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A case study of the possibility, consequences and synergies for Södra Cell in Mörrum to invest in a steam turbine

Lund University

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Thesis for the degree of Master of Science in Engineering
Division of Efficient Energy Systems
Department of Energy Sciences
Faculty of Engineering | Lund University

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Mattias Svensson

November 2018, Lund

This degree project for the degree of Master of Science in Engineering has been conducted at the division of Efficient Energy Systems, Deparment of Energy Sciences, Faculty of Engineering, Lund University and at Södra Cell in Mörrum.

Supervisor at the division of Efficient Energy Systems was Professor Magnus Genrup
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Foreword

I, Mattias Svensson, conducted this study during the autumn semester of 2018. For 4 and a half years, I have studied the program of 'Ekosystemteknik' / Environmental engineer at Lunds Tekniska Högskola, LTH, and with this thesis, I will finish my Master within Energy Systems. This study was conducted at the Department of Energy Science.

The potential electricity production in this study originates from biofuels and steam that is considered a 'leftover'. If its potential is realized, it can increase the supply of sustainable electricity. Considering this, I thought it was interesting and inspiring to investigate a potential energy supply that is originating from such 'leftovers'. Questions such as this have motivated me throughout my education and are the reason I originally choose this field of study.

I would like to express a sincere thank you to the individuals guiding and supervising me throughout this study. Employees at Södra Cell Mörrum have been incredibly polite and welcoming. It has been inspiring and motivating spending time at the factory in Mörrum. I would further like to thank my supervisor at LTH, Magnus Genrup, for his knowledge as well as pleasant meetings and helpful guidance. Also a big thank you to my supervisor at Södra Cell Mörrum, Roland 'Rolle' Mårtensson, for such an inspiring experience and for his guidance throughout my time doing this study. I would also like to thank Nilla Dahlin, who helped me initiate this study as well as supervising me whilst working on this study. I am so grateful for all the supervision and guidance I have received from these knowledgeable individuals. Their expertise has further inspired me to continue learning.

Finally, I would also like to thank lecturers and professors at LTH for their inspiration and motivation, my classmates, friends, family and girlfriend who have supported and helped me throughout my time studying.

Lund, November 2018

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Mattias Svensson

Abstract

The purpose of this study was to investigate whether Södra Cell Mörrum, SCM, could invest in a steam turbine to produce profitable electricity from excess steam, which is currently being released into the atmosphere. Furthermore, this study investigated the potential side effects from this installation and suggests solutions. This study was conducted in two phases: collecting data which was then sent to a range of suppliers for budget offers and performance estimates. The next phase was to evaluate and quantify the profitability of the potential investment. Results of the study proved that a normal Rankine Cycle turbine was more profitable for SCM than an Organic Rankine Cycle, ORC. This was mainly believed to be because of heat losses occuring when the steam is used to heat the organic medium used in the ORC turbine. The overall electricity produced by the steam turbine, will, according to the analysis, vary between 13 992 500-42 251 600 kWh/ year. While the financial key values considered varied significantly with modified variables, an investment is believed to be profitable within a realistic time perspective of 10 years. Conclusions made from this study suggests that approximately 186,1 - 13 098 ton CO_2 emissions can be prevented by installing this turbine, dependant on which reference country is used. The potential production of electricity is equivalent to % of SCM's production and consumption, respectively. Furthermore, a synergy is quantified from the installation which will either generate more electricity or enable a larger amount of bark to be made available for sale. A mix between the two will most likely occur in the future, whereas the latter is proven to be most profitable. This, as well as the future profitability, will depend on the spot price and the certificate price of electricity.

Keywords: Paper pulp mill, Turbine, Financial analysis

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1. Introduction

One of the biggest global challenges facing the 21st century is how to solve problems surrounding the usage of fossil fuels and how to find sustainable energy sources. The industrial revolution resulted in an exponential acceleration of the usage and demand for energy. Historical sources of such energy has predominantly been fossil fuels. Current years are no exception, with approximately 81 % of the global energy usage in 2015 originating from fossil fuels (Energikommissionen 2017).

Towards the end of the 20th century, discussions regarding fossil fuel began to arise and continued to accelerate on a global level. Questions were asked, such as: ‘What correlations exist between the usage of fossil fuels and climate change?’. Such questions, however, have created conflicts, with the cause of climate change still not in mutual agreement between politicians. However, climate change is believed by many to be a result of anthropogenic contributions (Shi, 2003).

Today’s energy usage is dominated by three categories: transport, electricity, and heating and cooling (British Petroleum, BP, 2018). One can suggest that a continued sustainable energy development for these three categories, that is still able to supply the global energy demand, could be implemented by an increased usage and production of electricity. Such a transformation may have already began, with electric cars slowly replacing conventional combustion cars, as well as the usage of heat pumps instead of oil heaters. As summarised in BP’s technology outlook 2018: *‘Power currently accounts for 42% of primary energy demand globally and has greater potential than transport or heat for reducing greenhouse gas emissions, economically and at scale’.*

Currently, a variety of control methods are used in the EU to enhance a sustainable production and consumption of energy. Every country does, however, have its own conditions, possibilities, laws and visions, which affects the methods applied within the country (Hennlock, Tekie & Roth, 2015).

Sweden is a good example of a country with conditions that are enabling further sustainable electricity production, as well as having economic instruments which act to enhance a sustainable, fossil free development of energy (Ibid). Sweden currently has one of the highest petrol prices in the world (Global Petrol Prices 2018), however, also one of the lowest carbon dioxide (CO_2) intensity of electricity (IPCC 2005, p.194), thanks to its hydropower and nuclearpower, among other factors (Energiläget 2017).

One particular control method used to enhance Sweden’s sustainable electricity production is the ‘Certificate System’, which ensures that electricity companies are engaging in sustainable energy practices. The increased production of sustainable electricity due to the ‘Certificate System’ has however been counterproductive in some respects and resulted in decreasing certificate prices. Consequently, this has decreased the incentives and the planning of further production of sustainable power plants (Energikommissionen 2017, p.199).

While certificate prices have decreased, the need for sustainable electricity remains (Bergman, L. 2014). This is especially the case if the full potential of electricity is to be taken advantage of; that is, to meet any further potential demands from additional sectors, such as transport and heating and cooling, as aforementioned. When accounting for this, there is therefore a greater demand for electricity than currently required (BP 2018).

While implementation of economic instruments are necessary to meet society's goals and visions of a sustainable future, one could suggest that many industries work towards this vision regardless of the policy makers economic instruments. Moreover, it is often the case that sustainable action has both environmental and economic benefits. For example, turning the light off when exiting a room not only saves energy but also saves money on the electricity bill. The same principle is valid for the Swedish industries, which are furthermore responsible for 140 TWh, that is 38 %, of the energy usage in Sweden 2015 (Energiläget 2017 p.18).

One particular industry which historically has worked towards a more sustainable process, regardless of methods implemented by politicians, is the paper and paper pulp industry in Sweden (WWF 2013). Initially, their main purpose was to produce paper and paper pulp, which today, should not be considered their only product. The industry has found potential in residual products that are further developed by taking consideration to the advantages within these products, instead of leaving them unused.

Södra Cell is one such example, with the majority of their factories running off almost completely self-sufficient energy (Södra 2017). By taking advantage of the many characteristics of a paper pulp production, Södra Cell have managed to supply and assist numerous industries throughout Sweden, in addition to their own factories. This includes producing textiles for the current unsustainable textile industry, tall oil for the production of biodiesel, and lastly heat and electricity for themselves as well as for numerous municipalities. In addition, Södra Cell uses the energy content from internally produced steam. While steam was initially released through chimneys, today it is used to produce electricity and district heating (Ibid).

Södra Cell's factory in Mörrum, SCM, is no exception. However, in certain aspects of their production, excess steam is released despite its energy content and potential usage. Despite this, due to the low electricity price in Sweden over the last couple of years (Bixia 2018), it becomes difficult to financially motivate investments such as steam turbines. Additionally, due to the number of increasing initiations of renewable electricity production, it becomes more complex to approximate the future profitability due to varying certificate prices. On an important note however, whilst sustainable electricity has increased in Sweden, the need for non-intermittent electricity production has also increased (Bergman, L. 2014).

Since 2017, there has been an increase in the excess stream from production at SCM. This increase in excess steam is mainly due to the investment of a new, more efficient, Evaporation Process installed that year. Steam supply at the factory is normally maintained by combustion of SCM's own side products during a chemical recycling process, that is the Kraft Process. The amount of steam is therefore a result of recycling chemicals and is thus not a supplied amount with respect to demand. Since the installation of the new, more efficient Evaporation Process has resulted in additional excess steam, SCM believes that this installation has further motivated an investigation into future possible usage of the excess steam. Specifically, SCM are considering the installation of a steam turbine, which initiated this present study.

In addition to the potential installation of a steam turbine, additional factors must also be considered. One such factor is that SCM would like to use internally treated water to condense the steam after it has been used in the turbine. This water is consequently heated from this process. Further considerations in this study therefore must acknowledge the different processes that use this water after it has been used to condense the steam. An overview of the potential turbine with internal cooling water is illustrated in *Figure 1.1*.

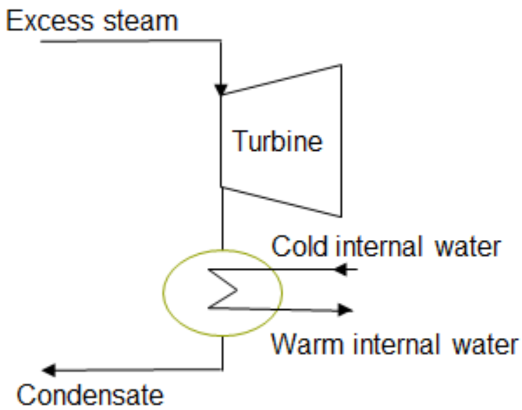

Figure 1.1: An overview of the proposed turbine with internal cooling water.

The uncertainties and need regarding future renewable electricity, in conjunction with the new Evaporation Process and outcomes at the SCM factory such as an increased excess steam and warmer water, resulted in the need for investigations carried out in this study.

The study was conducted in cooperation with SCM and investigated whether a steam turbine will be profitable. In addition to this, the practical problems and solutions emerging from such an implementation at the SCM factory have also been identified. A theoretical overview of steam turbines and of the SCM factory is presented throughout this study, as well as an overview of the possible future profitability and saved CO_2 emissions.

1.2 Purpose

The purpose of this study was to investigate the consequences and future profitability if SCM was to invest in a steam turbine that will produce electricity from excess steam. The purpose furthermore was to present a technical understanding of a steam turbine, of general energy technologies and the processes affected and required by a temperature increase of the internal water, used to condense the steam. In addition to identifying these processes, the purpose of this study was also to investigate possible solutions so that the processes remain unaffected. This is to enable a sustainable electricity production from the steam turbine.

1.3 Study aims

In order to investigate possible consequences of the installation of a steam turbine at SCM, a thorough overview of the factory was required. The cost of the turbine, as well as additional costs included in the investigation, will be analysed with different financial key values such as Net Present Value (NPV), Internal Rate of Return (IRR) and PayBack time (PB). The potential production of electricity from the steam turbine will be compared with the average intensity of CO_2 emissions from electricity generation in Sweden, EU and the Nordic countries, not including Norway and Iceland.

With electricity prices and certificate prices decreasing over the last couple of years, it was beneficial to gain a better understanding of whether investing in a steam turbine will be profitable. Earlier projects carried out at SCM have managed to put a value on the excess steam based on its potential. This study considered this value while further investigating the potential electricity production as well has how different scenarios might affect the profitability. To gain an understanding of the impact of warmer internal water, an overall basic understanding of a paper mill was required.

The following questions needed to be answered in order to establish prerequisites for a steam turbine installation at the SCM factory:

[1] What is the basic understanding of a turbine needed for this study?

[2] Which are the affected processes and what are the implications of this installation at the SCM factory? What are the possible solutions for these processes?

[3] Is the installation profitable with consideration to certain economical key values?

[4] A synergy is known; however, how large is it and how does it affect the profitability?

[5] How can the profitability be affected with respect to the electricity and certificate price, the source of the steam, and the flow of steam and cooling water?

[6] What is the equivalent of the electricity production in regards to the Swedish paper mill industry's, Södra's and SCM's overall electricity production and consumption?

[7] What is the potential savings of emissions of CO_2 with respect to the average intensity of CO_2 emissions from electricity generation in Sweden, EU and the Nordic countries, not including Norway and Iceland?

1.5 Method

This study was conducted in two phases.

Phase 1 included collecting historical data of the steam and internal process water that were further sent to suppliers for budget offers and performance estimates for a possible turbine. Critical processes affected by a warmer internal water were identified and investigated. Possible solutions were also investigated whereas theire historical data was sent to suppliers for budget offers and performance estimates. In order to be able to send relevant data, certain assumptions had to be made for multiple processes.
To get a broad perspective of where the heat originates from, an overview of the factory was studied. The final steps within the first phase were to gather experienced employees at SCM to discuss the suggested solutions. Additionally, costs for instruments, monitoringsystems and pipes among other needed equipment were estimated.

The second phase of the study included quantifying the different synergies that can appear if a turbine is installed. The budget offers were received, investigated and compared. Potential electricity production as well as all costs were analysed in a profitability analysis were the motst advantageous turbine was chosen. Relevant variables were thereafter modified to estimate a potential future profitability interval.

2. Theoretical background

2.1 Background, the Swedish forest industry and Södra

This section will provide a brief overview of the Swedish forest industry and furthermore of the paper and paper mill industry in Sweden and its export. The industry's overall usage of electricity has been thoroughly examined and compared to the overall Swedish electricity usage. The company of Södra will be introduced, as well as the factory in Mörrum, SCM. Södra's and SCM's electricity usage, paper and paper pulp production will also be presented.

2.2 The Swedish forest industry

Skogsindustrierna i Sverige, a business organisation for the forest industry in Sweden, believes that trees are of great importance and valuable for a future sustainable development (Skogsindustrierna 2018d). They believe that trees not only bind CO_2 from the air, they also enhance the development of fossil free energy as well as provide sustainable conditions for additional industries, such as tall oil, pellets, and textiles (Skogsindustrierna 2018a).

The forest industry is one of the largest and most important industries in Sweden (Skogsindustrierna 2018d). Companies considered a part of this industry are those which use the forest as a raw material in their production. Among these companies are producers of paper, paper pulp, saw mills and biofuels (Ibid). While an average of 1 % of the country's total forest is harvested every year, the forest plantations have still doubled in the last 90 years (Skogsindustrierna 2018b). The average yearly forest growth is almost 130 million cubic meters whilst the average yearly harvest is approximately 100 million cubic meters (Skogsindustrierna 2018e). A total of 12,2 million tons of paper pulp, 10,3 million ton paper and 18 million cubic meter of sawed wood was produced in Sweden in the year of 2017 (Skogsindustrierna 2018b).

2.2.1 Export

The forest industry accounts for 9-12 % of Sweden's volume of business and export (Skogsindustrierna 2018b). 90 % of the country's produced paper and paper pulp is exported outside the country (Skogsindustrierna 2018d). The Swedish export of these products are globally the third biggest and in the year of 2017, Sweden exported these products to a value of 132 billion kronor (Skogsindustrierna 2018b). In 2016, Sweden accounted for 6% of the total global paper pulp production and almost 3 % of the paper production (Skogsindustrierna 2018c).

2.2.2 Energy usage

The paper and paper pulp industry in Sweden consumed 51 TWh biofuels, almost 20 TWh electricity and a total of 73 TWh energy, including additional energy, in the year of 2015 (Energiläget 2017). With a total energy usage in Sweden the same year of 370 TWh, the paper and paper mill industry accounts for almost 20% of the country's total usage of energy. The electricity consumption of 20 TWh is equivalent to more than 15 % of the country's total electricity usage (Ibid). The usage of electricity has, however, decreased over the last ten years. The Swedish industries consumed 49 TWh electricity in the year of 2015, whereas the corresponding consumption peaked in 2007, with a total usage of 57 TWh (Ibid). The main decrease is believed to be due to a more effective usage of electricity in the paper industry (Ibid).

A side product from the process of making paper and paper pulp is biofuels. Biofuels can be used by the factory itself or sold and used as fuel, for example in combined heat and power plants. When used by the factory itself, electricity and heat can be produced and used by the factory or sold to the national grid. In addition to selling the biofuels, the factory sells leftover heat and electricity produced from the biofuel. The demand for energy sources which originate from industries such as the paper and paper pulp industry is high since it is renewable (Energimyndigheten 2011). Biofuels which originate from the forest industry are initially side products or residual products and a noticeable part of the Swedish biodiesel originates from tall oil, that is a side product (Skogsindustrierna 2018a). The increased usage of biofuels in Sweden, from 33 TWh in 1970 to 57 TWh in 2015, is believed to be mainly due to an increased usage of biofuels in the paper and paper mill industry, which accounts for almost 90 % of the total usage of biofuels within all of the country's industries (Ibid).

While the industry contributes to a considerable amount of Sweden's energy consumption, it also produces the majority of the used energy itself as well distributing excess energy. Approximately 5,7 TWh electricity and 18 TWh heat and pellets is produced and distributed to municipalities (Energimyndigheten, 2016).

2.3 Södra

The company of Södra is the biggest forest owner compound in Sweden, with 3400 employees and 51 000 owners and members. It is divided into three companies; Södra Wood, Södra Skog and Södra Cell. Södra Cell is the subdivision responsible for the pulp production, producing both paper pulp and textile pulp from conifers and deciduous trees. Over the last few years, Södra has carried out investments, with an aim to increase production by 20 % within the upcoming 5 years (Södra 2017).

2.3.1 Production.

The Södra Cell division itself has 3 factories that produce pulp: Värö, Mönsterås, and the Mörrum factory. The total yearly production for these 3 factories reached almost 1,7 million ton in 2017 (Södra 2017). The investments carried out by Södra aim to result in a yearly production of over 1,9 million ton pulp (Ibid).

2.3.2 Electricity usage and production

In this section, the electricity usage and production of the overall company of Södra will be analysed. The amount of consumed, produced, purchased and sold electricity will be gathered in *Table 2.1* and originates from the company's annual accounting report.

Södra consumed 1410 GWh electricity in the year of 2017 (Södra 2017). The company was, however, as presented in *Table 2.1*, a net producer of electricity. During the same year, it decreased its electricity consumption by 3 % compared to 2015 and increased the overall production to 1719 GWh, compared to 1326 GWh 2016. The company purchased 359 GWh and sold 668 GWh during 2017 (Ibid).

Table 2.1: Overview of electricity at Södra.

	Consumed (GWh)	***Produced (GWh)***	***Purchased (GWh)***	***Sold (GWh)***
Electricity	1410	1719	359	668

Of further note, is that the majority of the energy usage at the company originates from the company's own production. Only 0,7 % of Södra's energy therefore originates from fossil fuels and the majority of the remaining originates from its own biofuels. By investing in the efficiencies at the factories, as well as using as much biofuels as possible, Södra managed to decrease the usage of fossil CO_2 by 9% from 2015 to 2017. In summary, the majority of the energy that Södra is using is produced by the company itself (Södra 2017). Södra can continue to increase its independent energy supply by investigating into installations that take advantage of excess energy, such as steam.

2.4 Södra Cell Mörrum, SCM

In regards to SCM, the factory is the smallest of the three pulp factories which make up Södra Cell. It is however the only factory that produces textile pulp. SCM have 360 employees of the total 3400 at the entire company of Södra. Over the last couple of years, 1,7 billion kronor has been invested into SCM, which has allowed for the installation of a new Evaporation Process, among other things, as aforementioned.

2.4.2 Production

As a result of the investment, the expansion at SCM will allow for an annual capacity of approximately 470 000 ton pulp. These 470 000 ton will be divided into 300 000 ton paper pulp and 170 000 ton textile pulp (Södra 2017 p.13).

2.4.3 Electricity usage and production

The electricity usage at SCM will be analysed below. The amount of consumed, produced, purchased and sold electricity is presented in *Table 2.2* and is collected from the SCM's annual accounting report.

During 2017, SCM consumed 314 992 MWh electricity and the overall production was 313 086 MWh. The company also purchased 17 777 MWh and sold 15 870 MWh (SCM 2017).

Table 2.2: Overview of electricity at SCM.

	Consumed (GWh)	***Produced (GWh)***	***Purchased (GWh)***	***Sold (GWh)***
Electricity	315	313,1	17,8	15,9

Of further note, is that, alike Södra, the majority of the energy usage at SCM originates from the factory's own production. Only 0,99 % of SCM's energy therefore originates from fossil fuels, with the majority of the remaining originating from SCM's own biofuels. SCM can continue to increase its independent energy supply by investigating into installations that take advantage of excess energy, such as steam. An example of such an installation is the steam turbine investigated in this study.

2.5 The SCM factory, a brief overview

After working at SCM for only a matter of weeks, one can acknowledge that SCM is continuously working towards more sustainable and effective processes. In doing so, they are trying to increase efficiency as well as take advantage of as many of the side products as possible. These side products can be anything from material-based to excess energy such as heat and electricity. SCM also try to recycle as much as possible, with chemicals used for the Kraft Process and the bleaching of the paper recycled to a good extent. A similar approach is taken with the lime, needed in the Blast Furnace, which is also recycled.

There are numerous different processes in a paper mill such as SCM. In the following overview however, only the processes relevant for the understanding of this study are discussed. It is important to understand where the heat at SCM originates from and why a turbine, such as the one investigated in this study, has become of interest. This overview can hopefully give the reader a better perspective of this and additionally of such synergies and problems identified in later sections. *Figure 2.1*, presented in Swedish, illustrates the whole process overview at the factory. The relevant processes within this figure will be translated and analyzed in the following sections.

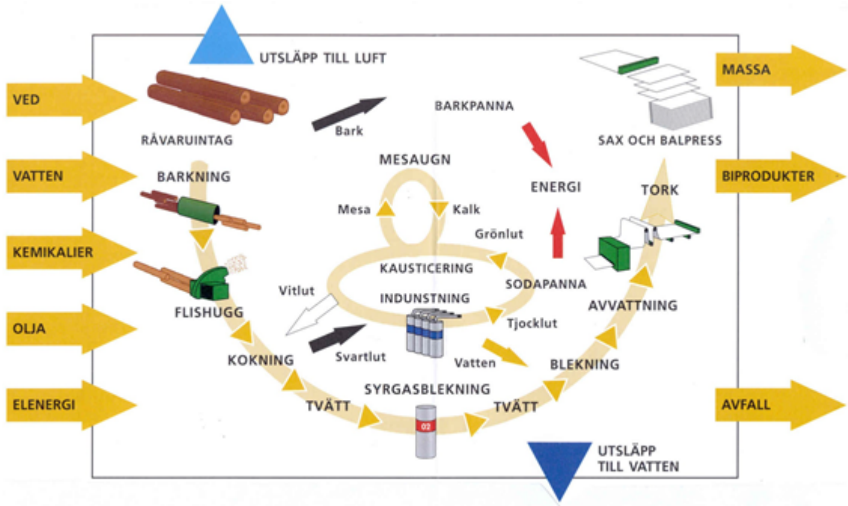

Figure 2.1: The process overview at SCM (Ferm 2014).

2.5.1 Bark removal process

Figure 2.1 illustrates the process of converting wood to paper pulp. One of the first steps in the paper pulping process at SCM's factory is removal of the bark - *'Barkning'*. As the bark darkens the pulp and consists of relatively few fibres it is not desired [1]. Once the bark has been removed, the remaining wood is made into wood chips, which continue along in the process as the main component in making the paper pulp.

The bark is stored as it can easily be combusted for additional heat, used when the normal source of heat and steam from the Recovery Boiler fail to supply the entire demand of heat. SCM are also investigating additional options of how to best use the stored bark. One option is that the bark can be sold to energy companies in addition to being used as energy at the factory. At the present time however, SCM cannot sell the entire excess of bark since they require it as backup energy (Ferm 2014). The value of the bark is therefore equal to the market price, in situations when the factory want to sell it, or to the price of a substitute energy source needed during circumstances when the boiler can not maintain the steam balance[1].

