Economic and Environmental Analysis of Excess Heat at Pulp Mills

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Examiner: Magnus Karlsson
Abstract

European industries have realized that a reduction of primary energy usage is not only a European requirement but can also be of great economic interest. Especially both energy and resource intensive industries like the pulp and paper industry will benefit. Industrial excess heat as a by-product of industrial processes needing energy has a great potential to be a key factor in reducing primary energy usage. Both excess heat utilization and heat integration are potential ways for Kraft pulp mills to increase their energy efficiency, to decrease their primary energy use and thus greenhouse gas emission, and to support the pulp and paper industry to achieve sustainability goals and meet EU regulations.

This thesis examines the total excess heat potential in the Swedish Kraft pulp industry through pinch analysis and optimization on a modelled average Swedish Kraft pulp mill (FRAM). Different excess heat recovery technologies (EHRTs) are identified based on their applicability and are evaluated regarding their environmental and economic benefits for the Swedish pulp industry by using the energy price and carbon scenarios tool (ENPAC tool).

An excess heat potential in the Swedish Kraft pulp mill industry of 2.03 TWh at 60°C, and 3.53 TWh at 25°C is found in this study. Heat delivery to the district heating network (DH), cooling delivery to the district cooling network (DC), electricity generation with a condensing turbine (CT), phase-change material engine (PCM) and organic Rankine cycle (ORC) are identified as suitable excess heat recovery technologies for Swedish Kraft pulp mills.

A payback time calculation in this study found the condensing turbine as the EHRT to be of highest economic benefit in 2018 (less than 3 years). With predicted future energy prices of the years 2030, 2040 and 2050 all considered recovery technologies become economically feasible (payback time of less than 3 years). The CT and combinations of CT with DH and DC are furthermore the recovery technologies with the highest CO₂ savings of 100.000 t/a in 2018.

All in all, this study suggests investing in a CT, or combinations of it with DH and DC, to create the greatest economic and environmental benefits in 2018. With future price changes on the energy market and an uncertain future energy demand an investment in combinations of recovery technologies generating both heat, cooling and electricity is found to be the most sustainable choice.

Keywords: FRAM, industrial excess heat, excess heat recovery technology, ENPAC
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Abbreviations

4GDH  4th generation district heating
ADt   air-dry-tonne, 10% water content
CCS   carbon capture and storage
CHP   combined heat and power
COP   coefficient of performance, $COP = \frac{\text{heating/cooling provided}}{\text{work required}}$
CT    condensing turbine
DC    district cooling
DH    district heating
DME   dimethyl ether
EHRT  excess heat recovery technology
ENPAC energy price and carbon balance scenarios
EO1–5 oil quality (1 = light fuel oil → 5 = thicker fuel oil)
FRAM  future resource adapted pulp mill
GCC   grand composite curve
NG    natural gas
NGCC  natural gas combined cycle
ORC   organic Rankine cycle
PBT   payback time
PCM   phase change material engine
TEG   thermoelectric generator
1 Introduction

One goal of the 2020 energy strategy paper set by the European commission is a 20% reduction of primary energy usage in 2020 compared to the level in 1990 (International Energy Agency, 2013). Sweden is on track to reach this goal but is required to make stronger efforts than it has already achieved with its energy-saving target for 2016 (ibid.). However, most companies have realized by now that a reduction of primary energy usage is not only a European requirement but can also be of great economic interest for itself. Specifically, the pulp and paper industry is both energy and resource intensive. More than half of the energy use in the industrial sector in Sweden is accounted for by the pulp and paper industry (Swedish Energy Agency, 2017). For Kraft pulp mills to be competitive on the market, energy and resource efficiency measures are a key factor for success. In particular, both excess heat utilization and heat integration are potential ways for Kraft pulp mills to increase their energy efficiency, decrease primary energy use and thus green-house gas emission and support the pulp and paper industry as a whole to achieve sustainability goals and meet EU regulations.

1.1 Background

A recent study by Broberg et al. (2012) defined a total of 21 TWh/a of unused primary (2 TWh/a) and secondary (19 TWh/a) excess heat in the industrial sector in Sweden. Whereas primary excess heat can be fed directly into the district heating grid, and secondary excess heat needs to be upgraded to a suitable temperature with for example heat pumps beforehand (Grönkvist et al., 2006). One of the major reasons of why this energy potential is unused and wasted is the lacking collaboration of energy companies and industries (Grönkvist et al., 2006). A major factor is the lack of communication and knowledge about the potential benefits, so that stakeholders willing to invest in excess heat utilization are missing crucial facts to assess their investments (Thollander et al., 2010). After all, studies were able to show both environmental (Holmgren, 2006; Ajah et al., 2007) and economic (Persson et al., 2011; Sandvall et al., 2016; Karlsson et al., 2009) benefits of industrial excess heat utilization in district heating systems. Also, Thollander et al. (2010) found that in the case of district heating, universities could help disseminate information through application of energy system optimization.

Results of this study will be used in the research project “Development and application of new methods for identifying efficient ways to use industrial excess heat”, which aims at systematically identifying and quantifying the availability of industrial excess heat in Sweden. Moreover, technologies for utilization of industrial excess heat are identified and evaluated on the basis of their consequences regarding energy efficiency, climate impact and economic feasibility. This project is currently being carried out at the
Division of Energy Systems at Linköping University together with Chalmers University of Technology and the consulting firm Profu and is funded by the Swedish Energy Agency. As already mentioned, the pulp and paper industry in Sweden accounts for more than 50% of the total energy usage in the industrial sector (Swedish Energy Agency, 2017). Therefore, the excess heat potential of this specific industrial sector is assessed to give an estimate of the overall heat potential and is thus of great importance for the whole industrial sector in Sweden.

1.2 Research Objective

To develop energy efficiency and sustainability of Kraft pulp mills in Sweden further, both economic and environmental incentives of excess heat utilization need to be identified and evaluated on an applicability basis. The term applicability is defined in this study as the ability of excess heat recovery technologies (EHRT) to make use of the specific excess heat at Kraft pulp mills in Sweden. Factors that influence applicability are: Which heat carrier medium can be used by EHRT? At what temperature does EH have to be supplied? Is the EHRT commercially available? Once the potential excess heat at Kraft pulp mills is identified it is crucial to know how to best utilize it. Therefore, an understanding of which excess heat recovery and utilization technologies can be applied to achieve the highest economic and environmental value is of great importance for the Kraft pulp industry.

In this thesis an energy balance for an average Swedish Kraft pulp mill (FRAM type mill) is set up and potential excess heat quantity and quality are identified. Technologies for excess heat utilization are identified and evaluated based on applicability. With a Matlab-based framework for process integration studies, the utilization of excess heat with each of the identified technologies at the FRAM type mill is optimized and their economic and environmental impacts are assessed. Performance of these technologies are compared, and the excess heat utilization potential of the Swedish pulp industry as a whole is evaluated.

The findings of this study benefit Swedish society to be aware of potential excess heat at Kraft pulp mills in Sweden and discover ways of becoming more resource and energy efficient. The Kraft pulp mill industry will benefit from knowledge about state of the art EHRT and how these can have a positive effect both economically and environmentally. Also, this study contributes to decreasing the knowledge gap and lack of information between heat/electricity-market participants to make it easier for industries to sell their EH or electricity generated from EH on the market.
1.3 Scope

This thesis aims at identifying the total excess heat potential in the Swedish pulp industry. Only Kraft pulp mills will be assessed in this study. An additional goal is to identify and analyse different excess heat utilization technologies based on their applicability and evaluate them regarding their environmental and economic benefits for the Swedish pulp industry. The following research questions are answered throughout the study, in order to achieve the main objective of this thesis:

1. What is the energy balance of an average Swedish Kraft pulp mill?
2. Which amount of potential excess heat is available in the Swedish Kraft pulp mill industry and of what quality is it?
3. What technologies for utilization of excess heat exist and can be applied at Swedish Kraft pulp mills?
4. What are the economic benefits of utilizing excess heat with these technologies, what are their CO$_2$ emission savings, and which one is most effective and economically suitable for Swedish Kraft pulp mills?
2 Theoretical and System Background

The following chapter describes the Kraft pulp process which is commonly used by the Swedish pulp industry to produce pulp from wood. Also, the term excess heat is explained and defined in its industrial context. As mentioned before, for all calculations and settings one virtual average Kraft pulp mill is used which is also explained and further illustrated in the following as well as its steam system and energy balance.

2.1 The Kraft pulp process

This paragraph only briefly illustrates the Kraft pulp process and focuses on the energy intensive steps as well as on those that are important for excess heat assessments. The first step in the pulp process is to pre-treat the wood entering the Kraft pulp mill. The bark is removed by special debarking drums and the wood is chopped up to chips that are fed into the cooking unit. Compared to other pulp processes like the mechanical or the sulphite one, the Kraft pulp process consists of a cooking unit or digester, where the woodchips are boiled with white liquor to separate the cellulose fibres from the lignin. White liquor consists mainly of sodium hydroxide and sodium sulphide, and thus, is very alkaline and is therefore used in the digester to break the cellulose bonds of the wood chips (Gullichsen et al., 1999). During the digestion stage low-pressure steam is used to remove non-condensable gases from within the woodchips and the woodchip and white liquor mixture is heated up to 160-175°C. The mix of used chemicals and dissolved organic compounds from the woodchips called ‘black liquor’ is collected and combusted later in the recovery boiler to win back valuable reactants. Due to the dissolved organic compounds, the black liquor is a valuable source of energy for a Kraft pulp mill. The hot steam generated in the recovery boiler can be used for internal processes, such as, for example, in a turbine for electricity generation. Before the black liquor is fed into the recovery boiler, its water content is reduced in an evaporator to make it suitable for combustion. The residues from combustion called ‘green liquor’ are mixed with lime to trigger a cascade of reactions until white liquor and hydrated lime develops (Gullichsen et al., 1999). The white liquor is then used in the digester again and the hydrated lime is burned in a rotating furnace (called ‘limekiln’) with temperatures above 1000°C, in order to recover it back to lime. Another energy intensive process step is the drying of pulp by either convection drying or flash drying. A simplified process diagram can be seen in Figure 1.
Modern Kraft pulp mills in Sweden produce excess steam with their recovery boiler, which they often use for both electricity generation and heat delivery to for example the district heating network. A certain amount of the produced steam is consumed for cleaning the recovery boiler from soot residues, called soot blowing. Additionally, the bark, which is removed during the first process step, is often burned in another boiler to generate steam for internal processes or district heating. Kraft pulp mills that have the opportunity and equipment to additionally function as power producers have a competitive advantage over those that produce only pulp (Lundberg et al., 2013). However, the generated quantity and quality of excess heat varies from one Kraft pulp mill to another and with this also its utilization potential. The concept of excess heat and its various forms are explained next.

