by replacing utilities with internal heat exchangers. The work has been carried out at the Division of Heat and Power at Chalmers University of Technology in cooperation with Preemraff Göteborg and COWI.

We would like to express our gratitude to our supervisors Cecilia Hellman at Preemraff, Viktor Andersson at Chalmers and Sofia Ohlsson at COWI for all helpful inputs and support. We would also like to thank the process engineers at Preemraff Göteborg for much valued help during this project.

Göteborg, June 2011

Robin Gottfridsson and Isabelle Johansson

Notations

A	Heat exchanger area [m^2]
CC	Composite Curve
Cp	Specific heat capacity [J/kg K]
F	Flow rate [Sm^3/d, Nm^3/h]
GCC	Grand Composite Curve
HP	High pressure steam, 15 barg
HX	Heat exchanger
h	hour
h_1	Heat transfer coefficient for stream 1 [kW/(m^{2}K)]
h_2	Heat transfer coefficient for stream 2 [kW/(m^{2}K)]
J	Joule
kW	kilowatt
LP	Low pressure steam, 3,5 barg
MER	Maximum energy recovery
MK1	Diesel with environmental classification 1, containing low sulphur
MWh	Megawatt hour
PBP	Payback period [yr]
Q	Heat duty [W]
RME	Rapeseed Methyl Esther
U	Overall heat transfer coefficient [kW/(m^{2}K)]
ΔT_C	Temperature difference on cold side [K]
ΔT_H	Temperature difference on hot side [K]
ΔT_{lm}	Logarithmic mean temperature difference [K]
ΔT_{min}	Minimum temperature difference [K]

1 Introduction

In today's energy-consuming society it is important, from both an economical and an environmental aspect, to decrease the energy demand and to find more sustainable solutions for providing the required energy. As fuel and electricity prices rise, using energy more efficient is of growing importance. To reach a more sustainable future worldwide, the EU adopted a new energy and climate policy in 2008 which includes targets for the year 2020, the so called "20/20/20"-package. It involves 20% reduction of greenhouse gases based on the levels in 1990, 20% reduction of energy consumption through energy efficiency and that 20% of the energy supply should come from renewable sources[1]. [2]

Refining oil is an energy-intense process. In 2009, the fuel consumption and electricity demand at Preemraff Göteborg was 2570 GWh and 150 GWh respectively. [3] If this is compared to 25 MWh, the energy consumption in a Swedish normal household in a year, Preemraff Göteborg corresponds to 110 000 normal households. [4] The refinery is situated at Hisingen and has a capacity of refining 6 million ton crude oil every year. [5]

Preemraff Göteborg is working hard to decrease their environmental impact. One example is the newly developed bio refinery unit producing bio diesel from tall oil for mixing with fossil diesel, which was built in 2010. [1] They also mix renewable components such as RME[2] and ethanol with diesel and gasoline and drive the question to increase the maximum allowed levels of these additives. In the latest study from Solomon Associates, a consulting company that performs a bench marketing study of participating refineries every second year, Preem was ranked in the top compared to other refineries in Europe. It shows that Preem emits 25% less CO_2, 70% less NO_x and 95% less SO_2 compared to an average refinery in Western Europe. [1] A reason for this is the opportunity to deliver district heating. This is due to that the refinery produces a lot of heat at temperatures which are to low to be used at most places in the process. Instead of cooling to the surroundings Preemraff heats the district heating system with it.

This excess heat is delivered to Göteborg Energi AB, GEAB, via two separate systems, one going straight to Volvo Torslanda and one connected to the municipal district heating system. During the cold seasons, when demand for district heating is high, the refinery's cooling demand is met mainly by the district heating system but during summer excess heat must be removed by air fans. It is desirable to instead make use of the excess heat internally in the process and thereby minimize the fuel consumption and the need for cooling during summer.

---

[1] For Sweden this means that 50 % of all energy will come from renewable sources by 2020. [1]
[2] Rapeseed Methyl Esther

1.1 Objective

The aim of this master thesis is to investigate the opportunity for an increased use of internal heat exchanging at Preemraff Göteborg using pinch analysis. Investigation of the refinery's energy consumption and current system will result in a retrofit proposal that increases internal heat recovery, thereby decreasing the fuel consumption and the resulting emissions. It is also desirable to compare today´s energy consumption and the minimum energy needed if the studied system was constructed as a MER[3] network.

1.2 Problem analysis

To simplify the data collection as much as possible it is important to first identify a system boundary. This because the data collection is a very large and time consuming part that can easily slow down the work if there is no clear structure. The studied system, further explained and limited in *1.4 Limitations* includes streams heated or cooled using utilities at all units of the refinery. To be able to calculate the individual duty for all streams density, flow, start and target temperature and specific heat capacity or enthalpy have been extracted.

1.3 Method

The project consists of three main parts; literature study, data collection and an evaluation of the data.

The literature study will focus on oil refining in general and at Preemraff Göteborg in particular. Pinch technology will also be studied more closely. The second part includes collection of all necessary data and is the most time consuming part. This information is used to identify misuse of utilities and streams with a potential for heat exchanging.

In the third part of the project the data is analysed using pinch analysis. Streams suitable for heat exchanging are identified and a rough economical estimation, for the suggested retrofit, is performed.

1.4 Limitations

To be able to perform this master thesis within 20 weeks a complete pinch study including all streams at the refinery will not be performed. Instead the system boundaries are set so that only streams heated or cooled with utilities such as steam, furnaces, air cooling and district heating are included. This means that all process streams currently heat exchanged with other process streams are rejected. Apart from streams using utilities some streams not presently used for heating or cooling will be included. These are mainly effluent flue gases where further cooling is possible and cold feed of combustion air into furnaces with the potential for preheating.

---

[3] Maximum Energy Recovery

The data, and therefore, the pinch analysis will be valid for a summer case when the need for cooling is at its highest. During the winter, cooling is performed by the district heating system and air coolers combined, but during the summer air coolers are used to a larger extent since the demand for district heating is low.

Apart from air cooling and cooling through the district heating system there is a cooling water system at Preemraff. It has been decided, in discussion with Preemraff Göteborg, not to include this system due to seasonal intermittence and lack of data. The cooling water system is small compared to the other cold utilities included in the analysis. Note that the district heating system and the cooling water system are two separate systems.

2   Pinch analysis

Pinch analysis was developed at the Institute of Science and Technology in Manchester in the late 1970s by Professor Bodo Linhoff. It is a methodology to systematically determining the minimum heating and cooling demand of a process and a tool for optimizing the energy recovery and thereby minimizing the need for hot and cold utilities. Pinch analysis is a useful tool when performing energy analysis on both existing industrial plants and for grass rot designs, in order to save both energy and money. [6]

2.1   Theory

This chapter only covers pinch analysis briefly. For further information refer to the book: *Pinch Analysis and Process Integration* where most of the information in this section is originally from. [7]

When starting to use pinch analysis all streams requiring heating or cooling must be identified as a hot or cold stream. A hot stream is, regardless of its temperature, a stream which requires cooling and a cold stream is for the same reason a stream requiring heating. Each stream has a start and target temperature as well as a duty.

By combining all the individual loads and the corresponding temperature intervals of the hot streams it is possible to produce a hot Composite Curve, CC. Doing the same for the cold streams produces the cold composite curve. The two composite curves can be seen as a summation of all individual hot and cold streams. If these curves are plotted in a temperature/enthalpy-diagram valuable information about the systems energy demand can be drawn. See *Figure 1* for an example of composite curves.
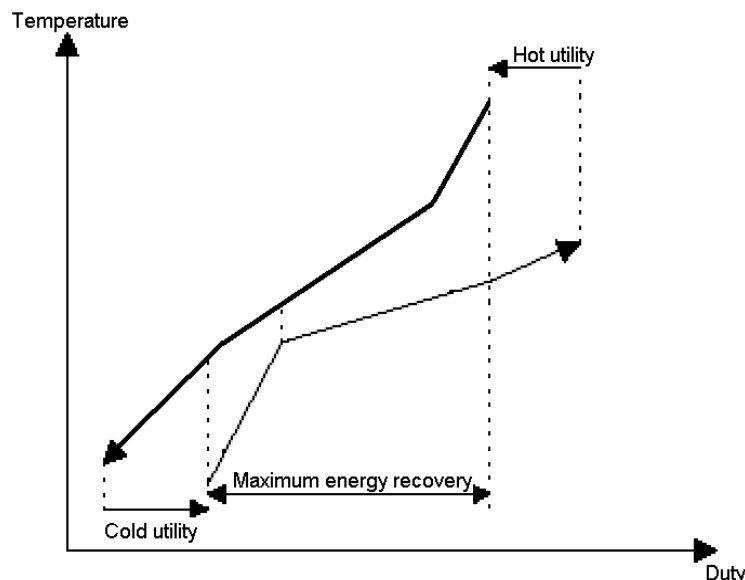

Figure 1. Hot and cold composite curve. Bold line represents the hot composite curve and the thin line the cold composite curve.

The different streams in the composite curves have different slopes since the slope corresponds to the product of flow and specific heat. It is preferable to use the

5

available heat from the hot stream as much as possible. As seen in *Figure 1* the maximum possible energy recovery is the area where the hot and cold composite curves overlap. As long as the hot composite curve, (which needs cooling) has a higher temperature than the cold composite curve it is possible to recover energy by internal heat exchanging. Also shown in the figure is the minimum hot and cold utility demand which is the need for external heating and cooling if maximum energy is recovered. A network which meets this target of maximum energy recovery and thereby minimizing the need for external utility use is called a Maximum Energy Recovery, MER, network.

The shortest distance between the two composite curves is called the pinch. The temperature where the pinch is situated is therefore called the pinch temperature. The temperature difference between the hot and cold composite curves at the pinch is called the minimum temperature difference, (ΔT_{min}), and represents the lowest acceptable temperature difference between the hot and the cold streams in a heat exchanger. The minimum temperature difference is free to choose but is usually in the region of 10-20 K. One can select an individual ΔT_{min} in all heat exchangers or use a global value throughout the process. The temperature difference has however significant impact on the heat exchanger cost, remembering that:

$$Q = U\,A\,\Delta T_{lm} \qquad (1)$$

Where
Q= Duty [W]
A= Area [m^2]
ΔT_{lm} = Logarithmic mean temperature difference [K]
U= Overall heat transfer coefficient [W/m^{2}K]

As seen the temperature difference is inverse proportional to the size of the heat exchanger required between two streams. With a large temperature difference between two heat exchanging streams the driving force will be large and consequently the heat exchanging area decreases, whilst the need for external utility increases. This can be seen in the above figure since with a larger ΔT_{min} the cold composite curve must be shifted to the right causing internal energy recovery to decrease and thereby external utility need to increase. Because of this, choosing ΔT_{min} is important since it is correlated to operating cost and investment cost.

The pinch temperature divides the system into two thermodynamically separate systems. The system acting above the pinch temperature will have a heating demand and the system acting below the pinch will have a cooling demand. Hot streams above the pinch temperature can be used to heat the cold streams above the pinch. The cold streams below the pinch can be heated using the hot streams below the pinch. Deviations from a MER network, resulting in increased demand of utilities, can be explained by violations to the three pinch rules:

- Do not use coolers above the pinch
- Do not use heaters below the pinch
- Do not transfer heat through the pinch
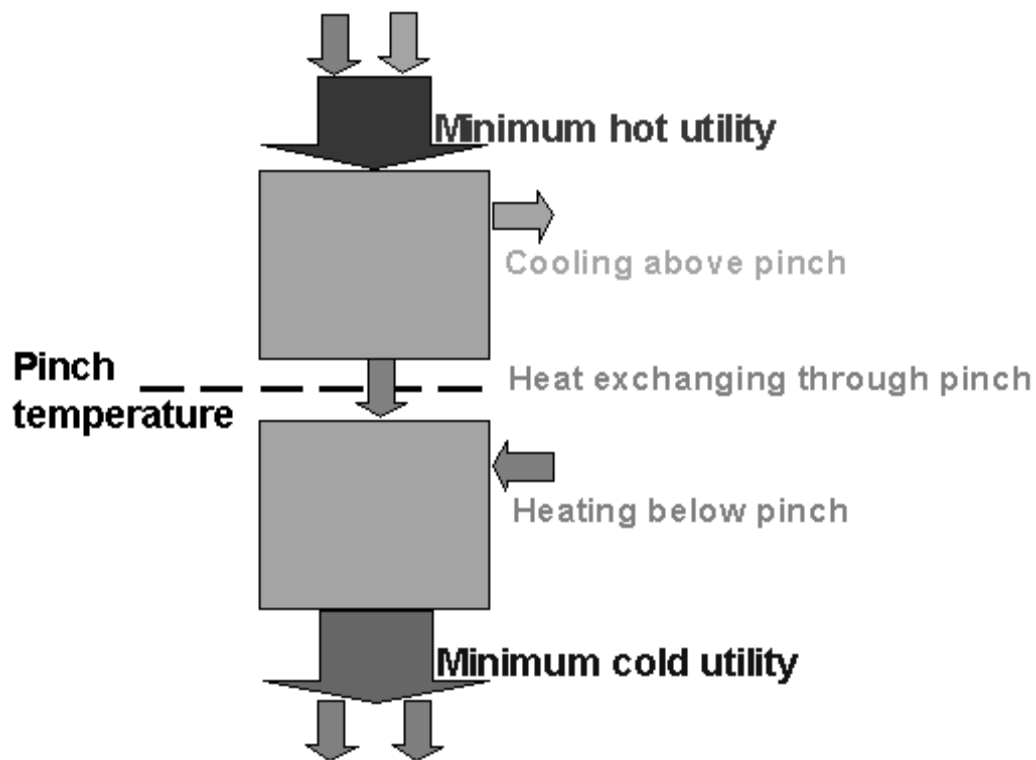
Figure 2: Illustration of the three pinch rules. [22]

As seen in the figure above, breaking these rules will result in a heating and cooling demand that is higher than the minimum possible. Cooling above the pinch, where heat is needed, will result in a larger heating demand above the pinch. Heating below the pinch, where there is a heat surplus, will for the same reasons result in an increased cooling demand. Transferring heat through the pinch will lead to a higher utility demand on both sides of the pinch, since removing heat from above the pinch results in a higher hot utility demand and adding heat below the pinch will result in a larger need for cooling. Instead internal heat exchanging above and below the pinch should be used to ensure that no energy is wasted.