The Recovery Boiler can normally maintain the threshold limit for the demand of steam at the factory. However, during irregular parts of the year, the heat from the boiler fails to supply the steam demand and the bark is used as a backup, as previously mentioned. The Recovery Boiler is feed with a slurry consisting of liquor and lignin from the Kraft Process named black liquor, see *Figure 2.2*, which is used as a fuel (Ibid). The Recovery Boiler heats water and thereafter feeds the steam to the factory's two steam turbines, which produce electricity, along with various processes throughout the factory that is using it as heat. One of these processes, which will be mentioned below, is to heat the liquid liquor in the Kraft Process to 170 °C (Ibid).

Due to the relevance for this study, the remaining overview of the factory will be focused to the inner circle of *Figure 2.1,* which is partly illustrated in *Figure 2.2*. The following sections will

[1] Private communication with Roland Mårtensson, process engineer at SCM, continuously from July to November 2018.

also explain the different processes in *Figure 2.2,* so that a better understanding for the whole figure can be obtained.

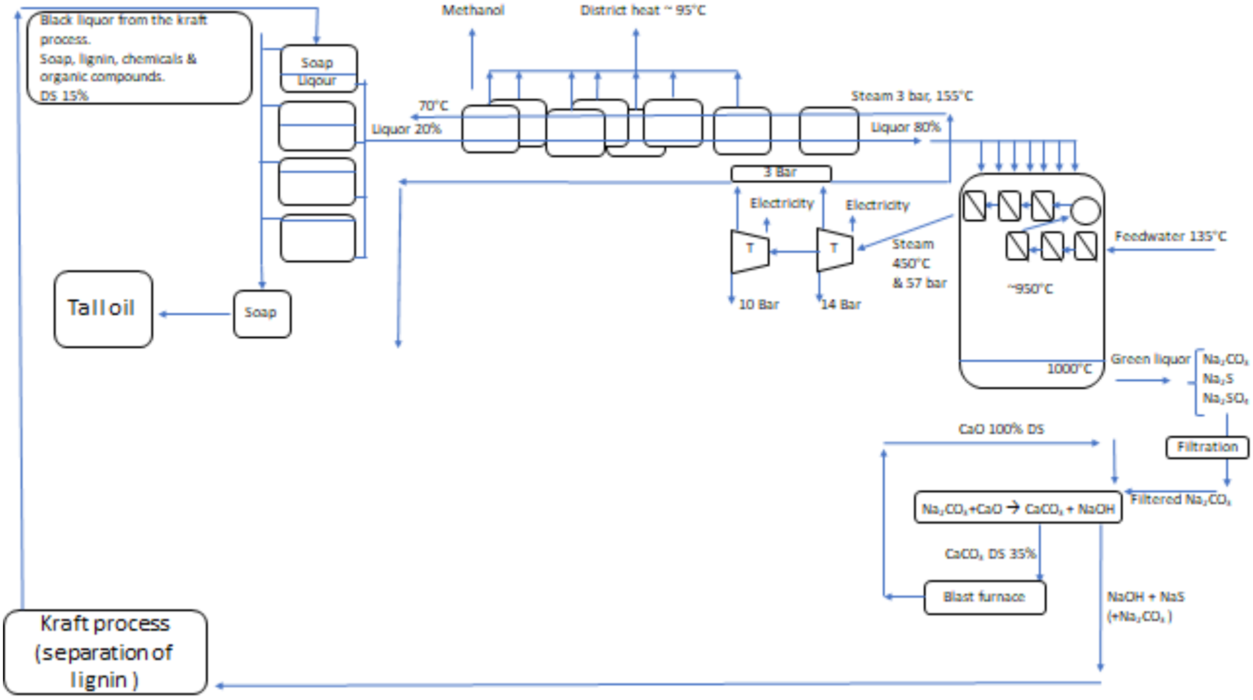

Figure 2.2: Overview of the processes included in the inner circle of Figure 1

2.5.2 Kraft Process

In the Kraft Process - '*Kokning*' in Figure 2.1, the wood chips are boiled along with white liquor at approximately 170°C. The white liquor consists of sodium hydroxide, NaOH, sodium sulphide, Na_2S and sodium carbonate, $NaCO_3$. The total concentration of these together is approximately 120-130g/l of liquor. The purpose of the white liquor is to separate the lignin and hemicellulose from the cellulose in the wood. This is because less than half of the actual wood consists of cellulose that is used to produce the pulp (Ferm 2014). *Table 2.5* shows an approximation between the different components in wood used for paper pulp.

Table 2.3: The components of cellulose, hemicellulose and lignin in conifer and deciduous trees (Ferm 2014 p.39).

Component	***Conifer trees***	***Deciduous trees***
Cellulose %	41 - 16	42 - 49
Hemicellulose %	25 - 32	23 - 34
Lignin %	26 - 31	20 - 26
Resin %	ca 1	ca 5

The cellulose consists of long straight molecule chains which makes the paper strong, whereas the hemicellulose consists of shorter molecule chains (Ibid). However, it is not relevant to look further into the actual making of the paper pulp from cellulose. It is, however, relevant to gain an understanding of the recycling of the liquor and the separation of lignin.

Lignin consists of complex molecules and is used to glue the fibres in the wood to one another. The lignin can, however, not be used in the paper pulp since it decreases the binding between the fibres in the paper which will make it weaker. Ligning is also affected by ultraviolet light so that paper with too much lignin easy becomes yellow. It is therefore desirable to separate this from the cellulose, hence the Kraft Process (Ibid). The white liquor in the Kraft Process dissolves the lignin whilst the fibres, consisting of cellulose, consequently are exposed. The NaOH and the Na_2S in the white liquor is dissolved according to the following process in *Reaction 2.1-2.3* (Ibid):

$$NaOH \rightarrow Na^+ + OH^- \qquad (2.1)$$
$$Na_2S \rightarrow 2Na^+ + S^{2-} \qquad (2.2)$$
$$S^{2-} + H_2O \rightarrow HS^- + OH^- \qquad (2.3)$$

The sodium ion, Na^+, acts only as a carrier, since the active components are the hydroxide ion, OH^- , and the hydrosulphide ion, HS^-. Thus, it is the active components which reacts with the lignin and furthermore dissolves 85-97% of the lignin into the liquid liquor. After this reaction has taken place, the liquid liquor becomes darker and is instead called black liquor. It is of great importance to have a sufficient amount of ions in this process since a lack of ions can result in lignin that is recondensed to the fibres. Once doing so, the lignin becomes harder to remove from the fibres and the pulp becomes harder to bleach. To prevent this, the active components weight should correspond to approximately 18-20% of the wood weight (Ibid).

After the Kraft Process, the black liquor consists of water and organic material from the wood chips, such as lignin and resin consisting of acids and alcohols, seen in *Figure 2.2*. Initially, the majority of the resin consists of hydrocarbons such as phenols, fat- and resin- acids and esters made up from these acids. These react with the sodium during the Kraft Process and create a soap. This soap dissolves in the liquid and is therefore also separated from the cellulose, exiting the Kraft Process along with the black liquor. The soap decreases the surface tension of the liquor and is separated via multiple tanks (Ibid) illustrated in *Figure 2.2*. The density of the soap is lower than that of the liquor, which makes it easier to separate via pipes connected to the top of the tanks[1].

As further illustrated in *Figure 2.2*, the soap can be used for production of tall oil. This is achieved by neutralizing the soap with leftover acids from the production of chlorine dioxide, (ClO_2), used for bleaching the pulp, as explained in more detail below. The neutralized soap is additionally heated in a reactor and tall oil is produced. The tall oil can be used in the factory or be sold for further refining. Depending on the species of wood, that is deciduous and conifer trees, and where the wood was grown, the amount of tall oil that can be extracted varies between 12-70 kilos per ton pulp (Ibid). SCM can use this oil instead of using fossil oil[1]. Other substances that can be extracted from the black liquor is methanol, which also can be used in the factory as energy (Ibid). The steps explained above are illustrated in *Figure 2.3*, which shows a more focused part of *Figure 2.2*.

Followed by the separation of the soap, a more concentrated black liquor exits the separation process. It contains approximately 98% of the sodium and sulphur that initially was added to the Kraft Process. These chemicals are attached to the organic compounds separated from the cellulose, that is the lignin and the hemicellulose. In this stage, the black liquor contains approximately 80% water and 20% dry substance, illustrated in *Figure 2.2* and *2.3*. After the soap has been separated, the concentrated, wet black liquor is taken to the Evaporation Process (Ibid), as illustrated in *Figure 2.2*.

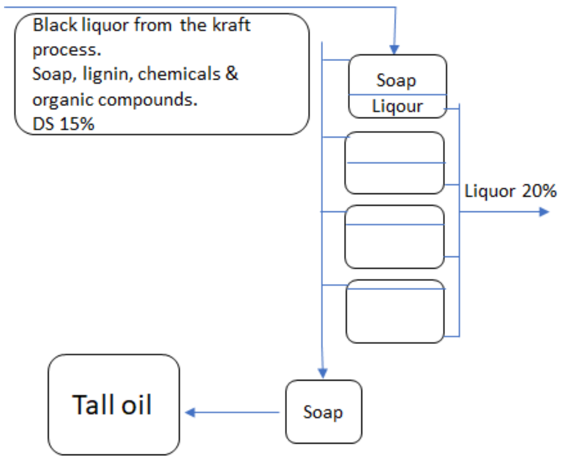

Figure 2.3: Shows a focused part of figure 2, that is the separation of soaps from the black liquor.

2.5.3 Evaporation Process

The purpose of the Evaporation Process is to increase the dry matter in the black liquor (Ferm 2014). When the black liquor enters the Evaporation Process its wet substance is approximately 80 %, as mentioned. The reason for the higher requirement of dry matter is because the black liquor becomes the fuel in the Recovery Boiler. To be able to combust the black liquor, the dry matter must reach at least 60-70%. Thus, a higher percentage of dry matter is desirable. To heat the liquor, so that the water is evaporated and the dry substance is increased, steam is added (Ibid), as illustrated in *Figure 2.2 and 2.5.*

The steam that is feeding the evaporation initially comes from the Recovery Boiler, having passed two turbines. The turbines produce electricity from the 57 bar steam produced in the Recovery Boiler and expand it to different desirable pressures including 3 bar. The 3 bar steam heats the Evaporation Process, among other processes. During this process, the water in the black liquor is evaporated and the black liquor obtains a dry matter of 80 % when it exits the process. Additionally, the higher content of dry matter, that is the organic compounds, the higher the boiling temperature of the liquid. A requirement is therefore that the warmest steam should heat the liquid with highest amount of dry matter. Since the black liquor that exits the Evaporation Process has a dry matter of approximately 80%, it requires a higher temperature to evaporate than the liquor with a dry matter of 20% (Ibid).

The working principle for one apparatus in the Evaporation Process is illustrated in *Figure 2.4, 'Indunstningsapparat'* and is explained below (Ibid):

- 7 evaporation apparatus in a series are receiving liquor from the left - '*Lut in*' in *Figure 2.4*, and steam from the right - '*Ånga in*'.
- The liquor is heated to boiling temperature in each apparatus.
- The steam that is produced from the liquor is used to heat the liquor in the following apparatus, that is the '*Ånga ut*' in *Figure 2.5* below. The temperature of this steam is consequently not as high as the steam used for heating in this apparatus.
- The steam used to heat the liquor to boil is condensed, '*Kondensat'*.

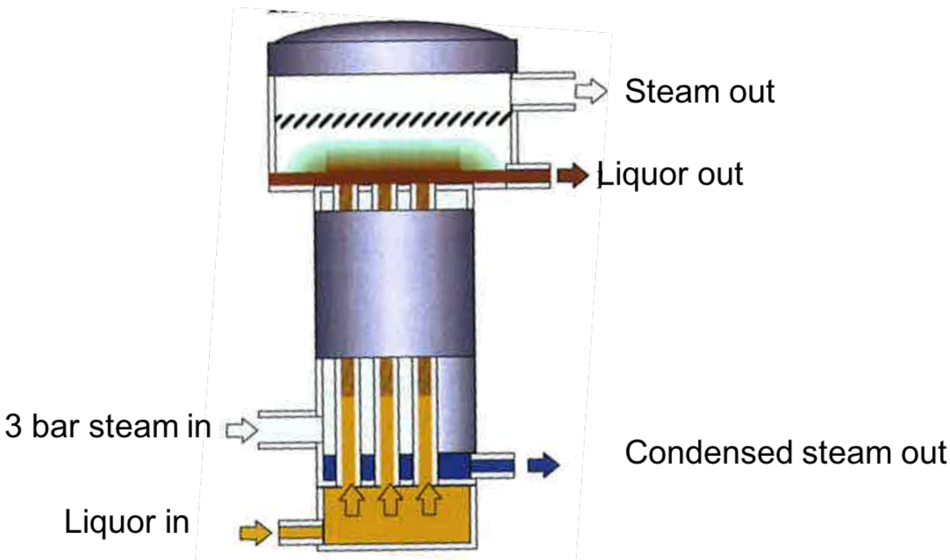

Figure 2.4: The working principle of the Evaporation Process at the SCM factory (Ferm 2014).

The condensate is consequently from the water that was heated to boiling temperature and turned to steam in the previous apparatus. As a result of this serial connection, 5 apparatus can evaporate 5 tons of water by initially adding 1 ton of steam (Ibid). The temperature of the steam decreases after each apparatus due to losses. Consequently, the warmest steam enters the last apparatus with the liquor with highest amount of dry matter. This can be seen in *Figure 2.2* and *2.5,* where the steam enters the evaporation apparatus to the right. This hence fulfills the requirement that the warmest steam should heat the liquid with highest amount of dry matter.

The steam from the last apparatus is led to a condenser for condensation. The condenser works as a heat exchanger and cold water is heated when the steam is condensed. When the steam is cooled and condensed, a vacuum is created which makes the steam in the 6 previous apparatus flow towards the last 7th apparatus (Ibid). The steps explained in this section are illustrated in *Figure 2.5,* which shows a more focused part of *Figure 2.2.*

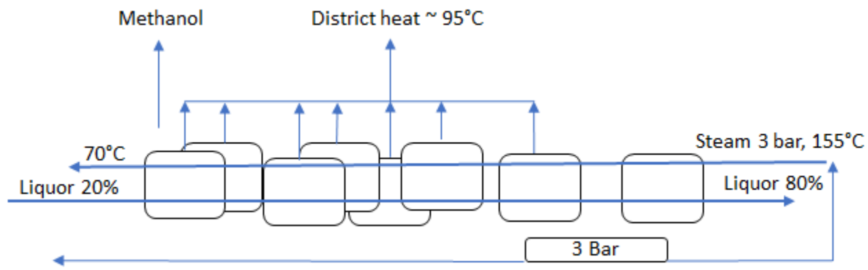

Figure 2.5: Shows a focused part of figure 2, that is the Evaporation Process, addition of 3 bar steam and extraction of steam to heat district heat water.

During the autumn of 2017, SCM invested in a new Evaporation Process, which is more effective compared to the old process which consisted of only 5 apparatus. This investment has resulted in a lower amount of 3 bar steam needed to fulfill the requirement of 80 % dry matter in the black liquor. As a consequence, more excess 3 bar steam is available. Today, the best option to make usage of the steam is to condensate it and use the condensed water in different processes throughout the factory. Approximately 70 % of the steam is condensed. The majority of the rest is used as direct heat, while the remaining is released to the air as steam, simply because there is no better usage of it. As a result of the new Evaporation Process, it is thus the latter that has increased[1], which is represented by an arrow pointing to nothing in *Figure 2.2* and *Figure 2.5.* It is the increase of this excess steam that has motivated this study and an investigation into a turbine that can make usage of the steam.

As can be further seen in *Figure 2.2* and *2.5*, the Evaporation Process also provides steam for district heat. By separating a small amount of the steam in 6 out of the 7 steps in the Evaporation Process, the steam is distributed to heat exchangers where water used for district heat is heated. This is however a small part of the overall steam used in the process[1].

Black liquor also consist of methanol, among other pollutants, which will evaporate along with the water in the Evaporation Process. These substrates evaporate at a lower temperature and will hence be included in the condensate from the apparatus to the left in *Figure 2.5*. Compared to the clean condensed water that is taken to the mixbeds, explained later, the polluted condensed water, also called foul condensate, is taken to a stripper where the methanol is turned to gas. This gas is combusted in either the Recovery Boiler or the Furnace Blaster (Ibid).

To summarize *Figure 2.5*, the black liquor enters the Evaporation Process with a dry substance of 20% and leaves with a dry substance of 80 % and is now ready to enter the Recovery Boiler. Along the Evaporation Process, methanol and steam is extracted for fuel usage and district heat.

2.5.4 Recovery Boiler

In this process, the chemicals from the white liquor initiates their recycling. Firstly, however, a recap of what has happened with the chemicals so far is summarized below:

- In the Kraft Process, the white liquor dissolves the lignin in the wood chips. The liquid is turned black, now called black liquor, and Na^+ and S^{2-} are existing as ions which are not bonded to OH^- , nor to each other as in the white liquor. The concentration of these are further increased in the Evaporation Process where water is evaporated. The purpose of the complete recycling is hence to regenerate the Na^+ and S^{2-} to NaOH and Na_2S, that is white liquor.

The Recovery Boiler is the first step for the recycling of the chemicals. The black liquor that enters has a complex chemistry and a high viscosity, which, if kept below 100 °C, turns into a consistency similar to tar. When entering, the black liquor has a dry matter of approximately 80% which furthermore contains ⅔ dissolved organic matter from the wood chips and ⅓ non organic compounds from the liquor, that is the chemicals. The black liquor that enters the boiler has two purposes (Ferm 2014):

- It contains the chemicals that needs to be recycled.
- It contains the organic compounds, such as lignin, that is used as a fuel for the entire Recovery Boiler. The heat is needed to enable the recycling of chemicals.

The black liquor that is fed to the boiler is the only fuel needed for the entire factory during ideal circumstances. Today, as already mentioned, bark is occasionally combusted to maintain the steam balance. The aim is however, to have a self sufficient mill with consideration only taken to the residual heat released from the Recovery Boiler[1].

The sulphur in the black liquor is prior to this stage, that is from the Kraft Process, bonded to the lignin or exists as S^{2-}- and as SO_4^{2-}- ions. The sodium, Na, post Kraft Process exists as Na^+ ions. The OH^- is also bonded to the lignin. To recycle the chemicals, primarily the active hydroxide and sulfur ions, they must therefore be released from the lignin, which is done in the Recovery Boiler (Ibid).

When the organic compounds in the black liquor are combusted, a slurry is created in the bottom of the boiler which consists of Na_2S, Na_2CO_3 and approximately 0,5-3 % Na_2SO_4. This slurry is called green liquor and is produced according to *Reaction 2.4-2.6* below when the black liquor has been heated (Ibid):

$$2\,Na^+ + 2OH^- + CO_2 \rightarrow Na_2CO_3 + H_2O \qquad (2.4)$$

$$2\,Na^+ + S^{2-} \rightarrow Na_2S \qquad (2.5)$$

$$Na_2S + 2O_2 \rightarrow Na_2SO_4 \qquad (2.6)$$

The active ions are released from the lignin and present in new compounds.

The Na_2S that did not react further in *Reaction 2.6* has completed its recycling and is in its desired composition for the white liquor in the Kraft Process. Whilst the Na_2CO_3 will continue to react in the causticization, the Na_2SO_4 continues throughout the processes and is considered a burden. A high reduction rate, according to *Equation 2.1* below, is therefore desirable (Ibid):

$$\text{Reduction rate } \% = \frac{Na_2S}{Na_2S + Na_2SO_4} \times 100 \qquad \text{Eq.2.1}$$

The reduction rate in the Recovery Boiler is normally 95-99% and is a measurement of the Recovery Boiler chemical efficiency (Ibid). The process explained above is illustrated in *Figure 2.6* below.

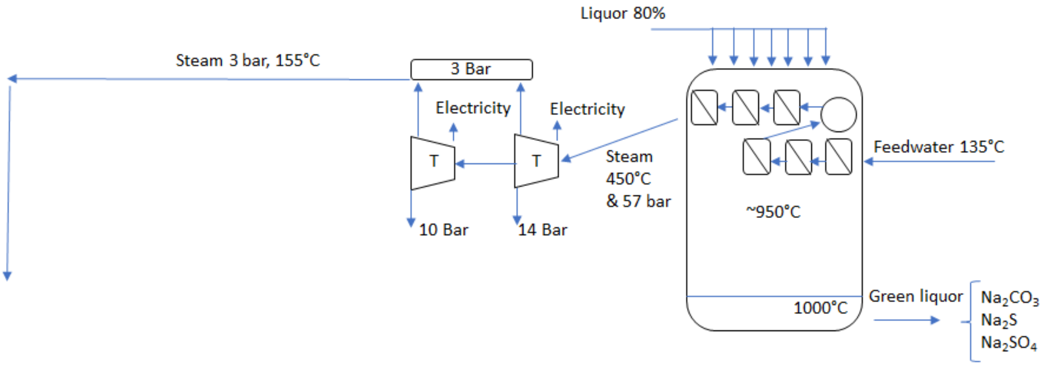

Figure 2.6: Shows a focused part of figure 2, that is the Evaporation Process and the Recovery Boiler with the produced steam and green liquor.

The other outcome of combusting the black liquor, the energy production, is released as steam. Feedwater, collected throughout several processes in the factory, is fed through a series of heat exchangers in the Recovery Boiler, as seen in *Figure 2.6*. The water is consequently heated and the created steam, at 57 bar, is taken to the steam turbines[1]. The green liquor produced in the Recovery Boiler continues to the causticization where the recycling of chemicals, primarily Na_2CO_3, continues (Ibid).

2.5.5 Furnace Blaster and causticization

The process explained in this section is illustrated in *Figure 2.2*, however, is more focused in *Figure 2.7*.

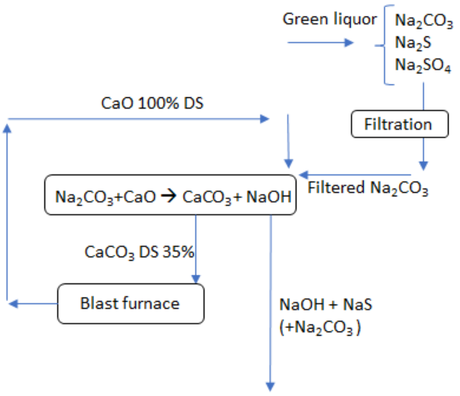

Figure 2.7: Shows a focused part of figure 2, that is the production of NaOH in the Furnace Blaster and the recycling of CaO.

In the causticization process, the green liquor is mixed with calcium oxide, CaO. The Na_2CO_3 is reacting with the CaO according to *Reaction 2.7* below (Ferm 2014):

$$Na2CO3 + CaO + H2O \rightarrow NaOH + Na2CO3 + CaCO3 \quad (2.7)$$

The desirable products in *Reaction 2.7* are the NaOH and the $CaCO_3$. Whilst the $CaCO_3$ will continue to the Furnace Blaster, the Na_2CO_3, that did not manage to react, continues throughout the processes and is considered a burden. A high causticization rate, according to *Equation 2.2* below, is therefore desirable (Ibid).

$$\text{Causticization rate } \% = \frac{\text{NaoH}}{\text{NaOh+Na}_2\text{CO}_3} \text{ x } 100 \qquad \text{Eq.2.2}$$

When the green liquor has reacted with the CaO in the causticization process, its composition is the following (Ibid):

- Na_2S from the Recovery Boiler.
- NaOH from the causticization .
- A little Na_2CO_3 from the causticization.
- Lime particles as $CaCO_3$ from the causticization.