2.2 Excess heat

As of now, there is no single generally accepted definition of excess heat and terms like waste heat, surplus heat and secondary heat are used in literature to describe heat released form an industrial process as a by-product. “Excess heat is heat that is left over after an industrial process has become (thermodynamically) optimized” and “Excess heat [is heat] that cannot be used directly in the industrial process” are two definitions used by Grönkvist et al. (2008). However, as Broberg-Viklund (2015) states it is difficult to determine when an industrial process is completely thermodynamically optimized. She therefore defines excess heat as follows: “Industrial excess heat is heat
(bound in liquids, gases, or hot materials) generated in an industrial process and currently not used internally in the processes. This definition is also used in this thesis. Bendig et al. (2013) introduce the terms of avoidable and unavoidable heat streams in their definition of excess heat. According to them, any heat as a by-product of an industrial process which is not optimized (with regard to energy efficiency) is an avoidable heat stream. Developing ideas further, Thekdi et al. (2011) and Bendig et al. (2013) discuss that any possible utilization of avoidable heat streams will have lower economic value than the reduction of those heat streams by improving the energy efficiency of the related industrial processes. However, certain instruments such as CO₂ allocations, energy and environmental policies and subsidies will affect that determination. Thekdi et al. (2011) formulate a hierarchy of how to treat excess heat from industrial processes most effectively:

1. Reduction – the excess heat streams should be reduced by means of efficiency measures within the industrial process itself.
2. Recycle – the excess heat streams should be reused in the industrial process from which it arose
3. Recovery I – the excess heat streams should be used in other industrial processes of the plant or externally (e.g. DH)
4. Recovery II – the excess heat streams should be used for generation of electricity

As mentioned in the introduction, Broberg et al. (2012) found 2 TWh/year of unused industrial primary excess heat potential in Sweden and a total of 21 TWh/year (primary and secondary)¹. This suggests that apart from a certain order of how excess heat streams should be used to be economically feasible, excess heat streams also come with an internal quality constraint. The quality of excess heat is determined by the temperature it can be utilized by. The higher the temperature, the more technologies can be applied and the higher the efficiency and effectiveness of its utilization. A comprehensive study of potential excess heat should therefore evaluate the amount and also the temperature of all available excess heat levels (Brueckner et al., 2014). Only then it can be assessed which utilization technologies can be applied reasonably. As Ammar et al. (2012) and Broberg-Viklund (2015) state, there are several options for the recovery and utilization of industrial excess heat. The following sections list currently available as well as potential prospective excess heat utilization technologies and mention their characteristics and their working principle.

¹ Primary and secondary excess heat are terms used by Grönkvist et al. (2006) to describe the quality of industrial waste heat as potential delivery to the DH network. The terms will be applied to quality demands for excess heat of each utilization technology.
2.3 Excess heat recovery technology

In general, excess heat is either used for heating, cooling or electricity production. However, not all utilization technologies are able to work with the same kind of excess heat streams to produce heating, cooling or power. As mentioned before, the quality of excess heat determines the efficiency of certain utilization technologies, and which of these technologies can be applied in the first place. The following list explains the working principles of currently available technologies and categorizes them with regard to their excess heat quality demand and purpose. A study by Broberg-Viklund et al. (2014) uses a categorization of heat harvesting, heat storage, heat utilization and heat conversion. For this thesis heat harvesting and heat storage are not relevant, and therefore, the utilization technologies presented in the following are categorized as either heat utilization or heat conversion.

2.3.1 Heat utilization

The EHRTs in this category make use of excess heat energy directly without converting it into another form of energy beforehand. This includes district heating, district cooling and heat synergies through for example industrial symbiosis.

District heating

A DH network consists of one or more heat suppliers, a piping network and heat consumers. Consumers can be residential buildings, schools, universities, and industries. Most heat suppliers in a collective heating system produce heat specifically for a DH network while converting primary energy into heat, such as CHP plants. Another option is to use industrial excess heat in DH networks. However, after an increase from 2006 until 2010, the amount of industrial excess heat deliveries into Swedish DH networks has stagnated at 4 TWh (Energi företagen, 2015). The heat is supplied to consumers through a grid piping system. Most systems use water as a heating medium, since the heat losses using steam are greater. The supply temperatures in Swedish DH networks differ between 80°C during summer and 110°C in winter with 50°C and 55°C return temperatures respectively (Friberg et al., 2013). In a recent study by Lund et al. (2014) the concept of 4th generation DH is expected to work with supply temperatures of 50°C and return temperatures of 30°C, which could make industrial excess heat a much more likely energy supply source. In order to use industrial excess heat at lower temperatures than the supply temperatures of the targeted DH network, the excess heat can be upgraded by heat pumps for example to achieve a suitable temperature (secondary industrial excess heat). The investment costs for any industry to connect their heating system to a DH network depend on the distance between the two systems (piping) and the amount of heat exchangers needed (Eriksson et al., 2015). A more detailed view of how capital and operational costs are
allocated to each EHRT is found in section 3.3 (‘Economic and environmental analysis’, p.23).

4th generation district heating

A recent study by Lund et al. (2014) introduces a new concept of a DH network, called 4th generation DH (4GDH). 4GDH is the latest development of the conventional DH and uses the same working principles. The main goal is to combine DH with smart energy and smart thermal grids including buildings with lower heat demand. However, most important for this study is that 4GDH can potentially use supply water with temperatures as low as 50°C. Reasons for this are more efficient heat exchangers at both supply and demand sites and improved grid insulation. A combination of 4GDH and another EHRT, which utilizes excess heat at a higher temperature level, could yield in a better utilization factor, since they do not compete for the same excess heat amount and quality.

District cooling

DC networks work in a similar way as DH networks. Water is cooled down in a centralized place and is then distributed through a grid pipe system to end consumers. Absorption chillers are able to exploit industrial excess heat so that it can be used in the cooling process of a DC network. Absorption chillers consist of an evaporator, condenser, absorber and generator. Warm return water from a DC network is cooled down by evaporation of a refrigerant at low pressure in the evaporator. The cooled water is then distributed as supply water to the DC network. The evaporated refrigerant is transferred to the absorber, where it is absorbed by a salty liquid (e.g. Lithium-Bromide). Afterwards, both are pumped to the generator. In the generator heat (e.g. industrial excess heat) is supplied to evaporate the refrigerant from the salty liquid, which is then transferred as steam to the condenser to condense. The liquid refrigerant is then pumped back to the evaporator again (Svensson, 2011). One big advantage of absorption chillers is that excess heat can be used in summer when cooling demand is high, compared to a low demand of DH. Today, about 1 TWh of DC is distributed in Sweden and this number is expected to rise in the coming years (Jönsson, 2017). Absorption chillers operate with a COP of 0,7 and need electricity for pumping the refrigerant of about 2% of the total produced cooling (Broberg-Viklund et al., 2014). According to Fahlén et al. (2012), a cooperation of absorption cooling in the Swedish DH and DC network could lead to a reduction of primary energy use, and also CO2 emissions, and make use of industrial excess heat in low heating demand times.

As can be seen in Figure 2 the DH and DC demand vary with outside temperatures over the year. In winter when it is cold outside the DH demand is higher than in summer when the outside temperatures are higher and the need for heating is lower. The
opposite is valid for the DC demand. Therefore, it is important to note that DH and DC demand are limited and not constant over the year.

![DH and DC demand over a year](image)

**Figure 2 Schematic illustration of the DH and DC demand over a year (derived from Gadd et al. (2013))**

### Heat synergies

Another possibility to use industrial excess heat is for several plants and industries in an area to connect and exchange energy and material streams. This concept of cooperation is called industrial symbiosis (IS), which results in competitive advantages for the whole cluster cooperation (Martin et al., 2011). Although, the concept of industrial symbiosis is not analysed regarding economic and environmental benefits in this thesis, it is worth noting that many studies have found advantages for industries in industrial symbiosis (Chinese et al., 2005; Li et al., 2012; Andrews et al., 2011).

#### 2.3.2 Heat conversion

The following EHRTs transform thermal energy into electric energy. This paragraph includes the Rankine cycle, the thermoelectric generator, thermophotovoltaic, the Stirling engine and the phase change material engine.
2.3.2.1 Thermodynamic cycles

Rankine cycle

The Rankine cycle includes in principle four processes. Compression, heat addition, expansion and heat release (Figure 3). A pressurised liquid is pumped into an evaporator, where it is heated and led into a turbine in order to expand and perform work and generate electricity. The steam is cooled in a condenser, and the liquid is pumped back to the evaporator to close the loop. However, the Rankine cycle uses water as a working liquid and needs temperatures of ~300°C, which makes it unsuitable for most industrial excess heat (Guo et al., 2011). There are other cycles such as the organic Rankine cycle (ORC) and the Kalina cycle which use working mediums with a lower boiling point that are suitable for low temperature excess heat streams (Dai et al., 2009).

Figure 3 Illustration of the working principle of a Rankine cycle (derived from Guo et al. (2011))

Condensing turbine

A condensing turbine is one application of the Rankine cycle to transform heat energy into electric energy and is installed in many pulp and paper mills already. The capacity of such turbines can vary from few kW to 1000 MW and is therefore, suitable for most industrial excess heat streams. High-velocity steam is led through rotating blades that are connected to a shaft and start to rotate. The shaft is connected to a generator which turns kinetic energy into electric energy (Fiaschi et al., 2007).

Stirling engine

The combustion of fuel which moves the piston in a traditional engine takes place outside of the cylinder in a Stirling engine. The hot combustion gases heat a working
medium inside the Stirling engine -usually helium or hydrogen- and water or air cools that working medium. The expansion and compression of the working medium moves a piston in the cylinder due to cooling and heating. Then, a connected generator can in turn generate electricity (Kong et al., 2004). Similar to the thermoelectric generator, the temperature difference of the cool and hot side determine the efficiency of the process (Hsu et al., 2003).

2.3.2.2 Thermoelectric generator

The thermoelectric generator works on the principle of the Seebeck effect which describes a voltage difference in a conductor or semiconductor due to a temperature gradient in that material. Closing an electric circuit over such a semiconductor results in electric current (Figure 4). The Seebeck coefficient is the voltage achieved for a unit of temperature difference (Kasap, 2001). Several semiconductors connected in series and temperature wise in parallel form a module. One or more modules together with a cooling unit form a thermoelectric generator (TEG). The higher the temperature gradient of the modules in a TEG, the higher the efficiency of generating electricity (Hadjistassou et al., 2013).

2.3.2.3 Thermophotovoltaic

The principle of thermophotovoltaic is the same as traditional photovoltaic technology. Infrared radiation is absorbed by photodiode cells and transformed into electricity. The heat source needs to have a high temperature (~1000°C), in order to emit sufficient radiation (Chubb, 2007).
2.3.2.4 Phase change material engine

This engine makes use of the change in volume of a material during a phase change. Heat is supplied to a material which changes its state from solid to liquid under high pressure and increases in volume. A cooling medium is then used, in order to cool the liquid back to its solid state and to decrease in volume. This change of volume is used in an hydraulic system and transferred to first kinetic and then electric energy through a connected generator (Broberg-Viklund et al., 2014).

2.4 The type mill

All assessments in this thesis are done on a virtual Kraft pulp mill which has all the characteristics of an average Nordic Kraft pulp mill and are scaled up in the end to represent the whole Swedish pulp producing industry. This average Kraft pulp mill was developed in an R&D project called “Future resource adapted pulp mill – FRAM”, supported among others by the Swedish Energy Agency\(^2\). All information about the FRAM type mill are collected from a study by Delin et al. (2004). The type mill has an annual pulp production of ~327,000 ADt and operates 7,838 h/a. A summary of all key operating data can be found in Table 1. Even though it is known that real Kraft pulp mills have frequent stops, quality changes, and thus sometimes have unbalanced operation, the type mill is assumed to run at steady state.