When performing a pinch analysis it is convenient to work with so called interval temperatures. The interval temperature is calculated by subtracting $\Delta T_{min}/2$ from all hot streams and adding $\Delta T_{min}/2$ to all cold streams. By plotting the net heat flow against the shifted temperatures a Grand Composite Curve, GCC, can be created as seen in *Figure 3*. This represents the net heat flow to the interval temperatures. From this it is possible to see not only the minimum amount of cooling and heating necessary to run the process but also at what temperatures this heating and cooling demand must operate, which is a large benefit. Another advantage of this GCC is that it can be used for studying different potential for heat integration and use of waste heat.
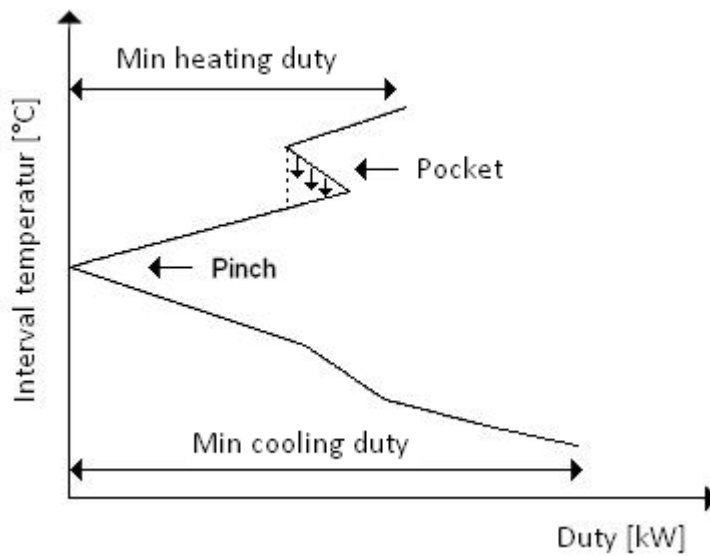
Figure 3. Grand composite curve showing the minimum hot and cold utility demand

The minimum heating and cooling demand of the process are easily read of from the GCC above. A so-called "pocket" can also be seen in the GCC and represent a region where the cold stream is not in need of external heating using utility, since it can be heat exchanged with a hot process stream within the process. The pinch temperature is found where the GCC touches the temperature axis and divides the process in the two networks above and below the pinch. It is important to note that a change in ΔT_{min} can have a drastic effect on the shape of the GCC and thereby also the pinch temperature, since a change in ΔT_{min} changes the need for external heating and cooling supplied by utility.

As mentioned before, a MER network can be created if all energy possible to recover is recovered. This implies that all heat exchangers are placed according to the pinch rules so that no pinch violation is present. The MER network will have the same heating and cooling demand as the one shown in the GCC. It is however not economically feasible to construct all heat exchangers recommended in the MER network. That would require building a heat exchanger network with unreasonable large heat exchanger area, numerous small heat exchangers and large piping distance.

2.2   Retrofitting a heat exchanger network

Rebuilding an existing plant to follow all pinch rules requires extensive reconstructions which is often costly. A better alternative is to do a retrofit. When using pinch analysis to modify an existing process, the energy demand can be decreased in an economically feasible way. The goal when retrofitting is never to construct a maximum energy recovery network. Built-in constraints, lack of space and economical issues are limiting the options of possible heat recovery as the investment cost increases with increasing internal heat recovery.

The basic principle when retrofitting a heat exchanger network is to retrain existing heat exchangers in their original positions as far as possible. Existing heat exchangers have already been invested in and although they might not be perfectly fitted in the network it would not be economically feasible to replace all of them. Instead

8

modification of some of them can be done in order to make them fit in the new process. Of course some new heat exchangers must be invested in. It is also preferable to re-pipe as little as possible since piping is expensive and might require other changes in the process. In a proposed heat exchanger network it will always be a compromise between energy savings and economy.

The goal is to make economically sustainable and effective heat exchangers that follow the pinch rules and also to eliminate current pinch violations as much as possible.

2.2.1 Matrix method

When performing a retrofit it is important to include as many streams as possible to keep all opportunities open and not exclude streams because one may think that it is unnecessary due to temperature, location etc. All this should be left to the pinch analysis. The way to find the best retrofit design can be a very complex and iterative process since it includes a lot of different choices when it comes to heat exchanger alternatives.

The Matrix method, developed at the division of Heat and Power Technology at Chalmers, is a strategy for retrofitting heat exchanger networks and to identify energy-saving and economically feasible heat exchanging possibilities. It is well suited to handle a large number of possible heat exchanger alternatives and the economic aspects. Instead of only looking at the cost for the new heat exchanger area which in most cases only refers to one part of the total cost of the retrofit, the Matrix method also takes parameters as piping costs, maintenance costs and costs associated with pressure drop into account. The area costs are easily calculated compared to the piping and maintenance costs that must be approximated with the site in mind as they are dependent of distance, type of material and space respectively. [8] To simplify the analysis only investment costs based on the heat exchanger area and piping costs are considered in this thesis.

The base in the Matrix method is two matrices, one above and one below the pinch, containing all heat exchanger possibilities and the resulting cost. In both matrices rows correspond to hot streams and columns correspond to cold streams. When dividing all streams into these two matrices, pinch violations due to existing heat exchangers are taken into account and often the pinch rule has to be omitted. This results in some pinch violations that are considered acceptable, since it is not economically feasible to for example, install two new heat exchangers, one operating above and one below the pinch instead of using the already existing one operating to some extent through the pinch.

The construction of the network is an iterative process where the cheapest heat exchanger is placed first. An existing heat exchanger has low or none cost whereas a new one has a higher cost. After heat exchangers are placed between all possible streams the Matrix is recalculated for the new setup and placing of heat exchangers continue until all streams have reached their target temperature. It is possible when selecting a cheap heat exchanger first that one may end up with a really expensive one in the end, so it is important to look out for these effects and test different paths. When heat exchanging between two streams no longer is possible the remaining duty must be met by utility.

2.3 ProPi

Propi is an add-in in Excel developed by CIT Industriell Energy AB and is a helpful tool when working with pinch analysis. [8] By having a start and target temperature as well as the duty for all streams as input data, graphs of CC and GCC can easily be constructed showing the minimum hot and cold utility and naturally the pinch temperature. It is also possible to construct a heat exchanger network and locate pinch violations in existing networks.

3 Preem refinery

Preemraff Göteborg is essentially a hydroskimming refinery. A hydroskimming refinery is fairly simple compared to the more complex coking refinery. In addition Preemraff Göteborg has been equipped with an advanced desulphurization system that produces fuels with less than 10 ppm sulphur content and also a new biodiesel production, classifying it as a small complex refinery. [9]

3.1 The process

Crude oil is delivered by ship to Torshamnen, mainly from oil wells in the Nordic sea. The crude oil is distilled in one of two identical systems to form five fractions; top fraction, two light gas oils (LGO and LLGO), heavy gas oil (HLGO) and heavy fuel oil as shown in *Figure 4*. The heavy fuel oil is used as the main component in heavy fuel oils (Eo3-Eo5) while the other fractions are sent to different desulphurizing systems where sulphur is removed with H_2 producing H_2S.

The top fraction is sent to the distillate hydro treating unit (DHT) where it is desulphurized and separated into kerosene, light naphtha and naphtha. The kerosene is sent to storage while the naphtha is sent to a reformer unit (CRU) which increases the octane number[4] of the naphtha while producing hydrogen. The light naphtha is sent to an isomerisation unit which increases the octane number together with the Molex unit. Both naphtha and light naphtha are main components in gasoline while the kerosene is used mainly as a diesel component. [10]

After an initial desulphurization of the light gas oils a fraction is sent to storage to be used as diesel component. The rest is sent to further desulphurization and dearomatization in the synergetic saturation unit (SYNSAT) where it becomes low sulphur diesel.

The heavy gas oil is sold to other refineries equipped with a cracking unit for further processing.

The H_2S produced in the desulphurizing units is purified in a sulphur recovery unit, SRU, where liquid sulphur is separated from the hydrogen.

---

[4] The octane rating of a fuel corresponds to its activation energy. A high octane number is preferable for engine performance.
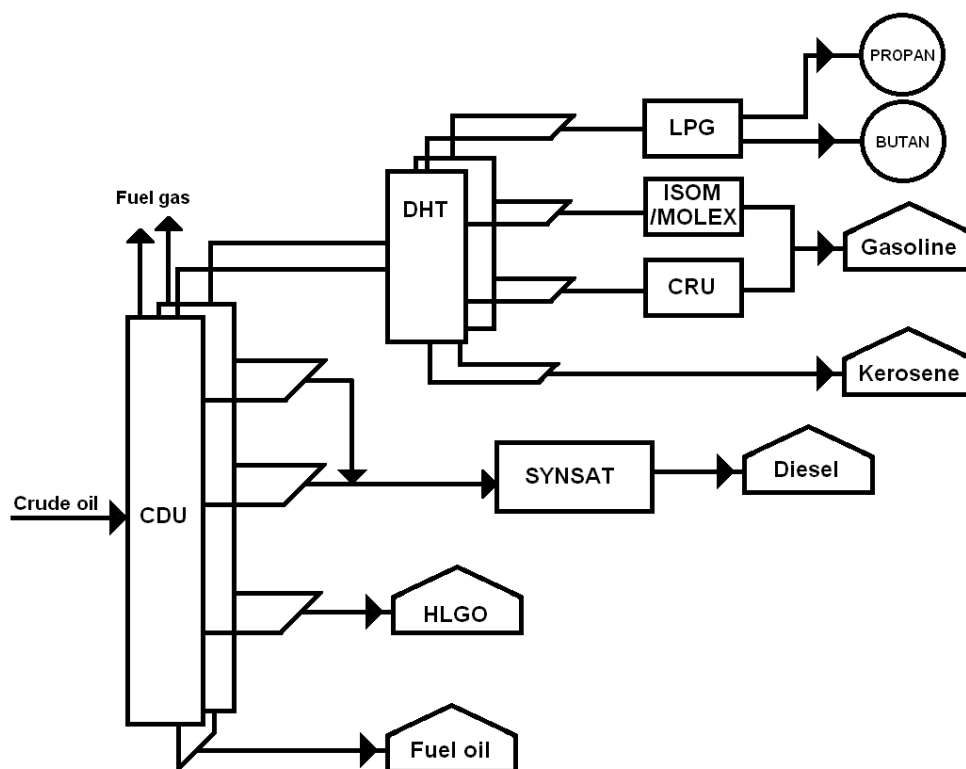
Figure 4: Schematic figure of the process.

3.2   Energy

The energy demand of the refinery is provided by fuel gas and fuel oil produced on site and imported natural gas as a complement. The fuel gas consists of the non-condensable gases ethane, methane and hydrogen but butane and propane are also used. An excess of fuel gas can arise if problem occurs in one of the units, and in that case the fuel gas is lead to the flare. [11]

Earlier Preemraff had a gas turbine to generate electricity on site, but since it broke down in 2004 all electricity is imported. [11] In 2009, the refinery used 2566 GWh of energy. Most of this was used to heat streams and produce steam. 152 GWh was electricity mainly used to drive equipment like compressors and pumps. [12]

Both HP and LP steam is produced on site in steam boilers and are explained further in *3.2.2 Utilities*. When the process at Preemraff is running on its maximum on all units the total demand of steam is approximately 110 ton/h. During the cold seasons the demand is increased with 10-15 ton/h to heat tanks and pipes. [11] The largest consumers of HP steam are the reboiler to the benzene tower in the reformer unit, a reboiler and a preheating exchanger within the isomerisation unit (ISOM) and steam turbines for running pumps. For the LP consumers the large units are Molex, crude oil units, Amin, LPG, tanks and pipes. [11]

There are several furnaces and steam boilers on Preemraff Göteborg. They mainly use gaseous fuels although some of them can be powered with fuel oil. The two furnaces preheating the crude oil, before distillation, are the largest in terms of effect.