The calcium carbonate, $CaCO_3$, is separated from the liquid. This separation is done in a sedimentation tank, which allows the particles to sink to the bottom of the liquid. Additionally to this, the liquid is filtered. The clean liquid, now consisting of NaOH, a little Na_2CO_3 from the causticization process, and Na_2S from the Recovery Boiler, is white liquor and the recycling is fulfilled. This filtration is however not the same filtration illustrated prior to the causticization in *Figure 2.7*. This filtration is to separate sludge from the green liquor. This sludge consists of manganese which disturbs the bleaching process. By filtering the green liquor, 90 % of the manganese is filtered and removed (Ibid).

In the Furnace Blaster, the calcium carbonate, $CaCO_3$, is recycled and regenerated to CaO, which is further added back to the causticization again. The reaction is endoterm and the energy that is added to the blaster can come from combusting gas, potentially methanol gas from the Evaporation Process, as described above. $CaCO_3$ is a poorly soluble substrate and must therefore be separated from the white liquor. Once separated from the liquor, it becomes a sludge that is called mesa. Mesa is further taken to the Furnace Blaster where CaO is produced (Ibid).

2.5.6 Bleaching

The paper pulp at the SCM factory is bleached due to customer demand[1]. The majority of all lignin is dissolved from the wood and separated from the pulp along with the leftovers from the white liquor, now called black liquor. However, all lignin does not manage to dissolve in the Kraft Process and the small amount left in the pulp is enough to turn it yellow. This is because the lignin from the wood chips turns dark during the Kraft Process, just as the white liquor becomes black liquor. If all lignin were separated during the Kraft Process, the pulp would be white when it leaves. To manage this is not impossible. However, to boil the pulp in the Kraft Process until it is white would consequently result in weaker fibres and thus a weaker pulp. The remaining lignin in the pulp therefore depends on what pulp is desired and the amount varies between 3 and 15%. This can be controlled and the time spent boiling in the Kraft Process depends on the type of pulp that is to be produced. Hence, the desired fibre strength decides the time spent in the boiler in the Kraft Process. The stronger fibres that are desired, the more lignin is in the pulp and thus the browner it is (Ferm 2014).

The bleaching at SCM simply means that bleaching chemicals are added which removes as much lignin as possible from the pulp. When the chemicals are added, the lignin dissolves and can be washed away. However, just as in the Kraft Process, these chemicals also affect the cellulose but are less harmful. As much of the lignin as possible is removed without harming the pulp. Historically, chlorine gas has been used in this matter. In Sweden however, this has been discontinued due to its harmful environmental impact. The pulp at SCM is therefore bleached with Elementary Chlorine Free bleaching, ECF. This means that instead of bleaching the pulp with chlorine gas, it is bleached with ClO_2. Due to its toxicity and risk of explosion at high concentrations however, the ClO_2 is produced onsite at the SCM factory. To produce the gas, the factory imports $NaClO_3$, which reacts with H_2SO_4 and H_2O_2 in a series of reactors (Ibid) according to *Reaction 2.8* below:

$$2\ NaClO_3 + H_2O_2 + 4H_2SO_4 \leftrightarrow 2ClO_2 + 2NaHSO_4 + O_2 + 2H_2O \qquad (2.8)$$

The pureness of these reactants is of great importance since the smallest presence of organic matter can result in explosions. The desired chemicals are mixed in various stages, as illustrated in *Figure 2.8,* and finally collected in the ClO_2 tank - '*Klordioxidlager*'. It is from this tank that the ClO_2 is distributed to the bleaching process (Ibid).

The side product in *Reaction 2.8*, $NaHSO_4$, can be used to neutralize the soap from the Kraft Process to produce the tall oil, as aforementioned (Ibid). In the absorption tower, *'ClO2 Abs.torn'*, in *Figure 2.8*, the produced ClO_2 is absorbed and distributed to the ClO_2 tank. However, some leftover gases are distributed to the residual gas tower, see *Figure 2.8*. The purpose of this tower is to enable as little of the ClO_2 gas as possible to be released into the atmosphere. The reaction that occurs in the residual gas tower can be seen below in *Reaction 2.9* where ClO_2 is dissolved in a solution. The pureness of the added water is essential.

$$2ClO_2 + 5HSO_3^- + H_2O \rightarrow 2Cl^- + 5So_4^{2-} + 7H^+ \qquad (2.9)$$

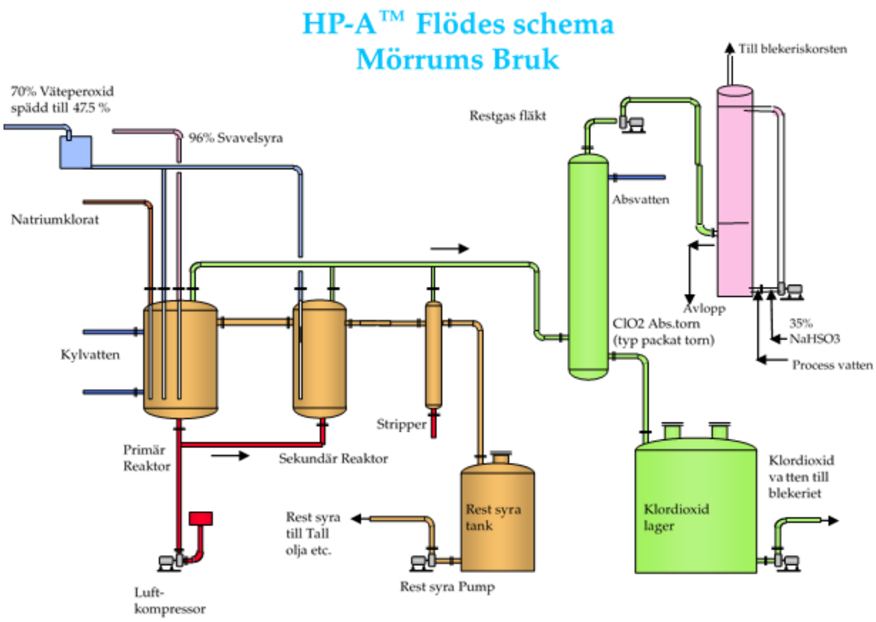

Figure 2.8: An overview of the flow chart for the chloride dioxide production. The exception is the residual gas tower, pink above, which is illustrating release of gas to a chimney, Till blekeriskorsten, but in reality it is released to the air (SCM 2017).

2.5.7 Water

Water is used for various processes at the SCM factory. The water used is taken from the Mörrum River, which is located near the factory. The water is then treated at the factory's own water treatment plant[1]. The amount of water varies over the year, from around 700-800 liters per second (l/s) during winter and around 1200 l/s during the summer. The intake of water is illustrated in *Figure 2.9*. The higher water flow required during the summer can partly be explained by the higher demand for cooling the equipment.

At the water treatment plant, water is treated to different purity levels, which are all used in different processes and equipment. Where water is present in a chemical reaction, such as the absorption of ClO_2 gas in the residual gas tower, explained above in *Reaction 2.9*, a higher degree of treatment is required compared to the water used to put out fire[1]. The different definitions of the treated waters are explained below.

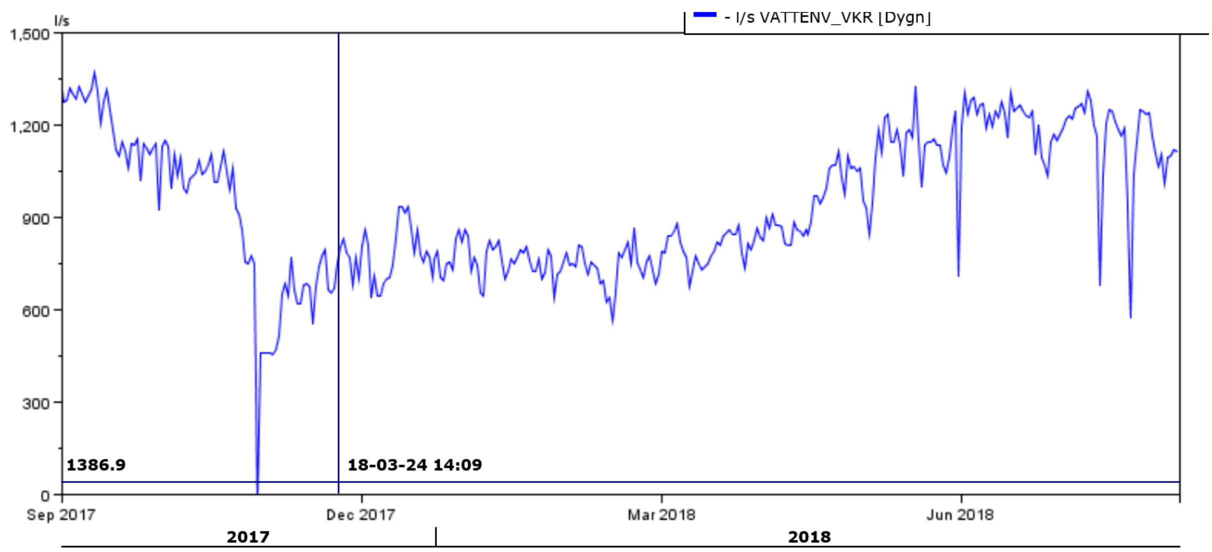

Figure 2.9: An illustration of how the intake of water from the Mörrum River varies over the year.

2.5.7.1 Water cold mechanically cleaned, VKM

After the water has been taken from the river, it is distributed to mechanical filters where particles are allowed to settle. It is thus only the larger visible particles that are sedimented. This water is called cold mechanically cleaned water, (VKM, Vatten Kallt Mekaniskt renat). All water that is taken from the river undergoes this treatment. After this treatment, VKM is distributed either further in the treatment process or to different equipment where the requirements of the waters purity is low[1].

2.5.7.2 Water cold chemically cleaned, VKK

Of all VKM, approximately 400 l/s is taken to be chemically treated. Firstly, it is cleaned by adding chemicals and secondly, it is flocculated so that unwanted particles clump together. Lastly, the water is taken through a sand filter, where these clumped particles are filtered out. This water is called cold chemically cleaned water, (VKK, Vatten Kallt Kemiskt renat). After its use in various processes, the majority of VKK is heated to 125°C and distributed to a feedwater tank. The heating of VKK is done in multiple heat exchangers where the 3 bar steam is used as the heating source[1]. Regardless of the potential installation of a turbine, prior to the heating, VKK will be fixed to 25 °C from the autumn of 2018, instead of varying with the temperature of the river, as historically done. As a consequence of the possible installation of a turbine, VKK will be used to cool the turbine and condensing the steam. The outcome will be a temperature increase of VKK to 35°C instead of 25°C.

2.5.7.3 Water cold deionized, VKA

Of the VKK, a yearly average of approximately 35l/s is treated to be deionized. The VKK is taken through an ion exchange filter where the water consequently is deionized. It is therefore called water cold deionized, (VKA, vatten kallt avjoniserat)[1].

2.5.7.4 Water warm deionized, VHA

Water warm deionized (Vatten Hett Avjoniserat, VHA) is the same water as VKA, the only difference is that VHA is heated to 65-70 °C. It is hence called water warm deionized. The heating is carried out just as for VKK, by heating VKA in a heat exchanger where the heat source is the 3 bar steam[1].

2.5.7.5 Feedwater, condensed steam and VKT

Along with VKK, condensed steam is also taken to the feedwater tank, which is maintained at a temperature of 125°C. The VKK is mixed with condensed steam and the tank is heated with normal 3 bar steam to maintain the required temperature. As mentioned, a lot of steam is used at the factory to heat up processes. When the steam is condensed, as much water as possible is gathered and fed to the feedwater tank. In this case, the more water delivered the better, as this water is pure and less water needs to be taken from the Mörrum River to the water treatment facility. The water taken from this tank is called feedwater.

Before the condensed steam is taken to the feedwater tank and mixed with VKK, it is taken through a bed with deionization filters to clean the water from an- and cations. The condensed steam is called VKT after it has been taken through these filters (Vatten Kallt Totalavsaltat). VKT can also be produced at the water treatment plant by letting VKK, instead of condensed steam, be treated in the same way. The production of VKT from VKK and steam is thus done at two separate locations[1].

2.5.8 Treatment of wastewater

SCM has different processes with different reactions, with a few mentioned so far. Of those including water, the water may serve different functions. Examples of these functions can be: cooling the equipment, involvement in different chemical reactions, cleaning of areas were chemicals and pollutants have been used or where other kinds of unwanted wastes might be present (Ferm 2014). The water that has been used in these processes normally have:

- High content of total organic carbon, TOC, other organic compounds, nitrogen and phosphorus which initially originates from the wood.
- Fiber.
- Adsorbable Organically bound halogens, AOX, and chlorate which originally comes from the bleaching process (Ibid).

The different pollutants or particles, now found in the water, affects the water recipient that receives the water (Ibid). All water at SCM is therefore treated before it is finally released along a 5,6 km pipe in the bay outside Mörrum, Pukaviksbukten. The last 1800 meters of the pipe contains holes to allow a more diluted effect when the water is released. In cooperation with the state of Blekinges cost water treatment association, *Blekingekustens vattenvårdsförbund*, water samples are regularly taken to ensure minimal environmental impact from the treated wastewater that is released[1].

Before the waste water reaches the recipient, that is the ocean, it has to be treated in different steps. The method used in these different steps depends on which pollutants that are present in the water. However, the pollutants in the water differ from each other, depending on where in the processes the water was used. Waste waters from different processes are therefore not mixed with one another. Instead, waste waters are treated separately before released to the recipient. By doing this, an optimal treatment of the different wastewaters is maintained. In general, however, the water used for cooling purposes does not need any special treatment. It can be recirculated back to the factory again. In the case for the following wastewaters however, treatment is essential (Ibid):

- The wastewater from the bleaching processes. It is firstly treated in a sedimentation pool for sedimentation of particles from the wood. Secondly, it is biologically treated in the biological treatment basin.
- Some condensate, for example that from the evaporation step and from different boiling processes. The water does not contain any fibers but does, however, contain organic compounds that consumes oxygen. This condensate is distributed to the biological treatment basin.
- In the sawmill, where the wood chips are made, water is used to clean the wood prior to sawing, among other things. The wastewater contains wood particles and fibers which is firstly treated through a fiber and particle sedimentation. Secondly, the water is biologically treated in the biological treatment basin.

2.5.8.1 BOD and COD

In order to measure the amount of dissolved wood particles and organic compounds in the water, the amount of oxygen consumed in the water during a degradation process is measured. The amount of oxygen that is consumed can be measured according to two methods:

- Biological Oxygen Demand, BOD.
  By adding a certain amount and type of bacteria to a sample, the amount of oxygen that has been consumed during a certain amount of time can be measured (Ibid).

- Chemical Oxygen Demand, COD.
  By adding a strong oxidizing compound, like potassium permanganate, the amount of oxygen consumed during the oxidizing can be measured. The result is consequently a measurement of the amount of oxygen needed to degrade all organic material to CO_2 and water (Ibid).

2.5.8.2 Biological treatment basin

As one of the last steps before being released into the ocean, the water is treated in a biological treatment basin, as mentioned above. Water that contains wood particles and organic compounds that are dissolved in the wastewater are degraded by bacterias. There are two methods that are mainly used for this degradation (Ibid):

- Anaerobic degradation: where no oxygen is added and the bacterias are producing methane gas. This gas can be used as fuel.
- Aerobic degradation: where the degradation is taking place in an environment with oxygen. This is mainly implemented by adding oxygen into the wastewater.

The wastewater taken to the biological treatment pool at SCM is aerobically treated and taken through an aerated earth dam. The residence time in the dam varies from 5 to 20 days. Air is added by a surface aeration device. This device includes something similar to a turbine that is rotating just underneath the water surface. It forces water up towards a surface that consequently distributes the water particles over a big radius around the device. The water particles therefore acquire oxygen from the air.

The majority of the organically dissolved material is degraded and the oxygen consuming compounds, measured as BOD, is reduced by 70-90 % and measured as COD, approximately by 50 %. The aeration is to maintain an environment that can ensure such conditions that are essential for the bacteria's survival. If this is not ensured, the bacteria might die and the degradation is hence affected. The bacteria and their activity are also dependent on the temperature in the water. It is out of great importance to keep the temperature at approximately 36°C but at a maximum of 37°C[1].

It is generally safe to release the water to the recipient after it has been treated in a biological treatment pool, since the treatment of the water is almost the same as the one carried out in nature; allowing micro-organisms eat the pollutants. However, if criterias, such as the temperature of the water, are not fulfilled, longer residence time and lower degradation might be a consequence due to deceased bacteria (Ibid).

2.6 Turbine

The overview of relevant processes at SCM required for the understanding of this study was thoroughly explained above. In this section, a similar overview is presented but for the understanding of turbines.

2.6.1 Aerodynamics

In the case for SCM, the potential turbine will be included in a system where the main purpose is the production of electricity. An electricity generator is run by the turbine, which serves as a work producing unit (Alvarez 1990, p.782). The work done by a turbine originates from a working fluid that makes it move, such as air, water, or steam. There are two types of turbines, axial and radial. The stream of the working fluid on a radial turbine is in a perpendicular plane with respect the the turbine (Ibid). This is very much like the same principle as the water that drives a water mill. The second type of turbine, the axial, is also the most common type of turbine, especially for steam (Ibid). In the case for the axial turbine, the working fluid runs along the direction of the turbine axis. This can be illustrated for example when air drives a wind power turbine. When the air is flowing the same direction as the shaft, it hits the blades which in turn rotates.

To calculate the effect transferred from the working fluid to the turbine shaft, the illustration in *Figure 2.10* can be considered along with *Equations 2.3-2.4.*

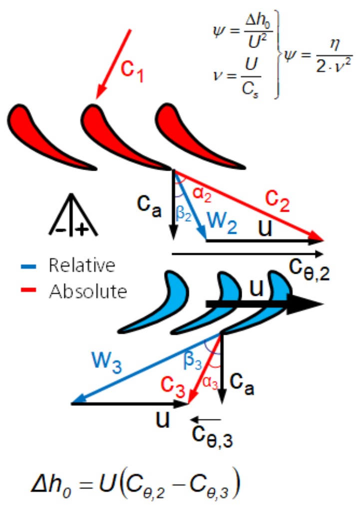

Figure 2.10: Illustrates the principle of how the working fluid, C_1, hits the turbine blades and how the force is further distributed to produce work from the blades.

The relevant vectors illustrated in *Figure 2.10* are the following:

- *U = The velocity of the blades.*
- *C_1 = The fluids absolute velocity at the entrance of the blades.*
- *Cθ = The tangential component of the absolute velocity.*

The exchange of energy between the fluid and the shaft is decided by the moment of momentum, M, which causes the blades to rotate. The moment of momentum is decided according to *Equation 2.3* with the additional variables (Ibid):

- r_1 = the radius of the shaft.
- r_2 = the radius from the centre of the shaft to the end of the blades.

$$M = \dot{m} \cdot (\boldsymbol{r_1} \cdot C\theta 3 - \boldsymbol{r_2} \cdot C\theta 2) \qquad \text{Eq.2.3.}$$

where ṁ is the stationary mass flow.

The moment of momentum is valid regardless of if the turbine is a radial or axial.

The effect, P, transferred from the fluid to the blades, depends on the moment of momentum and the angular velocity of the shaft, ω, according to *Equation 2.4* (Ibid).

$$P = M \cdot \omega \qquad \text{Eq.2.4.}$$

In a steam turbine, it is hence the heat energy from the steam, that is the total enthalpy, that is converted into work in the turbine blades.

When carrying out calculations of a steam turbine, considerations must be taken to the fact that the working fluid, in this case steam, is compressible. The laws of thermodynamics must therefore be applied (Ibid), which will be explained in the following section. There is thus a correlation between the aerodynamic and the thermodynamic. This is expressed in *Figure 2.10* as $\Delta h_0 = U \cdot (C_{\theta 2} - C_{\theta 2})$ where Δh_0 equals P in *Equation 2.4* and is hence the effect obtained from the turbine. The effect is hence equal to the velocity of the blades multiplied with the difference in the tangential components of the absolute velocity[2].

2.6.2 Thermodynamics

To understand the basic principles of the conversion from heat energy in the steam to power from the blades, the underlying behaviour of the steam is explained below. By considering *Figure 2.11,* which illustrates water that is heated at atmosphere pressure from approximately 20°C to 300°C. The specific volume v (m^3/kg), that is illustrated at the X-axis, is increased with higher temperature since the volume increases (Boles & Cengel 2015).

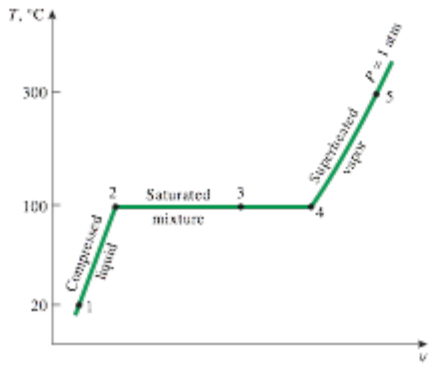

Figure 2.11: The heating process of water at 1 atm illustrated in a T-v diagram (Boles & Cengel 2015, fig 3-10).

From 20-100°C, the water exists at its liquid phase and is called a compressed liquid. By continuing to heat the water and keeping the pressure constant at atmosphere pressure, the water will expand slightly whilst being heated (Ibid). Once the water has reached 100°C, any further heat addition will cause some of the liquid to vaporize. In this case, the liquid is called a saturated liquid, that is a liquid that is about to vaporize (Ibid).

[2] Private communication with Magnus Genrup, professor in Thermal power engineering, continuously from July to November 2018.

The straight line in *Figure 2.11* illustrates the fact that, as long as there is still liquid water, the heating will force more and more liquid to vaporize at 100°C, which will hence take up a larger volume since the pressure is constant. In case of heat loss, the vapor will condense back to liquid water. This vapor is called saturated vapor, that is, a vapor that is about to condense at such a heat loss.

After all the liquid has vaporized, there is no phase change to consider and further heat addition results in an increase in both temperature and specific volume (Ibid), as illustrated in *Figure 2.11*. Once the temperature of the steam has started to increase even further, a potential heat loss will not force the water to condense. This is provided that the steam is still above 100°C. In this case, the vapor is called superheated vapor, that is, a vapor that is not about to condense (Ibid). *Figure 2.12* below illustrates the same principle as *Figure 2.11* above but for water at different pressures.

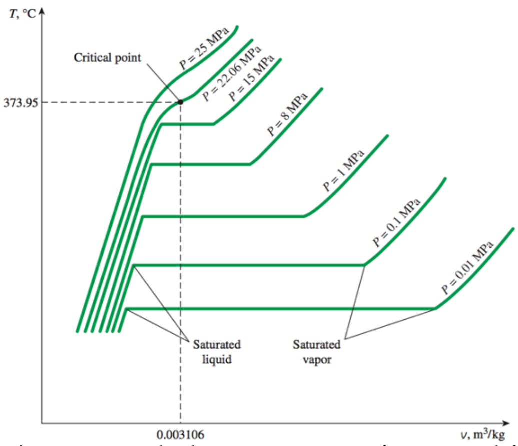

Figure 2.12: *The heating process of water at different pressures illustrated in a T-v diagram. Each line represent a constant pressure (Boles & Cengel 2015, fig 3-15).*

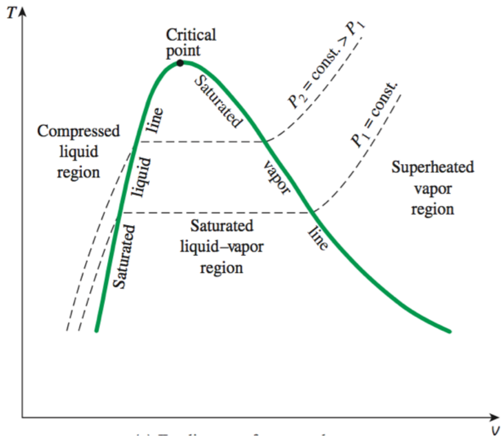

Figure 2.13: The saturation line for water illustrated in a T-v diagram (Boles & Cengel 2015, fig 3-17).