\(^2\) All relevant partners and financiers can be found in Delin et al. (2004)
Table 1 Key operating data of FRAM Kraft pulp mill

<table>
<thead>
<tr>
<th>Raw material</th>
<th>unit</th>
<th>value</th>
<th>Evaporation Stage</th>
<th>unit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood to digester</td>
<td>t/24 h</td>
<td>2.065</td>
<td>Weak black liquor to evaporation, excl. spill</td>
<td>t/h</td>
<td>441</td>
</tr>
<tr>
<td>Dried pulp from dryer</td>
<td>ADt/24 h</td>
<td>1.000</td>
<td>Weak black liquor to evaporation, excl. Spill, dry solids content</td>
<td>%</td>
<td>16,9</td>
</tr>
<tr>
<td>Operating days</td>
<td>d/a</td>
<td>355</td>
<td>Strong black liquor, dry solids content incl. Ash</td>
<td>%</td>
<td>73</td>
</tr>
<tr>
<td>Mill availability</td>
<td>%</td>
<td>92</td>
<td>Evaporated recycled spill</td>
<td>t/h</td>
<td>21</td>
</tr>
<tr>
<td>Annual production</td>
<td>ADt/a</td>
<td>326.600</td>
<td>Total evaporation, including spill</td>
<td>t/h</td>
<td>359</td>
</tr>
</tbody>
</table>

**Digester Plant**

<table>
<thead>
<tr>
<th>Kappa number&lt;sup&gt;3&lt;/sup&gt;</th>
<th>#</th>
<th>27</th>
<th>Estimated higher heating value of virgin, DS</th>
<th>MJ/kg</th>
<th>13,99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unscreened</td>
<td>%</td>
<td>46,1</td>
<td>Strong liquor virgin solids to mixing tank</td>
<td>t/24 h</td>
<td>1,778</td>
</tr>
<tr>
<td>Alkali charge on wood</td>
<td>NaOH, %</td>
<td>20</td>
<td>Strong liquor virgin solids to mixing tank (bleached)</td>
<td>ton/ADt</td>
<td>1,778</td>
</tr>
<tr>
<td>Sulphidity (white liquor)</td>
<td>mole-%</td>
<td>35</td>
<td>Net useful heat from liquor, virgin solids</td>
<td>MJ/kg</td>
<td>9,45</td>
</tr>
</tbody>
</table>

**Oxygen Stage**

<table>
<thead>
<tr>
<th>Kappa number after oxygen stage</th>
<th>#</th>
<th>14</th>
<th>Causticizing and Lime Kiln</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali charge as NaOH</td>
<td>kg/ADt</td>
<td>25</td>
<td>Causticizing efficiency</td>
<td>mole-%</td>
<td>82</td>
</tr>
<tr>
<td>Oxygen charge</td>
<td>kg/ADt</td>
<td>20</td>
<td>Total white liquor production</td>
<td>m³/24 h</td>
<td>3,984</td>
</tr>
</tbody>
</table>

**Washing Department**

| Dilution factor in the last     | m³/Adt   | 2,5     | Active CaO in lime                                                                | %      | 90      |
|                                 |          |         |                                                                                    |        |         |

### 2.4.1 Steam system

The type mill runs a backpressure turbine which is too small to generate a steam surplus, which is why a boiler combusting the residual bark is necessary to provide additional steam. Consequently, no condensing turbine is installed in the type mill. The high-pressure steam (HP-steam) is supplied at 60 bar and 450°C. The MP-steam

---

<sup>3</sup> Kappa number is an indicator of the lignin content and thus bleachability of pulp (ISO 302:2015)
(medium-pressure) is supplied at 10 bar. Soot blowing takes up 1.5 GJ/ADt of the totally produced steam to clean the recovery boiler unit from soot residues. The type mill has a total steam consumption of 17.25 GJ/ADt.

2.4.2 Energy balance

When it comes to energy balance, the type mill is completely self-sufficient. A total amount of energy of 791 kWh/ADt or 259 GWh/a is needed, which corresponds to a total power use of 33 MW. The FRAM type mill can generate 35 MW of power with the back-pressure turbine alone. Figure 5 illustrates the energy use for every process unit at the type mill in kWh/ADt. The pulp machine and the bleaching process are the two major power consumers with 130 and 100 kWh/ADt respectively.

![Power consumption in kWh/ADt for every process unit of the type mill](derived from Delin et al. (2004))
Additionally, Table 2 shows the power consumption in %. Both pulp machine and bleaching process make up almost 30 % of the total power consumption. Chemical preparation and raw water treatment are the two processes with the lowest power consumption, adding up to less than 5 %.

Table 2 Power consumption in % for every process unit of the type mill (derived from Delin et al. (2004))

<table>
<thead>
<tr>
<th>Process Unit</th>
<th>Power Consumption [%]</th>
<th>Process Unit</th>
<th>Power Consumption [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood yard</td>
<td>5,7</td>
<td>Evaporation</td>
<td>3,8</td>
</tr>
<tr>
<td>Digester</td>
<td>5,6</td>
<td>Causticizing, lime kiln</td>
<td>3,8</td>
</tr>
<tr>
<td>Washing and screening</td>
<td>11,4</td>
<td>Boiler house</td>
<td>12,6</td>
</tr>
<tr>
<td>Oxygen stage</td>
<td>10,1</td>
<td>Raw water treatment</td>
<td>2,8</td>
</tr>
<tr>
<td>Bleaching</td>
<td>12,6</td>
<td>Effluent treatment</td>
<td>3,8</td>
</tr>
<tr>
<td>Final screening</td>
<td>5,7</td>
<td>Chemical preparation</td>
<td>1,3</td>
</tr>
<tr>
<td>Pulp machine</td>
<td>16,4</td>
<td>Miscellaneous, losses</td>
<td>4,4</td>
</tr>
</tbody>
</table>
3 Method

A literature study was conducted for this thesis to assess the current scientific state of industrial excess heat potential and utilization methods in Sweden. State of the art technologies for industrial excess heat utilization were collected. The most important ones established are parameters of temperature range, efficiency and applicability, since these were used in the Matlab modelling process and economic and environmental evaluation. Data of the FRAM type mill was gathered and information about hot and cold process streams collected. These streams are used in process integration simulations for the assessment of industrial excess heat potential. Pinch analysis was performed to identify minimum heating and cooling demands for the pulp process at the FRAM type mill. The theoretical process heat recovery potential which results from pinch analysis is utilized in further simulations by each recovery technology. Results from those simulations are evaluated in an economic analysis and life cycle assessment.

3.1 Pinch analysis and optimization with MAT4PI

For the purpose of this thesis, the individual industrial processes of the studied Kraft pulp mill are assumed to be optimized - at least to an economically reasonable degree. Furthermore, a pinch-analysis and process integration study of this Kraft pulp mill ensures, that excess heat streams are used within the mill. This thesis, therefore, focuses only on the third and fourth level of the excess heat utilization hierarchy mentioned in section 2.2 (‘Excess heat’, p. 6). Since this thesis also focuses on the environmental benefits that come with utilizing excess heat in a certain way, the order of utilization should not solely depend on this hierarchy.

3.1.1 Pinch analysis

Pinch analysis is a tool to analyse complex industrial processes, in order to use energy more effectively and thus decrease costs and/or environmental impacts. Complex industrial processes consist of many different units which are all in some way connected through process flows. These flows either carry thermal energy or material from one unit to another. Pinch analysis aims to connect all units in the best way possible, in order to minimize the thermal energy demand within the whole process. As a result from pinch analysis, the total heating and cooling demands for an industrial process as well as the amount of heat that can be recovered internally is known. Consequently, the amount of heat which is not used internally in the process can be identified. The following key concepts are essential for carrying out a pinch analysis (Kemp, 2007).
• A hot stream is a process stream which requires cooling to change its initial temperature down to its target temperature. Such a stream indicates a cooling demand for the whole process.

• A cold stream has to be heated to reach its target temperature, and thus implies a heating demand.

• Internal heat exchangers are used to transfer heat from a hot stream to a cold stream.

• External heat exchangers, also called heaters/coolers, transfer heat from an external heat source to an internal cold stream or from an internal hot stream to an external cooling source (heat sink).

• Both types of heat exchangers are restricted to transport heat from one stream to another by the lowest temperature difference which must prevail between two process streams, $\Delta T_{\text{min}}$.

• Hot and cold composite curves are ways to handle more complex thermal systems (more than 1 hot and 1 cold stream). All hot streams, their heat loads over a given temperature range, are added together to create a single hot composite curve in a temperature vs. heat load diagram. The same is done for cold streams. (Figure 6)

• The grand composite curve (GCC) represents the difference between the heat demand and availability at a given temperature. A net heat flow vs. temperature (Figure 7).

The first step of pinch analysis is to gather data of all process streams, determine their initial and target temperatures, their specific heat load and $\Delta T_{\text{min}}$ for each of them. For the FRAM type mill these process streams were identified and categorized as either hot or cold streams (Appendix 1). The stream data was then used as an input in the \textit{MAT4PI} (Morandin et al., 2011) framework for the programming environment \textit{Matlab}$.^4$

The assumptions made for pinch analysis and optimization with \textit{Matlab} can be found in Table 3.

$^4$ \textit{Matlab} is a programming environment developed by MathWorks:
https://se.mathworks.com/products/matlab.html
<table>
<thead>
<tr>
<th>Recovery Boiler</th>
<th>Back-pressure Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat generation</td>
<td>16,79 GJ/ADt</td>
</tr>
<tr>
<td>Heat load</td>
<td>55 MW</td>
</tr>
<tr>
<td>Sootblower</td>
<td>1,71 GJ/ADt</td>
</tr>
<tr>
<td>Black liquor LHV</td>
<td>12,2 MJ/Kg</td>
</tr>
<tr>
<td>Model size factor</td>
<td>4,85 MW</td>
</tr>
</tbody>
</table>

### Condensing Turbine

| Steam generation pressure level | 80 bar | Efficiency of first turbine group | 0,75 |
| Final superheating temperature | 480 °C | Efficiency of second turbine group | 0,75 |
| Steam condensation pressure level | 0,1 bar | Global $\Delta t_{\text{min}}^5$ | 5 °C |
| Efficiency of the turbine section | 0,85 | Heat transfer coefficient for every stream | 2.000 kW/m²K |
| Efficiency of the pump | 0,75 |

#### 3.1.2 MAT4PI

The underlying concept of MAT4PI is the automatic calculation of linear programming optimization problems. This is specifically used to solve energy system synthesis and design optimization with taking constraints for heat exchange between thermal streams into account. MAT4PI consists of several scripts and functions that can be used in Matlab in order to perform energy targeting analysis of thermal systems. The scripts allow for an automatic generation of linear inequality constraints to be included in simple linear programming optimization problems. The scripts and the MAT4PI environment was developed at Chalmers University between 2011 and 2017. It can be used to solve energy system cooperation and optimization including constraints of heat transfer between those systems. The framework can generate a report with data or graphs of the studied thermal system as a result. This concept combines process integration analysis, energy targeting analysis, heat integration analysis and pinch analysis. The overall analysis procedure with MAT4PI can be broken down into the following steps:

1. Problem definition and formulation
2. Methodology identification
3. Calculation

$^5 \Delta t_{\text{min}}$ for individual streams can be found in Appendix 1
4. Result evaluation

However, $MAT4PI$ was mainly developed to support analyses such as Pinch analysis with the calculation task. In the case of pinch analysis and process integration the following Figure 6 and Figure 7 exemplify a possible graphical output. The red line in Figure 6 represents the composite curve of all hot streams and the blue line the composite curve of all cold streams. The point where the two curves touch is called the pinch point. That is the point which divides the thermal system into two parts. Above the pinch point is a heat deficit and below is a heat surplus. Another way of representing this is by plotting the grand composite curve (Figure 7). From the GCC one can also read the temperature at which a heat surplus or deficit occurs in a system. Furthermore, the parts where curves overlap (pockets) show at which temperature heat can be recovered within the system.