12

3.2.1 District heating

Gothenburg has a well developed district heating system that delivers approximately 3800 GWh of heat every year. The heat is mainly produced by Sävenäs CHP-plant, Rya CHP-plant and excess heat from industries. Preemraff Göteborg is only a small contributor; approximately 7 % (310 GWh) of the heat supplied by GEAB comes from Preemraff. [3, 13]

There is also a separate district heating system for Volvo Torslanda. Preem delivers approximately 140 GWh to Volvo with peaks in winter. [3] The heat to Volvo is delivered at 130-140 °C compared to 90 °C for the GEAB system. The reason for this is that Volvo, unlike GEAB, is not only using the heat for heating buildings but also in the process. The two district heating systems at Preemraff are working independently but there is a possibility to transfer heat from one system to the other. Both systems are constructed in the same way and consist of a number of parallel circuits that pick up heat in different heat exchangers and economizers at different temperature levels throughout the process. A large amount of the heat delivered to Volvo comes from cooling the residue and HGO[5] from the crude distillate towers. The heat to GEAB is transferred from all over the plant. [14]

The district heating system's need for heat varies over the year. During the summer when the district heating demand is low Preemraff Göteborg remove their excess heat by air fans and to some degree by cooling towards GEAB's system.

3.2.2 Utilities

The utilities used at Preemraff Göteborg are:

- Steam
- District heating
- Air coolers
- Furnaces
- Cooling water
- Steam generators

Steam is mainly produced in 4 steam boilers as high and low pressure steam at 15 and 3,5 barg respectively. Preemraff has a capacity to produce 136 ton/h of HP steam and 33 ton/h of LP steam [11]. The steam is mainly used in reboilers to evaporate hydrocarbons being distilled. District heating is used both as a cold and a hot utility since it is used for cooling high temperature hydrocarbon streams but also to preheat air into one crude furnace and to heat raw water going to the deionization unit. Air is used both as the cooling media in air-cooled exchangers and as a safety system. The air coolers consist of finned tubes containing the hot streams and a fan used to increase heat transfer to the air. The air-cooled exchangers are often used as a complement to the district heating coolers, either as a replacement when the need for district heating is low, or to cool streams further down in temperature.

---

[5] Heavy Gas Oil

Furnaces are used to heat streams to temperatures where steam cannot be used. The furnaces are powered mainly by fuel gas. The fuel gas mainly consists of non condensable gases from the process and includes methane and ethane. Other gases produced on site are also used and among them are propane, butane and hydrogen. The hydrogen is used for the desulphurization processes as described in *3.1 The process*. Imported natural gas covers the remaining fuel gas demand and is considered as the margin fuel. [11]

Steam generators are used for cooling streams of high temperatures and produce steam. They are fed with low pressure steam condensate which is evaporated by the process streams to produce low pressure steam.

4 Methodology

Much of the work in this master thesis has been to study the plant and collect all the necessary data to analyze the existing situation at the plant. All data collection was carried out at Preemraff Göteborg, mostly using the program Aspen Process Explorer that stores all continuously measured data.

4.1 Data collection

Data was collected for process streams heated or cooled with utilities. A summer case with MK1[6] production was studied since the process runs slower when producing MK1 diesel creating a smaller load of excess energy as compared to MK3 that runs faster and thereby creates more excess energy. Since Preemraff is turning more and more towards producing MK1 diesel it is reasonable to only look at this mode. The studied periods were 16/6 – 28/6, 15/7 – 1/8 and 10/8 – 19/8 in 2010 because at these times MK1 production was stable for longer periods of times.

Most data were retrieved from online sensors via Aspen Process Explorer. Parameters such as temperature, flow and duty were taken as a mean over the period in question. If the variation of the value was large, a reasonable average was taken with help from the process operator and process engineers at Preemraff Göteborg. Apart from this, intermittent data and disabled streams could be identified.

In some cases data was not found since no measurements existed or it was not possible to calculate it through heat- and mass balances. In these cases data was taken as estimations from process engineers at site. No measurements were done in the plant since this would have given misleading information as the data collection took place during the winter when the heat profile is different. With a limited time schedule in mind these measurements would also have taken too much time.

Heat capacity, enthalpies, density and, in some cases, degree of condensation was collected from simulations in PROII, a process simulation program used at Preemraff. Data has been extracted from previously made simulations to save time. By modifying an already existing stream in PROII to correspond to the actual temperature in the studied period, it was possible to recover the necessary data. For streams undergoing phase change, the heat of vaporisation and the temperature at which it occurs was extracted. For cases where there is a phase change occurring over several temperatures a mean temperature over the interval has been used.

4.2 Evaluation of the data

All values such as flow and temperature were taken for the process side of the utility units in order to calculate the loads, except for the district heating units where reliable duties were available to extract straight from Aspen Process Explorer. This resulted in close to 150 streams, which can be quite overwhelming. To reduce the number of streams, only hot streams with a starting temperature higher than 65 °C were included. This resulted in 71 hot streams and 39 cold streams, in total 110 streams.

---

[6] Environmental class 1 diesel

4.2.1 Stream representation

Using the Excel add-in ProPi, it is important that all streams have a constant value of specific heat enthalpy, Cp, within its temperature interval. This will not be true for streams that undergo a phase change as well as a temperature change. These steams have to be split in two separate streams, one representing the phase change and one representing the temperature change, both with a constant value of Cp. The duty for condensing or evaporating streams was calculated using heat of vaporisation for streams extracted from PROII simulations.

All streams have been assigned individual temperature differences depending on phase and can be seen in the table below.

Table 1: Individual ΔTmin/2

Phase	ΔTmin/2 [K]
Gas	10
Liquid	5
Mixture of gas and liquid	7
Condensing and evaporating	5

The streams can have soft or hard temperature targets. An example of a soft target is preheating of combustion air to the furnaces. The target temperature is currently set to 150 °C, but can be heated both to a higher and lower temperature. A hard target on the other hand requires that the target temperature is reached. An example of a hard target is a reboiler, it cannot function if the temperature target isn't reached. When constructing the heat exchanger network it is important to keep in mind which targets that are soft and which are hard. [15]

Regarding the streams identified as having a potential for internal heat exchanging a target temperature was selected. For all flue gas streams a target temperature of 180°C was chosen since this is the lowest acceptable temperature for the flue gases. If cooled further, compounds containing sulphur start to precipitate. [19]

4.3 Economical aspects

The equipment cost for the retrofit proposals were based on the heat exchanger area. The area was calculated using the duty (Q), the overall heat transfer coefficient (U) and the logarithmic mean temperature difference (ΔT_{lm}) as mentioned below in the equations. Both the duty and the logarithmic mean temperature difference were taken from ProPi whereas the overall heat transfer coefficient was approximated with equation (1). The heat transfer coefficients (h_1 & h_2) were taken from *Chemical Engineering Design*. [16] For the individual h-values used in this thesis see Appendix 2 – heat transfer coefficient.

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} \qquad (2)$$

$$\Delta T_{lm} = \frac{\Delta T_c - \Delta T_h}{ln\left(\frac{\Delta T_c}{\Delta T_h}\right)} \qquad (3)$$

$$Q = U \cdot A \cdot \Delta T_{lm} \rightarrow A = \frac{Q}{U \cdot \Delta T_{lm}} \qquad (4)$$

In this master thesis, focus was on finding locations where a utility heat exchanger can be swopped for an internal heat exchanger and therefore only cost of new heat exchangers has been considered. Costs for the new equipment were derived from equations in *Chemical Engineering Design* [17] using cost index (CE) from *Chemical Engineering* [18, 19].

$$C = (a + b \cdot S^n) \cdot \frac{CE_{11}}{CE_{07}} \cdot v \qquad (5)$$

Where for a U-tube shell and tube heat exchanger in carbon steel:

C = Purchased equipment cost in SEK for 2011
a = {Cost constant} = 24 000
b = {Cost constant} = 46
S = Size parameter in this case the area calculated from eq. 3
n = {Exponent for a certain type of equipment} = 1,2
CE_{11} = {Cost index for jan 2011} = 564,8
CE_{07} = {Cost index for jan 2007} = 509,7
v = {Currency value} = 7 SEK/USD

To get a better approximation of the costs for the possible heat exchangers in the Matrix method a cost for piping has to be added. According to Preemraff the costs for the pipe and to get it in place is roughly 1000 SEK/m. The distance between the two locations was estimated with help of an air photo where the pipe route could be followed.

To account for expenses such as installation, engineering cost, labour etc. a Lang factor was multiplied to the capital cost. The Lang factor is an empirically decided constant used to estimate the final price when all costs are taken into account. Since this is a system where fluids are handled a factor of 4,7 is used. [17]

4.4   The Matrix method

When using the Matrix method all possible heat exchanger loads where first calculated above and below the pinch in two separate matrices. By using this together with the overall heat transfer coefficient and the logarithmic mean temperature two new matrices could be created containing all heat transfer areas. With help of equation (5) the corresponding costs could be calculated and by summation with the piping costs a total estimation of all possible heat exchangers were made. If the Matrix method is to be followed strictly, the costs for maintenance and pressure drop should also be included. This has not been done due to time limitation.

A new matrix including possible load per Swedish crown was also made above and below the pinch, making it easier to compare all the potential heat exchangers.

Heat exchangers where selected from the matrices. It is always preferable to satisfy at least one of the streams heating or cooling demand. All selected heat exchangers identified as having potential for being used internally was disused with Preemraff Göteborg. Some choices that from the first point of view looked preferable had to be excluded due to reasons like costs, distance, technical issues etc.

5 Present situation

The studied system at Preemraff does not exchange heat internally instead it is strictly using utilities for heating and cooling. The utilities used for heating cold streams are low and high pressure steam, district heating water and furnaces. The utilities used for cooling hot streams are air (by air-cooled exchangers), district heating to Volvo and GEAB and steam generators producing low pressure steam. The present use of utilities, within the studied system, is:

Table 2: Present use of hot utilities

Hot utility	Load [MW]
Low pressure steam	20,0
High pressure steam	16,3
Furnace*	78,0
Total	**114,3**

* Note that not all furnaces are included in this study. The effect above is only including preheating of combustion air and process streams to furnaces.

Table 3: Present use of cold utilities

Cold utility	Load [MW]
Air cooling	102,1
Volvo district heating	23,6
GEAB district heating	27,7
Steam generator	6,1
Total	**159,5**

For more information on which streams are included see section *4.1 Data collection*.

5.1 Composite curves

The heating and cooling demand of the present system can be studied and evaluated using composite curves as described in chapter *2.1*. By using ProPi, both a composite curve and a grand composite curve have been constructed, and these are shown in *Figure 5* and *Figure 6* below. The pinch temperature was determined to be 134 °C, as seen in the GCC.
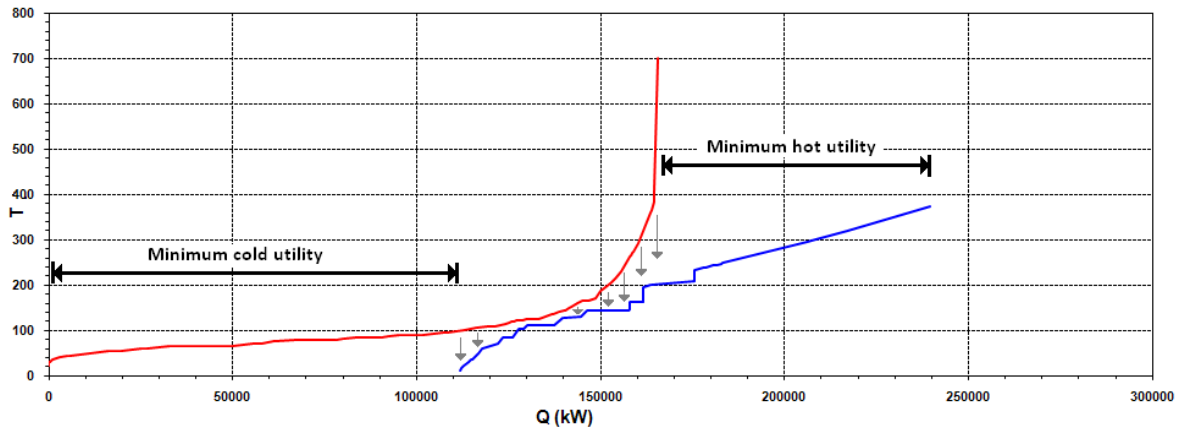
Figure 5: Composite curve. The grey arrows represent potential internal heat exchanging
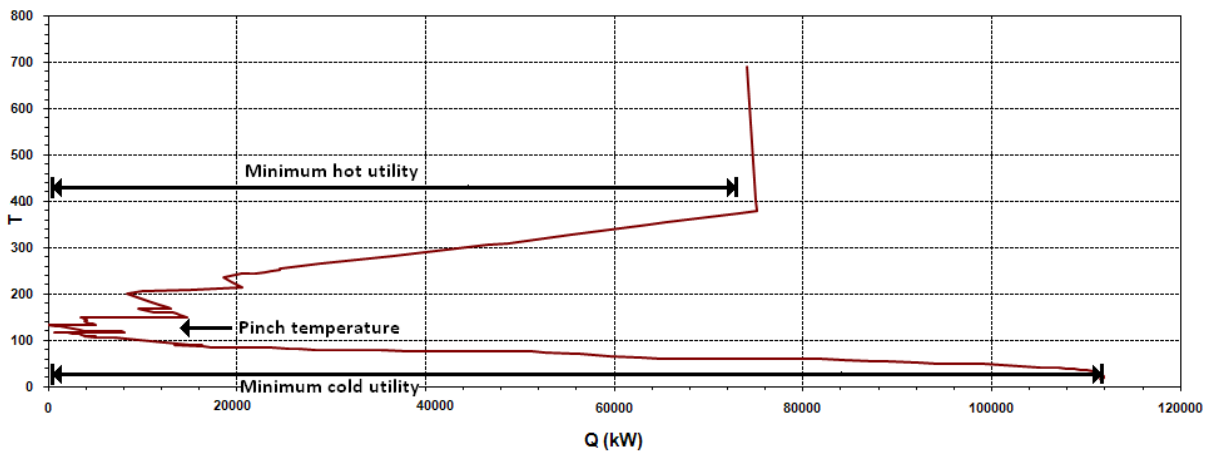
Figure 6: Grand composite curve. The individual ΔTmin/2 used are: 10 K for gases, 5 K for liquids and phase changes. 7 K is used for mixtures of gas and liquid.