Figure 2.13 further illustrates the saturation line. That is, when making a line for all points at different pressures where the saturated liquid starts to occur and additionally for all the points where the saturated vapor starts to occur.

2.6.2.1 Entropy

By introducing the concept of entropy, further clarifications can be carried out regarding the basic idea of the thermodynamics for a turbine. Entropy is a property and, as with many other properties, it has a known value at specified states. The value of the entropy change can be obtained by integrating *Equation 2.5* (Ibid).

$$\delta S = \frac{\delta \mathrm{Q}}{\mathrm{T}} \qquad [\mathrm{kJ/K}] \qquad \text{Eq.2.5.}$$

Where δQ is the transferred heat and T the temperature in Kelvin. δS hence results in a kj/K-unit. By considering the value of entropy in the compressed liquid and superheated vapor regions, the following saturation line is obtained in *Figure 2.14* (Ibid), just as in the case for the T-v diagram in *Figure 2.13*. The surface under the diagram approximately equals the work obtained or produced from a system (Ibid).

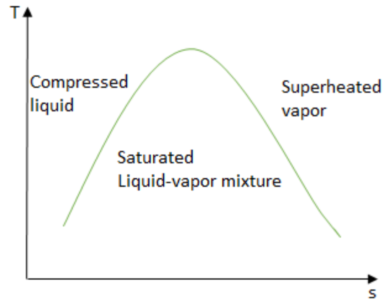

Figure 2.14: The saturation line for water illustrated in a T-s diagram.

An isentropic process of ideal gases is obtained when the change in entropy is zero. This furthermore implies that there is no addition or removal of heat in *Equation 2.5,* where both sides consequently equal zero (Ibid).

2.6.2.2 Rankine Cycle

The ideal Rankine Cycle is the ideal cycle for vapor power plants and is the cycle that the steam will go through in a closed system (Ibid). However, the system for the steam entering the turbine at the SCM factory is not a closed system and does not go through all these stages. The best way to explain the energy transfer would be to consider the Rankine Cycle.

A characteristic part of the Rankine Cycle is the superheated steam that enters the turbine in stage 3, illustrated in *Figure 2.15*. It is furthermore completely condensed to compressed liquid in stage 1 (Ibid).

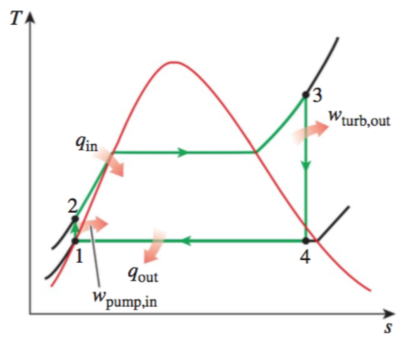

Figure 2.15: The 4 stages of the Rankine Cycle illustrated in a T-s diagram where the red line is the saturation line and the green line the Rankine Cycle (Boles & Cengel 2015, fig 10-2).

The ideal Rankine Cycle, illustrated in *Figure 2.15,* consists of the following four processes (Ibid) that are further illustrated in *Figure 2.16,* that is an overview of a typical Rankine Cycle.

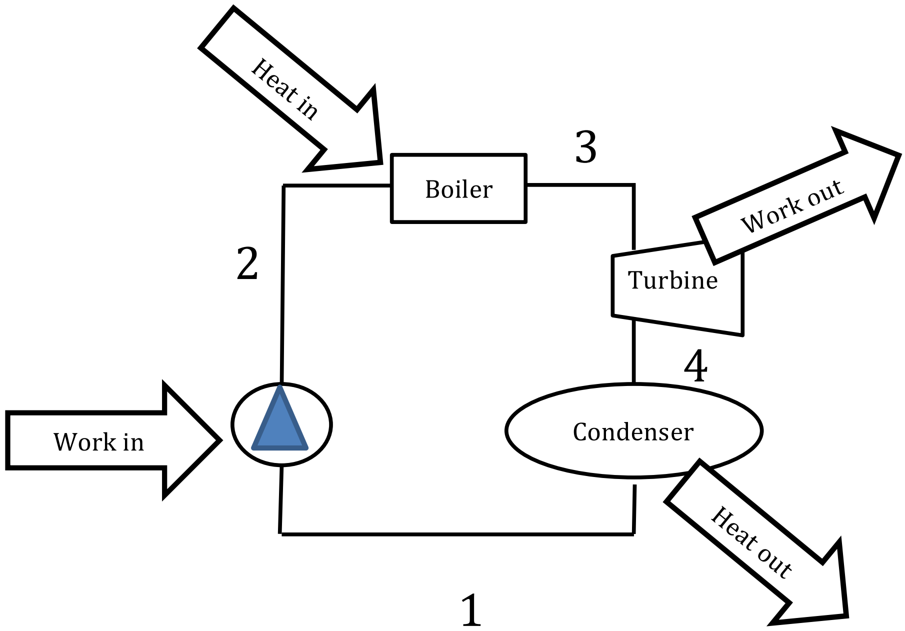

Figure 2.16: The 4 stages of a Rankine Cycle illustrated in a closed loop system.

- 1-2 Isentropic compression in a pump.
- 2-3 Constant pressure heat addition in a boiler.
- 3-4 Isentropic expansion in a turbine.
- 4-1 Constant pressure heat rejection in a condenser.

1-2. In the Rankine Cycle, water enters a pump at stage 1, where it is isentropically compressed. The compression results in a slight decrease in specific volume and hence a slight increase in temperature. This increase, illustrated in *Figure 2.15,* is greatly exaggerated for clarity. The compression, which consequently increases the pressure, enables the steam to enter the boiler with a high pressure.

2-3. Point 2 is when the compressed water enters the heating stage, potentially a boiler. It is heated until it is a saturated liquid as explained above. It is further heated until it is a saturated vapor and finally a superheated vapor as in stage 3.

3-4. After leaving the boiler, the superheated vapor enters the turbine in stage 3. When the steam cools down it expands isentropically. Due to this expansion, it contributes with energy to equation 3 above, which hence result in a moment of momentum. When it expands, the moment of momentum causes the shaft to rotate, which will hence produce work. When the shaft is connected to an electric generator it will produce electricity. The difference in enthalpy at stage 3-4, that is Δh_0, is thus equal to the Δh_0 in *Figure 2.10.*

4-1. At stage 4, the condensator stage, the steam has left the turbine as a saturated liquid-vapor mixture. The steam is condensed at constant pressure. The condensation takes place in a condenser, which is basically a large heat exchanger, where the steam cools down and is condensed whilst the cooling water is heated. Saturated liquid finally exits the condenser and re-enters the pump at stage 1, completing the cycle (Ibid).

As mentioned above, a potential turbine at SCM will not go through all 4 stages, instead, enter as superheated steam at stage 3 and leave as condensed steam before compressed at stage 1.

2.6.2.2.1 Increase the output of Rankine Cycle

There are different ways to increase the output of the Rankine Cycle. Additionally to increasing the steam flow, one other option will be analyzed below due to its relevance.

The area in *Figure 2.14* illustrates the work output. This area will therefore have to increase if the output should increase. When the steam exits the condenser, it exits as a saturated mixture at the saturation temperature corresponding to the pressure of the condenser. By lowering the pressure of the condenser, alternatively decreasing the temperature of the cooling water, it automatically lowers the temperature of the steam. This can further be reached if the flow of cooling water to the condenser is increased, which will be considered later. This is illustrated in *Figure 2.17,* where the shaded area is the increased output.

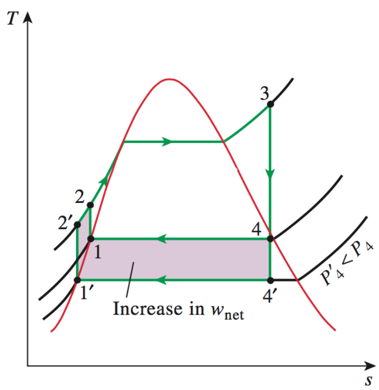

Figure 2.17: The increased output of the Rankine Cycle by decreased temperature of the cooling water or lowering the pressure of the condenser (Boles & Cengel 2015, fig 10-6).

The increase in energy is provided that everything else remains the same, such as the turbine inlet state. During these circumstances, the overall result from lowering the pressure in the condenser increases the output of the cycle. It does, however, also increase the moisture content in the steam. A higher moisture content can decrease the efficiency and erode the turbine blades. This problem can be solved by heating the superheated vapor even further, which decreases the moisture content (Ibid).

2.6.2.2.2 Deviations of Rankine cycle

As aforementioned, the Rankine Cycle describes the ideal cycle, whereas the actual vapor cycle differs. Some of these deviations will be explained in this section. The most common deviations are irreversibilities in various components such as fluid friction and heat loss to the surroundings. Consequences of fluid friction include: pressure drops in the boiler, condenser and the piping between different components. As a possible outcome, steam leaves the component at a lower pressure. The friction also results in a lower pressure at the turbine inlet compared to the turbine exit, due to a pressure drop in the pipes. By pumping the water to a sufficiently higher pressure than that of the ideal cycle, the higher pressure compensates for the pressure drops. This therefore requires a larger work input from the pump and consequently a larger pump (Ibid).

Heat loss from the steam is the other main source of deviation. The irreversibility appears as the steam flows through the different components. Steam can potentially leak out during the cycle and air can leak into different components. This lowers the cycle temperature. As a consequence of the undesired heat losses, the output decreases. By transferring more heat to the steam, the same level of output is maintained and the further heat addition therefore compensates for the heat losses. The heat addition does however decrease the cycle efficiency (Ibid).

2.6.2.3 Organic Rankine cycle, ORC

An alternative for using the normal Rankine Cycle is the Organic Rankine Cycle, (ORC). Just as in the normal steam cycle, the ORC is a thermodynamic cycle that converts heat into work and is carried out in the same 4 stages. The main difference between the conventional steam cycle and the ORC is the medium that is used and expanded in the turbine. The ORC system vaporizes an organic fluid instead of water. The organic fluid replaces the steam in the closed loop system illustrated in *Figure 2.15* and *2.16*, and is heated in a heat exchanger with the steam. The steam is hence used to heat the organic fluid instead of being utilized in the turbine itself[2].

The main characteristic of the organic fluid is a molecular mass higher than that of water. The usage of particular organic fluids has shown to be well suited for low temperature heat source exploitation (Moro, Piero & Reini 2008). This is due to the lower boiling temperatures of the organic fluids that are used compared to water (Rettig et. Al. 2011). The technology of ORC can therefore convert thermal energy at temperatures considered rather low compared to that of steam. The organic fluid can vaporize at lower temperatures due to the lower evaporation temperature. An ORC cycle can consequently, at a higher efficiency, take advantage of the energy from lower temperatures than steam (Goldschmidt, 1994). The organic fluid can vaporize and expand in the turbine at a temperature down to 70°C[2].

ORC is believed to play an important role in improving energy efficiency of existing and new applications (Rettig et. Al. 2011). The ORC therefore has advantages regarding power generation from lower temperatures such as industrial waste heat, solar energy, geothermal energy and biomass energy (Yo-Ting et. Al. 2014). Some of the main possible positive features of an ORC compared to the conventional steam cycle are listed below:

- Slower rotation of the turbine.
- Minimal blade erosion and minimal damage of pipes and valves, which results in a longer lifetime (Moro, Piero & Reini 2008).
- Lower temperature requirement, as stated above.

As illustrated in *Figure 2.18,* the organic fluids have a smaller entropy difference between saturated liquid and saturated vapor than that of water. For the same amount of thermal power, a greater mass flow rate of the organic fluid, than that of steam, is therefore required. A consequence of this is a higher energy consumption for the pump (Mahmoud Ahmed Sharafeldin, no year). Further illustrated in the diagram is the shape of the organic mediums compared to the water. The illustrated shape of that of the water enables an isentropic cooling to take place in the turbine. After an isentropic cooling of the organic medium, the medium is still super heated, which can be seen in *Figure 2.18*. To prevent this, a deheater is normally installed in combination with the condenser. A normal steam cycle turbine, at lower temperatures, has a higher potential for decreased efficiency and furthermore a higher potential for an increasing amount of droplets causing erosion on the blades (Rettig et. Al. 2011).

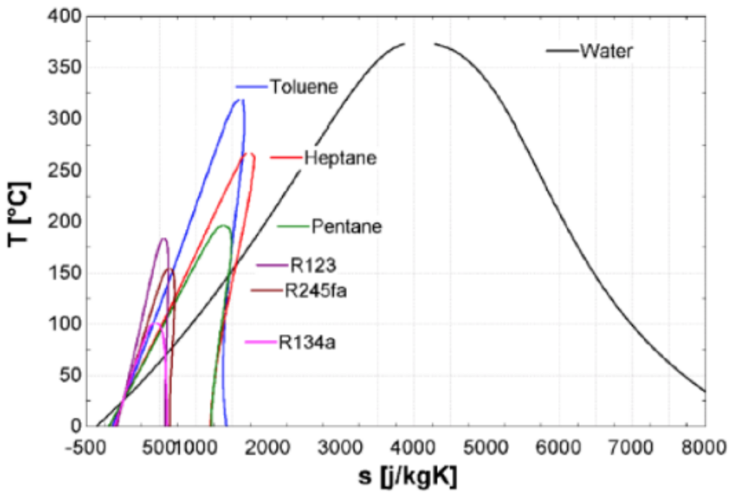

Figure 2.18: The saturation line for different fluids (Mahmoud Ahmed Sharafeldin, no year, Figure 5).

An overview of a typical ORC can be seen below in *Figure 2.19.*

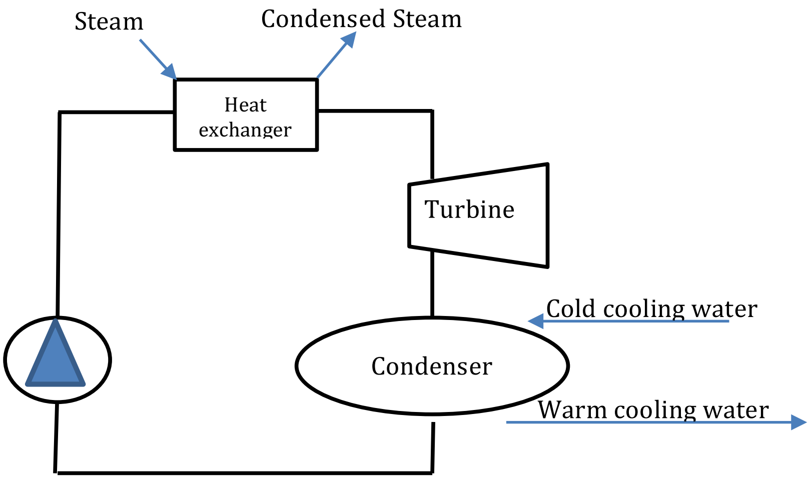

Figure 2.19: A basic overview of an Organic Rankine Cycle with a closed loop system for the organic fluid and an extern heat and cooling source.

There are heat losses in the exchange of heat from that of the steam to the organic fluid. In contrast to the typical system, illustrated in *Figure 2.18,* the medium which is heated in a boiler is not used in the actual turbine. The heat, in this case 155°C steam from SCM, will heat the organic fluid in a heat exchanger, which will serve as the working fluid. The organic medium will be heated whilst the steam will condensate. The organic fluid is furthermore cooled in a heat exchanger after it has expanded in the turbine. In the case for SCM, it will be cooled with VKK which consequently will be heated.

After cooling, the organic fluid will be reheated again, since the organic fluid circulates in a closed system. The heating of the organic medium and the cooling of the steam is illustrated in *Figure 2.20* below where the shaded area represents the heat loss.

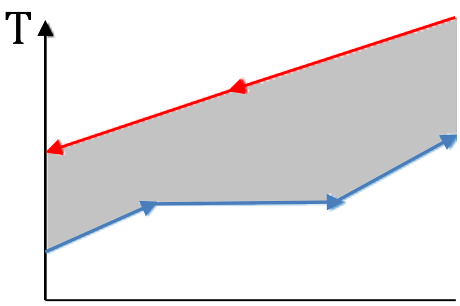

Figure 2.20: Illustrates the heat losses, shaded in grey, from heating of a medium, blue line, with another medium, red line.

2.6.2.4 Stodola's Cone Rule

As a part of this study, different variables were modified to analyse how the output of the turbine varies. When this was conducted, a model based Excel file was used. An overview of the theory behind this model is presented below.

There is an empirical correlation between the temperature of the steam, as well as the pressure for the steam, and for the flow of steam. This correlation was measured in the beginning of the 20th Century and is called the Stodola's Cone Rule or the 'Swallowing Capacity' for a given turbine. This rule states that the flow is always proportional to the temperature or pressure of the steam. This is expressed as in *Equation 2.6* where $C_{T,i-j}$ is the proportional constant.

$$\dot{m}_{i-j} = C_{T,i-j}\sqrt{\frac{p_i^2-p_j^2}{p_i \cdot v_i}} \qquad \text{Eq.2.6}$$

The pressure of the condenser, that is p_j, is normally much smaller than that of the steam and can therefore be neglected. *Equation 2.7* is therefore obtained:

$$\dot{m}_{i-j} = C_{T,i-j}\sqrt{\frac{p_i}{v_i}} \qquad \text{Eq.2.7}$$

Additionally, since $V = \frac{nRT}{P}$ according to the ideal gas law in *Equation 2.8*

$$PV=nRT \qquad \text{Eq.2.8}$$

where:

P= Pressure.
V= Volume.
n= Number of moles.
R= The gas constant.
T= Temperature.

The following correlation in *Equation 2.9* is obtained where K is a second constant with a different value than that of $C_{T,i-j}$.

$$\dot{m} = K\frac{p_i}{\sqrt{T_i}} \qquad \text{Eq.2.9}$$

With given data, K can be calculated and is hence constant for the given turbine. Once it is obtained, different variables can be modified to analyse how the other variables vary. Such a modification can include the variation of the steam flow and cooling water flow to obtain new turbine outputs. This can be obtained since K is considering different deviations discussed above (Gicquel 2012 p.976). To analyse this, Stodola's Cone Rule results in an iterative function. Excel is therefore used to solve the equations when modifying the variables.

2.7 Heat exchangers

A heat exchanger can be used in situations where a medium is to be heated with a second medium that consequently is cooled. By assuming no heat loss, the effect transferred within the heat exchanger can be calculated according to *Equation 2.13* and *2.15*

$$P = \dot{m} \cdot Cp \cdot (t1 - t2) \qquad \text{Eq.2.13}$$

where:

P = The effect.
ṁ= The mass flow.
C_p = The specific heat [kj/kg·K].
t = The temperature.

The effect of the heat exchanger calculated in *Equation 2.13* is the same regardless of if the considered medium is the cold flow, which is heated, or the warm flow, which is cooled. The two are however equal to each other as in *Equation 2.14*

$$\dot{m}_1 \cdot Cp \cdot (t_{H1} - t_{H2}) = \dot{m}_2 \cdot Cp \cdot (t_{C1} - t_{C2}) \qquad \text{Eq.2.14}$$

where H considers the hot flow and C the cold flow.

In the case that the effect is known but the flow and 1 temperature is unknown, *Equation 2.15* can be used instead.

$$P = A \cdot k \cdot LMTD \qquad \text{Eq.2.15}$$

Where:

A= The total area of the heat exchanger.
k= The heat transfer coefficient.
LMTD is called the logarithmic average temperature and is calculated according to *Equation 2.16* below:

$$LMTD = \frac{v' - v''}{ln\frac{v'}{v''}} \qquad \text{Eq.2.16}$$

The temperature differences between the different sides of the heat exchanger, that is v' and v'', can be illustrated as in *Figure 2.21*.

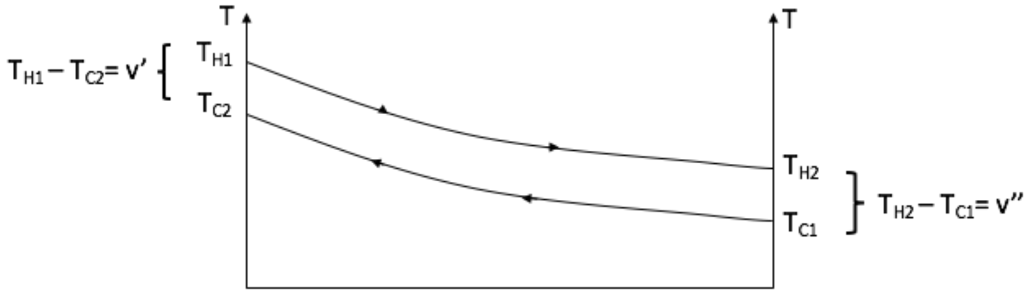

Figure 2.21: Illustrates the initial and final temperatures of the two flows in a heat exchanger. Consequently v' and v'' is obtained and can be used to calculate LMTD.

All temperatures can thus be obtained in *Equation 2.16* and furthermore, the required flow by using *Equation 2.13* or *2.14.*

As a summary, all three equations, *Equation 2.13-2.15*, equal each other, with the same *P*, for a given heat exchanger and a given k-value.

2.8 Economy

As is the case for many investments, it is not always the best performing option that is chosen. If the second best performing option is significantly cheaper, it might be more profitable to invest in this item, instead of in the best performing one. To be able to make this decision, different investment calculations are used all over the world that take consideration to performance data, investment costs, profitability over time, lifetime, and yearly maintenance costs, among other factors. The different calculations express the profitability with different key values.

One part of this study was to compare different turbines in order to decide which options will be most profitable. Secondly to this, the financial key values were used to gain an understanding of the potential future profitability of the investment. For this study, the considered key values are the NPV, IRR and PB. This section will therefore give a brief overview of these key values and the equations which will later be used to compare the different alternatives. The discount rate of 10 % was used in this study.

2.8.1 Net Present Value, NPV

The NPV is the sum of all future costs and payments with consideration to today's economic value. The time perspective can be chosen and most often the lifetime of the item or a pre-decided time perspective for which the investment needs to be profitable is considered. During this time perspective, the present value of the payments are compared to the present value of the costs.

The NPV also depends on the discount rate, that is the requirement of yield. The NPV expresses the further profitability of the investment after the yield of the discount rate is fulfilled. An investment is therefore profitable if the NPV is larger than or equal to zero. If it is equal to zero, the requirement of discount rate is fulfilled (Nilsson & Persson 1999).

See below in *Equation 2.22* for NPV:

$$NPV = -G + a\sum_{k=1}^{n} \frac{1}{(1+i)^k} \pm \frac{s}{(1+i)^n} \qquad \text{Eq.2.22}$$

where:
G = The total investment cost.
a = The yearly sum of payments minus costs.
n = Amount of years.
i = Discount rate.
S = The potential payment or cost of selling alternatively dismantling the item (Ibid).

2.8.2 Internal Rate of Return, IRR

This method can be illustrated as the NPV backwards. Whilst the NPV is the further profit after the yield of discount rate is fulfilled, the IRR is the interest when the investment has a NPV equal to zero. It is thus a measurement of the investment's procentual yield. The investment is therefore profitable if the IRR is larger than the pre-decided discount rate (Ibid).

See below in *Equation 2.23* for IRR:

$$IRR = -G + a\sum_{k=1}^{n} \frac{1}{(1+r)^k} \qquad \text{Eq.2.23}$$

where:
G = The total investment cost.
a = The yearly sum of payments minus costs.
n = Amount of years.
r = Internal rate.

Since *Equation 2.23* needs to be zero or larger for the investment to be profitable, the value for r, that is the internal rate, can be calculated by putting the equation equal to zero (Ibid).

2.8.3 Payback time, PB

PB is the time it takes for the sum of all payments to equal the costs of the investment. It can be obtained by using the same variables as for NPV and with *Equation 2.24:*

$$G = a \cdot \frac{(1+i)^n - 1}{i(1+i)^n} \qquad \text{Eq. 2.24}$$

With known G, a and i, n can be obtained, which is hence the payback time for the investment (Ibid).