![Hot and Cold Composite Curve](image.png)

*Figure 6 Illustration of exemplary hot (red line) and cold (blue line) composite curves (generated with MAT4PI)*
The heat surplus of a thermal system which is calculated by pinch analysis and shown in Figure 7 (red line) illustrates the minimum need for cooling in the system. After a pinch analysis of the FRAM mill was done, the data for excess heat was used in calculations for the various EHRTs. The excess heat potential at the FRAM type mill is scaled up to represent the whole Swedish pulp industry. A specific excess heat in kWh/ADt of pulp is calculated and multiplied by the total amount of pulp produced at Swedish Kraft Pulp mills in a year to get the total amount of excess heat.

3.2 Excess heat recovery

As mentioned before, excess heat from the FRAM mill was calculated to be used in DH/DC and as means of electricity production. For some settings both DH/DC and electricity were used simultaneously. The industrial excess heat assessed in this thesis has a maximum temperature of ~150°C, which is why thermophotovoltaic (>1000°C) and the thermoelectric generator (low efficiency at 150°C) are not further considered in this study. The following paragraph describes how the energy recovery potential for each EHRT was calculated.

District heating

A new DH unit and one stream was introduced in the MAT4PI framework to simulate the district heating delivery. This stream has an initial temperature of 60°C and a target temperature of 100°C corresponding to the supply and return temperatures of Swedish
DH network. The maximum amount of DH load which can be supplied without decreasing the overall power target of the FRAM mill (33 MW) can then be calculated with the framework. Several iterations are done to see which DH load does not violate the power target but can still be supplied to the DH network, since there is a lower DH demand in summer compared to winter.

**District heating 4\textsuperscript{th} generation**

Similar to the conventional DH, a new 4GDH unit and stream was introduced in the MAT4PI framework. Initial temperature of the stream was set to 30°C and the target temperature was set to 50°C, corresponding to return and supply temperatures in the 4GDH network (Lund et al., 2014).

**District cooling with absorption chillers**

As mentioned before, absorption chillers can use excess heat to produce cooling. Although the COP of absorption chillers is lower than the COP of compression chillers, they might still be competitive when heat is easier/cheaper available than electricity, which is needed for compression chiller. In this study the COP for absorption chillers is assumed to be 0.6. Initially, the COP of modern absorption chillers is assumed to be 0.7, however, the small amount of electricity used for pumping is included in a lower COP. The initial stream temperature for absorption chilling is set to 86°C and the target temperature is set to 95°C (Zabala, 2009).

**Condensing turbine**

The condensing turbine is one of the EHRTs that come as a predefined built-in feature for the framework in Matlab, and which is used for pinch analysis. This unit template for a steam cycle was used to simulate a condensing turbine for the FRAM type mill. The condensing turbine is assumed to use high pressure steam of 480°C at 60 bar, a pump efficiency of 0.75 and a turbine efficiency of 0.85 (Delin et al., 2004). This study includes settings where DH, DC and a condensing turbine are used simultaneously.

**Organic Rankine Cycle**

Electricity calculation for the ORC is done with equation (1) (Asp et al., 2008):

\[
Q_{el} = Q_{th} \times \eta \times \frac{T-(30+T_{diff})}{T-30}
\]

(1)

Where \(Q_{th}\) is the energy content of the heat source, \(\eta\) is the efficiency of the ORC, \(T\) is the temperature of the heat source, \(T_{diff}\) is the temperature difference between the excess heat flow and the working medium inside the ORC, and 30 is used as the
evaporation temperature of the working medium. It is assumed that $T_{\text{diff}}$ is 20°C in this study (Asp et al., 2008).

Phase change material engine

For PCM, equation (2) was used to calculate electricity output (Johansson et al., 2013):

$$Q_{el} = Q_{th} \times 0.024 \times \frac{T_{diff}}{25} \times \frac{1}{k^2} \times \sum_{i=0}^{k-1} (k - i)$$

(2)

Where $Q_{th}$ is the energy content of the heat source, $T_{diff}$ is the temperature difference between the excess heat flow and the cooling water in the PCM, and the value of $k$ varies between 1 (for $20^\circ C \leq T_{diff} < 40^\circ C$), 2 (for $40^\circ C \leq T_{diff} < 60^\circ C$) and 3 (for $60^\circ C \leq T_{diff} < 80^\circ C$) depending on seasonal changes to $T_{diff}$ as defined by Johansson et al. (2013).

3.3 Economic and environmental analysis with ENPAC

The economic and environmental feasibility of each recovery technology was assessed with the help of the energy price and carbon balance scenarios tool (ENPAC).

![Diagram of ENPAC tool](enpac_diagram.png)

*Figure 8 Calculation procedure of ENPAC tool. Green arrows represent user input data (e.g. CO$_2$ emission charges), black arrows represent internal information flow and blue arrows represent output data from the model (i.e. market parameters) (derived from Axelsson et al. (2010)).*
The ENPAC tool considers possible developments of future energy market conditions and develops scenarios for energy price variations. All possible scenarios of the ENPAC tool were initially developed by Axelsson et al. (2010). The calculation procedure of ENPAC is illustrated in Figure 8. User input data for the ENPAC tool include the assumed fossil fuel prices, the assumed CO₂ emission charge and assumed support for use of biomass fuels. The ENPAC tool proposes energy market prices for large-volume customers, based on world market fossil fuel price data and assumed values for energy and climate mitigation policy instruments. Assumptions that had to make beforehand, fossil fuel prices and charges for CO₂ emissions, are shown in Table 4.

Table 4 Fossil fuel prices and CO₂ emission charges assumed for ENPAC tool (International Energy Agency, 2017)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>€/MWh</td>
<td>37,7</td>
<td>48,5</td>
<td>46,1</td>
<td>46,3</td>
<td>44,2</td>
<td>66,8</td>
<td>57,7</td>
<td>55,6</td>
<td>42,1</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>€/MWh</td>
<td>22,0</td>
<td>27,2</td>
<td>26,9</td>
<td>26,6</td>
<td>25,9</td>
<td>33,2</td>
<td>31,8</td>
<td>30,7</td>
<td>27,0</td>
</tr>
<tr>
<td>OECD Coal</td>
<td>€/MWh</td>
<td>6,1</td>
<td>8,1</td>
<td>8,0</td>
<td>7,9</td>
<td>7,6</td>
<td>11,1</td>
<td>10,3</td>
<td>10,0</td>
<td>8,5</td>
</tr>
<tr>
<td>CO₂ charge</td>
<td>€/ton</td>
<td>13</td>
<td>17</td>
<td>18</td>
<td>21</td>
<td>29</td>
<td>27</td>
<td>32</td>
<td>49</td>
<td>87</td>
</tr>
<tr>
<td>Marginal el. production</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>NGCC⁶</td>
<td>NGCC</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model year</th>
<th>Fossil fuel Scenario</th>
<th>2040</th>
<th>2040</th>
<th>2040</th>
<th>2040</th>
<th>2050</th>
<th>2050</th>
<th>2050</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude Oil</td>
<td>€/MWh</td>
<td>82,6</td>
<td>67,4</td>
<td>63,0</td>
<td>38,9</td>
<td>98,4</td>
<td>77,2</td>
<td>70,4</td>
<td>35,6</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>€/MWh</td>
<td>38,9</td>
<td>35,5</td>
<td>34,5</td>
<td>29,2</td>
<td>44,5</td>
<td>39,2</td>
<td>38,4</td>
<td>31,5</td>
</tr>
<tr>
<td>OECD Coal</td>
<td>€/MWh</td>
<td>12,3</td>
<td>10,6</td>
<td>10,4</td>
<td>8,3</td>
<td>13,5</td>
<td>10,8</td>
<td>10,8</td>
<td>8,0</td>
</tr>
<tr>
<td>CO₂ charge</td>
<td>€/ton</td>
<td>39</td>
<td>47</td>
<td>74</td>
<td>137</td>
<td>51</td>
<td>62</td>
<td>100</td>
<td>187</td>
</tr>
<tr>
<td>Marginal el. production</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
</tr>
</tbody>
</table>

The ENPAC tool uses eight scenarios for the time-period from 2018 to 2050. The eight scenarios are a result of combining two levels of fossil fuel prices and four levels of CO₂ charge. Two levels of fossil fuel prices represent different developments on the fossil fuel world market. Four levels of CO₂ emission charges represent everything from no to strong ambitions to decrease CO₂ emissions. The output data most

⁶ Natural-Gas-Combined-Cycle plant
⁷ Carbon Capture and Storage
interesting for this study are electricity market and heat market parameters. Based on these parameters, (especially fossil fuel price and CO₂ emissions) a willingness to pay (WTP) for heat and electricity generated from industrial excess heat on these two markets can be assumed. The WTP is closely linked to electricity and heat market prices, meaning that customers are willing to pay as much for electricity/heat generated from industrial excess heat as they are for electricity/heat generated from the base technology with the lowest electricity/heat price on the market (Axelsson et al., 2014; Axelsson et al., 2010).

With the resulting willingness to pay (WTP) for electricity and heat produced from industrial excess heat for all eight scenarios a revenue generated by each recovery technology can be calculated. The revenue together with investment costs, annual operation and maintenance costs (O&M) were used to calculate the payback time (PBT) over the expected operation time of the recovery technology. The investment for each recovery technology is assumed to be constant in 2018, 2030, 2040 and 2050 to make calculations simpler. Also, the operation and maintenance costs are assumed to stay constant in those years. The revenue, however, changes with energy prices in those years and is therefore the only changing variable in the PBT calculations for each year. Equation (3) is used to calculate the PBT:

\[
PBT = \frac{P_{\text{inv}}}{(P_{\text{rev}} - P_{\text{O&M}})}
\]  

(3)

Where \(P_{\text{inv}}\) is the investment cost of the recovery technology in €, \(P_{\text{rev}}\) is the revenue cash flow for each year in €/a, and \(P_{\text{O&M}}\) is the operation and maintenance cost of the technology in €/a for each year.