The minimum cooling and heating demand of the system is seen in both the CC and the GCC and are as following.

- Minimum hot utility demand   74,1 MW
- Minimum cold utility demand   111,7 MW

When comparing the minimum utility demand to the amount actually used within the process, shown in *Table 2* and *Table 3*, it can be seen that 47,8 MW and 40,2 MW of cold respectively hot utility can be saved.

In order to achieve the theoretical hot and cold minimum demands presented above all pinch violations must be removed. In *Table 4* below, the major pinch violations in the present system are listed together with the utility in use.

20

Table 4: Major present pinch violations. Notice that there is no heat transfer through the pinch, since the network consists of only heaters and coolers. The summed pinch violations in the table include the minor violations not specified in the list.

Stream	Present utility	Cooling above [kW]	Heating below [kW]
60C-5	LP steam	0	5007,5
rökH-48	Volvo district heating	3987,5	0
15H-10	Steam horse	3716,7	0
tankC-39	LP steam	0	3534,7
6C-2	LP steam	0	2945,6
16H-25	Steam horse	2371,6	0
60C-6	LP steam	0	2356,5
rökH-47	GEAB district heating	2000,0	0
15H-12ab	Air cooling	1991,0	0
2H-42	Volvo district heating	1625,7	0
31C-10	Volvo return water	0	1387,0
1H-46	Volvo district heating	1323,6	0
6C-1	LP steam	0	1148,8
tankC-40	LP condensate	0	1108,3
12C-7	HP steam	0	1008,4
5H-30a	Volvo district heating	713,2	0
luftC-12	Volvo district heating	0	1223,6
rökH-51	Volvo district heating	410,8	0
16H-27	Air cooling	402,3	0
17H-19ab	Air cooling	302,2	0
rökH-49	Volvo district heating	250,1	0
1H-45	Volvo district heating	227,8	0
2H-41	Volvo district heating	227,8	0
Cold feed of cumbustion air to furnace	Furnace	0	7688,6
Total		**19670,1 kW**	**27433,7 kW**
		47,1 MW	

The main pinch violations are cooling above the pinch using district heating and heating below the pinch using low pressure steam. A reason for this is the temperature intervals at which these utilities work. Low pressure steam is condensed at 146 °C, only 12 °C higher than the pinch temperature. District heating water is delivered at 90 °C and 130°C to GEAB and Volvo respectively, which means that many of the streams used to heat the district heating system must be cooled above the pinch. Another large contributor to the pinch violations is heating of the combustion air in the furnaces below the pinch temperature. This follows from that cold combustion air is currently directly injected in the most furnaces without any preheating.

The chosen value of $\Delta T_{min}/2$ can have drastic effect on the shape of the GCC and hence the minimum heating and cooling demand. It was tested using half and double the actual value of $\Delta T_{min}/2$, with a change in the pinch temperature of only a few degrees Celsius and no significant change in minimum hot and cold utility need. The main pinch violations mentioned above still remained in both cases.

6   Retrofit suggestion

As has been shown in the analysis of the present system there is potential to decrease the energy consumption at Preemraff Göteborg. As earlier described the system boundaries are limited to streams using utilities, and streams identified as having a potential for heating or cooling like preheating of the combustion air and further cooling of flue gases. The possibility for energy savings can be summed in 6 points.

1. Preheating of combustion air. This will decrease the fuel demand in the furnace.
2. Preheating cold process streams before heated in a furnace. This will decrease the energy consumption in the furnace.
3. Further cooling of flue gases. Currently most furnaces have stack temperatures that are higher than necessary.
4. Replacing whole or part of a steam-driven heater with a hot process stream.
5. Replacing whole or part of an air cooled exchanger with a cold process stream.
6. Produce steam in steam generators and thereby decreasing the production of steam in the steam boilers.

The Matrix method, presented in chapter *2.2.1 Matrix method* and *4.4 The Matrix method*, has been used to select streams for the retrofit proposal. The large number of streams has made the selection strict, keeping only the streams with highest potential from an energy and economical point of view. See *Appendix 3 – Matrix with duty above the pinch* and *Appendix 4 – Matrix with duty below the pinch* for the matrices above and below the pinch, containing the corresponding duties for all possible matches between the process streams.

6.1 Retrofit proposal

A retrofit proposal, presented below, has been produced using the Matrix method.

Table 5: Retrofit proposal

Hot stream	Cold stream	Duty, [kW]	Individual duty hot/cold, [kW]	Piping distance, [m]	Utility in use, hot/cold stream
Flue gases [rökH-47]	Crude oil [förvC-27]	1974	2000/26100	0	District heating/ Furnace
Reactor effluent [5H-30cd]	Reboiler [6C-2]	2946	20000/2946	190	Air cooling / LP steam
Residue [2H-41]	Reboiler [6C-1]	1149	2088/1149	200	District heating/ LP steam
Flue gases [rökH-50]	Combustion air [luftC-14]	459	459/578	0	Flue gas/ Combustion air
Reactor effluent [3H-31]	Combustion air [luftC-23/24/25]	1265	4249/2182	300	Air cooling/ Combustion air
Flue gases [rökH-54]	Reboiler [9C-4]	1571	1571/5007	0	Flue gas/ LP steam
Condenser [9H-7ab]	Reboiler [60C-5]	1442	1656/5007	550	Air cooling/ LP steam
Product to tank [12H-24]	Water to deionization [tankC-40]	665	1514/665	100	Air cooling/ LP condensate
Condenser [15H-12ab]	Reactor inlet [12C-7]	1452	1991/1452	480	Air cooling/ HP steam
Total		**12923 kW**			

From *Table 5* it can be seen that the retrofit suggestion is able to recover 12,9 MW by internal heat exchanging of process streams. This will save 12,9 MW of hot utility and 10,9 MW of cold utility. The lower value of cold utility is a consequence from that the flue gases is not cooled with any cold utility with exception for rökH-47 that is connected to the GEAB system.The major decrease in usage of utilities is distributed as:

- 1,45 MW of HP steam
- 7,11 MW of LP steam
- 1,72 MW of fuel gas by preheating of combustion air
- 1,97 MW of fuel gas by preheating of streams heated in the furnace

- 7,77 MW of air cooling
- 1,15 MW of Volvo district heating
- 1,97 MW of GEAB district heating

The main decrease in cold utilities is the air cooling. Compared to the district heating system the air coolers do not bring any income, it is also preferable to lower the dependence on the air-cooled exchangers during the summer. The air cooled exchangers are, in some cases, replacing coolers connected to the district heating system during the summer since the need for district heating is low. Due to the studied period it is likely that the decreased deliveries to the district heating system will decrease further during winter. The deliveries to the district heating system is decreased by 3,1 MW in the retrofit proposal.

It is not always wanted to replace a district heating cooler, in many cases the district heating water itself can be used to replace more expensive hot utilities with small piping costs. This is shown further in chapter *6.3 District heating*. For saving fuel gas in the furnaces preheating has been proposed at both the air and process streams heated in the furnaces. Heat is brought both from replacing air and district heating coolers and from cooling the flue gases further than that is presently done.
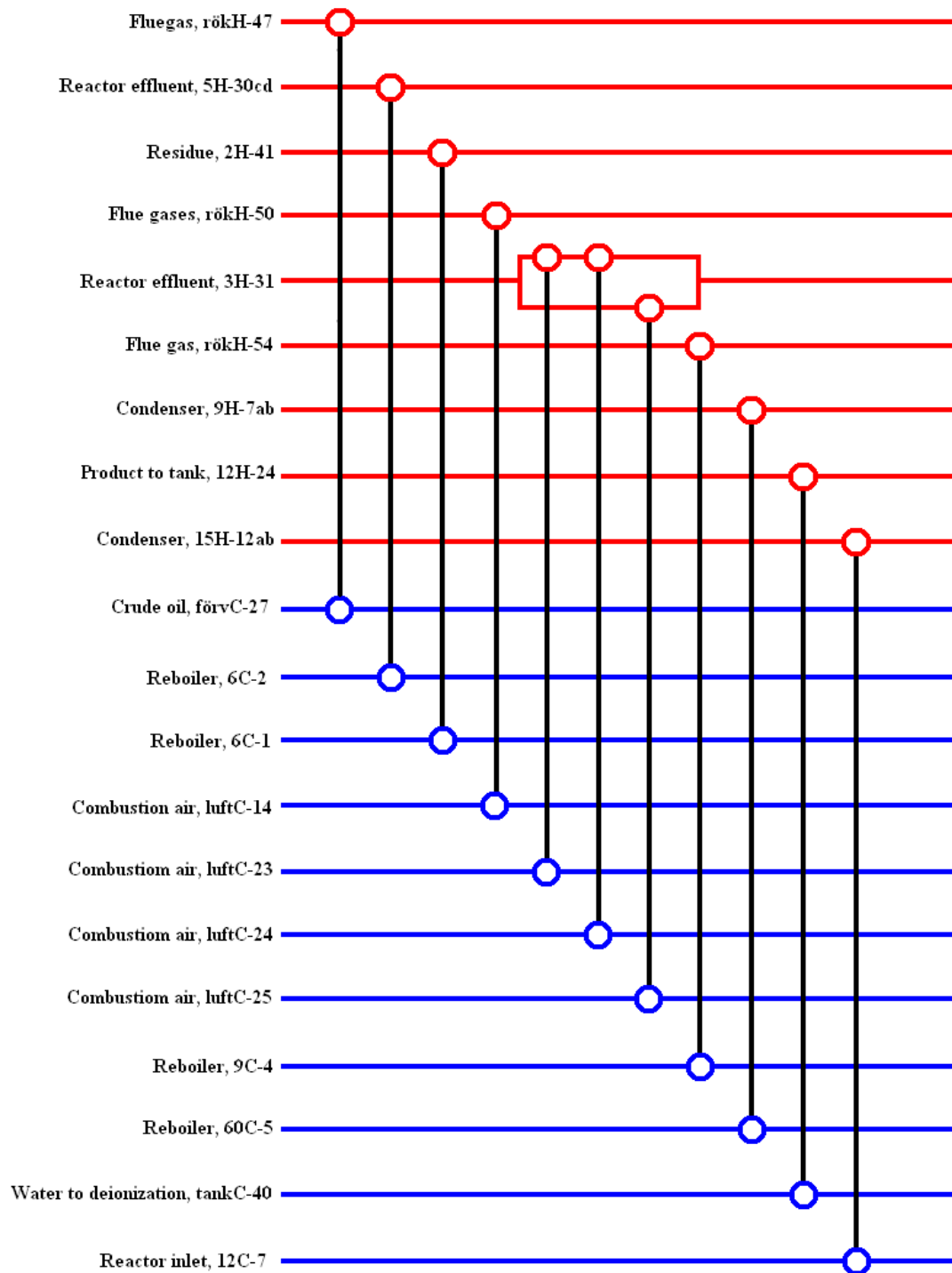
Figure 7: The proposed retrofit. Unchanged streams are not displayed.

6.1.1 Pinch violations

When doing a retrofit using pinch analysis one of the goals is to remove pinch violations from the existing system, and not bringing any new violations into the system. In the proposed retrofit design there are three pinch violations shown in *Table 6*, all of the character heating through the pinch.

Table 6: Pinch violations for the retrofit proposal above

Hot stream	Cold stream	Pinch violation, [kW]
Residue [2H-41]	Reboiler [6C-1]	228
Flue gases [rökH-50]	Combustion air [luftC-14]	459
Condenser [15H-12ab]	Reactor inlet [12C-7]	1008
Total pinch violation		**1695 kW**

The suggested heat exchangers will have approximately 1,7 MW of pinch violations.

The proposal will remove in total 11,5 MW pinch violations from the existing system. The reason this value does not equal the 12,9 MW presented in the retrofit proposal is that the match between rökH-54 and 9C-4 don't lead to any elimination of pinch violations. They were, however, not connected before making the proposed heat exchanger between them save energy, in this case LP steam.