2.9 Electricity and certificate prices

An additional part of this study was to analyse the profitability of the potential investment of a steam turbine. It furthermore considered the electricity price of 0,24 kronor per kWh and a certificate price of 0,07 kronor per kWh. This section will give a brief overview of how the considered prices have varied historically in Sweden. It will further provide the underlying information for the prices of electricity and the certificates later used in the profitability analysis.

2.9.1 Spot price

The price that SCM will obtain by selling the produced electricity is called the spot price. This varies daily, depending on different circumstances regarding the overall ability to produce electricity in Sweden (Bixia 2018). Below in *Figure 2.22*, the historical annual averages of the electricity price in Sweden are presented. The average during the considered years is 347,5 SEK/MWh, that is 0,3475 kronor / kWh.

Figure 2.22:The historical spot prices of electricity in kronor/MWh on the Nordic electricity market, Nord Pool, from year 2007 to 2017 (Bixia 2018).

2.9.2 Certificate price

The certificate price has, just as the spot price, varied greatly over previous years. *Figure 2.23* illustrates the average price in June from the year 2005 to 2018. The yearly averages however varied differently. June has been used as a reference in this diagram to illustrate a significant variation. The average between considered years is 184 SEK/MWh, that is 0,184 kronor / kWh (SKM 2018).

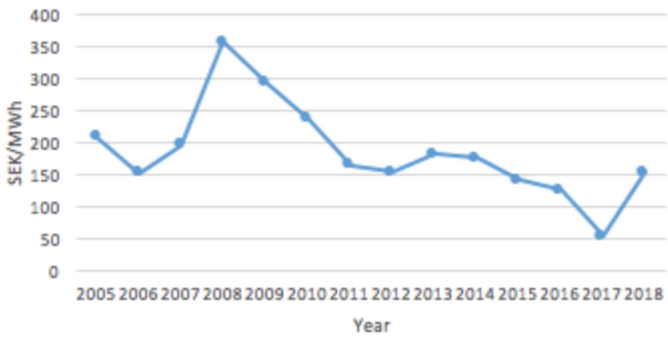

Figure 2.23: The average historical certificate prices of electricity in kronor/MWh in June from year 2005 to 2018 (SKM 2018).

2.10 CO_2 emission intensity from electricity generation

The purpose of the electricity certificates is to increase the incentives for sustainable electricity production. The electricity production in Sweden has, compared to many other countries, a small rate of CO_2 emissions. More than 95 % of the electricity in Sweden is based on such production so that no emissions of fossil greenhouse gases are released (Lejestrand 2017). *Figure 2.24* illustrates the CO_2 emission intensity from electricity production from different European countries in year 2016 (EEA 2018).

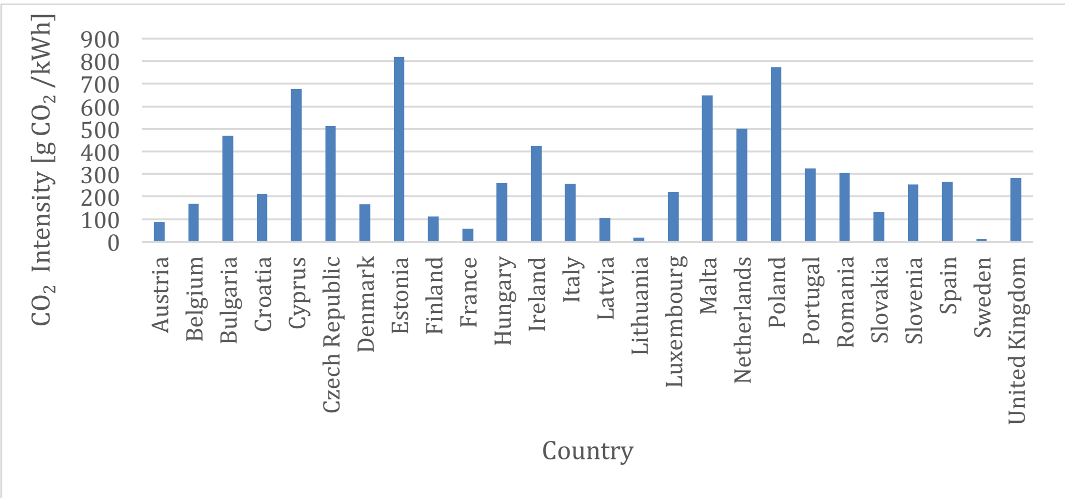

Figure 2.24: The emissions of CO_2 caused by electricity generation in European countries year 2016..

Electricity production in Sweden emits 13,3 g CO_2/kWh, as seen in *Figure 2.24*, and is, in total, equivalent to approximately 4,5 % of the country's total emission of CO_2. The emissions can however vary with the weather and the annual availability of water. The availability of water affects the country's emissions since almost 50 % of the total production is based on hydropower (Energikommissionen 2017).

The average between the considered European countries is 310 g CO_2 / kWh, and that of the included Nordic countries is 97,4 g CO_2 / kWh. On an important note however, is that the emissions only consider the intensity from the actual generation of electricity. No life-cycle perspective of the equipment is therefore included.

The point of including additional countries, other than Sweden, in this study is due to the future plans of a joint power grid in Europe. The Nordic countries have already joined up their grids and Northern Europe plans to within a matter of years (Energimarknadsinspektionen 2017). Thus, if sustainable electricity is produced in Sweden, it can be used in Denmark where the average emission intensity is 166 g CO_2 / kWh. A large amount of CO_2 emissions are therefore prevented provided that Sweden does not need to substitute the distributed electricity with a more CO_2 intensive electricity.

3. Case study

3.1 Layout

As previously explained, the new Evaporation Process at SCM has resulted in a higher amount of excess 3 bar steam. This section will present the historical flow of this steam and was obtained from SCM's internal monitoring system. It is from this historical data that the potential electricity production, the budget offers for the turbine, and hence the financial analysis, were based on. This section will also provide an overview of the layout requested and initiated by SCM.

The residual 3 bar steam that originates from the Recovery Boiler and is used in multiple processes at the factory, for example the Evaporation Process, is to be used by a potential steam turbine to produce electricity. Today, 70 % of this steam is condensed and reused, whereas the rest is either used as direct heat or released through chimneys, as aforementioned[1].

Excess steam exists continuously to prevent shortage of steam to the factory and to district heating. Additionally, excess steam must exist to increase the flexibility that is required at the factory's processes that have a varying instantaneous demand of steam[1].

The concept of the potential turbine is that excess steam will be used for electricity production and condensed via cooling with VKK. Thus, the supply of condensed steam is maintained, electricity has been produced, as well as VKK has been heated, which saves energy required to heat it in the feedwater tank. As a consequence of warmer VKK and saved heat, further steam will be available for electricity production, which results in a synergy. More of this is however discussed in later sections.
A main purpose of this study was to investigate possible consequences of a steam turbine installation. Instruction manuals, which provided requirements for the affected processes, were therefore investigated in this study. Such processes are those affected by a warmer VKK.

The average historical data of excess steam in kilos per second (kg/s) is summarized in *Table 3.1*. Moreover, the average flow of VKK produced at SCM is also summarized. Of note here, is that the monitoring of the VKK flow was inaccurate until the 20th of June. The column '*VKK l/s*' is the monitored and therefore inaccurate flow of VKK. It is believed that the inaccuracy can be estimated to 50 *l/s* too much. The column *'adjusted VKK flow'* has taken consideration for this. 50 l/s has therefore been removed from March to May and two thirds of 50 l/s in June has been removed since the monitoring problem was solved on the 20th of June, that is after two thirds of the month had passed.

Table 3.1: Average steam flow and VKK flow from March 2018 to 19th of July 2018.

	Steam kg/s	***VKK flow l/s***	***Adjusted VKK flow l/s***
March	3,3	420,2	370,2
April	7,4	427,9	377,9
May	6,9	436,8	386,8
June	9,2	402,2	369,2
July including the 19th	8,3	384,3	384,3
Average	7,04	414	378

The collected data for the steam flow, along with the adjusted VKK flow, was sent to turbine suppliers for budget offers and potential production estimates. It was stated by SCM that the temperature of VKK should be considered as 25°C when distributed to the turbine and 35°C when distributed from the turbine. As mentioned in *Section 2.5.7.2*, the temperature of the VKK will be fixed at 25°C, regardless of the turbine. The 35°C limit was investigated and chosen in a study carried out in the spring of 2018[1]. This temperature limit was chosen to create minimal impact for the processes that use VKK after the turbine. The layout of the turbine and the flows and temperatures of steam and VKK, distributed to and from the turbine, is illustrated in *Figure 3.1*.

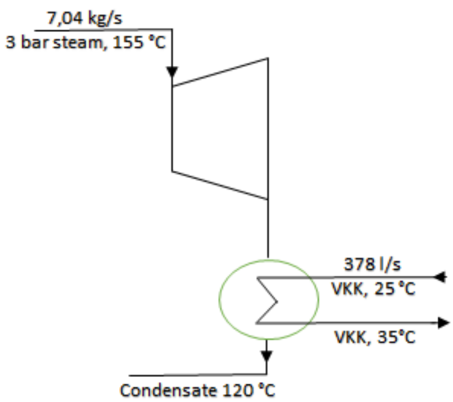

Figure 3.1: The layout of flows and temperatures distributed to and from the turbine.

3.2 Overview of the identified critical processes

According to the reasoning presented in *Figure 2.16*, when cooling water enters the condenser, the output of the turbine increases the more the steam is cooled. Additionally, the cooling water becomes warmer as the output increases. The output of the turbine will therefore be limited to the temperature requirements of VKK; that is, the further processes in the factory that are using VKK after the turbine.

The mentioned study, conducted in the spring of 2018, identified the most critical processes with a warmer VKK and a maximum VKK temperature was decided at 35°C[1]. These processes were considered in this study, among others that were identified after further interviews with experienced employees at SCM.

This section investigated whether a temperature of 35°C will be sustainable for the identified processes. Moreover, an investigation was carried out to clarify possible consequences of warmer VKK, as well as the threshold limit values that the temperature must maintain so that the processes remain unaffected. Potential solutions for any identified consequence were also analysed.

A brief overview of identified critical processes, as well as their function and threshold limits, are presented below.

3.2.1 Feedwater pumps and variable speed drives

Pumps used for pumping the feedwater are called feedwater pumps. It is of great importance that these pumps function, since different processes rely on the water supplied from them. Currently, VKK is used to cool these pumps. The process chart is illustrated in *Figure 3.2.*

According to the operating instructions, the recommended temperature of the incoming cooling water should be between 20 and 45°C. In addition, the quality of the water is important (SCM 2018). Changing the cooling water to a less pure water is therefore not an option.

VKK does not cool the pumps directly. Rather, it is used to cool an oil, seen in the bottom tank in *Figure 3.2*, and this oil is used to cool the pumps. The temperature of the oil is therefore important and while it generally requires cooling, this cooling is occasionally turned off. Very seldomly, heat is actually added to this oil during cold winters[1].

To control the feedwater pumps, variable speed drives are used. These are however located at a seperate location at the factory. Just as with the feedwater pumps, these variable speed drives are cooled with VKK, as illustrated in *Figure 3.2* (see '*Frekvensomriktare'* 1 and 2). These variable speed drives are however not directly cooled with the water but rather with air that is cooled with VKK. Approximately 1,5l/s is required for the cooling of these variable speed drives.

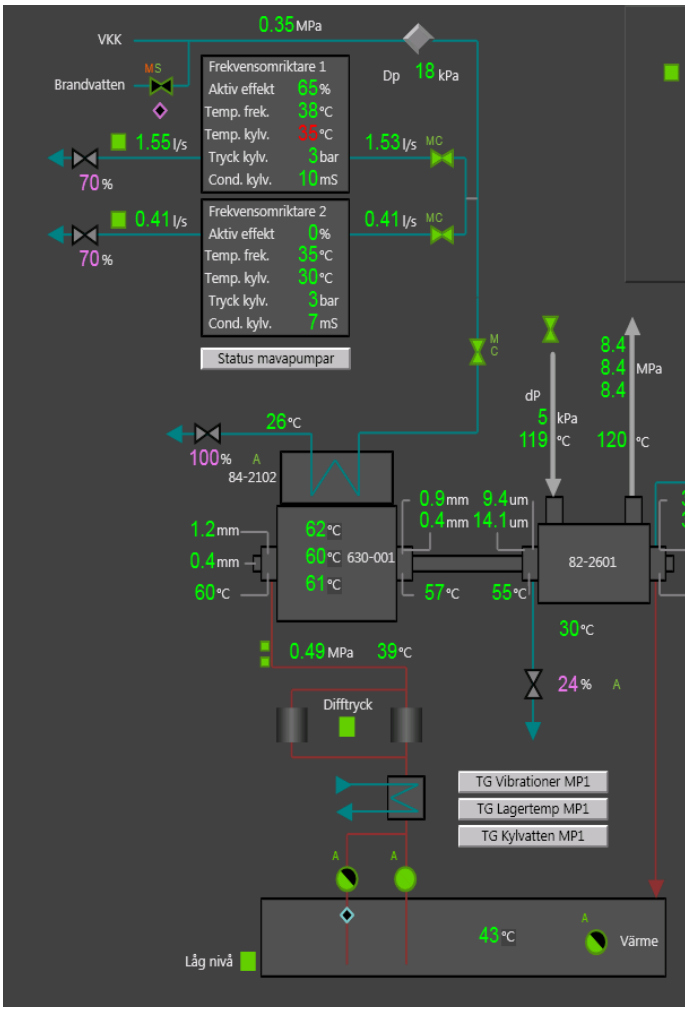

Figure 3.2: Is the process chart of the feedwater pumps and the variable speed drives and furthermore the VKK used to cool these devices.

The cooling effect of the variable speed drives are critical. An automatic alarm is set to indicate if the temperature exceeds 32°C. As no archive data was found recommending a threshold limit, a 27°C temperature was obtained via interviews with experienced employees at SCM[3] and is considered in this study.

To summarize, a VKK temperature of 35 °C falls within the allowed temperature interval for the pumps, however, is too warm for the variable speed drives. The pureness of the cooling water, currently VKK, which flows at approximately 1,5 l/s to the variable speed drives is, however, not as important as in the case for the pumps.

[3] Private communication with Ulf Wilhelmsson, electrical engineer at SCM, continuously from July to November 2018.

3.2.2 ClO_2 in the absorption tower

The bleaching process is briefly explained above and a part of its process chart can be seen below in *Figure 3.3*:

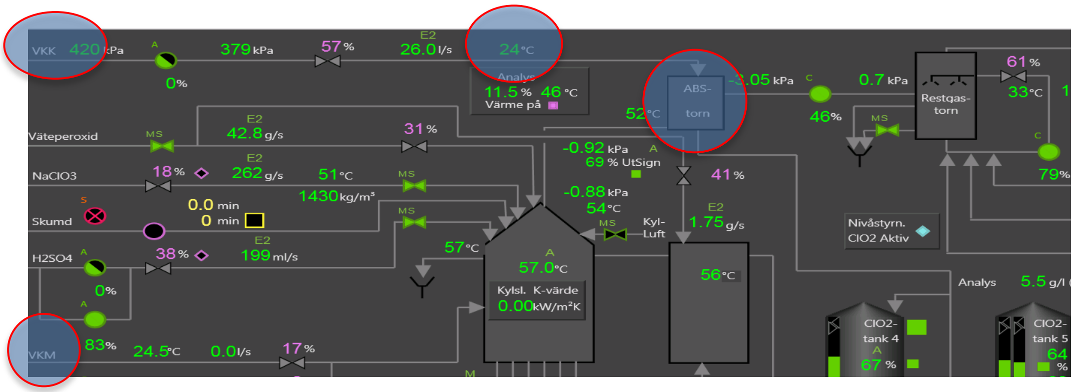

Figure 3.3: Is a part of the process chart of the chloride dioxide production and illustrates the flow of VKK that enters the ABS tower and the VKM pipe currently not used.

The ClO_2 enters an absorption tower, '*ABS-torn*', along with VKK. The VKK is the water in *Reaction 2.9* and illustrated in *Figure 3.3* at a temperature of 24°C. It can therefore not be exchanged to VKM, as in the case for variable speed drives 1 and 2, since the purity of the water is important.

Due to the $NaClO_3$, which is very expensive and used in *Reaction 2.8*, the SCM target is to produce the ClO_2 gas with a 96% yield. In the year of 2017, investigations at the factory concluded that the production averaged at a 94 % yield, which resulted in a further investigation carried out during the summer that year. Results from this investigation showed that the absorption tower accounts for approximately 10% of the overall yield loss in the production of ClO_2, that is 6%. The remaining 90 % of the losses are believed to occur earlier in the ClO_2 production process. The overall yield loss due to the absorption tower was estimated at 0,59 %, meaning that the ClO_2 is absorbed into the water, that is VKK, with a 99,35 % efficiency according to *Calculation 3.1*

$$\frac{1-6\%}{1-90\%\cdot 6\%}\cdot 100 = 99{,}35\% \qquad \textit{Calculation 3.1}$$

Different reasons were discussed as to why this was not 100%, with the conclusions summarized below:

- One factor, which is most relevant in this report, is the temperature of the water that absorbs the gas, that is VKK. The investigation showed that a higher temperature of VKK resulted in a higher concentration of ClO_2 in the residual gas that is released to the air. This is due to the fact that colder water can absorb more gas. A higher VKK temperature consequently results in a higher yield loss. This can be seen in *Figure 3.4*, where a trend line has been added to illustrate the relationship between the temperature of the VKK and the concentration of Cl in the residual gas (SCM 2017).

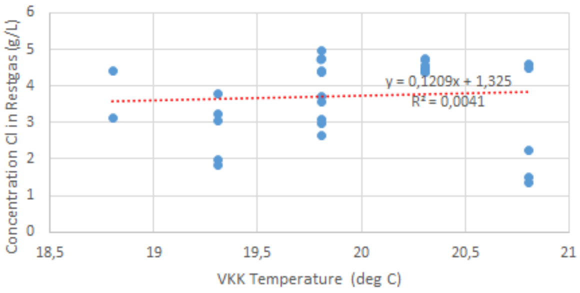

Figure 3.4: The correlation between the Cl concentration in the residual gas tower and the temperature of the incoming VKK.

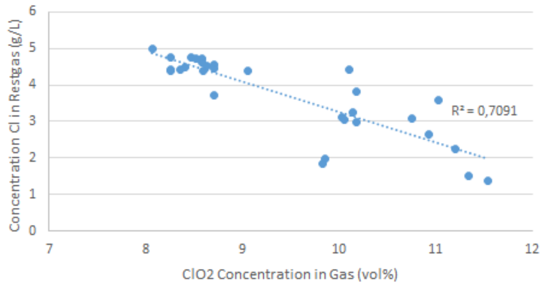

Figure 3.5: The correlation between the Cl concentration in the residual gas tower and the concentration of Cl in the inlet gas.

- The yield loss in the absorption tower, which accounts for 10% of the overall losses (6%), is believed to be most affected by the incoming concentration of ClO_2 (Ibid). This is illustrated in *Figure 3.5*.

Even though *Reaction 2.9* is temperature dependent, the investigation concluded that the temperature is not the most affecting factor. This is illustrated in *Figure 3.6,* where the increase in ppm of ClO_2 after 20°C is more affected by the initial concentration of ClO_2 rather than by the temperature of VKK.

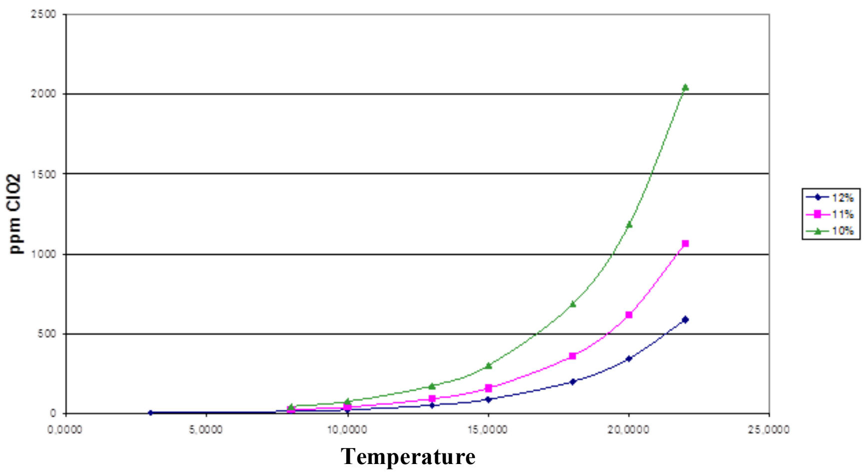

Figure 3.6: Illustrates that a variation in 2°C has a much smaller impact than a variation in 2% gas concentration of ClO_2 escaping the absorption tower (SCM 2017).

Of important note, is that the temperature disfavours the reaction and the increased temperature for VKK is therefore limited to the desired performance. While there is no maximum temperature set to this reaction, after talking to experienced employees at SCM, a maximum VKK temperature was set as 25°C. Employees did, however, believe that the temperature potentially can be warmer and 25°C is used as a safety margin.

3.2.3 Heating of VKK

An average of 69,7 liters of VKK per second arrives to a series of heat exchangers *'VVX'*. This is illustrated in *Figure 3.7* as entering at 22,8 °C, where VKK is heated before it ends in a feedwater tank.

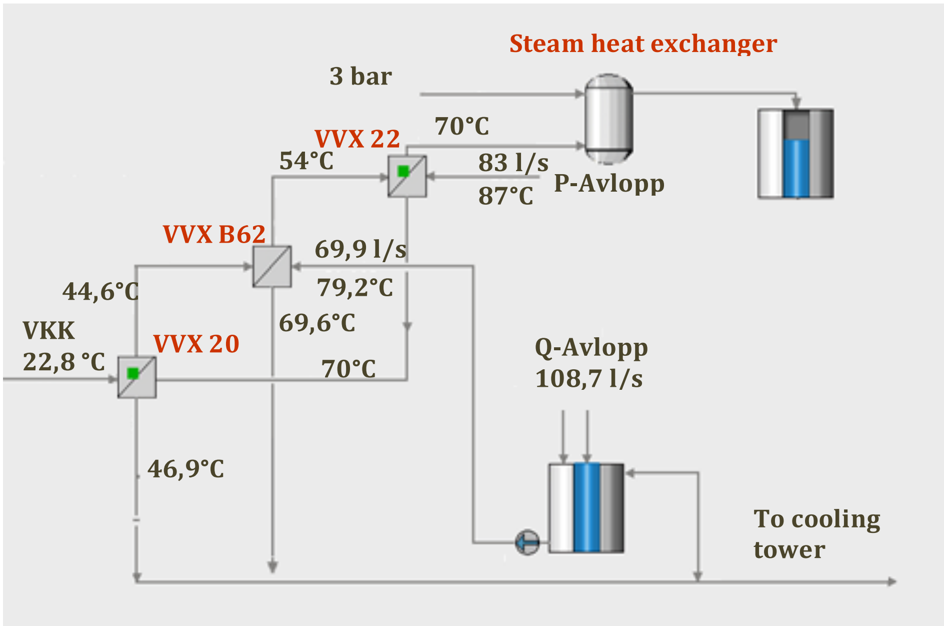

Figure 3.7: Illustrates the series of heat exchangers heating VKK. Additionally it illustrates the two counter flows, P-Avlopp and Q-avlopp that is cooled. The picture originates from SCM's internal monitoring system.

This 22,8 °C temperature will, as mentioned, be changed to 25°C as of the autumn of 2018. As the VKK is heated by the three of the illustrated heat exchangers, it cools the counter flows - *'P-avlopp'* and '*Q-avlopp'*. If the VKK will be 35 °C at the initial stage, it will further affect the temperature of the two flows.

The two flows join up prior to being distributed to a cooling tower, which is followed by the biological treatment basin. This basin is, as mentioned, strictly temperature dependent and if the VKK enters at 35 °C in heat exchanger VVX 20, both flows will be warmer before they join prior to the cooling tower. By accident, the basin reached 38°C during week 31 of 2018. As a result, the water treatment in the basin was affected for three weeks due to deceased bacteria[1].