The ENPAC tool can be used to calculate CO₂ emissions from energy plants and thus, substituted primary energy use from excess heat utilization. Assumptions made for CO₂ emissions of fossil fuels are shown in Table 5.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>EO1</th>
<th>EO5</th>
<th>Coal</th>
<th>NG</th>
<th>Diesel</th>
<th>Gasoline</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ [kg/MWh]</td>
<td>287</td>
<td>293</td>
<td>364</td>
<td>224</td>
<td>284</td>
<td>280</td>
<td>4</td>
</tr>
</tbody>
</table>

Industrial excess heat from the FRAM type mill is considered to have net-zero CO₂ emissions, since excess heat is generated anyway and would otherwise be discharged unused into the environment. Additionally, all energy supplied to the Kraft pulp mill is biogenic (biomass-based energy) and is thus considered CO₂ neutral. Table 6 displays all recovery technologies used in this study and their parameters and assumptions used to calculate PBT and CO₂ emissions.
Table 6 Parameters of EHRTs

<table>
<thead>
<tr>
<th>mechanism</th>
<th>District heating(^8)</th>
<th>District cooling(^8)</th>
<th>Condensing turbine(^9)</th>
<th>ORC(^11)</th>
<th>PCM engine(^12)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>heat exchange</td>
<td>absorption cooling</td>
<td>turbine-generator</td>
<td>phase change: liquid-gas</td>
<td>phase change: solid-liquid</td>
</tr>
<tr>
<td>temperature [(^\circ)C]</td>
<td>60-100</td>
<td>86-95</td>
<td>400-600</td>
<td>60-80</td>
<td>60-80</td>
</tr>
<tr>
<td>size [MW]</td>
<td>10-38</td>
<td>6-23</td>
<td>10-15</td>
<td>2-3</td>
<td>1-2</td>
</tr>
<tr>
<td>technical lifetime [year]</td>
<td>20-30</td>
<td>20</td>
<td>30-50</td>
<td>20-30</td>
<td>20</td>
</tr>
<tr>
<td>electric efficiency [(\eta) / COP]</td>
<td>-</td>
<td>0,6</td>
<td>0,4-0,45</td>
<td>0,05-0,2</td>
<td>0,025-0,09</td>
</tr>
<tr>
<td>O&amp;M [(\text{€}/\text{MWh})]</td>
<td>neglected</td>
<td>17,5</td>
<td>6</td>
<td>4,5</td>
<td>4,5</td>
</tr>
<tr>
<td>investment cost [(\text{€}/\text{kW})]</td>
<td>270</td>
<td>150</td>
<td>900</td>
<td>1.600</td>
<td>2.000</td>
</tr>
</tbody>
</table>

\(^8\) (Broberg-Viklund et al., 2014)  
\(^9\) (Zabala, 2009)  
\(^10\) (Zhang et al., 2016)  
\(^11\) (Vélez et al., 2012)  
\(^12\) (Johansson et al., 2013)

The operation and maintenance costs for the district heating option were neglected in this study. These costs are small in relation to the investment costs and not significant for the feasibility assessment (Rudra et al., 2017). A study taking operation and maintenance costs of DH into account would be more accurate. However, for the purpose of this study an overview of the performance of these recovery technologies can be conducted without taking the operation and maintenance costs for DH into account. Investment costs for an installation of a connection between a Kraft pulp mill and a DH network were estimated according to assumptions made by the authors of the ENPAC tool (Table 7). An average distance of 10 km between the Kraft pulp mill and the closest DH network is assumed.

Table 7 Assumed piping prices in \(\text{€}/\text{m}\) for DH networks (Axelsson et al., 2010)

<table>
<thead>
<tr>
<th>load [MW]</th>
<th>(\text{€}/\text{m})</th>
<th>distance [m]</th>
<th>investment [(\text{€})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>538</td>
<td>10.000</td>
<td>5.380.000</td>
</tr>
<tr>
<td>20</td>
<td>374</td>
<td>10.000</td>
<td>3.740.000</td>
</tr>
<tr>
<td>5</td>
<td>252</td>
<td>10.000</td>
<td>2.520.000</td>
</tr>
</tbody>
</table>
3.4 Settings

Several settings consisting of various combinations of EHRTs are used for calculations in this study. The following paragraph introduces each setting, describes which EHRT is used and how they are combined. Table 8 gives an overview of all settings used in this study.

*Table 8 Description of used settings by means of heat/cooling/electricity generation*

<table>
<thead>
<tr>
<th>Setting</th>
<th>Heat generation</th>
<th>Cooling generation</th>
<th>Electricity generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>DH</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2</td>
<td>-</td>
<td>DC</td>
<td>-</td>
</tr>
<tr>
<td>S3</td>
<td>DH</td>
<td>DC</td>
<td>-</td>
</tr>
<tr>
<td>S4</td>
<td>-</td>
<td>-</td>
<td>CT</td>
</tr>
<tr>
<td>S5</td>
<td>-</td>
<td>-</td>
<td>ORC</td>
</tr>
<tr>
<td>S6</td>
<td>-</td>
<td>-</td>
<td>PCM</td>
</tr>
<tr>
<td>S7</td>
<td>DH</td>
<td>-</td>
<td>CT</td>
</tr>
<tr>
<td>S8</td>
<td>DH</td>
<td>DC</td>
<td>CT</td>
</tr>
<tr>
<td>S9</td>
<td>DH</td>
<td>DC</td>
<td>ORC</td>
</tr>
<tr>
<td>S10</td>
<td>DH</td>
<td>DC</td>
<td>PCM</td>
</tr>
<tr>
<td>S11</td>
<td>4GDH</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The settings were chosen in such a way that only one of each type of industrial EH recovery technology was used in a combination (heat/cooling/electricity generation). Settings S1 and S2, and settings S4, S5 and S6 represent sole heat, cooling or electricity generation respectively. Settings S1 and S2 generate heat and cooling respectively over the whole year. In all other settings which combine DH and DC, heating is only generated during half of the year (winter) and cooling during the other half (summer). Each setting was evaluated based on energy output and CO₂ emissions first independently and then compared to each other. Setting S11 is an exception, since 4GDH utilizes EH at very low temperatures which is not used by any of the other EHRT. Therefore, combining 4GDH with any other setting in the end does not affect their performance. Thus, if the evaluation of 4GDH shows beneficial results, a combination with any other beneficial setting would not decrease performance of the whole combination but rather increase it.
4 Results

Results from pinch analysis and optimization with Matlab as well as from calculations with the ENPAC tool will be described in this chapter.

4.1 Pinch analysis

The combined GCC of the pulp process and the recovery boiler shows the available heat load at a given temperature from the recovery boiler and heat demand at that temperature of the pulp process (Figure 9). It can be observed that the recovery boiler generates more heat than needed by the pulp process at all temperatures.

![GCC of pulp process and recovery boiler](image)

*Figure 9 GCC of pulp process and recovery boiler (shown as ‘others’)*

The hot and cold composite curves of the pulp process alone are shown in Figure 10. It can be seen that the pinch point is between 60°C and 70°C, and the minimum heating utility is almost three times bigger than the minimum cooling utility.
The resulting GCC of the FRAM Kraft pulp process can be seen in Figure 11. The minimum heating demand of the FRAM type mill is 122 MW and the minimum cooling demand is 44 MW.
Table 9 illustrates the key findings of excess heat at the FRAM type mill and scaled up at Swedish Kraft pulp mills in total. The total excess heat potential at Swedish Kraft pulp mills was calculated with a produced total of 2.232kt pulp in 2015.

Table 9 Key results from pinch analysis and specific excess heat potential

<table>
<thead>
<tr>
<th>Specific excess heat (&gt;60°C)</th>
<th>Specific excess heat (&gt;25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kW/ADt]</td>
<td>0,12</td>
</tr>
<tr>
<td>[kWh/ADt]</td>
<td>911</td>
</tr>
</tbody>
</table>

Total excess heat potential at Swedish Kraft pulp mills [TWh]

<table>
<thead>
<tr>
<th>Pinch point [°C]</th>
<th>Hot utility [MW]</th>
<th>Cold utility [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>65,6</td>
<td>122</td>
<td>44</td>
</tr>
</tbody>
</table>

Based on the above presented data and a minimum feasible heat/cooling/electricity output corresponding to each recovery technology, the energy delivery, investment, net revenue, payback time and CO₂ savings for each setting were calculated (Table 10).
### Table 10: Key results of net revenue, CO₂ savings, energy output, investment and payback time for each setting

<table>
<thead>
<tr>
<th></th>
<th>S1 DH</th>
<th>S2 DC</th>
<th>S3 DH-DC</th>
<th>S4 CT</th>
<th>S5 ORC</th>
<th>S6 PCM</th>
<th>S7 DH-CT</th>
<th>S8 DH-DC-CT</th>
<th>S9 DH-DC-ORC</th>
<th>S10 DH-DC-PCM</th>
<th>S11 4GDH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net revenue [M€/a]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>2.0</td>
<td>0.4</td>
<td>1.7</td>
<td>5.1</td>
<td>1.1</td>
<td>0.7</td>
<td>4.4</td>
<td>4.1</td>
<td>1.3</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>2030</td>
<td>5.3</td>
<td>2.4</td>
<td>5.4</td>
<td>8.8</td>
<td>1.8</td>
<td>1.2</td>
<td>8.4</td>
<td>7.7</td>
<td>3.0</td>
<td>3.5</td>
<td>2.7</td>
</tr>
<tr>
<td>2040</td>
<td>7.8</td>
<td>2.8</td>
<td>7.5</td>
<td>9.6</td>
<td>2.0</td>
<td>1.3</td>
<td><strong>10.0</strong></td>
<td>8.9</td>
<td>3.7</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>2050</td>
<td>10.3</td>
<td>3.2</td>
<td>9.6</td>
<td>10.3</td>
<td>2.1</td>
<td>1.4</td>
<td><strong>11.4</strong></td>
<td>9.9</td>
<td>4.5</td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>CO₂ savings [t/a]</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>67.246</td>
<td>54.760</td>
<td>82.691</td>
<td><strong>103.432</strong></td>
<td>21.237</td>
<td>13.483</td>
<td>100.692</td>
<td>96.100</td>
<td>40.644</td>
<td>44.572</td>
<td>33.623</td>
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<tr>
<td>2030</td>
<td><strong>80.472</strong></td>
<td>22.582</td>
<td>73.372</td>
<td>42.653</td>
<td>8.758</td>
<td>5.560</td>
<td>62.193</td>
<td>49.964</td>
<td>29.162</td>
<td>28.715</td>
<td>40.236</td>
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<tr>
<td>2040</td>
<td><strong>80.112</strong></td>
<td>14.772</td>
<td>68.451</td>
<td>27.901</td>
<td>5.729</td>
<td>3.637</td>
<td>51.449</td>
<td>38.067</td>
<td>25.536</td>
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<tr>
<td>2050</td>
<td><strong>74.043</strong></td>
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<td>36.357</td>
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<td>22.781</td>
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<td><strong>Yearly energy output [GWh]</strong></td>
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<td></td>
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<tr>
<td>Heat</td>
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<td>148.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>78.4</td>
<td>39.2</td>
<td>47.0</td>
<td>39.2</td>
<td>100.0</td>
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<tr>
<td>Cooling</td>
<td>0.0</td>
<td>150.0</td>
<td>89.4</td>
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<td>0.0</td>
<td>0.0</td>
<td>23.5</td>
<td>28.2</td>
<td>23.5</td>
<td>23.5</td>
<td>0.0</td>
</tr>
<tr>
<td>El.</td>
<td>0.0</td>
<td>0.0</td>
<td>113.3</td>
<td>23.3</td>
<td>14.8</td>
<td>81.5</td>
<td><strong>81.5</strong></td>
<td><strong>15.9</strong></td>
<td>10.9</td>
<td>0.0</td>
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<tr>
<td><strong>Load [MW]</strong></td>
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<tr>
<td>Heat</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>26</td>
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<tr>
<td>Cooling</td>
<td>0</td>
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<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>El.</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>3</td>
<td>2</td>
<td>10</td>
<td>10</td>
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<tr>
<td><strong>Investment [M€]</strong></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>10</td>
<td>4</td>
<td>14</td>
<td>14</td>
<td>5</td>
<td>4</td>
<td>12</td>
<td>13</td>
<td>8</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>2030</td>
<td>1.9</td>
<td>1.5</td>
<td>2.6</td>
<td>1.5</td>
<td>2.6</td>
<td>3.4</td>
<td><strong>1.4</strong></td>
<td>1.7</td>
<td>2.6</td>
<td>1.9</td>
<td>1.5</td>
</tr>
<tr>
<td>2040</td>
<td>1.3</td>
<td>1.2</td>
<td>1.8</td>
<td>1.4</td>
<td>2.4</td>
<td>3.1</td>
<td><strong>1.2</strong></td>
<td>1.5</td>
<td>2.0</td>
<td>1.6</td>
<td><strong>1.0</strong></td>
</tr>
<tr>
<td>2050</td>
<td><strong>1.0</strong></td>
<td>1.1</td>
<td>1.4</td>
<td>1.3</td>
<td>2.2</td>
<td>1.1</td>
<td>1.4</td>
<td>1.7</td>
<td>1.3</td>
<td><strong>0.8</strong></td>
<td></td>
</tr>
</tbody>
</table>
4.2 Heating, cooling and electricity generation