6.1.2 Economy

All investments must be able to pay for themselves, either by allowing a higher production capacity or by decreasing the need for energy. An easy way to measure an investment´s economical potential is the simple payback period which is defined as

$$Pay\ back\ period = \frac{Investment\ Cost}{Annual\ income\ or\ savings} \qquad (6)$$

The heat exchangers proposed in the retrofit, their cost and the payback period is shown in *Table 7* below. The price for a heat exchanger is explained in section *4.3 Economical aspects*. The annual income is given by the price of the saved energy. Many of the new heat exchangers will require new pumping equipment due to the increased pressure drop. The cost for pumps, fans or compressors are however not included in the cost presented below. To include more indirect costs for the equipment a Lang factor[7] of 4,7 is used.

---

[7] A Lang factor is an empirical constant representing the many small expenses not included in the equipment cost.

The price for steam is given as SEK/ton while the furnaces are given as SEK/MWh fuel. The efficiency of the furnaces and boilers are estimated as 85% and 90% respectively. Air cooling is assumed to be free, and the electric cost for running the fans is neglected. The income from district heating has been approximated as the mean price over the whole year and is given in SEK/MWh.

Table 7: Investment cost and pay-back-period for both individual and total retrofit proposal.

Hot/cold stream	Duty, [kW]	Heat exchanger and piping cost, [MSEK]	Annual saving, [MSEK/yr]	PBP, [Year]
Flue gases/Crude oil [rökH-47/förvC-27]	1974	7,04	7,53	0,94
Reactor effluent/Reboiler [5H-30cd/6C-2]	2946	3,50	14,00	0,25
Residue/Reboiler [2H-41/6C-1]	1149	1,52	1,46	1,04
Flue gases/ Combustion air [rökH-50/luftC-14]	459	1,02	1,75	0,58
Reactor effluent/ Combustion air [3H-31/luftC-23/24/25]	1265	5,94	4,56	1,30
Flue gases/Reboiler [rökH-54/9C-4]	1571	1,57	7,47	0,21
Condenser/Reboiler [9H-7ab/60C-5]	1442	2,30	6,85	0,34
Product to tank/ Water to deionization [12H-24/tankC-40]	665	1,12	2,39	0,47
Condenser/Reactor inlet [15H-12ab/12C-7]	1452	1,82	8,11	0,22
Total		**25,8 MSEK**	**54,1 MSEK/yr**	**0,48 yr**

6.2 Emission savings

The possible energy savings, from the proposed retrofit, also results in decreased emissions. This contributes to a smaller impact on the environment and an economical saving for Preemraff because fewer carbon credits have to be bought. In *Table 8* below one can see the individual emission savings for all suggested heat exchangers and the total. The calculations is based on that natural gas is on the margin with an emission factor of 15 gC/MJ. [21] An efficiency of 0,85 for the furnaces and 0,9 for the boilers is also used by consultation with Preem. [19]

Table 8: Resulting decrease in CO$_2$ emission

Hot stream	Cold stream	Replaced utility	Q$_{eff}$, [kW]	Q$_{eff}$, [TJ/yr]	Q$_{fuel}$, [TJ/yr]	Emissions, [ktCO$_2$/yr]
Flue gases [rökH-47]	Crude oil [förvC-27]	Flue gas/ Furnace	1974	62,3	73,2	4,03
Reactor effluent [5H-30cd]	Reboiler [6C-2]	Air/ LP steam	2946	92,9	103,2	5,68
Residue [2H-41]	Reboiler [6C-1]	Volvo/ LP steam	1149	36,2	40,3	2,21
Flue gases [rökH-50]	Combustion air [luftC-14]	Flue gas/ Furnace	459	14,5	17,0	0,94
Reactor effluent [3H-31]	Combustion air [luftC - 23/24/25]	Air/ Furnace	1265	39,9	44,3	2,44
Flue gases [rökH-54]	Reboiler [9C-4]	Flue gas/ LP steam	1571	49,5	55,0	3,03
Condenser [9H-7ab]	Reboiler [60C-5]	Air/ LP steam	1442	45,5	50,5	2,78
Product to tank [12H-24]	Water to deionization [tankC-40]	Air/ LP condensate	665	21,0	23,3	1,28
Condenser [15H-12b]	Reactor inlet [12C-7]	Air/ HP steam	1452	45,8	50,9	2,80
Total			**12923**	**407,5**	**457,8**	**25,2**

The suggested retrofit will decrease the carbon dioxide emissions with approximately 25 kton, 4,7 % of the total CO$_2$ emissions from Preemraff Göteborg, annually. [23] For comparison an average car emits 2,7 ton CO$_2$ per year, see *Appendix 5 – Emissions for a car* for assumptions and calculations. Making this reduction correspond to emissions from approximately 9300 cars.

The reduction of CO_2-emissions results in an annual saving of 4,82 MSEK in carbon credits, based on a carbon credit cost of 18,7 Euro/tCO_2 and the assumption that 1 Euro costs 9 SEK . Apart from decreasing the emission of carbon dioxide, other pollutants such as sulphur- and sodium oxides also decrease. These can cause acidification, eutrophication, health issues and a reinforcement of the global greenhouse effect. [11]

6.3   District heating

The district heating system is used to remove excess heat from the process plant. GEAB and Volvo pays for the delivered heat but during the summer when need for district heating is low, the economical winning are small. When district heating cannot be used to remove excess heat, air coolers are used as a replacement. The capacity of the air coolers is limited and it would be beneficial both from an energy savings perspective and a process robustness view to be able to use the energy elsewhere.

One way of utilizing the excess energy better during the summer is to use the district heating water system as a hot utility on site. Presently it is only used in two places but the hot district heating water has the potential to replace low pressure steam and preheat combustion air in many places. In *Table 9* below are a few suggestions of places where district heating could be used as a hot utility.

Table 9: Some potential internal uses for district heating

Cold stream	T$_{start}$, °C	T$_{target}$, °C	Duty, kW	Utility
Reboiler, [60C-5]	112	112	5007	LP steam
Reboiler, [60C-6]	112	112	2356	LP steam
Caustic water, [12C-9]	37	47	25	LP steam
Resudie tank, [tankC-39]	60	70	1108	LP steam
All combustion air, [luftC-XX]	17	150	216 to 3278	Furnace

A stream with large potential for using district heating is tankC-39, heating of the residue tanks. At present the heat is delivered through low pressure steam. The location in the tank-park makes it inappropriate to heat exchange with any stream in the main refinery area, due to the distance and that currently used pipes is not constructed to high temperatures. The pipes delivering district heat to Volvo however passes close to the tanks and to reroute a portion of the hot water might be possible.

Preheating of combustion air is also an option. Volvo district heating water is currently used to preheat the combustion air into one of the furnaces that heats the crude oil, and is something that could be done on more furnaces.

Apart from being able to use the district heating system as a hot utility there are some streams that could be cooled by the district heating system. The possibility to produce more district heating has not been investigated further although some conclusions and suggestions are given in the discussion.

7   Discussion

The studied system has a theoretical potential for saving 40,2 MW of hot utility and 47,8 of cold utility. It would however not be economically feasible to reconstruct the system to achieve this saving. Instead a retrofit proposal containing 10 new heat exchangers saving 12,9 MW of hot and 10,9 MW of cold utilities has been identified.

The data used in this pinch analysis is collected for a summer case when producing MK1 diesel. During the summer, demand for district heating is low leading to an increased use of air cooling. Differences in air temperature between seasons are of smaller meaning since most energy consumers are well isolated, even if some pipes need extra heating to avoid freezing during the winter. The production of MK1 diesel requires less energy than other qualities due to lower production rates. Further studies concerning the impact of producing a different quality, or seasonal aspects, is necessary. When producing the retrofit proposal deviation from the studied period has been kept in mind.

7.1   Retrofit

The retrofit proposal presented in *Table 5* consists of 10 pair of streams that can be heat exchanged instead of using utilities for cooling and heating.

As mentioned earlier, the proposal has been discussed with Cecilia Hellman at Preemraff Göteborg. Some of the aspects brought up and some general comments about the proposed heat exchangers are listed below.

- *RökH-47 / förvC-27*

The purpose of this heat exchanger is to preheat the crude oil, using the hot flue gases, before entering the furnace. The proposed heat exchanger would replace ECO-4 which currently cools flue gases to the district heating system. The economizer is located after the superheater but before the recuperator[8]. An option to this suggestion would be reconstruction of either the convection bank or the air preheater to allow for a replacement of eco-4. Studies have been done at Preemraff Göteborg about modifying the superheater but they have all assumed that ECO-4 remains in its place. Preheating the crude oil would mean higher driving forces than possible in a reconstructed superheater.

- *5H-30cd / 6C-2*

The fan, 5H-30cd, is presently working with a high load. Removing some of its load is wanted also from a process robustness view. [19] As seen in *Table 5: Retrofit proposal*, the fan will still be needed to a large extent. Only a smaller side stream needs to be extracted from it. The low temperature required in the reboiler, 6C-2, means that the Volvo district heating water could be used to heat it. Unfortunately, the Volvo district heating system is not present close to the reboiler and much piping would be needed.

---

[8] Heat exchanger heating combustion air using flue gases

- *2H-41 / 6C-1*

The residue is currently cooled to the district heating system and by cooling water. The residue must be cooled to a certain temperature, meaning that the cooling water will still be needed. The piping needed to connect the residue to the reboiler is rather large.

- *rökH-50 / luftC-14*

Preheating the combustion air to the furnace means that less fuel is needed. The combustion air is currently brought in through several individual inlets, one for each burner. This means that, besides the recuperator itself, an air channel and a fan is needed.

- *3H-31 / luftC23/24/25*

3H-31 has been studied earlier with the purpose of creating district heating but it has not been found economically possible. [11] Two of the air inlets above are connected to the same air channel meaning that only two units in total are needed. The third furnace is situated separately from the other two. The temperature of the combustion air will be below the intended 150°C although it is not a problem because of its soft target.

- *rökH-54 / 9C-4*

rökH-54 is the flue gas from the incinerator. The purpose of the incinerator is to combust sulphur containing gas at a high temperature where it is degraded. It would therefore require reconstruction before being able to cool its flue gases. The distance to 9C-4 is small.

An alternative to this proposal is to produce steam in the incinerator whilst heating 9C-4 with district heating water. Using district heating water for 9C-4 would require extensive repiping though.

- *9H-7ab / 60C-5*

The unit where 60C-5 is situated is built separately from the rest of the refinery, meaning that long piping is required for this proposal. Otherwise it is very beneficial, space to build is available and there is no competition with the district heating system.

- *12H-24 / tankC-40*

Heating the raw water a few degrees will both increase efficiency in the water treaters and save fuel in the steam boilers. Distance between the two streams is small and there is plenty of room to build around the raw water pipe.

- *15H-12ab / 12C-7*

15H-12ab is an air cooled exchanger operating as a complement to the district heating system. Distance between the two streams is unfortunately rather long.

Some potential retrofitted heat exchangers are not included in this proposal. Reasons for rejecting possible matches are mainly distance between the matching streams and construction limitations. The process plant is very large and the streams subjected to this study are brought from all areas of the site making long distances possible. When deciding whether a distance is too long, duty and other variables have been taken into account. There are more reasons for not recommending a heat exchanger to be constructed than distance. For example removing a steam generator, producing LP steam, and instead using it to replace a reboiler using HP steam are not economically possible. Exchanging heat between flue gases and combustion air has been limited to being possible only in the same furnace due to the large pipes required for gas at atmospheric pressure.

There are complications that are of a more complex nature. These can be of the mechanical sort, for example it is not possible to preheat the combustion air to some of the furnaces due to location and type of the existing air inlet. The most obvious problems have been detected with help from Cecilia Hellman [19] and been avoided.

This retrofit proposal has 1,7 MW of pinch violations built in, however 11,5 MW is removed by constructing it. The pinch violations that will be built in by the retrofit proposal will not directly increase the energy demand of the refinery. They will however, make future retrofits more expensive since the pinch violations must be removed in order to get closer to a MER network.

7.2   The district heating system

As shown there are many possibilities for exchanging process streams directly with each other. However the profitability and logic of this is decreased when one of them is a cooler to the district heating system, since this generates revenue. Even so it is always preferable to make use of the energy on site, since this lower the demand of utilities. The district water systems are all over the site meaning that there is seldom a long distance to the nearest pipe, as opposed to building a process/process heat exchanger requiring lots of piping. As shown in *Table 9* the possibilities for replacing some low pressure steam heaters with the current district heating water system is good. There are some requirements of how much heat can be taken out of the system and especially at high temperatures of the district heating system. It should be noticed that the district heating system does not operate at one temperature; the delivered temperature is always the same though. This makes the usage of it more complex.

A good side of using the present district heating system is that it can bring heat out of the system also in the summer and thereby increase the capacity and take some load of the fans. Using the district heating system would also mean some, potential, flexibility.

Two of the places where using the district heating system for internal purposes seems to be most beneficial are for preheating combustion air and to heat the residue tanks, tankC-39. The residue tanks are currently using LP steam for heating the tanks to between 60°C and 70°C. The low temperature makes switching to another, cheaper, heat source possible.