The temperature of the basin is dependent on the cooling tower which the two flows pass prior to the basin. After speaking to experienced SCM employees, it was concluded that the cooling tower should be able to cool approximately 470 liters of 60 °C water per second to 36 °C[3]. Consequently, the tower can cool warmer water to required temperatures in case of a smaller flow. However, during the summer of 2018, problems occurred at 360 l/s and 60 °C. The long-lasting warm temperature outside caused a decreased performance of the tower. This event affected this study since the planned steps of a potential turbine installation must consider a lower performance of the tower. Due to this, any planned arrangement and/or solution must be able to function in the case of further warm summers. For the outcome of this study, the requirements must therefore consider that the two flows can not exceed 60 °C when conjoining prior to the cooling tower. It is assumed that the cooling tower will be unable to cool the two flows *'P-avlopp'* and '*Q-avlopp'* to 36°C if the water exceeds 60°C, regardless of the flow.

Attempts were made to estimate the outgoing temperature of the two flows *'P-avlopp'* and '*Q-avlopp'* whilst the ingoing VKK temperature was set to 35°C. Due to the connections between the heat exchangers however, it was difficult to approximate the outcome of a VKK temperature of 35°C. This resulted in an iterated function. Attempts were made to iterate in Excel but due to the fact that some variables must be fixed, such as the effect, K-value or temperature, the estimation was hard to obtain as these variables also depend on one another. These attempts therefore failed due to too many unknown variables. The maximum temperature of VKK in this process is therefore not yet decided. Further assumptions were therefore used for this study which were considered in the solution for this process. These will however be discussed in *Section3.4.3*.

3.2.4 Mixbeds

As a consequence of warmer VKK, VKT from the water treatment plant, seen in blue in *Figure 3.8*, will also be warmer. Just as in the case for VKK, VKT ends up in a feedwater tank where steam is added to maintain the required temperature of 125°C. In *Figure 3.8*, the steam can be seen as a flow of 6,1 kg/s. In this tank, illustrated in the top right corner in *Figure 3.8,* VKT is mixed along with newly produced VKT from the mixbeds, seen in yellow.

The condensed steam is prior to the tank, as earlier mentioned, distributed through a series of mixbeds to deionize the water from cat- and anions. The condensed steam needs to be cooled before taken to the beds. This is because the filters, that the condensate is taken through, contains plastic pores. If the water is too warm, the pores are destroyed and the active surface that is deionizing the condensate is decreased. Historically, when the condensate has been too warm, it has resulted in damages and large restoring costs approximated to 100 000 kronor each time [1].

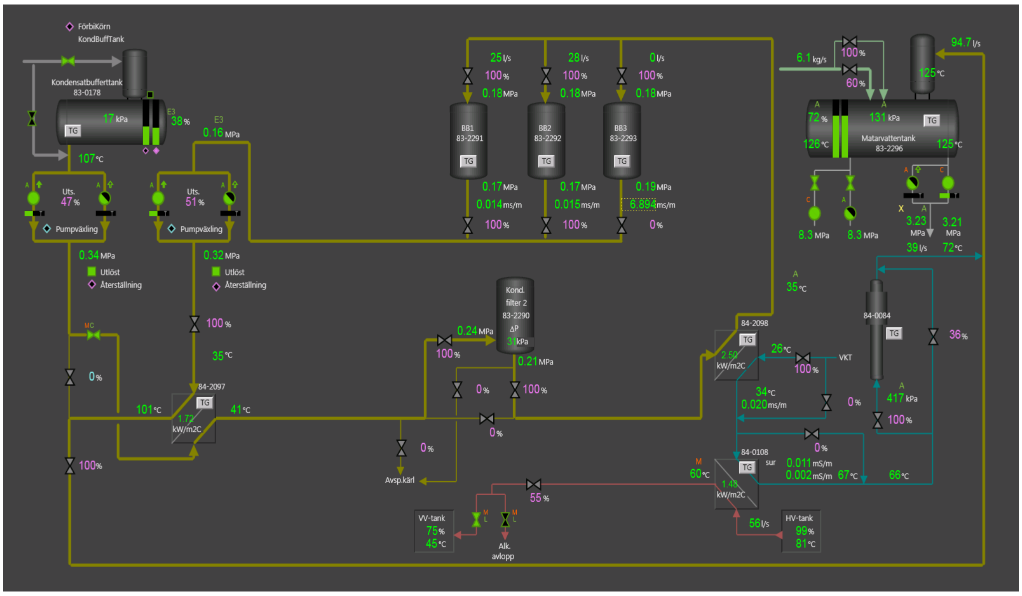

Figure 3.8: Illustrates the process chart of condensed steam, in yellow, distributed to the mix beds and prior to this cooled in a heat exchanger with VKT, in blue. The picture originates from SCM's internal monitoring system.

Since the VKT needs to be heated and the condensed steam needs to be cooled, a heat exchanger is currently used to enable this exchange. The heat exchanger can be seen in *Figure 3.8*, with the VKT as the cold medium and the condensate as the warm. The condensate is thereafter taken to the mixbeds BB1, BB2 and BB3.

Since the temperature of the condensate within these beds is essential, a 10°C warmer VKT may have an impact, causing negative consequences. Data was found in the archive and the temperature of the condensate cannot exceed higher than 50°C (SCM 2018). This does, however, only consider the temperature of the condensate, not that of the VKT. To maintain a safety marginal, 45°C was set as a maximum for the condensate. Additionally, as can be seen in *Figure 3.9*, the average temperature of VKT during May-July was 23°C before entering the heat exchanger and the condensate was 12°C warmer, that is 35°C, after exiting the heat exchanger.

Since both average flows are approximately the same, assumptions were made that an increase of VKT from 23°C to approximately 35°C would result in an increase in temperature of the condensate from 35°C to 47°C, that is 12°C warmer. The margins are therefore exceeded and the absolute maximum temperature of 50°C is near. The maximum temperature of the VKT should therefore be 12°C colder than 45°C, that is 33°C.

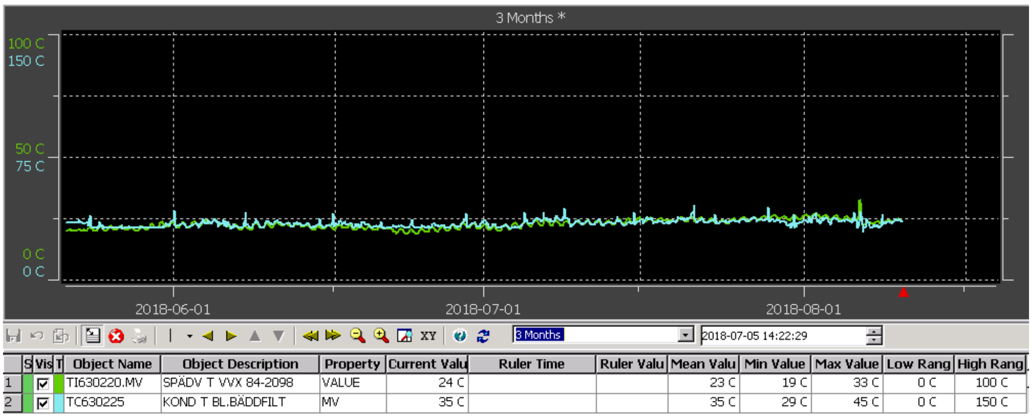

Figure 3.9: The temperature of VKT before entering the heat exchanger and that of the condensed steam before entering the mixbeds from May-July 2018. The picture originates from SCM's internal monitoring system.

3.2.5 Compressors

The compressors at SCM are used to produce pressured air. There are three major compressors, with two of them using VKK as cooling water. The third compressor uses VKM. The incoming cooling water must stay below 40°C according to instructions found in the archive (SCM 2018). A VKK temperature of 35°C is therefore acceptable. However, the quality of the compressed air can be affected by an increase in temperature. When the cooling water is warmer, so is the entire compressor and its condenser. The air from the condenser consequently contains more water[1]. Employees at SCM were asked regarding which VKK temperature that is required to maintain the quality of the air, with the response of a temperature not exceeding 24°C[1].

3.2.6 Vacuum pumps

There are multiple pumps in use at SCM. A number of them were identified as being critically affected in case of warmer VKK. In addition to the feedwater pumps, the vacuum pumps are believed to be affected by warmer VKK. The vacuum pumps are used in the drying stage of the paper pulp. When the paper pulp is produced it contains much water which needs to be removed. The vacuum pump achieves this by sucking the water out of the pulp. The pumps are cooled by the VKK, or additionally, the pumps use the VKK to cool the air that creates the vacuum.

Two sets of vacuum pumps were identified as being affected with warmer VKK: the Sulzer pumps and the Nash pumps. Both sets of pumps are located within the same area of the factory. While the pumps are both vacuum pumps and cooled with VKK, their usage of VKK differs and they will therefore be investigated separately below.

3.2.6.1 Sulzer pumps

As in the case for the feedwater pumps, the Sulzer pumps are indirectly cooled with VKK and directly cooled with oil. The restrictions of the oil, found in the archives, are temperatures preferably between 35 - 40°C but must not exceed 50°C (SCM 2018). This does, however, only consider the temperature of the oil, not that of the VKK. The requirement for the VKK is not set since it depends on external factors, such as the outside air temperature. As long as the oil does not get too warm, the temperature of the VKK can vary. To gain a better understanding of the correlation between the temperature of the VKK and that of the oil, historical data of the two temperatures from May - July were analyzed and are presented in *Figure 3.10*. It is evident that the mean temperatures of the oil in the two different Sulzer pumps are 32 and 33°C, whilst the mean temperature of the VKK is 23°C.

The conclusion is therefore that the VKK is, on average, 10°C colder than that of the oil. Since the requirement of the oil temperature is 35 - 40°C during preferred conditions, the temperature of the VKK should preferably be 25 - 30°C, that is 10°C cooler.

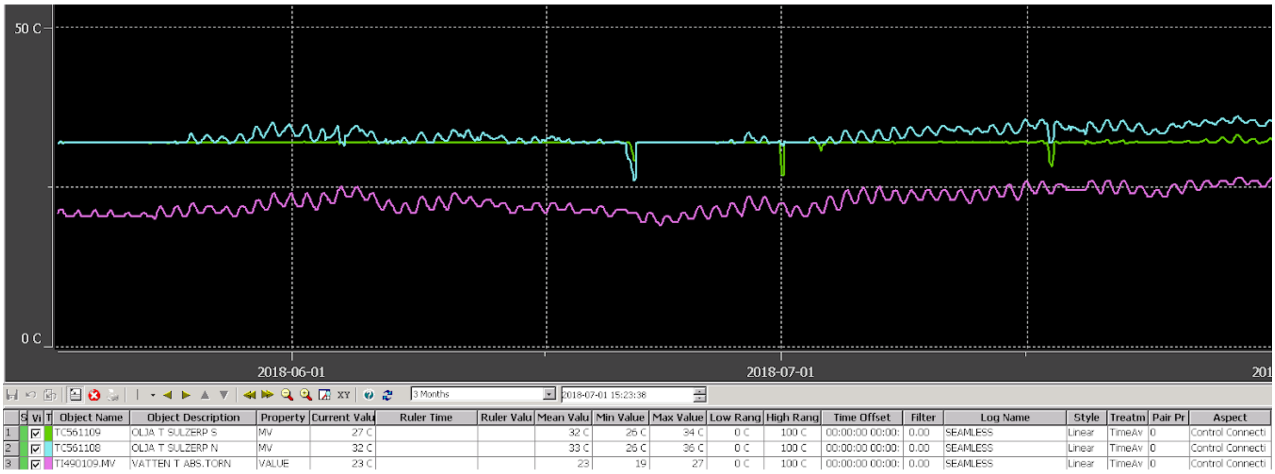

Figure 3.10: *The temperature of the VKK, purple, cooling the oli that cools the sulzer pumps. Additionally, the temperature of the oil, blue and green, is illustrated. The data is from May-July 2018. The picture originates from SCM's internal monitoring system.*

3.2.6.2 Nash pumps

There are 4 Nash pumps at SCM and, unlike the Sulzer pumps, they are cooled directly with VKK. The recommended operating temperatures for these pumps where found to be 60 - 93°C (SCM 2018). The requirement for the cooling water was however not found and the supplier was therefore contacted. According to the supplier, Follatech[4], there are no restrictions of the VKK temperature, as long as sufficient cooling of the pumps is reached. Since the temperature of the pumps are monitored and the temperature interval is known, SCM can ensure that this sufficient cooling is achieved. While there are no restrictions of the VKK temperature, the temperature of the pumps does affect the frequency of service among other factors.

A warmer VKK will result in a higher demand of VKK flow to ensure that the required temperatures of the pumps are maintained. An approximation of this increase was difficult to estimate since the flow of this VKK is not monitored. However, after speaking to employees at SCM, it became clear that the flow of VKK used to cool these pumps are insignificantly low and an increase will not affect the overall factory[1].

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[4] Private communication with Mats Elofsson, Sales manager at Follatech, skype meeting at the 14th of August 2018.

One effect of warmer VKK however, will be the performance of the pumps. According to the operating instructions found in the archives, VKK is used to cool the air that is further used to evacuate water from the pulp (SCM 2018). It was further noticed that the maximum capacity is 84 m3 air per minute (Ibid). If the temperature increases, the capacity of air decreases. At 25°C, air has a density of 1,184 kilos / m^3 and at 35°C it has a density of 1,145 kilos / m^3 (Boles & Cengel 2015). The 10°C interval further decreases the amount of air with 3,4% according to the *Calculation 3.2*:

$$100 \cdot \left(1 - \frac{1{,}184}{1{,}145}\right) = 3{,}4\% \qquad \text{Calculation 3.2}$$

Thus, the performance of the Nash-pumps will decrease by approximately 3,4 % if the temperature of VKK increases from 25°C - 35°C. The cooling will, however, not be affected.

3.2.7 Mechanical seals

A majority of the pumps installed at SCM have a mechanical seal to prevent leakage from the pumps. VKK is used for the cooling of these seals. After talking to the supplier of the seals, John Crane, it was clarified that the seals can operate with a 35°C VKK[5]. The seals will, however, demand a higher flow to ensure sufficient cooling. This is due to the cooling operation of the seals that is thermostatically controlled.

VKK cools the seals so that they maintain a temperature of around 65°C. When VKK cools the seals, the water is consequently heated. When VKK has reached 65°C, it is released and replaced with new, cooler VKK. The result of a warmer ingoing VKK will be a shorter residence time, which will increase the flow needed to cool the seals[5].

To gain an idea of the potential flow increase, an approximation was done in Excel. The values of the historical flows from the 2nd February to the 3rd August, 2018, were entered in a diagram along with the temperature at that time. The historical flows were limited and hence did not consider the flow to all of the mechanical seals at SCM. However, the percentage increase can be considered since the overall flow of VKK to the mechanical seals is known at approximately 40 l/s[1]. Even though the temperature of 35°C has never been reached, an approximation could be carried out according to the figure and obtained trend line in *Figure 3.10.*

[5] Private communication with Håkan Zetterling, Sales at John Crane Sverige AB, skype meeting at the 13th of August 2018.

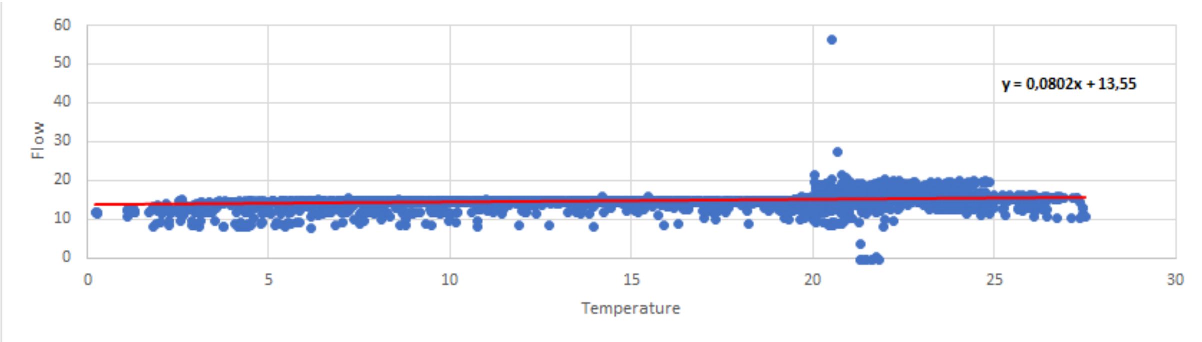


Figure 3.10: Illustrates the correlation between the temperature and the flow of VKK cooling the mechanical seals between the 2nd February and 3rd of August 2018. A trend line, red, is added.

After adding a trend line, seen in red in *Figure 3.10* above, the equation for the linear regression, *Equation 3.1*, could be obtained

$$Y = 0{,}0802X + 13{,}55 \qquad \text{Eq.3.1}$$

where X equals the temperature and Y the flow.

After putting X equal to 35°C, the obtained flow is 16,36 l/s. The average considered flow from the previously mentioned dates is 14,9 l/s. The approximated increase is hence 9,8%. If the approximated overall flow is 40 l/s, the increased flow of 9,8% is consequently 4 l/s. In this context, 4 l/s is considered small and insignificant.

An alternative calculation, that is *Equation 2.14*, can also be used to estimate the increase in flow, just as the equation can be used to estimate the effect in a heat exchanger. The reasoning is valid since the water must be able to reach the required cooling and if the temperature of the water increases, the flow must increase as well, just as in the case for a heat exchanger. It is hence a required effect that must be reached. An alternative estimation of the increase in flow was calculated in *Calculation 3.3* according to *Equation 2.14,* where C_p has been divided on both sides.

$$\delta T_1 \cdot Q_1 = \delta T_2 \cdot Q_2 \rightarrow (65 - 25)°C \cdot 40\frac{l}{s} = (65 - 35)°C \cdot Q_2 \rightarrow Q_2 = 53\frac{l}{s} \qquad \text{Calculation 3.3}$$

The increase to 53 l/s is also believed to be insignificant for SCM[1]. The chosen considered increase in flow, that is between approximately 44l/s or 53l/s, therefore does not matter for the outcome of this study.

3.2.8 Summarizing

Section 3.2 explained and discussed the identified critical processes, and in some cases the possible consequences, of warmer VKK. The VKK was, in most of the cases, used for cooling and the eventual consequences will hence be a decreased cooling capability. The processes and their temperature requirements of VKK are summarized in *Table 3.2*.

Table 3.2: A summary of the temperature requirements for the identified processes in Section 3.2.

Critical process	***Requirements***	***Other***
Feedwater pumps	20-45 °C	Pureness important
Variable speed drives	Maximum 27°C	-
ClO_2 - absorption tower	Maximum 25°C	-
Mixbeds	Maximum 33°C	-
Heat exchangers for VKK heating	-	-
Compressors	Maximum 24°C	-
Mechanical seals	No maximum	A 9,8% increase in flow
Sulzer pumps	25-30°C	-
Nash pumps	No maximum	A 3,4% decrease in performance

3.3 Synergies

Increasing the VKK temperature from 25 to 35°C not only results in costs originating from problems mentioned in *Section 3.2* but also results in synergies. That is, further positive outcomes are associated with the installation of a steam turbine and the generation of electricity. These synergies are discussed below.

3.3.1 Heating of VKK

After the VKK has passed through numerous equipment and processes, a section of it will be heated before it is distributed to the feedwater tank, illustrated in *Figure 3.7*. The flow of VKK distributed to the series of heat exchangers varies throughout the year. The average flow between the months of February and August was 69,69 l/s.

After being heated in the three heat exchangers, VKK is again heated prior to being lead into the feedwater tank, however this time by steam. Coincidentally, this is the 3 bar steam also used in the turbine. This consequently means that with a higher initial temperature of VKK, less steam is needed in this step to heat the VKK. This further results in a higher amount of excess steam that is available for electricity production in the turbine. The additional excess steam will hence depend on the extra energy that VKK has when it enters the steam heat exchanger. This extra energy further depends on the mass flow of the water and its temperature increase. The temperature increase is 10°C and a realistic mass flow can be approximated from the average flow between February and August, that is 69,69 l/s, to 69,69 kg/s.

With a known water temperature, the enthalpy of the water is thus also known (Boles & Cengel 2015). The addition of extra energy to this heat exchanger, as a consequent of warmer VKK, is calculated according to *Equation 3.2* and summarized in *Table 3.3*.

$$\text{Increased energy } kj/s = Q\ kg/s \cdot \Delta h\ kj/kg \qquad \text{Eq.3.2}$$

Where Q equals the mass flow and h the specific enthalpy at each temperature, that is 104,83 kj/kg at 25°C and 146,64 kj/kg at 35°C (Ibid).

The extra energy addition from a VKK flow of 69,69 kg/s with a temperature increase from 25 - 35°C is calculated in *Calculation 3.4*:

$$69{,}69\ kg/s \cdot (146{,}64-104{,}83) kj/kg = 2914\ kj/s \qquad \text{Calculation 3.4}$$

With known information about the pressure and the temperature of the steam, that is 3 bar and 155°C, its energy content per kg is known after interpolating in *Table A-6* in Boles & Cengel, that is 2739 kj/kg. With this information, the decreased demand in steam was calculated in *Calculation 3.5* since it equals the extra energy added (Ibid).

$$\frac{2914\ kj/s}{2739\ kj/kg} = 1{,}064\ kg/s \qquad \text{Calculation 3.5}$$

Another positive outcome is the ability to control the temperatures of the two flows - *'P-avlopp'* and *'Q-avlopp'*. During warm summers, such as in 2018, there may be a demand for a solution regardless of the installation of the turbine and the further temperature increase of VKK. As mentioned, these flows were accidentally too warm during a period, which caused problems in the biological treatment basin and deceased bacteria. Two positive outcomes are therefore obtained if a solution controls the temperature of the flows in *Figure 3.7*. These are:

- Ensuring that the installation of the turbine can proceed as well as enabling an increased electricity production with a further addition of steam, that is 1,064 kg/s.
- Controlling the temperature of the water flowing to the cooling tower located before the biological treatment basin. This might be needed regardless of the installation of the turbine.

3.3.2 Mixbeds

An additional synergy from heating the VKK is the warmer VKT that originates from the water treatment plant. This is because the VKT produced at the water treatment plant is produced from VKK and therefore also has the same temperature. This synergy can be visualized in *Figure 3.8*, where the VKT (in blue) becomes approximately 35°C instead of 25°C. This is mixed along with the condensate (in yellow) and further distributed to a feedwater tank with a desired temperature of 125°C. To maintain the temperature of 125°C, steam at 3 bar is used to heat the tank. If VKT is warmer, less steam is needed to reach the required temperature for the feedwater. Consequently, the turbine receives more steam, since less is needed for the feedwater tank. Using the same interpretation as in *Section 3.3.1*, the average mass flow between February and August can be approximated to 54,4 kg/s.

Equation 3.2 was used again in *Calculation 3.6,* but to calculate the extra energy addition from a VKT flow of 54,4 kg/s with a temperature increase from 25 to 35°C. It is further summarized in in *Table 3.3*.

54,4 kg/s · (146,64-104,83)kj/s = 2274 kj/s Calculation 3.6

The decreased demand of steam was in *Calculation 3.7* calculated to:

$$\frac{2274\ kj/s}{2739\ kj/kg} = 0{,}83\ kg/s \qquad \text{Calculation 3.7}$$

While warmer VKT enables this synergy, the installation of a turbine still requires a solution so that the condensate is not to warm when it enters the mixbeds. A positive outcome, as a result of such a solution, is the ability to control the temperature of the condensate flowing towards the mixbeds. Historically, there has been a demand for controlling this temperature due to too warm VKT. This results in warmer condensate which is damaging the an- and cation pores in the beds. By solving the problem in this process, it will prohibit these damages as well as enabling a higher VKT temperature and consequently additional steam of 0,83 kg/s to the turbine. In this case, a solution for the problem might be a good investment regardless of the turbine installation since the cost to restore the beds is high.