Possible DH and DC deliveries in a year were assumed to be maximum 200 and 150 GWh respectively, although in settings S1 and S2, DH delivery would theoretically be as high as 298 GWh and DC delivery 179 GWh respectively. This assumption gives credit to the problem of a maximum DH and DC demand over a year in a region connected to a Kraft pulp mill in Sweden. As described in chapter 2.3.1 (‘Heat utilization’, p.8), the demand for DH and DC varies over the year and is limited. Therefore, the Kraft pulp mill can only deliver a certain amount of DH and DC to the network even though, it could generate more heat and cooling. The following Figure 12 displays the energy delivery by type of each setting.

![Energy delivery by type of each setting.](image)

As it can be seen, the greatest heat delivery to DH is achieved in setting S1 with 200 GWh per year. Setting S2 has the greatest DC delivery with 150 GWh a year. The highest electricity output occurs in setting S4 with 113 GWh a year. Settings S8, S9 and S10 are the only settings with combined heat, cooling and electricity output.

4.3 Investment, net revenue and payback time calculation

Based on the parameters described in Table 6, the following Figure 13 illustrates the investments necessary for each setting.
The highest investments are required for settings S3, S4, S7 and S8 with more than 12 M€. Settings S5, S6 and S11 demand investments of only 4 M€. Setting S2 has the lowest investment of 3 M€. These investments generate net revenues each year, which are displayed in Figure 14 (maintenance costs subtracted). Electricity and heat prices for each decade were assumed with the ENPAC tool.
As it can be seen, settings S4, S7 and S8 generate the highest net revenue in 2018 with 4 M€. However, during the following three decades settings S1 and S3 catch up and all five settings generate around 10 M€ each in 2050. The net revenue leads to a payback time which is displayed in Figure 15.
The payback time of each setting declines over the decades resulting in a payback time of less than three years with energy prices of 2050 for each setting. With 2018 energy prices setting S3 has the highest payback time of approximately eight years.
4.4 CO₂ savings

Figure 16 shows the CO₂ savings depending on future energy prices. In 2018, settings S4, S7 and S8 generate the highest CO₂ savings of around 100,000 t/a. With 2030, 2040 and 2050 energy prices, electricity is assumed to be generated more environmentally friendly, and thus, the CO₂ savings of substitutable electricity production from excess heat is lower. The marginal electricity production plants for each model year can be seen in Table 4.
5 Analysis & Discussion

The following chapter analyses the above-mentioned results and sets this thesis in relation to results from previous studies. The first results to analyse are the energy balance and pinch-analysis results of the FRAM type mill. With 38 MW of excess heat at temperatures above 60°C and 66 MW of excess heat above 25°C the FRAM type mill stands for a big share of the industrial excess heat available in Sweden. Scaled up, the total pulp industry in Sweden is assumed to have an excess heat potential of 2 TWh at 60°C and 3.5 TWh at 25°C. This lies in the range of readily available excess heat in Sweden (3.7-6.6 TWh for DH) as found by Grönkvist et al. (2006). This finding supports the assumption that the excess heat potential of the pulp and paper industry in Sweden is one of the biggest in the Swedish industrial sector and can have a major impact on the national climate goals and EU energy efficiency measures. These findings are based on the assumption that the FRAM type mill is an average Swedish Kraft pulp mill and can be scaled up to represent the total Swedish pulp industry. Nevertheless, in difference to the type mill, real mills operate in a more fluctuating way and have production stops for necessary quality check-ups and quality changes. This unbalanced operation of real Kraft pulp mills was not considered in this study and would lower the theoretical excess heat potential. However, it is difficult to quantify exactly by how much. One example of imbalanced production of real mills compared to the FRAM type mill given by Delin et al. (2004) is related to the pulp tower. During the process of emptying the pulp tower, excess liquid is severed, and fresh make-up water needs to be heated up for the next charge in the pulp tower. The resulting extra energy demand for heating the make-up water and the environmental impact of discharging the liquid are not considered in the FRAM type mill process. Additionally, the FRAM type mill was developed in 2004 and uses average technological parameters of that time. The modern Swedish Kraft pulp mills 14 years later are most probably further developed than they were back then and would raise the energy efficiency of a nowadays developed average Swedish Kraft pulp mill. A higher energy efficiency and more developed technology would result in less available excess heat. Taking this into account, the total excess heat potential at Swedish Kraft pulp mills is probably lower than the 2 TWh and 3.5 TWh at 60°C and 25°C respectively. However, an exact calculation of the resulting decrease in excess heat potential is impossible. Nevertheless, modern Swedish Kraft pulp mills are still going to have excess heat to take care of. Additionally, the bark boiler, which is together with the recovery boiler responsible for an excess of heat, will be most likely fired with bark and biofuels in the future to act as a CHP plant. The reason for this is that the bark boiler is already built and scaling it down due to a higher energy efficiency might be infeasible and keeping it as a power plant could lead to a higher profit in the future. To sum it up, it is only an assumption that the FRAM Kraft pulp mill is an average Swedish Kraft pulp mill. In real-
life, Kraft pulp mills are different and so will be the results of this study when compared to individual real Swedish Kraft pulp mills. The following paragraph discusses the energy performance of every setting.

5.1 Energy performance

Regarding heat and cooling deliveries to a DH/DC network, industrial excess heat suppliers and DH/DC companies face problems. As Thollander et al. (2010) found out, knowledge gaps and a lack of communication make it difficult for suppliers and DH/DC companies to come and work together. There is, however, another reason which makes it difficult for industries to deliver an unlimited amount of excess heat to DH networks. The demand for DH varies greatly with temperatures over the year. However, the DH companies are responsible to cover the demand during all times. Therefore, these companies have high capacity energy plants to be able to cover the high demand in winter, since failing to do so would result in fines. Their plants are already built and a supply of industrial excess heat results in lower demand in winter and the DH companies would not be able to run their plants at full capacity resulting in lower efficiency and thus, income. The same problem is valid for DC networks.

This is a reason why DH/DC companies cannot accept unlimited amount of excess heat. Therefore, the maximum amount of yearly heat delivery to a DH network was limited to 200 GWh and the maximum amount of yearly cooling delivery to a DC network was limited to 150 GWh. Therefore, the load for DH and DC technology was limited to 26 MW in setting S1 and 20 MW in setting S2. Also, DC with a cooling delivery of just 1 TWh and only 1000 km of built piping network is not yet as widely spread and popular in Sweden, while 47 TWh of heating was delivered in 2016 in Sweden (Jönsson, 2017). The heat delivery to 4GDH was limited to 100 GWh, since that network is not yet fully developed and the underlying concept of smart thermal grids still faces problems hindering the future development (Lund et al., 2010). Settings S1 and S2 deliver 200 GWh heat and 150 GWh of cooling, making them the settings with the highest heating and cooling delivery. Nevertheless, implementing either S1 or S2 could cause problems for the Kraft pulp mill, since it makes only use of their excess heat either in winter (S1) or summer (S2). The Kraft pulp mill is wasting most of their excess heat the other half of the year making the recovery settings S1 and S2 not effective. A combination of both as found in setting S3 recovers excess heat over the whole year. Settings S4, S5 and S6 recover excess heat for electricity generation with a great difference in efficiency (Table 6) and thus, greatly varying electricity production. With 113 GWh every year, setting S4 generates five times more electricity than S5 and seven times more than S6. For one thing, S5 and S6 use recovery technologies which are designed for small amounts of excess heat and seem to not be perfectly suitable for sole utilization of the big amount of excess heat available at Kraft pulp mills. The
condensing turbine used in setting S4, however, seems to be most suitable for sole electricity generation. Settings S8, S9 and S10 recover excess heat and generate heat, cooling and electricity all together. This makes these three settings extremely flexible since a varying demand of one type of energy delivery can be compensated by another. Furthermore, these settings are not as vulnerable to changes in energy prices over time as other settings with a more limited energy delivery. With a DC network not fully developed in all regions of Sweden, setting S7 of all settings with energy delivery combinations is most adapted to the current energy market situation. First of all, the DH network is fully developed and secondly, as discussed before, electricity is easier to sell on the market than heat or cooling generated from excess heat. This is likely to change over the coming years when cooling demand rises, and the DC network in Sweden is further developed. Setting S11 can be combined with any other setting since this setting uses excess heat at lower temperatures, and thus, it will not compete in the same temperature range. In the coming years, when the 4GDH network is fully developed and smart thermal grids are implemented, 4GDH and conventional DH could complement each other. Therefore, it can be expected that a combination of settings S11 and S1 would result in higher benefits in the long run.

5.2 Economic performance

One major difficulty for carrying out this study was to assume realistic investment and maintenance costs for each recovery technology. This chapter deals with the economic performance of each setting and evaluates the assumptions made beforehand. The first paragraph compares and evaluates investment costs required for the settings.

5.2.1 Investment costs

Settings S3, S4, S7 and S8 require the highest investment with more than 12 M€. It should be noted that for settings with a combination of recovery technologies the investment costs were summed up. Setting S4 has the highest investment costs for a single recovery technology with more than 13 M€. The lowest investment is required by settings S2, S5, S6 and S11 with less than 5 M€. This is, on the one hand, due to the fact that ORC and PCM are technologies with relatively small capacity compared to the available excess heat. On the other hand, although the investment costs in €/kW for 4GDH and conventional DH were assumed to be the same, and the capacity of 4GDH is less than half of that of conventional DH. This results in very low investment costs. The investment costs for DC were assumed to be 140 €/kW as shown in Table 6. These investment costs do not include the piping connection, since the DC network in Sweden is not fully developed and costs for piping depend heavily on the distance between the Kraft pulp mill and the nearest DC network. Thus, investment costs for settings including DC (S2, S3, S8, S9, S10) are incomplete and can only be considered as a rough estimate and guideline. Once the DC in Sweden is more sophisticated,
investment costs can be estimated more accurately. The investment costs for DH needed to be estimated as well. The ENPAC tool assumes a price for piping capable of working with specific capacities in €/m (Table 7).