As well as replacing LP steam in the tank park, the current district heating water can also be used to preheat combustion air. This has already been done in one of the

furnaces for the crude oil. The district heating water is first heated in an economizer, and part of that hot water heats the combustion air to 140°C. The target temperature of 150 °C is a soft target meaning that all district heating water of all temperatures can be used, even though they can't raise the temperature to 150 °C.

A side track brought from the pinch analysis and gathering of data is that there is a potential for more delivery to the district heating system. Some of the streams with possibility to deliver heat to the district heating system are shown below.

Table 10: Some streams with potential for delivering district heating

Hot stream	Duty, [kW]	Temperature, [ºC]
rökH-49	500	360-180
rökH-53	3455	293-180
rökH-54	1571	700-180
rökH-51	787	410-180
15H-13	7001	140-35
16H-27	2816	153-55

Both rökH-53 and 15H-13 are connected in series with cooler connected to the district heating system at present. Finding ways to use district heating system on site would mean that less heat would be sent to air cooled exchangers during the summer.

7.3   Economy

The economical estimates presented in the chapter *6.1.2* are approximate. Apart from the heat exchanger and piping there are many costs associated. It is likely that the proposed heat exchangers will introduce higher pressure drops than earlier requiring that a pump or a fan is installed. The installation cost is also a large contributor to the final cost. The main effect would be the PBP which would increase, however the PBP is very low at the moment so it would probably not lead to any new rejections.

A further and more accurate cost estimate is needed. As it is now the results are, as mentioned earlier, based on that all heat exchangers are of the type tube and shell which might not always be the best choice. In reality there are perhaps more efficient heat exchanger types suited for the job. For the gas/gas heat exchangers as well as the ones involving condensation and evaporation the model presented in chapter *4.3 Economical aspects* will not be as accurate.

The cost for constructing and installing a proposed unit can differ due to many reasons. For example preheating of combustion air into two of the high pressure steam boilers is easier than the other places since they have a prepared air inlet channel. Many of the proposed heat exchangers will not be necessary to construct from scratch. Reconstruction of tube and shell heat exchangers, as are used now, is common. Usually the tube bundle is replaced while keeping the shell thereby changing the area of the heat exchanger.

8   Conclusions

The studied system currently uses 114,3 MW and 159,5 MW respectively of hot and cold utility, and contains 47,1 MW of pinch violations.

The retrofit suggestion consists of 10 heat exchangers replacing usage of utilities completely or partly. It would decrease the hot and cold utility demand with 12,9 MW respectively 10,9 MW with an investment cost of 25,8 MSEK and a payback time of 0,48 year. The delivered load to the district heating system will decrease with 3,1 MW.

The heat exchangers are replacing hot utilities by preheating combustion air to furnaces, preheating hydrocarbon streams to furnaces, replacing part or whole reboilers and heaters using steam. The cold utilities are saved by replacing air cooled exchangers and coolers connected to the district heating system.

Apart from heat exchanging process streams directly, the district heating system could be used internally to replace hot utilities. Two places where utility usage could be decreased are heating of the residue tanks and preheating of combustion air. The residue tanks are currently heated with low pressure steam to 60 °C and many of the furnaces does not have preheating of the combustion air.

9   Further work

In a society with increasing costs of fossil fuel and carbon credits it must be remembered that earlier rejected investments can be both attractive and profitable in the future.

Based on the proposed retrofit it would be preferable to make more rigorous economic calculation of the proposed heat exchangers than the estimations done in this project. This includes better values for the overall heat transfer coefficient, more precise values for the piping distance and an evaluation of using other types of heat exchangers than a tube and shell heat exchanger. It would also be desirable to investigate the possibility to keep some of the existing heat exchangers and replace the utility with the process stream instead of investing in new heat exchangers and scrap the old ones. Another example worth investigating is the possibility to have two separate tube packet inside the same shell, one for a process stream and on for steam, instead of two heat exchangers in a sequence. This can be an option for the reboilers that are not completely satisfied with the heat integration and therefore still need a certain amount of steam, for example 13C-3 and 60C-5.

Because the possibility of preheating the crude oil feed from tank not was investigated since it includes process/process heat exchangers it is of large interest to look further into this. An advantage when doing so is that this master thesis has located possible heat sources that might be used. It is also preferable to look at the option to preheat the fraction of the feed to the two DHT units coming from tank, before entering the existing heat exchangers 3E-1 and 4E-1, since like the crude oil it would decrease the demand of the furnaces with equal amount.

One option that was discussed with our supervisor at Preem, Cecilia Hellman, was that an interesting point of view is if the district heating system instead is seen as a hot water system that can be used to preheat different process streams within the refinery. As it is constructed today the district heating system is well integrated in the plant and could be a good option to transfer heat throughout the process instead of building new pipes for the process streams. This results in that even more heat could be transferred into the district heating system without increasing the amount of heat delivered to GEAB and Volvo and is something that is recommended to further investigate.

10   References

[1]
Preem AB. (2010). *Årsredovisning 2009*. Available at:
http://www.preem.se/upload/Arsredovisning/PreemPres09-sv.pdf [2011-01-20]

[2]
European Commision. (2008). *EU action against climate change.* Available at:
http://ec.europa.eu/climateaction/eu_action/index_en.htm [2011-01-21]

[3]
Preemraff Göteborg (2009). Miljörapport 2009.

[4]
E.On. Jämför din förbrukning. Available at:
http://www.eon.se/templates/Eon2TextPage.aspx?id=47760&epslanguage=SV
[2011-05-09]

[5]
Preem AB (2009). *Årsredovisning 2008*. Available at:
http://preem.se/upload/Arsredovisning/PreemPres_sv_08.pdf [2011-01-25]

[6]
Ebrahim, M. (2000). *Pinch technology: An efficient tool for chemical-plant energy
and capital-cost saving*. Applied Energy vol. 65 p. 45–49

[7]
Kemp, I. C. (2007). *Pinch Analysis and Process Integration: A user guide on
process integration for efficient use of energy*. Second edition, Butterworth-
Heinemann, Oxford, UK p. 1-40

[8]
Berntsson, T and Franck, P-Å. (2008). *Pinch Analysis and Retrofit of Existing
Processes.* Gothenburg: Chalmers University of Technology. Course material in
Industrial Energy Systems, 2008

[9]
Wieringa, K and Nickson, J. (2005). *Energy Improvement Program at Preemraff
Gothenburg.* Gothenburg, Shell Global Solutions. Internal report at Preemraff
Göteborg

[10]
Fransson R. (1998). *Utökning av fjärrleveranser från Preem raffinaderi.*
Examensarbete vid institutionen för Kemiteknik och miljövetenskap/Värmeteknik och
maskinlära

[11]
Wennerberg, T. (2005). *Energiutredning enligt villkor E4 i deldom 2002-07-03*.
Unpublished report. Göteborg: Preem

[12]
Statens energimyndighet (2010). *Energiläget 2010*. Available at:
http://webbshop.cm.se/System/TemplateView.aspx?p=Energimyndigheten&view=def
ault&cat=/Broschyrer&id=6792e3736ce045c4a41f2c397b1eff97 [2011-01-25]

[13]
Göteborgs energi AB (2010). Göteborg energi årsredovisning 2009 del 2.
Available at:
http://www.goteborgenergi.se/Om_oss/Finansiell_information/Arsredovisningar?Gen
eralInfoListCategory=9851572 [2011-01-25]

[14]
Foster Wheeler. (2000). *Heating System Review.* Göteborg. Internal report at
Preemraff Göteborg

[15]
Kemp, I. C. (2007). *Pinch Analysis and Process Integration: A user guide on
process integration for efficient use of energy.* Second edition, Butterworth-
Heinemann, Oxford, UK p. 296

[16]
Sinnott, R. and Towler G. (2009). *Chemical Engineering Design*, Fifth Edition,
Butterworth-Heinemann, Oxford, UK, p. 817-821

[17]
Sinnott, R. and Towler, G. (2009). *Chemical Engineering Design*, Fifth Edition,
Butterworth-Heinemann, Oxford, UK, p. 312-317

[18]
Chemical Engineering. New York: May 2007. Vol. 114, Iss. 5; pg. 95

[19]
Discussions with Cecilia Hellman, process engineer and supervisor at Preemraff
Göteborg

[20]
Chemical Engineering. New York: Apr 2011. Vol. 118, Iss. 4; pg. 67

[21]
Azar, C. (2010) *Thinking about energy systems: Concepts and tools.* Gothenburg:
Chalmers University of Technology. Course material in Sustainable Energy Futures,
2010

[22]
Eriksson, L. and Hermansson, S. (2010) *Pinch analysis of Billerud Karlsborg, a
partly integrated pulp and paper mill.* Master thesis at the department of energy and
enviroment, Heat and Power technology. Göteborg: Chalmers university of
technology.

[23]
Preemraff Göteborg (2010). Miljörapport 2010.

11   Appendix 1 – Stream data

Hot streams

#	T_{start}, [°C]	T_{target}, [°C]	Cp, [J/kgK]	ΔH_{vap}, [kJ/kg]	Q, [kW]
6H-1	80	35	2720		363
6H-3a	90	55	2934		256
6H-3b	75	75		262	220
13H-4	80	80		332	11069
14H-5	265	165		2121[1]	37
9H-6	65	40	3510		2156
9H-7a	122	122		2202	1442
9H-7b	122	44	4200		215
60H-8	117	90	2578		1179
60H-9	105	87			250[2]
15H-10	172	150		2121[1]	3717
15H-11a	110	30	7239		1054
15H-11b	30	30		182	321
15H-12a	195	165	1870		35
15H-12b	165	165		1087	1956
15H-13	140	35	2364		7002
17H-14	122	45	4248		1275
17H-15a	119	119		1296	203
17H-15b	119	96	4298		2
17H-16	90	32	14400		543
17H-17	95	35	14400		562
17H-19a	150	65			2854[3]
17H-19b	110	110			1871[3]
17H-20	125	22	2361		63
12H-21	80	25	5213		114
12H-22	85	35	1902		1549
12H-23a	80	35	2291		65
12H-23b	60	60		317	1289
12H-24	82	35	2520		1514
16H-25a	230	160		2121[1]	2372
16H-26	144	22	2216		466
16H-27	153	55	2514		2816
16H-28a	153	120	2397		12
16H-28b	135	135		669	277
5H-29	70	33	2061		2010
5H-30a	150	128,2	3276		2593
5H-30b	125	125		365	3407
5H-30c	128,2	30	4036 (gas), 1989 (liq)		8966
5H-30d	65	65		601	11034

#	T_{start}, [°C]	T_{target}, [°C]	C_p, [J/kgK]	ΔH_{vap}, [kJ/kg]	Q, [kW]
3H-31	115	50	2315		4249
3H-32a	72	40	2010		71
3H-32b	55	55		327	1289
3H-33	105	30	2013		567
3H-34	115	60	2286		1415
4H-35	105	30	2091		221
4H-36	120	45	2315		5049
4H-37a	72	40	2010		95
4H-37b	55	55		327	1718
4H-38	115	35	2268		3185
2H-39a	100	80			5163[4]
2H-39b	85	85			6837[4]
2H-40a	80	44			9035[5]
2H-40b	65	65			3131[5]
2H-41	145	90	2036		2088
2H-42	215	55	2608		3423
1H-43a	100	80			4732[4]
1H-43b	90	90			6268[4]
1H-44a	80	45			8282[5]
1H-44b	65	65			2870[5]
1H-45	145	95	2036		1898
1H-46	205	55	2608		3008
rökH-47	365	264	1,45		2000
rökH-48	385	187	1,45		3988
rökH-49	360	180	1,45		500
rökH-50	275	180	1,45		459
rökH-51	410	180	1,45		787
rökH-52	210	180	1,45		175
rökH-53	293	180	1,45		3455
rökH-54	700	180	1,45		1571
rökH-56	270	180	1,45		254
rökH-57	275	180	1,45		172

(1) Enthalpy of vaporization for saturated water at 3,5 barg

(2) Load taken directly from Aspen Process Explorer

(3) The sum of loads of 17H-14 and 17H-19 where given directly by Aspen Process Explorer. The load of 17H-14 could then by subtracted.

(4) Load taken directly from Aspen Process Explorer and divided into the condensing fraction and cooling fraction.

(5) Load taken directly from simulation in PROII.