3.2.3 Heating of VHA

A similar synergy as that of the heating of VKK and VKT, described above, is obtained from the warmer VHA. This is due to the fact that the VHA originates from VKK and therefore also has the same temperature. As can be seen in *Figure 3.11,* VKA enters from the left and is heated in a series of heat exchangers to become VHA. VKA is heated by steam in the last heat exchanger. Again, this is the 3 bar steam that is also used for the electricity production in the turbine. A similar reasoning to that of the heating of VKK and VKT can be carried out for VKA, since warmer water added to the heat exchanger consequently results in less steam needed. In *Figure 3.11*, 1,75 kilo steam ,'*Ånga*', was added per second.

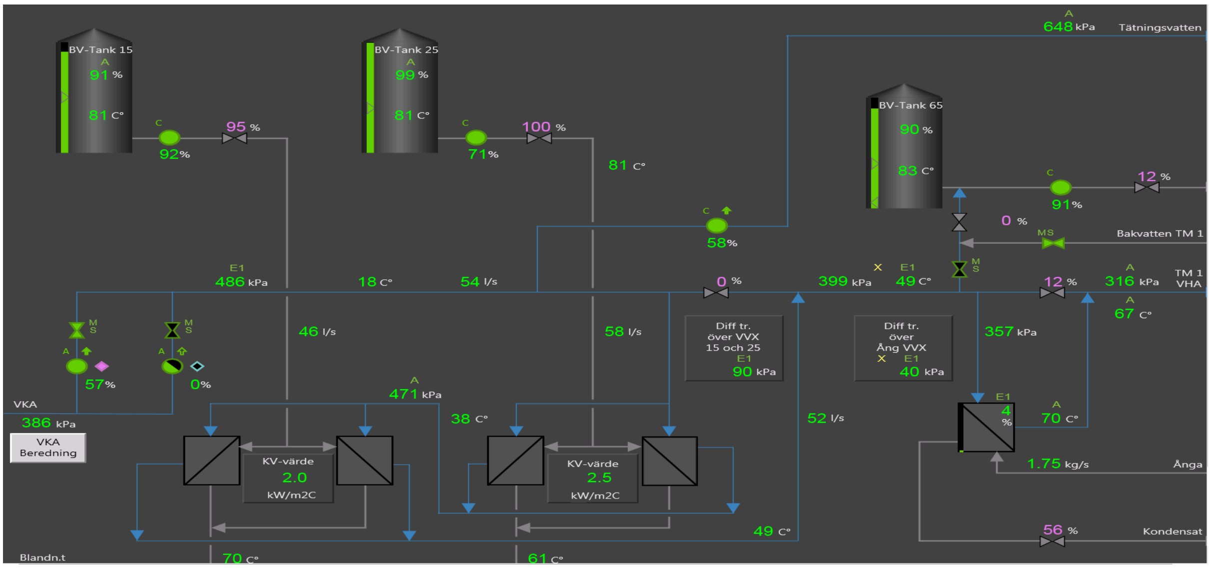


Figure 3.11: Is the process chart of the heating of VKA, in blue, to VHA. The picture originates from SCM's internal monitoring system.

Using the same interpretation as in *Section 3.3.1*, the average mass flow, in this case between May and August, can be approximated to 49,9 kg/s.
The extra energy addition to this heat exchanger, as a consequence of warmer VKA, is calculated according to *Equation 3.2* and summarized in Table 3.3.

The extra energy addition from a VKA flow of 49,9 kg/s and a temperature increase from 25 to 35°C was calculated in *Calculation 3.8*:

$$49{,}9 \text{ kg/s} \cdot (146{,}64\text{-}104{,}83) \text{ kj/s} = 2087 \text{ kj/s} \qquad \text{Calculation 3.8}$$

The decreased demand of steam was calculated in *Calculation 3.9*:

$$\frac{2087\ kj/s}{2739\ kj/kg} = 0{,}76\ kg/s \qquad \text{Calculation 3.9}$$

3.2.4 Summary

Three locations at SCM were identified where a warmer VKK can result in a synergy. Since these locations include heating of VKK, or water initially produced from VKK, the demand of steam can decrease if the VKK is warmer. In all these locations, heat is increased by adding 3 bar steam. If less steam is required for the heating of water, more steam is consequently available for electricity production in the turbine. The synergies at the 3 locations are summarized in *Table 3.3* with the sum of the additional excess of stem is equal to 2,65 kg/s. With an average excess of steam distributed to the turbine of 7,04 kg/s, see *Table 3.1*, these synergies results in an increase to 9,69 kg/s, that is an increase of 37,7%.

Table 3.3: A summary of the amount of saved steam with 10 °C warmer flows.

	Flow kg/s	***Temperature***	***Enthalpy kj/kg***	***Effect kj/s***
VKK flow	69,69	Increase = 25°C to 35 °C	Increase = 146,64-104,83	2914
VKT flow	54,4			2274
VHA flow	49,92			2087
Increase in effect, sum				7275
Steam		155°C	2739	2739 $\cdot kg^{-1}$
Saved steam = 7275 kj/s/ 2739 kj/kg = 2,65 kg/s				

3.3 Further positive outcomes

In *Section 3.2* above, 3 synergies were identified and quantified. In this section, further positive outcomes will be discussed.

3.3.1 Exchanging VKK to VKM

Many processes at SCM use VKK, which is more pure than VKM. A general ambition at SCM is that cooling with VKK is used only with processes that require pure water. This is so that pure water is not used unnecessarily. Therefore, exchanging VKK to VKM, is, in general, beneficial.

3.3.2 Compressor

Another positive outcome deals with the 3 compressors at SCM. What became clear from interviewing employees at SCM is that an increase in VKK temperature, to be used by the compressors, is not just critical in regards to the actual cooling effect but also from a performance perspective, as explained above.

The summer of 2018 is considered to have been abnormally hot and VKK occasionally reached 26°C. At this point, cooling was critical for the compressors and employees explained that the quality of the air was affected. A scenario with a 35°C VKK would therefore be devastating and unsustainable in a situation with such hot summers. However, regardless of whether a turbine is installed, there is still a demand for a solution that can ensure the cooling of the compressors. This point is even more valid if the temperature of VKK is set to 25°C all year around, considering the requirement of keeping it under 24°C. A solution will therefore enable both the installation of the turbine as well as keeping the temperature of the compressors below 24°C, which may be needed regardless.

3.3.3 Feedwater pumps and variable speed drives

Cooling of the variable speed drives was also insufficient during the warm summer of 2018, where the VKK reached 26°C. Furthermore, cooling was insufficient without any further heating of VKK, such as that from a potential turbine. Employees at SCM explained that the entire factory was close to being temporarily shut down due to this insufficient cooling[1]. Since the variable speed drives require a cooling water, currently VKK, below 27°C, at 26°C the drives were still able to function. If the VKK is set to be 25°C all year around, warm summers can create further problems, regardless of the installation of the turbine. Solving this problem might therefore be needed anyway.

While the feedwater pumps will remain unaffected by the potential VKK temperature increase, positive outcomes will still occur at such a temperature rise. As aforementioned, the cooling of the oil is occasionally turned off and heat is sometimes needed so that the oil does not get too cold. During such circumstances, energy will be saved by having a warmer VKK, as the oil will be kept warmer in the colder months. While no data for these circumstances, such as oil temperature, is available, calculations regarding saved energy cannot be obtained. However, the positive outcome can be noted.

3.4 Investigated solutions for the identified critical processes

This section will give an overview of the solutions that were investigated for the problems identified earlier. For many of the problems, VKM will be offered as a solution. The maximum temperature of the suggested VKM is derived from historical data, as well as from estimations from experienced employees at SCM. The maximum temperature of the VKM will, according to the data, reach 26°C. However, a maximum temperature of 23°C will be considered, rather than 26°C. This 26°C temperature was modified to 23°C by SCM, as 26°C is very rarely reached and 23°C is the normal maximum summer temperature of VKM. The critical processes that will change to VKM from VKK will therefore have to be able to reach sufficient cooling when VKM reaches its maximum of 23°C.

3.4.1 Feedwater pumps and variable speed drives

According to the requirements of the cooling temperature for the feedwater pumps, an increase in VKK temperature to 35°C will not result in complications. No further investigation therefore took place regarding this. The variable speed drives however have a maximum cooling temperature of 27°C, much lower. Four options where investigated as a solution for this:

- A cooling tower. This is currently used at one of Södras other factories, Värö, for this purpose. An advantage of this is that less planning will be required if a similar design as Värö's can be used.
- A heat exchanger to cool the VKK flow with VKM.

- A pipe to separate approximately 3 liters of VKK per second, which avoids the turbine and leads directly to the variable speed drivers.
- Exchanging VKK to VKM.

The conclusions regarding these options are as follows:

- Contact was initiated with employees at the Värö factory. It was stated that the design of the cooling tower at Värö accounts for additional processes, which SCM does not require the tower for. Such a tower would therefore be over-equipped at SCM for the single purpose of cooling the variable speed drives.
- A heat exchanger will be more expensive compared to the chosen option below.
- Due to the distance between the water treatment plant and the variable speed drives, it does not financially justify a new pipe. This justification is considering the option of exchanging VKK to VKM, which is believed to be easier and is hence chosen. This was a qualified conclusion from experienced employees at SCM.

3.4.2 ClO_2 in the absorption tower

Since the maximum temperature of the VKK in this process is 25°C, installation of a new turbine, which will consequently increase the VKK temperature to 35°C, requires a solution. Further, the VKK cannot be exchanged to VKM, as is the case for the variable speed drives, since the purity of the water is essential. Two solutions were investigated:

- A pipe to separate approximately 28,2 liters of VKK per second, a number justified below, which avoids the turbine and leads directly to the absorption tower.
- A heat exchanger to cool the VKK flow with VKM.

The following conclusions were made:

- Pipes potentially installed to separate the VKK prior to the turbine will be complicated and the distance between the water treatment plant and the absorption tower cannot financially justify this option.
- Since a heat exchanger is cheaper and more practical to install, compared to the pipes that must be installed for the option above, a heat exchanger was chosen. While pipes will also be needed for a heat exchanger, this will not be as complicated. SCM made this qualified conclusion, which did not involve any calculations.

A potential heat exchanger was therefore investigated, where the cooling medium will be VKM. Additionally, an existing VKM pipe is already installed close to the bleaching process at SCM, seen in *Figure 3.3*, however is not in use. This will further simplify the installation of a heat exchanger.

The maximum flow of VKK towards this process was obtained by considering data from the internal monitoring system during 6 months, February to August, 2018. The maximum flow was 28,2 l/s and the heat exchanger must thus be able to cool this flow. With a maximum allowed temperature of the VKK set to 25°C, the required effect from a heat exchanger was in *Calculation 3.10* calculated according to *Equation 2.13* by assuming that the maximum flow of 28,2 l/s equals 28,2 kg/s and a constant C_p of 4,18 kj/kg·T.

$$28{,}2\frac{kg}{s}\cdot 4{,}18\,\frac{kj}{kg\cdot K}\cdot(35-25)°C = 1179kW \qquad \text{Calculation 3.10}$$

If the existing VKM pipe is to be used however, it must be large enough to allow a sufficient flow of VKM. The diameter of the pipe was measured at 150 mm. The temperature increase of VKM required for 1179kW can be calculated according to *Equation 2.15,* where A was set to 100 and K to 3. These values were obtained from the chosen heat exchanger, which is discussed in the next section. The values for these variables were however needed in order to investigate whether the dimension of the pipe is large enough for the required flow of VKM, which is done in this section. The detailed characteristics of the heat exchanger will however not be presented. The temperature increase of VKM was calculated to 29,81°C. The flow of VKM was additionally calculated according to *Equation 2.13* in *Calculation 3.11*.

$$1179kW = \frac{4{,}18\frac{kj}{kg\cdot K}}{(29{,}81-23)°C} = 41{,}4\frac{kg}{s} \qquad \text{Calculation 3.11}$$

According to experienced employees at SCM, a 150mm pipe is large enough for a flow of 41,4l/s. During summer time, VKM temperature might occasionally be higher, with temperatures of up to 26°C reached. As a result, the amount of ClO_2 in the residual gas will increase compared to if the VKM temperature stays below 25°C. This can be monitored and if the threshold limits are exceeded, the turbine output must be adjusted so a colder VKK is obtained. The temperature of 25°C was however set with the intention of having some margins and experienced employees at SCM believe that warmer VKK during certain periods is tolerable.

The data sent to heat exchanger suppliers for a budget offer were the criteria in *Table 3.4.* These must be fulfilled for the possible heat exchanger.

Table 3.4: Data sent for a budget offer of a heat exchanger potentially to be used to cool VKK before being used in the residual gas tower.

	Heat exchanger for VKK in residual gas tower
Warm in (VKK) °C	35
Warm out °C	25
Maximum flow (VKK) l/s	28,2
Cold in (VKM) °C	23

3.4.3 Heating of VKK

As mentioned, the VKK that enters heat exchanger *'VVX 20'* in *Figure 3.7* will increase to 35°C. Due to connections between the heat exchangers, it was hard to estimate a potential temperature increase of the '*P-avlopp'* and '*Q-avlopp'* after the increase of VKK temperature. Since this outcome was unknown, it was difficult to initiate what solution that would be most suitable. Moreover, it was also hard to estimate what the dimensions of such a solution would have to be. A decision was made by SCM to investigate whether additional heat exchangers should be invested that are cooled with VKM. These could then be used to cool the two flows- '*P-avlopp*' and '*Q-avlopp*', to prevent the flows from being too warm when entering the cooling tower.

The series of heat exchangers were recently modified as heat exchanger *'VVX B62'*, see *Appendix 1,* replaced *'VVX 21'*, which was removed to have the final layout as in *Figure 3.7*. This location already has a platform for an additional heat exchanger. Moreover, pipes with VKM are already located nearby, which will simplify this installation if a heat exchanger were to be placed at the former location of *'VVX B62'*. In order to obtain a budget offer for this potential installation, historical data was analysed. However, in order to make conclusions of which relevant data should be sent to a supplier, certain assumptions had to be made. These assumptions were based on the following:

- Data from a period of approximately 20 hours was chosen from the data collected over February to August, 2018. This identified period of data was chosen as it had a high sum of the values of both the flow and the temperature of the '*P-avlopp'* and '*Q-avlopp*' exiting '*VVX 20'* and *'VVX B62'*. The reason that the sum of the 2 values was used is that the maximum value of temperature and flow, separately, often occur at different times. Therefore, if both these maximums were considered separately when planning, the heat exchanger will be too large. The consequence of this assumption is that the budget offer was based on the maximum sum of the flow and the temperature occuring at the same time.
- During this 20 hour period selected, the maximum flow and temperature of '*P-avlopp'* and '*Q-avlopp*' were identified and further considered.
- The maximum temperature was then modified. Since the average temperature of VKK will increase 10°C, the maximum temperature within the identified time period will increase by 70% of the VKK increase, that is 7°C instead of 10°C. This increase was estimated by employees at SCM.

The flow and modified temperature during the identified 20 hours is presented in *Table 3.5.*

Table 3.5: Presents the obtained and modified values from an identified 20h period from February to August 2018.

	Average flow l/s	***Maximum flow l/s***	***Average temperature °C***	***Maximum temperature °C***	***Modified maximum temperature °C***
VVX 20	111,9	112,9	63,9	67,69	74,69
VVX B62	84,2	84,79	75,7	78,53	85,53

The flows and temperatures considered are illustrated in *Figure 3.12.*

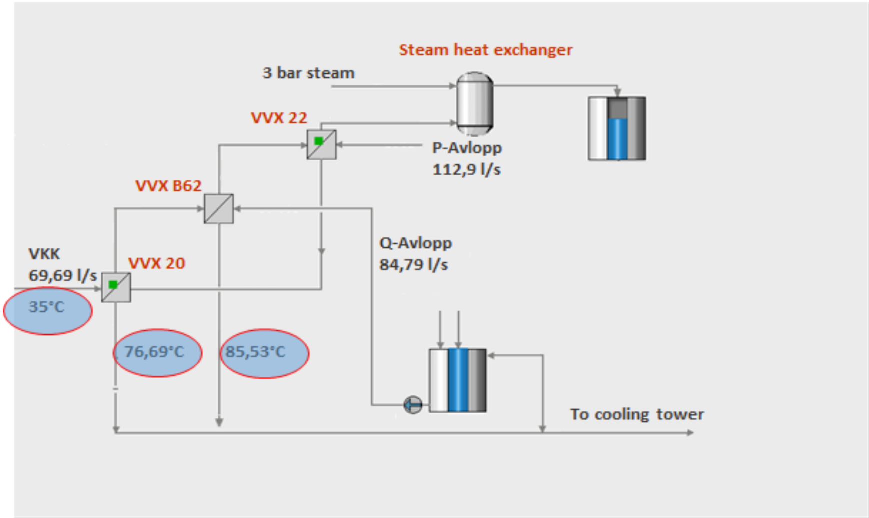


Figure 3.12: Illustrates the modified values of temperature and flow of VKK, P-avlopp and Q-avlopp in the serie of heat exchangers also illustrated in Figure 3.7. The picture originates from SCM's internal monitoring system but with the relevant values modified.

Initial assumptions were made that the removed heat exchanger *'VVX 21'* could be reused for this study. The effect of this heat exchanger was 11 290kW but it is believed by SCM employees that it only functions at approximately half of this, that is 5645 kW. The lowest temperature that this heat exchanger can decrease the *'Q-avlopp'* to was obtained from *Equation 2.13* and was calculated in *Calculation 3.12,* where the maximum flow in l/s was assumed to equal kg/*s*.

$$84{,}79\frac{kg}{s} = 4{,}18\frac{kj}{kg \cdot K} \cdot (85{,}53 - T)°C = 5645\ kW \qquad \text{Calculation 3.12}$$

This gives a T value of 69,6°C.

Since the maximum allowed temperature of the 2 flows combined is 60°C, the temperature that the *'P-avlopp'* flow must be decreased to was obtained from the following correlation in Calculation 3.13:

$$84{,}79\frac{kg}{s} \cdot 69{,}6°C + 112{,}9\frac{kg}{s} \cdot T\ °C = \left(84{,}79\frac{kg}{s} + 112{,}9\frac{kg}{s}\right) \cdot 60°C \qquad \text{Calculation 3.13}$$

which gives a T value of 52,78°C.

However, it was further clarified by employees at SCM that heat exchanger *'VVX 21'* would be unable to be used for this study. Two alternatives were therefore investigated.

1. Two heat exchangers could be installed, one for each flow - ‘*P-avlopp’* and ‘*Q-avlopp*’, after the existing heat exchangers ‘*VVX 20’* and *‘VVX B62’*. For simplicity, these 2 potential heat exchangers should fulfill the same criterias as the the two calculated above, which were obtained in *Calculation 3.14-3.15*:

   $$84{,}79\,\frac{kg}{s} = 4{,}18\,\frac{kj}{kg\cdot K}\cdot(85{,}53-69{,}6)°C = 5645\,kW \qquad \text{Calculation 3.14}$$
   $$112{,}9\,\frac{kg}{s} = 4{,}18\,\frac{kj}{kg\cdot K}\cdot(74{,}69-52{,}78)°C = 10\,339{,}8\,kW \qquad \text{Calculation 3.15}$$

   The heat exchanger used for ‘*Q-avlopp*’ will be located at the former location of ‘*VVX B62*’.

2. One larger heat exchanger could be installed at the same location as where *‘VVX B62’* was located. The *‘P-avlopp’* flow would therefore remain unchanged. This heat exchanger must be able to decrease the temperature of the ‘*Q-avlopp*’ so that the two flows combined will be a maximum of 60°C. The required temperature of *’Q-avlopp’* was calculated in *Calculation 3.16*:

$$84{,}79\,\frac{kg}{s}\cdot T°C + 112{,}9\,\frac{kg}{s}\cdot 74{,}69\,°C = \left(84{,}79\,\frac{kg}{s} + 112{,}9\,\frac{kg}{s}\right)\cdot 60°C \qquad \text{Calculation 3.16}$$

   which gives T a value of 40,43 °C.

   The required effect of the heat exchanger must therefore be able to reach 15 984 kW, obtained from *Calculation 3.17* by using *Equation 2.13*:

$$84{,}79\,\frac{kg}{s}\cdot 4{,}18\,\frac{kj}{kg\cdot K}\cdot(85{,}5-40{,}4)°C = 15\,984\,kW \qquad \text{Calculation 3.17}$$

The following data in *Table 3.6* was thereafter sent to possible suppliers. *Appendix 2 and 3* illustrates the locations for the possible heat exchangers.

Regarding the alternative with 2 heat exchangers, the data for option 1, presented in *Table 3.6*, was sent to suppliers for a budget offer. The location is illustrated in *Appendix 2.*

For alternative 2, installing one large heat exchanger, the data for option 2 in *Table 3.6* was sent to suppliers for a budget offer. The location is illustrated in *Appendix 3.*

Table 3.6: Data sent for a budget offer of heat exchangers potentially to be used to cool Q-avlopp, and possibly P-avlopp, before being distributed to the cooling tower.

	Option 1; 2 heat exchangers.		***Option 2; 1 heat exchanger.***
	Heat exchanger 1; P-Avlopp	***Heat exchanger 2; Q-avlopp***	***Heat exchanger 3; Q avlopp***
Warm in °C	74,7	85,5	85,5
Warm out °C	52,8	69,6	40,4
Flow warm l/s	112,9	84,8	84,8
Cold in °C	23	23	23

3.4.4 Mixbeds

As previously stated, the margins of the condensate temperature will be exceeded with a warmer VKT. To avoid this and to ensure that the process remain unaffected, that is if SCM was to invest in a turbine, the installation of an additional heat exchanger was considered for this process. This heat exchanger will also be cooled with VKM. The dimension of such a heat exchanger is based on the following:

- The maximum value of the flow and temperature of the warm fluid, that is the condensate, is 97,6 l/s and 47,5 °C. This was based on data obtained from February to August, 2018. As a consequence of warmer VKT, warmer condensate will be obtained. An estimated maximum temperature of the condensate was therefore assumed to be 10°C warmer, that is 57,5 °C, since both flows of VKT and the condensate is approximately the same. The possible heat exchanger must therefore be able to cool this flow to 45 °C.

The data sent to suppliers for a budget offer is presented in *Table 3.7*:

Table 3.7: Data sent for a budget offer of a heat exchanger potentially to be used to cool the condensed steam prior to entering the mixbeds.

	Heat exchanger for condensed steam
Warm in (VKK) °C	57,5
Warm out (VKK) °C	45
Maximum flow (VKK) l/s	97,6
Cold in (VKM) °C	23

The effect of the heat exchanger was calculated according to *Equation 2.13* in *Calculation 3.18,* where the maximum flow in l/s was assumed to equal kg/s.

$$97{,}6\frac{kg}{s}\cdot 4{,}18\frac{kj}{kg\cdot K}\cdot(57{,}5-45)°C = 5100\ kW$$ Calculation 3.18

Of further concern was the pump that supplies the flow, which ends in the heat exchanger, see *Figure 3.8*. The concern regarded whether the pressure could be maintained after pressure losses that will occur in the potential heat exchanger. This was however not further investigated in this study.

3.4.5 Compressors

Since the requirement is a maximum of 24°C, continued usage of VKK is precluded. As 1 of the compressors is already cooled with VKM, this therefore became the investigated solution for the other 2. All compressors are located at the same location at SCM and this would therefore only require the installation and extension of pipes from the pre-existing compressors currently cooled with VKM.

3.4.6 Vacuum pumps

Just as how clarification of the problems regarding these pumps were discussed, this section will now consider the different pumps separately.

3.4.6.1 Sulzer pumps

Since the requirement of the VKK temperature is 25 – 30 °C, in order to maintain an oil temperature of 35 – 40 °C, a continued usage of VKK is precluded. The single option that was investigated in this study was to exchange the VKK to VKM. However, this exchange requires that a less pure water, that is VKM, can be used. This alternative was brought up at a meeting with employees at SCM. The conclusion was that VKM can be used, provided that a filter is installed prior to the cooling to prevent clogging of the pipes. The price for such a filter is however not considered in the cost analysis. The small flow of cooling water to the Sulzer pumps did not financially justify a heat exchanger compared to this solution.