Similarly to the DC case, it is difficult to estimate the distance between each Kraft pulp mill in Sweden to the nearest DH network. However, since the DH network in Sweden is more widespread than the DC network, an average of 10 km was assumed and, consequently, the average piping costs estimated to have more reliable investment costs. Nevertheless, the investment costs for DH and DC are a source of errors and the real investment costs for each individual Kraft pulp mill in Sweden are likely to differ. Admittedly, the assumed investment costs give a rough estimate to get a better understanding of the economic possibilities for settings using DH and DC as EHRTs. The investment required for recovery technologies for electricity generation (CT, ORC and PCM) were easier to assess. Studies by Caputo et al. (2005), Sundberg et al. (2002), Zhang et al. (2016), Vélez et al. (2012) and Johansson et al. (2013) used investment costs for these recovery technologies in a similar range. When there were varying investment costs found in different studies for the same EHRT, this study used the investment cost of that study which was closest to the average investment cost of all studies. It should also be noted that the supporting infrastructure of feeding electricity into the national grid was already established during the building of every Kraft pulp mill. Therefore, the investment costs for electricity generating recovery technologies must only include the price for the technology itself and is independent of other parameters individual to the Kraft pulp mill (e.g. its location) in contrast to estimations for investments for DH and DC. The investment costs for CT, ORC and PCM in €/kW were assumed to increase for installations of lower capacity and decrease for installations of higher capacity. Also, calculations were done with the same investment costs for the four future energy price scenarios.

5.2.2 Operation and maintenance costs

The highest maintenance costs arise in settings S2 and S3 with more than 2,5 M€/a and more than 1,5 M€/a respectively. This is mainly due to costs for electricity demand of the pumps in the cooling cycle. As Keppler (2018) states in his study maintenance and operation of absorption cooling equipment demands special expertise which causes high related costs. Other studies by Yilmaz (2017), Stosic et al. (2017) and Rezaie et al. (2012) examined the techno-economic possibilities and benefits of DC, but only assumed maintenance costs for a complex system in total. The maintenance costs for the absorption cooling unit only depend heavily on the size of it and the quality of the heat used in the cooling process. In this case, quality of heat refers to a constant flow of the same temperature heat, which cannot always be guaranteed for industrial excess heat. Zabala (2009) made assumptions of ~20 €/MWh for maintenance costs in
her study for absorption cooling connected to a combined heat and power plant by taking both electricity and water demand into account. However, in her study less than 7 GWh of cooling were produced compared to for example 150 GWh of produced cooling in setting S2. Another study by Murugavel et al. (2010) assumed maintenance costs of 10 €/MWh for absorption cooling in residential buildings. Comparing maintenance costs assumptions of Zabala (2009) and Murugavel et al. (2010) this study assumed maintenance and operation costs of 17,5 €/MWh. Important to note is that industrial excess heat recovery for absorption cooling, as done in this study, is more similar to the industrial case study of Zabala (2009) and her assumption of 20 €/MWh. Maintenance costs for DH were neglected in this study as it was done in previous studies that assessed techno-economic parameters of excess heat use for DH as well (Svensson et al., 2008; Rudra et al., 2017; Morandin et al., 2014). All maintenance costs are assumed to stay constant over the four future energy price scenarios, and thus deviations from real life maintenance costs will not affect the comparison among each future energy price scenario. The smaller sized equipment needed for PCM and ORC technology cause settings S5 and S6 to require the least amount of yearly maintenance costs. Additionally, as with the investment costs, electricity generating EHRTs have their supporting infrastructure already in place (national electricity grid), which is another point demanding maintenance. Apart from settings S2 and S3, which use DC to a high degree, all other settings have maintenance costs in a similar range. A closer look into the revenue streams of each setting is necessary to assess whether a recovery technology is infeasible alone due to high maintenance and operation costs. DC might have high maintenance and operation costs but on the other hand, it is also a recovery technology that substitutes compressor cooling that is run by electricity. Therefore, the revenue and CO₂ emission reduction might be worth the maintenance costs compared to a recovery technology which substitutes, for example, heat generated by a bio CHP plant, and thus having lower revenue and CO₂ emission savings. The next paragraph evaluates the net revenue streams of each setting.

5.2.3 Net revenue

Setting S4 generates the highest net revenue stream in 2018 with 5 M€/a followed by S7 with 4,5 M€/a and S8 with 4 M€/a. This is due to high electricity generation from the condensing turbine in these settings and high electricity prices on the energy market in 2018. The next highest net revenue stream of 2 M€ is generated by setting S1. Although the price on the energy market for heating generated by industrial excess heat is low in 2018, the amount of heat that is produced in setting S1, and the fact that maintenance costs are neglected, lead to this net revenue stream. All other settings generate less than 2 M€/a which is mainly due to the fact that they produce smaller amounts of heat, cooling and electricity than settings S4, S7 and S8. Until 2050 prices for heat generated from industrial excess heat rise faster on the energy market than
prices for electricity. This is due to the assumption that marginal power plants for electricity generation will implement measures to reduce CO$_2$ emissions. For example, it is assumed that coal fired power plants install carbon capture and storage (CCS) measures from 2040 on. This way, these marginal power plants will reduce their costs for CO$_2$ emission charges which causes a decrease in the rate of change of the electricity price on the energy market. Additionally, the price on the energy market for heat generated from industrial excess heat will increase greater than in the years before 2040. This is because the drop of the electricity price effects the selling price of heat generated from CHP plants. In order to compensate for the decreased income generated by their electricity sale, CHP plants are likely to increase the selling price of their generated heat. Since the price for heat generated from industrial excess heat on the energy market is estimated by comparing the willingness to pay on the energy market for heat from a bio CHP to heat produced from a bio heat only boiler (HOB), a decrease of the electricity price on the energy market causes an increase of the WTP for heat generated from industrial excess heat. This is the reason, why in 2050, settings S1 and S3 are among the settings with the highest net revenue stream with around 10 M€/a. Therefore, one major finding of this study is that in the long run, the recovery of excess heat to provide heat for DH or to recover excess heat to generate electricity can have a similar net revenue stream, when efficient and effective recovery technologies are chosen in 2050. This is an interesting information for Kraft pulp mill owners who are in the position to choose one of the energy delivery types. Important to note is that maintenance costs for DH were not considered. Since electricity generation from excess heat is considered renewable electricity production, it is eligible to sell electricity certificates on the Swedish electricity certificate market (Nilsson et al., 2013). This extra income was not considered in this study to minimize complexity (the price for electricity certificates varies greatly) and because it is uncertain if this policy measure will still be available in the future. Nevertheless, it should be mentioned that the revenue from selling electricity generated from industrial excess heat would be even higher than shown in this study. An individual payback time for the investment made in each setting was calculated and will be discussed in the following paragraph.

5.2.4 Payback time

Only settings S1, S4 and S7 achieve a payback time of approximately three years in 2018. This is in accordance with studies by Fang et al. (2013) Huang et al. (2017) Law et al. (2013) and Law et al. (2016) who found thermodynamic cycles and heat deliveries to the DH network as the most feasible industrial excess heat recovery technologies. Contrasting to this, settings S2 and S3 have a payback time of more than six years and are thus considered less attractive and not interesting for Kraft pulp mill operators. This
is due to the high maintenance costs for absorption cooling. All other settings have a payback time of between four and six years and of these settings S5 and S6 have the highest payback time. Even though maintenance costs are not extremely high for ORC and PCM, their energy efficiency is too low to achieve higher net revenue and a lower payback time. Therefore, these settings should only be considered when their CO₂ savings are significantly higher than those of the settings S4 and S7. Due to increasing energy prices over the following three decades all settings achieve a payback time of less than three years by 2050. And except for settings S5 and S6 all settings achieve to pay their investment back within one to two years. Taking this into account, an investment in ORC and PCM technologies is not feasible at the moment, and even in the long run they are still outperformed by all other recovery technologies studied in this thesis. The major limiting factor for ORC and PCM technologies to become feasible is their extremely low energy efficiency and, compared to that their relatively high investment costs. An investment in 2018 should be made in settings S4 and S7 to ensure a payback time of less than three years. To be more flexible when it comes to the type of energy delivery, an investment in setting S8 could also be considered. In order to make the best economic decision the payback time should not be the only factor. Once, the investment in a recovery technology is paid back, it is of great interest to the Kraft pulp mill operator how much net revenue is generated in the following years. As discussed in chapter 5.2.3 (‘Net revenue’, p.43) settings S4, S7 and S8 generate the highest net revenue in 2018. Therefore, an investment in 2018 should be made in settings S4, S7 and S8. With the future energy prices in 2030, 2040 and 2050 the payback time of all settings does not vary greatly, and also settings S1 and S3 generate similar net revenue than settings S4, S7 and S8. A pure economic approach is not enough to determine the best performing setting now and in the future. Thus, a secondary parameter such as CO₂ emission savings should be taken into account to make a reasonable decision.

5.3 Environmental performance

The highest CO₂ emission savings in 2018 are achieved by settings S4, S7 and S8 with 100.000 tCO₂/a. This is mainly due to the fact that electricity production accounts for higher CO₂ emissions than heating production in 2018 (Table 5). Until 2050 CO₂ savings of all settings decrease to under 80.000 tCO₂/a, because it is assumed that electricity production in Sweden becomes more environmentally friendly and charges for CO₂ emission will increase (Table 4). Settings S2 and S4 which saved more than 50.000 tCO₂/a and more than 100.000 tCO₂/a in 2018 dropped to less than 20.000 tCO₂/a and less than 30.000 tCO₂/a in 2050 respectively. CO₂ emissions from heating production in Sweden are assumed not to change over the future energy price scenarios. Thus, settings S1 and S11 save about 70.000-80.000 tCO₂/a and 40.000 tCO₂/a respectively. This is in accordance with a study by Ivner et al. (2015) who found
that the use of industrial excess heat in DH networks in the EU can significantly benefit the reduction of greenhouse gas emissions. Taking a look at CO$_2$ emission savings alone, investments in electricity producing recovery technologies are most effective in 2018, whereas, in 2050 heat deliveries to DH and 4GDH are most effective in saving CO$_2$ emissions. Therefore, policies supporting these industrial excess heat recoveries have the potential for Sweden to develop their energy efficiency goals even further and anticipate stricter future demands. These CO$_2$ savings results are based on assumptions that future electricity producing power plants in Sweden implement measures to increase their environmental performance. In this case, ENPAC assumes carbon capture and storage for coal fired power plants. When these measures are not met in the future, electricity producing recovery technologies will achieve higher CO$_2$ savings. Nevertheless, if these measures are topped or the need for CO$_2$ intense power plants has significantly decreased due to for example wind and solar power plants, CO$_2$ savings from these recovery technologies will be even lower and would make little sense from an environmental point of view. Important to note here is that CO$_2$ emissions were considered as the only environmental indicator in this study. A more thorough and in dept life cycle analysis could result in a different environmental performance for certain recovery technologies. Another factor, like Olsson et al. (2015) suggested, is that when the climate impact related to industrial excess heat use is assessed, greenhouse gas emissions should also be allocated to the industry’s main product. In this case, since biomass is used for all electricity and heat generation needed for pulp production, negative CO$_2$ emissions should have been used instead of net zero CO$_2$ emissions. This would lead to even higher overall CO$_2$ savings for all recovery technologies. However, the found CO$_2$ emission savings in this study give a sufficient overview of whether a recovery technology has the potential to promote a more environmentally friendly electricity-, cooling- and heating production. Olsson et al. (2015) also found that the local conditions and requirements are the main factor influencing the climate impact of DH networks. Because of the nature of the average Swedish DH network connected to the FRAM type mill with no specific location the potential local conditions and requirements could not have been allocated or assessed.