Cold streams

#	T_{start}, [°C]	T_{target}, [°C]	Cp, [J/kgK]	ΔH_{vap}, [kJ/kg]	Q, [kW]
6C-1	103	103		2121[1]	1149
6C-2	84	84		2121[1]	2946
13C-3	144	144		1935[2]	11288
9C-4	129	129		2121[1]	5007
60C-5	112	112		2121[1]	5007
60C-6	112	112		2121[1]	2356
12C-7	104	140		1935[2]	1452,1
12C-8	162	162		1935[2]	3485,1
12C-9	37	47		2121[1]	24,743
31C-10	20	50	4182		1387
luftC-11	147	150	1,013		37
luftC-12	17	150	1,009		1521
luftC-13	17	150	1,009		333
luftC-14	17	150	1,009		578
luftC-15	17	150	1,009		410
luftC-16	17	150	1,009		699
luftC-17	17	150	1,009		3278
luftC-18	17	150	1,009		361
luftC-19	17	150	1,009		361
luftC-20	17	150	1,009		386
luftC-21	17	150	1,009		337
luftC-22	17	150	1,009		217
luftC-23	18	150	1,009		813
luftC-24	22	150	1,009		742
luftC-25	17	150	1,009		627
luftC-26	30	150	1,009		435
förvC-27	250	375	2762		26100
förvC-28	250	375	2762		25050
förvC-29a	243	243		6	33
förvC-29b	243	295	2705		1814
förvC-30	195	210	2716		6469
förvC-31a	245	245		6	33
förvC-31b	245	300	2705		1919
förvC-32	200	210	2716		7426
förvC-33	232	248	2960		5912
förvC-34a	238	238		551	867
förvC-34b	238	320	3440		2397
tankC-39	60	70		2121[1]	3535
tankC-40	10	35	4200		1108

(1) Enthalpy of vaporization for saturated water at 3,5 barg

(2) Enthalpy of vaporization for saturated water at 15 barg

12   Appendix 2 – heat transfer coefficient

Fluid	Phase	h- value [W/m^{2}K]
Air	Gas	50
Light oil	Gas	50
Light oil	Gas, high pressure	300
Light oil	Liquid	500
Light oil	Condensing	1000
Light oil	Evaporating	1100
Heavy oil	Liquid	800
Brine	Liquid	1000
Cooling tower water	Liquid	1250
Lean amin, (dilute aq)	Liquid	1500
Water	Condensate	2000
Water	Condensing vapour	2700

In the case were a stream consists of both gas and liquid a weighted value has been used based on the quota between gas and liquid.

13   Appendix 3 – Matrix with duty above the pinch

Name	förvC-27	förvC-28	13C-3	förvC-33	12C-8	förvC-31b	förvC-29b	luftC-12	12C-7	luftC-17
rökH-48	2416,67	2416	3987,5	2839,58	3485,12	1919,14	1814,46	1520,9	1452,13	3277
15H-10	0	0	3040,94	0	0	0	0	1520	1452	3277
rökH-53	856,27	856	3455,41	1406,63	3485,12	856,21	917,36	1520,9	1452	3277
5H-30a	0	0	0	0	0	0	0	1292,19	1250	2907
16H-25	0	0	2371,62	0	1965,06	0	0	1520	1452	3277
15H-12b	0	0	1956,1	0	0	0	0	1520,9	1452	3277
2H-42	0	0	1304,8	0	919,81	0	0	1520	1452	3277
rökH-47	1973,55	1937	2000	2000	2000	1919	1814,46	1520	1452	3277
1H-46	0	0	1022,75	0	661,78	0	0	1520	1452	3277
15H-13	0	0	0	0	0	0	0	1235	1048	2661
rökH-54	1314	1314	1570,83	1368	1570,83	1314,06	1320,1	1520,9	1452	1570
17H-19a	0	0	0	0	0	0	0	1292,19	968,09	2858
1H-45	0	0	0	0	0	0	0	1292	1048	1898
2H-41	0	0	0	0	0	0	0	1235	1048,76	2088
16H-27	0	0	0	0	0	0	0	1383	1120	2815
rökH-49	264,02	264	500,25	314,05	500,25	264,02	269,58	500,25	500,25	500,25
rökH-50	48,33	48	459,17	135,33	459,17	48,33	58	459,17	459	459,17
rökH-51	496,42	496	787,43	558,05	787,43	496,42	503,27	787,43	787,43	787,43
rökH-56	14,1	14	253,75	64,85	253,75	14,1	19,74	253,75	253,75	253,75
rökH-52	0	0	175,21	0	175,21	0	0	175,21	175,21	175,21
rökH-57	18,13	18	172,19	50,75	172,19	18,13	21,75	172,19	172,19	172,19
16H-26	0	0	0	0	0	0	0	427,69	114,56	420
14H-5	1,12	1	37,17	6,69	32,71	0	0,74	37,17	37,17	37,17
15H-12a	0	0	34,91	0	20,95	0	0	34,91	34,91	34,91
16H-28a	0	0	0	0	0	0	0	12,35	12,35	12,35

Name	förvC-34ab	luftC-23	luftC-24	luftC-16	luftC-25	luftC-14	luftC-26	luftC-15	luftC-19	luftC-18
rökH-48	3263,8	813,22	742,19	698,89	626,59	578,39	434,88	409,7	361,49	361,49
15H-10	0	813,22	742,19	698	626,5	578	434	409,7	361	361
rökH-53	1376	813,22	742,19	698	626	578,39	435	409,7	361	361
5H-30a	0	708,49	643,62	620,07	532,37	504,46	372,19	357,33	315,28	315,28
16H-25	0	813,22	742	698	626	578,39	434,88	410	361	361
15H-12b	0	813,22	742,19	698	626	578,39	434,88	410	361	361
2H-42	0	813,24	742,19	698,86	626,6	578,42	435	410	361,52	361,52
rökH-47	2000	813,22	742,19	698	626	578	435	410	361	361
1H-46	0	813,24	742,19	698,86	626,6	578,42	435	410	361,52	361,52
15H-13	0	659,2	591,43	567,51	508,81	469,67	345,91	332,69	293,54	293,54
rökH-54	1366	813,22	742	668	626	578	435	409,7	361	361
17H-19a	0	708,49	643	609,55	546,5	504,46	373	357,33	315,28	315,28
1H-45	0	690	626	593,79	532,37	491,41	362,4	348,09	307,13	307,13
2H-41	0	690	626	593,79	532,37	491,41	362,4	348,09	307,13	307,13
16H-27	0	739,29	672	635,83	570,05	526,2	391,39	372,74	298,98	298,98
rökH-49	311	813,22	742	698,89	500,25	500,25	434	409,7	361	361
rökH-50	130,5	459	459	459	459	459	434,88	409,7	361	361
rökH-51	554	787	742	698	626	578	434,88	409,7	361	361
rökH-56	62,03	253,75	253,75	253,75	253,75	253,75	253	253,75	253,75	253,75
rökH-52	0	175,21	175,21	175	175,2	175,2	175,2	175,21	175,21	175,21
rökH-57	48,94	172,19	172	172,19	122,5	172	172	172	172	172
16H-26	0	416,24	408	420,06	420,05	420,05	358	341,06	304,41	304,41
14H-5	6,32	37,17	37,37	37,17	37,37	37,37	37,37	37,37	37,37	37,37
15H-12a	0	34,91	34,91	34,91	34,91	34,91	34,91	34,91	34,91	34,91
16H-28a	0	12,35	12,35	12,35	12,35	12,35	12,35	12,35	12,35	12,35

Name	luftC-20	luftC-21	luftC-13	luftC-22	luftC-11	förvC-29a	förvC-31a	9C-4	förvC-30	förvC-32
rökH-48	385,59	337,39	332,57	216,9	36,97	33,4	33,4	3987	3524	3423
15H-10	385,59	337	332	216	36,97	0	0	3716	0	0
rökH-53	385,59	337	332	216	36,97	33,4	33,4	3455	2538	2385
5H-30a	336,3	294	290	189	0	0	0	713,25	0	0
16H-25	385,59	337	332,57	216	36,97	0	0	2371	847	677,6
15H-12b	385	337	332	216	36,97	0	0	1956	0	0
2H-42	385,61	337	332	216,9	36,97	0	0	1625,71	213,91	106,95
rökH-47	385	337	332	216	36,97	33,4	33,4	2000	2000	2000
1H-46	385,61	337,33	332	216,9	36,97	0	0	1323	0	0
15H-13	313,11	273,97	270,06	176,13	0	0	0	66,68	0	0
rökH-54	385	337	332	216,9	36,97	33,4	33,4	1570	1480	1465
17H-19a	336,3	294,26	290,06	189,18	0	0	0	302,19	0	0
1H-45	327,61	286,65	282,56	184,28	0	0	0	227	0	0
2H-41	327,61	286,65	282,56	184,28	0	0	0	227	0	0
16H-27	350,8	306,94	302,573	197,33	0	0	0	402,26	0	0
rökH-49	385,59	337	332	216,9	36,97	33,4	33,4	500	416,88	403
rökH-50	385	337	332	216	36,97	33,4	33,4	459,17	314,17	290
rökH-51	385	337	332	216,9	36,97	33,4	33,4	787,43	648,72	667,6
rökH-56	253,75	253,75	253,75	216	36,97	33,4	33,4	253,75	169,17	155
rökH-52	175,21	175,2	175	175,2	36,97	0	0	175,21	0	0
rökH-57	172,19	172	172	172,19	36,97	33,4	33,4	172,19	117,8	108,75
16H-26	318,9	284,12	280	179	0	0	0	0	0	0
14H-5	37,37	37,37	37,37	37,37	36,97	0	0	37,17	20,44	18,58
15H-12a	34,91	34,91	34,91	34,91	36,97	0	0	34,91	0	0
16H-28a	12,35	12,35	12,35	12,35	0	0	0	4,49	0	0

Numbers within the cells represents the potential heat exchanger duty. A zero indicates that heat exchanging is not possible due to temperatures.

14 Appendix 4 – Matrix with duty below the pinch

Name	60C-5	tankC-39	6C-2	luftC-17	60C-6	31C-10	luftC-12	6C-1	tankC-40	12C-7	luftC-23	luftC-24
13H-4	0	3534,7	0	1182,87	0,00	1387,03	548,9	0,00	1108,33	0	289,56	278,32
5H-30d	0	0	0	813,22	0,00	1387,03	377,37	0,00	1108,33	0	197,14	162,35
2H-40a	0	0	0	1133,59	0,00	1387,03	526,03	0,00	1108,33	0	277,23	266,72
5H-30c	382,41	3534,7	2939,09	2321,09	382,41	1387,03	1077,07	1148,78	1108,33	491,63	574,11	517,14
1H-44a	0	0	0	1133,59	0,00	1387,03	526,03	0,00	1108,33	0	277,23	266,72
2H-39b	0	3534,7	0	1306,09	0,00	1387,03	606,07	0,00	1108,33	0	320,36	278,32
15H-13	1133,60	3534,7	2945,58	2636,82	1133,60	1387,03	1223,58	1148,78	1108,33	1008,42	653,04	591,43
1H-43b	0	3534,7	0	1429,30	0,00	1387,03	663,25	0,00	1108,33	0	351,16	307,31
2H-39a	0	3534,6	258,14	1552,52	0,00	1387,03	720,43	0,00	1108,33	0	381,97	336,3
4H-36	0	3029,17	1413,61	2045,38	0,00	1387,03	949,13	134,63	1108,33	40,34	505,18	452,27
1H-43a	0	3534,7	236,63	1552,52	0,00	1387,03	720,43	0,00	1108,33	0	381,97	336,3
3H-31	0	2614,93	1045,97	1922,17	0,00	1387,03	891,96	0,00	1108,33	0	474,38	423,28
5H-30b	3407,10	3407,1	2945,58	2291,81	2356,47	1387,03	1063,49	1148,78	1108,33	443,71	566,79	510,26
4H-38	0	1791,64	836,1	2045,38	0,00	1387,03	949,13	79,63	1108,33	40,34	505,18	452,27
2H-40b	0	0	0	813,22	0,00	1387,03	377,37	0	1108,33	0	197,14	162,35
1H-44b	0	0	0	813,22	0,00	1387,03	377,37	0	1108,33	0	197,14	162,35
17H-19a	570,81	2316,83	1510,97	2551,87	570,81	1387,03	1223,58	873,01	1108,33	839,43	653,04	591,43
16H-27	488,46	1982,55	1292,97	2413,54	488,46	1387,03	1223,58	747,05	1108,33	718,32	653,04	591,43
9H-6	0	0	0	813,22	0,00	1387,03	377,37	0	1108,33	0	197,14	162,35
5H-29	0	0	0	936,44	0,00	1387,03	434,54	0	1108,33	0	227,95	191,35
5H-30a	1879,65	1879,65	1879,65	1879,65	1879,65	1387,03	1223,58	1148,78	1108,33	1008,42	653,04	591,43
17H-19b	0	1871,32	1871,32	1871,32	0	1387,03	891,96	0	1108,33	0	474,38	423,28
2H-41	645,41	1860,29	1708,43	1860,29	645,41	1387,03	1223,58	987,09	1108,33	949,13	653,04	591,43
4H-37b	0	0	0	566,79	0,00	1155,86	263,01	0	1108,33	0	166,34	104,37
2H-42	363,64	1475,97	962,59	1796,83	363,64	1387,03	1223,58	556,16	1108,33	534,77	653,04	591,43
1H-46	340,92	1383,72	902,43	1684,53	340,92	1387,03	1223,58	521,4	1108,33	501,35	653,04	591,43
12H-22	0	464,84	0	1306,09	0,00	1387,03	606,07	0	1108,33	0	320,36	278,32
12H-24	0	386,44	0	1232,16	0,00	1387,03	571,77	0	1108,33	0	301,88	260,93
1H-45	645,41	1670,47	1670,47	1670,47	645,41	1387,03	1223,58	987,1	1108,33	949,13	653,04	591,43
9H-7a	1441,8	1441,8	1441,8	1441,80	1441,80	1387,03	1029,18	1148,78	1108,33	322,7	548,31	492,86
3H-34	0	1157,67	540,25	1414,93	0,00	1387,03	949,13	51,45	1108,33	25,73	505,18	452,27
12H-23b	0	0	0	690,01	0,00	1289,01	320,19	0	1108,33	0	166,34	133,36
3H-32b	0	0	0	566,79	0,00	1155,86	263,01	0	1108,33	0	135,54	104,37
17H-14	0	860,78	463,5	1274,62	0,00	1275,62	1029,18	148,98	1108,33	132,43	548,31	492,86
60H-8	0	1179,49	1004,75	1179,49	0,00	1179,49	972	174,74	1108,33	121,01	517,5	463,87
15H-11a	0	461,13	144,93	961,78	0,00	988,13	834,78	0	1054	0	443,57	394,29
4H-35	0	297,61	93,54	620,73	0,00	637,74	620,73	0	637,74	0	443,57	394,29
3H-33	0	264,54	83,14	551,75	0,00	566,87	551,75	0	566,87	0	443,57	394,29
17H-17	0	187,2	0	542,88	0,00	561,6	542,88	0	561,6	0	351,16	307,31
17H-16	0	140,4	0	496,08	0,00	514,8	496,08	0	542,88	0	320,36	278,32
16H-26	64,92	263,49	171,84	408,60	64,92	416,24	408,6	99,29	545,42	103,1	404,78	389,51
6H-1	0	80,58	0	362,62	0,00	362,62	362,62	0	362,62	0	289,56	249,33
15H-11b	0	0	0	0	0,00	0	0	0	320,71	0	0	0
16H-28b	276,52	276,52	276,52	276,52	276,52	276,52	276,52	276,52	276,52	276,52	276,52	276,52
6H-3a	0	131,54	0	255,78	0,00	255,78	255,78	0	255,78	0	255,78	255,78
60H-9	0	250	152,78	250,00	0,00	250	250	0	250	0	250	250
6H-3b	0	0	0	220,14	0,00	220,14	220,14	0	220,14	0	220,14	220,14
9H-7b	0	142,99	76,98	214,50	0,00	214,5	214,5	24,73	214,5	21,98	214,5	214,5
17H-15a	0	202,53	202,53	202,53	0,00	202,53	202,53	202,53	202,53	202,53	202,53	202,53
12H-21	0	0	0	88,78	0,00	92,91	88,78	0	113,56	0	107,37	78,46
4H-37a	0	0	0	95,12	0,00	95,12	95,12	0	95,12	0	95,12	89,18
3H-32a	0	0	0	71,34	0,00	71,34	71,34	0	71,34	0	71,34	66,88
12H-23a	0	0	0	62,18	0,00	65,07	62,18	0	65,07	0	60,73	54,95
17H-20	0	30,52	15,87	53,71	0,00	54,93	53,71	4,27	61,04	3,66	53,1	50,66
16H-28a	6,36	7,86	7,86	7,86	6,36	7,86	7,86	7,86	7,86	7,86	7,86	7,86
17H-15b	0	2,27	1,97	2,27	0,00	2,27	2,27	0,09	2,27	0	2,27	2,27