As described in chapter 5.2.4 Payback time, the CO$_2$ emission savings of recovery technologies are merely a decisive factor for Kraft pulp mill operators when payback time and revenue streams of two or more recovery technologies are similar. It is unlikely that an economically infeasible recovery technology would be installed in a Kraft pulp mill just because it has high CO$_2$ savings. In order for CO$_2$ savings to become an issue for Kraft pulp mill owners, Sweden has to introduce new policies or develop existing policies supporting energy technologies with positive environmental performance further. Lake et al. (2017) and Ivner et al. (2015) also stress the importance of policies supporting the use of industrial excess heat and DH in general. In turn, this
would have an effect on the Swedish energy market leading to more environmentally friendly electricity-,
cooling- and heat producing power plants.

5.4 Limitations & Further work

The greatest limitation of this study is the underlying FRAM Kraft pulp mill created by Delin et al. (2004) to simulate an average Swedish Kraft pulp mill. All calculations and conclusions result from using assumptions based on the FRAM type mill. A study which is assessing the same research questions but is constructed as a case study to evaluate industrial excess heat on-site from every single Kraft pulp mill in Sweden will result in more accurate and realistic outcomes. Both in terms of overall excess heat potential and investment costs, the knowledge of individual on-site local conditions would benefit the accuracy of these results, especially in the case of DH and DC (Olsson et al., 2015). This was not possible in a study assessing an average Swedish Kraft pulp mill with no specific local conditions. Main results of the recovery technology evaluation are, however, unaffected by this limitation (apart from investment costs for DH and DC). A more accurate calculation of the available amount of potential excess heat at Kraft pulp mills would either relatively increase or decrease parameters like energy delivery, CO\(_2\) emissions or payback time, but it would not change the comparison among individual settings. There is a need for further studies to address local conditions and evaluate individual Kraft pulp mills on a case study basis, in order to make it easier to generalize and draw more accurate conclusions on a national level.

To ensure a certain quality standard for this study a preselection of all available industrial excess heat recovery technologies was carried out by the author. This carries the risk of better suitable recovery technologies being left out and not even being considered for this study. Also, for the range and purpose of this thesis, some heat conversion and heat utilization methods were examined more closely than others. The topic of industrial symbiosis in the context of this study is an interesting field to study as well but was impossible to evaluate and compare with the chosen recovery technologies in the given time frame. The synergies between industries utilizing their potential excess heat, is another interesting issue worth studying.

The environmental performance of the recovery technologies assessed in this study was evaluated only based on their CO\(_2\) emissions. Studying additional environmental factors, such as the impact of the use of industrial excess heat on other greenhouse gas emissions or resource efficiency, are ways to add to a complete picture of the environmental performance of recovery technologies.

The economic performance of the recovery technologies was significantly affected by European energy policies like the CO\(_2\) emission charges. It would be interesting to
know how great the influence of these policies on the use of industrial excess heat would be, and what other policies might have a positive effect on it.

Communication problems between energy companies and industries with excess heat to sell have been briefly mentioned in the introduction to this thesis and seem to be a major limiting factor when it comes to sale agreements for industrial excess heat. Further studies in this field could benefit both industries and energy companies.

Another problem between energy companies and industries with excess heat to sell are the time dynamics. Especially for DH and DC, there is a limited and varying demand with temperature variations over the year. Industries which want to deliver heat or cooling into the DH or DC network cannot deliver the same amount over the whole year. This makes it unpredictable for both industries and energy companies and difficult to come to agreements. This was a limiting factor for this study, especially in terms of assuming the right heat and cooling loads. It should also be considered in future research to find ways for a more constant DH and DC delivery over time.

Finally, since this thesis was carried out within the research project “Development and application of new methods for identifying efficient ways to use industrial excess heat”, further studies of the potential and use of excess heat at industries other than Kraft pulp mills help to create a clearer picture of the overall industrial excess heat potential and how its use can benefit Sweden on the way to becoming more energy efficient.
6 Conclusion

The objective of this thesis was to find the energy balance of an average Swedish Kraft pulp mill and to identify the potential excess heat quantity and quality. Technologies for excess heat recovery were identified and evaluated based on applicability. With a Matlab-based framework for process integration studies, the recovery of excess heat with each of the identified technologies at the FRAM type mill was optimized and its economic and environmental impacts were assessed. The performance of these technologies was compared to each other, and the excess heat utilization potential of the Swedish pulp industry in total evaluated.

1. What is the energy balance of an average Swedish Kraft pulp mill?

Optimization and analysis of the FRAM type mill with pinch-analysis in Matlab found a minimum heating demand of 122 MW, and a minimum cooling demand of 44 MW. The recovery boiler used in the FRAM type mill creates more heating than the pulp process needs at any given temperature. The average Swedish Kraft pulp mill has a high potential to run not only very energy efficiently, but also to produce surplus heat for further utilization.

2. Which amount of potential excess heat is available in the Swedish Kraft pulp mill industry and of what quality is it?

Based on the study of the FRAM type mill, the excess heat available in the Swedish Kraft pulp mill industry is significant and represents a large share of the total industrial excess heat potential in Sweden. This study found an unused potential of specific excess heat above 60°C of 911 kWh/ADt of produced pulp, and specific excess heat above 25°C of 1.582 kWh/ADt of produced pulp.

Assuming that the relationship of produced pulp and available excess heat in the FRAM type mill is valid for all Swedish Kraft pulp mills, the identified potential can be scaled up to a total of 2.03 TWh of excess heat above 60°C, and 3.54 TWh of excess heat above 25°C. Comparing these values to earlier studies which found a total industrial excess heat potential in Sweden of between 2 TWh of excess heat which can be directly fed into the DH network (primary) and 21 TWh of total (primary and secondary) excess heat, leads to the conclusion that the Swedish pulp industry is the main contributor of primary industrial excess heat in Sweden. Furthermore, this calls for future studies with an approach to identify the large scale industrial excess heat potential in Sweden.
3. **What technologies for utilization of excess heat exist and can be applied at Swedish Kraft pulp mills?**

For this thesis, heat utilization through DH, 4GDH and DC, and heat conversion through CT, ORC and PCM were studied. These technologies are those with the highest potential to be able to be applied at Kraft pulp mills and are commercially available. This thesis does not claim to show a complete picture of all excess heat utilization technologies available. There might be other technologies which are at an experimental scale and are not commercially available at the time this study was conducted.

4. **What are the economic benefits of utilizing excess heat with those technologies, what are their CO₂ emission savings, and which one is most effective and economically suitable for Swedish Kraft pulp mills?**

A payback time calculation found the condensing turbine as the EHRT with the highest economic benefits in 2018. The CT alone, in combination with DH, or in combination with DH and DC resulted in payback times around three years and are thus feasible for Kraft pulp mill owners. With assumed future energy prices all studied recovery technologies become economically feasible in 2030, 2040 and 2050. The CT, and combinations of CT with DH and DC, is also the recovery technology with the highest CO₂ savings of 100,000 t/a in 2018. DH and DC generate the highest CO₂ savings of 80,000 t/a in 2030, 2040 and 2050.

This study suggests investing in a CT, or combinations of it with DH and DC, in order to create the greatest economic and environmental benefits in 2018. With future price changes on the energy market and an uncertain future energy demand, an investment in combinations of recovery technologies generating both heat, cooling and electricity is found to be the most sustainable choice.

Independent of which recovery technology is used, this study found economic and environmental benefits for every recovery technology in the long run. An investment to utilize industrial excess heat makes sense for the Swedish Kraft pulp mill industry. Also, the findings in this study can be applied for analysing the excess heat recovery potential at other industries and in this way support Sweden as a whole to reach its sustainability goals. Not utilizing the great potential of industrial excess heat at Swedish Kraft pulp mills is a waste of a simple way to comply with European energy efficiency regulations, make the Swedish industry more sustainable, and create economic benefits for the Swedish pulp industry.
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## Appendix

### Appendix 1 Hot and cold streams of FRAM Kraft pulp mill used in pinch analysis

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>$T_{start}$ [°C]</th>
<th>$T_{target}$ [°C]</th>
<th>$\Delta T$ [K]</th>
<th>$Q$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>General cooling</td>
<td>Hot</td>
<td>40</td>
<td>35</td>
<td>3.5</td>
<td>8967.8</td>
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<tr>
<td>Chemical prep.</td>
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<td>48</td>
<td>47</td>
<td>3.5</td>
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<tr>
<td>D-filtrate</td>
<td>Hot</td>
<td>74.6</td>
<td>68.1</td>
<td>3.5</td>
<td>2090.7</td>
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<td>Surface condenser</td>
<td>Hot</td>
<td>61</td>
<td>60</td>
<td>2</td>
<td>51948.9</td>
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<tr>
<td>Steam smelt dissolver</td>
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<td>100</td>
<td>99.5</td>
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<tr>
<td>D-stage effluent</td>
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<td>38.9</td>
<td>3.5</td>
<td>9536.8</td>
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<td>OP-stage effluent</td>
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<td>74.5</td>
<td>38.9</td>
<td>3.5</td>
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<td>O2-stage effluent</td>
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<td>38.9</td>
<td>3.5</td>
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<tr>
<td>Q-filtrate</td>
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<td>3.5</td>
<td>1817.6</td>
</tr>
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<td>Hot</td>
<td>109</td>
<td>107</td>
<td>2</td>
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<td>Digester condensate 1</td>
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<td>107</td>
<td>75</td>
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<td>700.0</td>
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<td>Black liquor</td>
<td>Hot</td>
<td>105.2</td>
<td>92.7</td>
<td>3.5</td>
<td>4905.2</td>
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<tr>
<td>Digester bottom</td>
<td>Hot</td>
<td>90.3</td>
<td>88.7</td>
<td>3.5</td>
<td>798.1</td>
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<td>Excess condensate</td>
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<td>38.9</td>
<td>3.5</td>
<td>996.7</td>
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<td>Stripper condenser</td>
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<td>Trim condenser</td>
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<td>Pulp dryer effluent</td>
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<td>50</td>
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<td>Cold</td>
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<td>75</td>
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<td>85</td>
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<td>169.9</td>
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<td>201</td>
<td>0.5</td>
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<td>LP stripp.</td>
<td>Cold</td>
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<td>150.5</td>
<td>0.5</td>
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<td>Temp</td>
<td>Time</td>
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<td>MP</td>
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<tr>
<td>Bleaching (MP)</td>
<td>Cold</td>
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<td>Cold</td>
<td>99,9</td>
<td>100</td>
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