Name	luftC-16	luftC-25	luftC-14	luftC-15	luftC-20	luftC-18	luftC-19	luftC-21	luftC-13	luftC-22	12C-9	luftC-26
13H-4	252,23	226,14	208,74	147,86	139,16	130,46	130,46	121,76	120,03	78,28	24,74	126,84
5H-30d	173,41	155,47	143,51	101,65	95,67	89,69	89,69	83,71	82,52	53,82	24,74	72,84
2H-40a	241,72	216,72	200,04	141,7	133,36	125,03	125,03	116,69	115,02	75,02	24,74	119,59
5H-30c	494,94	443,74	409,6	290,14	273,07	256	256	238,93	235,52	153,6	24,74	294,23
1H-44a	241,72	216,72	200,04	141,7	133,36	125,03	125,03	116,69	115,02	75,02	24,74	119,59
2H-39b	278,51	249,69	230,49	163,26	153,66	144,05	144,05	134,45	132,53	86,43	24,74	144,96
15H-13	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
1H-43b	304,78	275,25	252,23	178,67	168,15	157,64	157,64	147,13	145,03	94,59	24,74	163,08
2H-39a	331,05	296,81	273,97	197,07	182,65	171,23	171,23	159,82	157,53	102,74	24,74	181,2
4H-36	436,15	391,03	360,95	255,68	240,63	225,59	225,59	210,55	207,54	135,36	24,74	253,68
1H-43a	331,05	296,81	273,97	194,07	182,65	171,23	171,23	159,82	157,53	102,74	24,74	181,2
3H-31	409,88	367,47	339,21	240,28	226,14	212	212	210,55	194,04	135,36	24,74	235,56
5H-30b	488,7	438,14	404,44	286,48	269,62	252,77	252,77	235,92	232,55	151,67	24,74	289,92
4H-38	436,15	391,03	360,95	255,68	240,63	225,59	225,59	210,55	207,54	135,36	24,74	253,68
2H-40b	173,41	155,47	143,51	101,65	95,67	89,69	89,69	83,71	82,52	53,82	24,74	72,48
1H-44b	173,41	155,47	143,51	101,65	95,67	89,69	89,69	83,71	82,52	53,82	24,74	72,48
17H-19a	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
16H-27	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
9H-6	173,41	155,47	143,51	101,65	95,67	89,69	89,69	83,71	82,52	53,82	24,74	72,48
5H-29	199,68	179,03	165,26	117,06	110,17	103,28	103,28	96,4	95,02	61,97	24,74	90,6
5H-30a	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
17H-19b	409,88	367,47	339,21	240,28	226,14	212	212	197,87	195,04	127,2	24,74	235,56
2H-41	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
4H-37b	120,86	108,36	100,02	70,85	66,68	62,51	62,51	58,35	57,51	37,51	19,79	36,24
2H-42	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
1H-46	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
12H-22	278,51	249,69	230,49	163,26	153,66	144,05	144,05	134,45	132,53	86,43	24,74	144,96
12H-24	262,74	235,56	217,44	154,02	144,96	135,9	135,9	126,84	125,03	81,54	24,74	134,09
1H-45	562,26	504,1	465,32	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
9H-7a	472,93	424,01	391,39	277,24	260,93	244,62	244,62	228,31	225,05	146,77	24,74	279,05
3H-34	436,15	391,03	360,95	255,68	240,63	225,59	225,59	210,55	207,54	135,36	24,74	253,68
12H-23b	147,13	131,91	121,77	101,65	81,18	76,1	76,1	71,03	70,01	45,66	24,74	54,36
3H-32b	120,86	108,36	100,02	70,85	66,68	62,51	62,51	58,35	57,51	37,51	19,79	36,24
17H-14	472,93	424,01	391,39	277,24	260,93	244,62	244,62	228,31	225,05	146,77	24,74	279,05
60H-8	446,66	400,45	369,65	261,84	246,43	231,03	231,03	215,63	212,54	138,62	24,74	260,93
15H-11a	383,6	343,92	317,46	224,87	211,64	198,41	198,41	185,18	182,54	119,05	24,74	217,44
4H-35	383,6	343,92	317,46	224,87	211,64	198,41	198,41	185,18	182,54	119,05	24,74	217,44
3H-33	383,6	343,92	317,46	224,87	211,64	198,41	198,41	185,18	182,54	119,05	24,74	217,44
17H-17	304,78	273,25	252,23	178,67	168,15	157,64	157,64	147,13	145,03	94,59	24,74	163,08
17H-16	278,51	249,69	230,49	163,26	153,66	144,05	144,05	134,45	132,53	86,43	24,74	144,96
16H-26	408,6	408,6	408,6	329,61	310,21	290,82	290,82	271,43	267,56	174,5	24,74	340,66
6H-1	252,23	226,14	208,74	147,86	139,16	130,46	130,46	121,76	120,03	78,28	24,74	126,84
15H-11b	0	0	0	0	0	0	0	0	0	0	0	0
16H-28b	276,52	276,52	276,52	276,52	276,52	276,52	276,52	261,29	257,55	167,98	24,74	326,16
6H-3a	255,78	255,78	243,53	172,51	162,35	152,21	152,21	142,06	140,03	91,33	24,74	155,83
60H-9	250	250	250	250	250	198,41	198,41	185,18	182,54	119,05	24,74	217,44
6H-3b	220,14	220,14	187	132,46	124,66	116,87	116,87	109,08	107,52	70,13	24,74	108,72
9H-7b	214,5	214,5	214,5	214,5	214,5	214,5	214,5	214,5	214,5	146,76	24,74	211,75
17H-15a	202,53	202,53	202,53	202,53	202,53	202,53	202,53	202,53	202,53	141,88	24,74	202,53
12H-21	99,11	88,78	88,78	88,78	88,78	88,78	88,78	88,78	88,78	70,13	24,74	61,94
4H-37a	92,12	95,12	95,12	95,12	95,12	95,12	95,12	95,12	95,12	57,08	24,74	65,4
3H-32a	71,34	71,34	71,34	71,34	71,34	71,34	71,34	71,34	71,34	57,08	24,74	49,05
12H-23a	62,18	62,18	62,18	62,18	62,18	62,18	62,18	62,18	62,18	62,18	24,74	43,38
17H-20	53,71	53,71	53,71	53,71	59,82	53,71	53,71	53,71	53,71	53,71	24,74	45,78
16H-28a	7,86	7,86	7,86	7,86	7,86	7,86	7,86	7,86	7,86	7,86	7,86	7,86
17H-15b	2,27	2,27	2,27	2,27	2,27	2,27	2,27	2,27	2,27	2,27	2,27	2,27

Numbers within the cells represents the potential heat exchanger duty. A zero indicates that heat exchanging is not possible due to temperatures.

15   Appendix 5 – Emissions for a car

$$Avarage\ driving\ distance = 15000\frac{km}{yr}$$

$$Fuel\ consumption = 0.07\frac{L\ gasoline}{km}$$

$$Energy\ content\ of\ gasoline = 34.5\frac{MJ}{L}$$

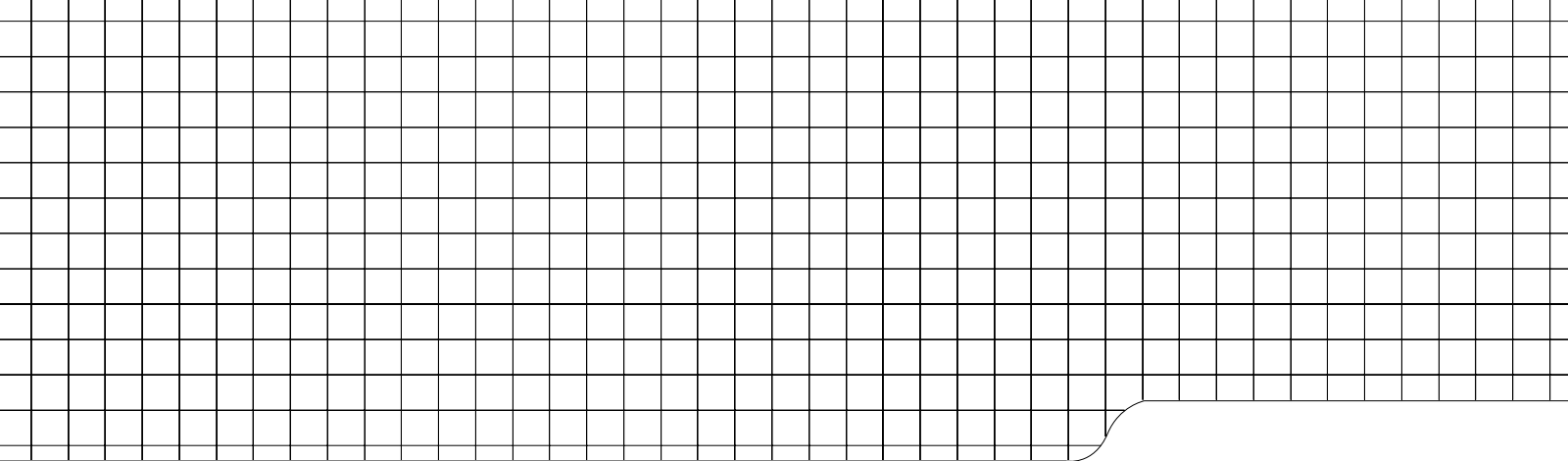$$Carbon\ emission\ factor = 20\frac{gC}{MJ}$$

$$Mole\ weight\ of\ CO_2 = 44\frac{g}{mol}$$

$$Mole\ weight\ of\ C = 12\frac{g}{mol}$$

Above values are all taken from the course book in *Sustainable Energy Futures*. [20]

Resulting emission from a car assumed driven on gasoline:

$$e = \frac{distance}{yr} \cdot \frac{consumption}{distance} \cdot energy\ content \cdot emission\ factor \cdot \frac{M_{CO_2}}{M_C}$$

$$e = 1500 \cdot 0.7 \cdot 34.5 \cdot 20 \cdot \frac{44}{12} = 2656500\frac{gCO_2}{yr} \approx 2.7\frac{tonCO_2}{yr}$$