3.4.6.2 Nash pumps

It has been established in this study that the Nash Pumps function with an increased temperature of VKK. However, an increased temperature may result in a decreased performance. Two options were therefore investigated as possible solutions for this process:

1 - Continued usage of VKK and a decreased performance.
2 - Changing to VKM, provided that cooling can proceed with less pure water.

In order to obtain a more qualified advisory opinion regarding the consequences of a higher temperature of VKK and the less pure VKM, contact was taken with the supplier, Follatech, about the two options. This was followed by a Skype meeting with Mats Elofsson of Follatech to clarify the following questions:

- Can the cooling water be less pure, such as VKM instead of VKK?
- If he could approximate any decrease of the performance as a result of warmer VKK.
- If there were other consequences, such as that of the lifetime, from using warmer cooling water or a less pure cooling water.

The following answers were given:

- It does not matter if the water is VKK or less pure, such as VKM. Lifetime and maintenance frequencies are not affected.
- In general, he recommends a maximum cooling water temperature of 25°C, since it otherwise would affect the performance. A decrease in performance of approximately 3,4 % seemed to be realistic.
- Overall, his recommendations were to choose the most economically advantageous option, that is between exchanging VKK to VKM, or continue with VKK but with a decreased performance[4].

Due to the complexity of calculating the consequences of a 3,4% decrease of the pumps, changing to VKM was considered in this study.

3.4.7 Mechanical seals

It has been established within this study that the mechanical seals function with an increased temperature of VKK. However, the increased temperature might result in an increased flow. After conversations with employees at SCM, it became clear that they would actually prefer an exchange from VKK to VKM. Two options were therefore investigated as possible solutions for this process:

1 - Continued usage of VKK and an increased flow.
2 - Changing to VKM, provided that cooling can proceed with less pure water.

To obtain a more qualified advisory opinion regarding the consequences of a higher temperature of VKK and less pure VKM, a range of mechanical seal samples were sent to the seal supplier, John Crane, which was followed by a Skype meeting with Håkan Zetterling of John Crane. The following questions were asked:

- Can the cooling water be less pure, such as VKM instead of VKK?
- Could he approximate any increase of the flow as a result of warmer VKK?
- Are there any consequences, such as that of the lifetime and the performance, if warmer cooling water or a less pure cooling water were to be used?

If the seals can operate with less pure cooling water, then the VKK can be exchanged for VKM, which, in general, is desirable. However, if both the purity and the temperature is essential, a heat exchanger is necessary to ensure the required cooling.

The answers given were the following:

- Theoretically, it should not create problems if the VKK were to be exchanged to VKM. On an important note however, is that the SCM factory does statistically have an exceptionally good lifetime on their mechanical seals, compared to other customers. The supplier believes this is due to the pure cooling water, that is VKK.
- The warmer cooling water will not affect the seals regarding lifetime and performance. However, a warmer cooling water will require a higher flow. The estimation that was calculated in this study, that is a 9,8% increase, was, according to him, a realistic increase.
- His qualified estimate was also that more humus and more dissolved particles from pipes will be a result of warmer cooling water. This will further affect the control systems of the seals, which will, in turn, cause large costs if damaged. He therefore recommended more frequent cleaning if warmer VKK is to be used as cooling water.
- Overall, his recommendations were continued use of VKK due to the statistical lifetime but a more frequent cleaning of pipes and of control systems[5].

The decision taken after the Skype meeting was therefore to continue using VKK, however with consideration taken to the more frequent cleaning of the pipes than currently performed.

3.4.8 Summary

Section 3.4 discussed the different solutions investigated. *Table 3.8* summarizes these solutions and *Figure 3.13* illustrates them. In appendix 4, an overview of *Figure 2.2* and *Figure 3.13* together is presented.

Table 3.8: A presents the different solutions investigated for each identified critical process.

Feedwater pumps	Continued usage of VKK
Variable speed drives	Change to VKM
Absorption tower ClO_2	Heat exchanger
VKK serie	Heat exchanger
Mixbeds	Heat exchanger
Nash pumps	Change to VKM
Sulzer pumps	Change to VKM
Compressors	Change to VKM
Mechanical seals	Continued usage of VKK

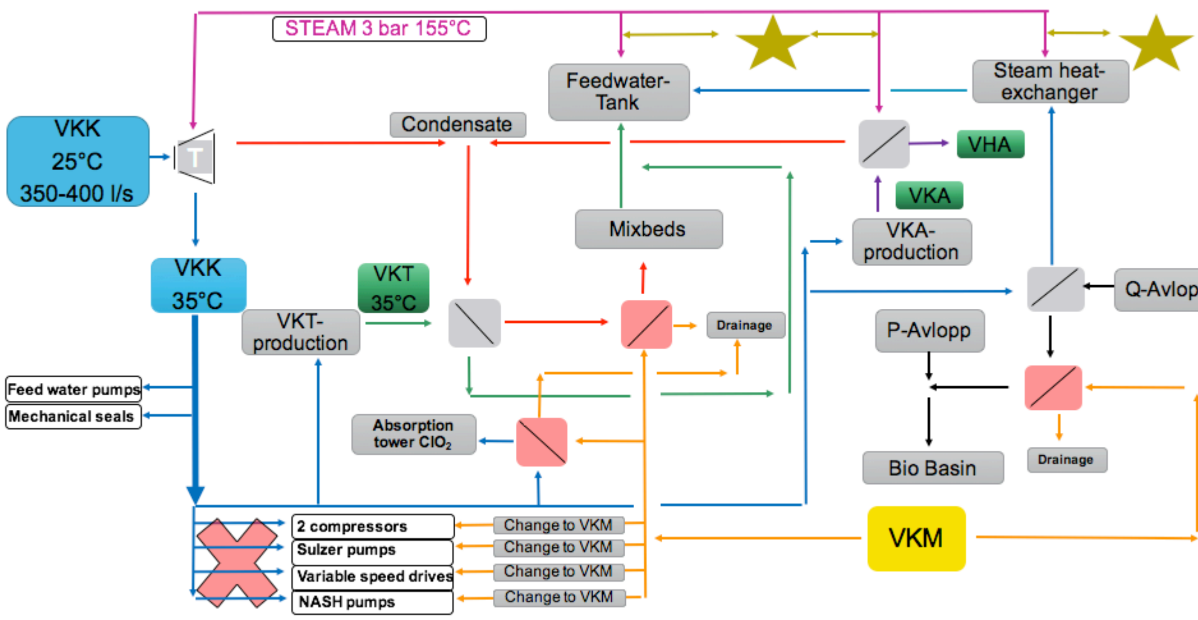


Figure 3.13: A summary of the affected flow, items and the suggested solutions where each colour represents a separate medium.The red heat exchangers are the suggested ones, the red cross symbolizes the repealed usage of VKK and the stars symbolizes the process where less steam is needed at warmer VKK.

3.5 Cost

The cost for the turbine installation cannot be derived only from the actual turbine. Solutions for the potential side-effects mentioned must also be ensured and the costs from this included. Additionally, the installation of all items, including the turbine, will need pipes and concrete, among other building materials and building associated costs. Another large cost would be the electricity and instruments for monitoring and controlling.

In this section, an overview of all costs associated with this study will be summarized. The actual items will, however, not be explained in detail. Every budget offer that was obtained is summarized in *Table 3.9, 3.10* and *3.12* and will be used in later sections when the profitability is examined. To gain a better perspective in regards to comparing one investment to another, the relevant performance is also summed up in *Table 3.10* and *3.12.*

The further costs were estimated internally by employees at SCM. Costs such as piping, electricity equipment, building, instruments and automation were assessed by experienced individuals and based on multiple meetings with suppliers, as well as observations at SCM. An example of one such observation is measuring the distances for pipes required inside the factory when exchanging VKK to VKM. The further costs included in this study are summarized in *Table 3.9*. Of important note is that costs orginiating from the processes that are assumed to change from VKK to VKM are included in the prices in *Table 3.9,* such as pipes.

Table 3.9: The further costs, in kronor, included in an investment of the turbine.

Building	***Electricity***	***Pipes***	***Automation***	***Instruments***	***Sum***
2 475 000	8 100 000	6 745 000	1 532 000	245 000	19 097 000

3.5.1 Heat exchangers

Two suppliers of heat exchangers were contacted, Company C and Company L. Company C was asked to give a budget offer of the cheapest alternative between installing 2 small heat exchangers and 1 big heat exchanger regarding P- and Q-avlopp. Company C therefore only gave 1 budget offer, that was for 1 big heat exchanger. The second supplier, Company L, gave budget offers for both alternatives. All budget offers are presented in *Table 3.10,* where the effect of the heat exchangers are presented inside the brackets.

Table 3.10: Presents the budget offers, in kronor, from two companies, Company C and L, for the heat exchangers. The effect of the heat exchangers are presented inside the brackets.

	Heat exchangers for P- and Q-Avlopp (option 1)	***Heat exchanger for Q-avlopp (option 2)***	***Heat exchanger for VKK in residual gas tower***	***Heat exchanger for condensed steam***
Cost (EUR) Company L	14 000 + 7000 (10 320 & 5650 kW)	14 300 (15 990 kW)	8450 (1179 kW)	8910 (5092 kW)
Cost (EUR) Company C		10 200 (15 454 kW)	6360 (1171 kW)	6000 (5018 kW)

3.5.2 Turbine

The data for the excess steam and the VKK flow, in *Table 3.1*, was sent to 2 companies, A and

W. Below, the main differences between the 2 will be summarized, with their performance and cost seen in *Table 11*.

3.5.2.1 Company W

The turbine suggested by company W was a conventional Rankine Cycle steam turbine, which, in the case for SCM, will work according to stages 3-4 and 4-1 in the Rankine Cycle. Stage 2 - 3 is not considered since there is no boiler or fuel which needs to be considered in the investment nor performance of a turbine. Stage 1-2 is not considered for a similar reason and the steam is already compressed at 3 bar after exiting the existing the 2 turbines in *Figure 2.2.* No pump or compression is therefore a part of the investment or affecting the considered net performance.

Company W did not give any estimations of their annual maintenance cost. However, as an approximation from employees at SCM, 2 % of the yearly production of kWh was used in this case. Company W furthermore gave no information about annual production but did however give further details of what the monthly average effect would be. This was based on the historical data that was sent for each month, see *Table 3.11*.

Table 3.11: The effect each month for Company W's suggested turbine. The effect is based on the historical values also presented in Table 3.1.

Month	***Steam flow kg/s***	***Adjusted VKK flow***	***Average effect kW***
Mach	3,3	370,2	1140
April	7,4	377,9	3070
May	6,9	386,8	2828
June	9,2	369,2	3700
July (incl 19th)	8,3	384,3	3400

This data was used to approximate an annual production according to *Calculation 3.19:*

$$\frac{(1140+3070+2828+3700+3400)kW}{5} \cdot 7900h = 22\ 338\ 000\ kWh \qquad \text{Calculation 3.19}$$

where 7900h is estimated by SCM as the amount of hours they are in production each year. The yearly maintenance cost of 2% is hence 446 760 kronor.

3.5.2.2 Company A

The suggestion given by Company A was an ORC turbine. The considered stages in the cycle will be the same as the turbine suggested by Company W, for similar reasoning. However, the steam supplied by the factory will heat up the organic fluid, which will expand in the turbine and condense after being cooled by VKK. One of the reasons for the lower performance of this turbine, see *Table 3.12*, is believed to be due to heat loss occurring in the heat exchange between the steam and the organic fluid. This was further illustrated in *Figure 2.20* as the shaded area. The yearly maintenance costs were informed as 4% of the yearly production of kWh, that is 11 160 000 kWh. 4% is hence 446 400 kronor

Table 3.12: Presents the cost, annual production and maintenance costs for the two turbines offered by Company W and A.

	W	***A***
Cost [kr]	29 395 000	28 000 000
Yearly production [MWh]	22 338	11 160
Yearly maintenance costs [kr]	(2%) 446 760	(4%) 446 400

3.6 Chosen instruments

The most advantageous turbine and heat exchanger, which in return was the chosen option, is outlined in this section. *Table 3.13* provides the reference scenario needed for this and the obtained key values for each turbine can be found in *Table 15*. The key values are calculated according to *Equation 2.22-2.24*

Table 3.13: The reference values used when identifying the most profitable turbine.

Electricity price	0,24 kronor per kWh
Certificate price	0,07 kronor per kWh
Steam flow	7,02 kg/s
Discount rate	10 %
Annual usage	7900 hours

3.6.1 Heat exchangers

Both companies, in which data was sent for budget offers of the 3 heat exchangers, were able to reach the desired cooling effect, see *Calculation 10,17* and *18* and *Table 3.10*. Company C however was chosen as they quoted a cheaper budget offer for all 3 heat exchangers. The total cost, including the installation of the heat exchangers, was estimated in *Calculation 3.20* by multiplying the cost for the exchangers with pi, that is:

$$225600 \cdot \pi = 708\ 384\ kronor \qquad \text{Calculation 3.20}$$

This calculation was devised by employees at SCM.

3.6.2 Turbine

The additional installation cost for both turbines was estimated by SCM and is the sum of all costs multiplied with 15 %. *Table 3.14* summarizes the performance and costs of the 2 turbines as well as the additional costs.

Table 3.14: Presents the maintenance costs and potential production for the 2 turbines as well as the initial cost for the 2 turbines. The further costs and the additional 15% costs are also presented.

	Company W	***Company A***
Cost Turbine[kr]	29 395 000	28 000 000
Further costs [kr]	19 097 000	19 097 000
Heat exchanger costs [kr]	708 384	708 384
15% installation costs [kr]	7 380 058	7 170 808
Yearly production [MWh]	22 338	11 160
Yearly maintenance costs [kr]	(2%) 446 760	(4%) 446 400

Presented in *Table 3.14* are all costs included in the investments of the potential turbine. The only difference is the price for the actual turbine and consequent additional costs, since all other costs are the same. As can be seen in *Table 3.15*, all key values are more advantageous for Compay W's turbine compared to Company A's. This turbine will therefore be considered in the following sections.

Table 3.15: Presents the final investment costs, annual productions and financial key values for the 2 turbines.

	Company A	***Company W***
Investment cost [kr]	54 976 192	56 580 442
Annual production [MWh]	11 160	22 338
Payback [years]	>20	14,3
IRR [%]	-9	13
NPV year 10 [kr]	-33 448	-10 298

3.7 Scenarios

Different values were modified in order to gain an idea of what the actual profitability might be, presented in *Section 4*. Gaining an exact estimate of the future profitability is difficult. By changing certain values however, an idea of the potential profitability range can be estimated. These modified values, which will be presented as different 'scenarios', are presented below and will be considered in *Section 4* to illustrate how the profitability can vary. The different scenarios that were considered are discussed in *Section 3.7.1 – 3.7.4.*

3.7.1 Scenario 1 - Different ways to make use of the further excess steam

So far, in *Table 3.13* and *3.15*, the average excess steam flow that has been considered is 7,04 kg/s. This was the data sent to the 2 suppliers and what their budget offers and production estimates were based on. As explained in *Section 3.2*, a synergy of using VKK as cooling water in the condenser is that, due to the VKK temperature increase, there will be a further increase in excess steam. This further excess steam was calculated at 2,65 kg/s. However, this can be valued in 2 different ways depending on the circumstances taking place at SCM, either as saved heat or as further electricity production. This depends on whether the bark heater is used to provide the necessary steam demand at the factory. In such a situation, warmer VKK can decrease the demand for heat and further decrease the bark needed in the heater. Therefore, with warmer VKK, more bark is saved. The price for saved bark has been estimated internally at SCM at 60 kronor per ton steam. The second option, that is using the steam for further electricity production, exists when all steam provided at SCM originates from the Recovery Boiler. In this case, the amount of steam cannot be decreased by using less fuel, as in the case for the first option. Instead, as much of the excess steam as possible can be taken advantage of. In this case, all the excess steam, that is 2,65 kilos, can be distributed to the turbine for electricity production.

4 values were analysed that are based on the percentage of the yearly total heat that is supplied by the bark. These are when 0%, 10%, 25% and 50% of the yearly heat is supplied by bark. Of important note however, is that only the additional 2.65 kilos of steam will be affected. The average of 7,04 kilos will always be distributed to the turbine regardless of the heat supply. The steam flow will therefore never be 7,04 kg/s in the analysis, since additional 100%, 90%, 75% or 50% of 2,65 kg/s is added. To vary the electricity production with further excess steam, that is the 2,65 kg/s, a linear relation is assumed between the percentage increase of available steam and the percentage increase of electricity production.

3.7.2 Scenario 2 - Variable steam flow

As seen in *Table 3.1*, which was sent to the turbine suppliers, the average steam flow varies every month. This analysis therefore considered a flow that varied by 10%, 20% and 30%. Furthermore, it is assumed that the percentage variation of 9,69 kg/s will be changing; according to *Equation 3.3:*

$$X \cdot 9{,}69 \frac{kg}{s} \qquad \text{Eq.3.3}$$

where X is the changing factor.

As a sub-scenario, the flow varied with the same factors, however, with 50% of the additional steam being supplied by bark. The steam flow was hence obtained according to *Equation 3.4:*

$$X \cdot (7{,}02 + 0{,}5 \cdot 2{,}65) \frac{kg}{s} \qquad \text{Eq.3.4}$$

where X is the changing factor.

The remaining steam in this sub-scenario was valued as ‘saved heat’. No heat was saved in the original scenario, where 9,69 kg/s varieed and nothing was assumed to originate from the bark heater.

3.7.3 Scenario 3 - Variable VKK flow

As seen in *Table 3.1,* which was sent to the turbine suppliers, the VKK flow varies every month. As will be discussed later, the output also depends on the available VKK. It is irrelevant how much steam is available if a sufficient amount of VKK is absent. This scenario therefore considered a VKK flow that varied with 10%, 20% and 30%, with the reference flow of 378 l/s, seen in *Table 3.1*.

To vary the steam flow, as in Scenario 2, and the VKK flow, as in Scenario 3, the model explained in *Section 2.6.2.4* was used to obtain a potential effect. The annual production was further obtained by assuming 7900 production hours per year.

3.7.4 Scenario 4 - Different electricity and certificate prices

The electricity and certificate prices used as a reference were 0,24 and 0,07 kronor per kWh, respectively. As explained in *Section 2.9* however, both electricity and certificate prices have varied over the last years. A range of prices were therefore considered to gain a broader overview of the potential investment and its profitability. Thus, a variable electricity price of +10%, +25%, +50%, -10%, -20% and -40% were considered and +50%,+100%,+200%, -10%,-25% and -40 % for the certificate price. The entire electricity production from the turbine was further assumed to only be sold to the national grid and not for own usage.

3.8 Reference values

Yearly maintenance costs equal 2 % of the yearly electricity production in kWh. The total of this was consequently changed in each scenario where the electricity production was changed. Furthermore, it affected the analyzed key values. The NPV at year 10 will be presented, as the lifetime of the turbine is unknown. *Table 3.16* presents the reference values which will be further modified in later tables in *Section 4*. Observe that these can differ from those values presented in *Table 3.13*. There are however 2 reference values for the annual production:

- 1 obtained from the supplier, that is 22 338 040 kWh, multiplied with the percentual increase in steam, that is 37,7%, which equals 30 768 724 kWh
- 1 obtained when using the model for 9,69 kg/s, that is 32 801 590 kWh.

The latter should therefore be considered when the model is used, that is, when varying the steam flow and the VKK flow. The first model should be considered when varying the percentage of bark usage and the price for electricity and certificates.

Table 16: Presents the reference values that will be considered and modified in the financial analysis in Section 4.

	Model based	**Company W + excess steam**
Electricity production [kWh]	32 801 590	30 768 724
Electricity price [kr/kWh]	0,24	0,24 kr
Sale [kr]	7 872 000	7 384 000
Certificate price [kr/kWh]	0,07	0,07
Sale [kr]	2 296 000	2 154 000
Steam flow [kg/s]	9,69	9,69
Payback [years]	7,2	8,5
Discount rate [%]	10	10
Internal interest rate [%]	20	18
NPV year 10 [kr]	11 382	4 892
Annual bark usage [%]	0	0
VKK flow [l/s]	378 +34% [6]	378

The average modified VKK flow during the analysed period reached 378 l/s. The result for the model based turbine in the reference table requires a flow that is 34 % higher than this, for the steam flow of 9,69 kg/s. As seen in *Table 4.1* and *4.2*, only the flow of the steam was modified and the required VKK flow was obtained. However, since the output also depends on the available flow of VKK, *Table 4.3* considered a modified VKK flow and consequently the maximum steam flow that can be taken advantage of for the given VKK flow. The analysis has however not taken any consideration to potential increases in cost with an increase of the VKK flow.

[6] *The average measured VKK flow was 378 l/s. But the VKK flow required for the flow of steam, that is 9,69 kg/s, in the model based reference scenario is 34% higher, that is 506,5 l/s. This VKK flow was never a measured average flow but however only a hypothetical flow.*

4. Results

4.1 Analysis of the profitability

Table 4.1: The yearly production, required VKK flow and financial key values obtained when varying the steam flow.

Steam flow [kg/s]	***9,69***	***+10 %***	***+ 20 %***	***+30%***	***-10%***	***-20%***	***-30%***
Yearly production [MWh]	32 801,6	36 373,2	39 356,2	42 251,6	28 929,8	25 064,3	21 216,2
Required VKK	+34%	+47%	+61%	+74%	+22%	+9%	-4%
Payback	7,2	6	5,3	4,7	9	11,9	18
Internal interest rate	20%	23%	25%	27%	17%	14%	11%
NPV year 10 [kkr]	11 382	18 782	24 963	30 962	3 360	-4 649	-12 622

Table 4.2: The yearly production, required VKK flow and financial key values obtained when varying the steam flow. The values obtained are in addition to Table 4.1 considering 50% of the additional heat of 2,65 kg/s being supplied by the bark heater.

Steam flow [kg/s]	***9,69***	***+10 %***	***+ 20 %***	***+30%***	***-10%***	***-20%***	***-30%***
Yearly production [MWh]	27 468,3	30 805,3	34 143,8	37 003,6	24 138,4	20 825,2	17 539,6
Required VKK	+17%	+28%	+39%	+50%	+6%	-5,5%	-17%
Payback	6,3	5,3	4,5	4	7,8	10,2	14,3
Internal interest rate	22%	25%	28%	32%	18%	15%	12%
NPV year 10 [kkr]	16 524	25 057	33 593	41 137	8 005	-479	-8 905
Annual saved heat [kkr]	*2 266*	*2 493*	*2 720*	*2 946*	*2 040*	*1 813*	*1 586*

Table 4.3: The yearly production, the maximum steam flow that can be taken advantage of and the financial key values obtained when varying the VKK flow.

VKK flow [kg/s]	***378***	***+10 %***	***+ 20 %***	***+30%***	***-10%***	***-20%***	***-30%***
Yearly production [MWh]	22 469,2	25 447,5	28 444,7	31 455,4	19 519,3	16 609	13 992,5
Maximum steam flow	-27% 7,1 kg/s	-19% 7,85 kg/s	-11% 8,6 kg/s	-3,5% 9,35 kg/s	-34,5% 6,35 kg/s	-42% 5,6 kg/s	-50% 4,87 kg/s
Payback	8,3	7	6	5,3	10	12,6	16,6
Internal interest rate	18%	20%	23%	25%	16%	13%	11%
NPV year 10 [kkr]	6 166	12 337	18 547	24 785	54	-5 976	-11 397

Table 4.4: The yearly production, annual payments and costs, annual savings from decreased usage of bark and financial key values obtained when varying the annual percentage of heat supplied by bark.

Bark as a percentage of total yearly heat production	***0%***	***10%***	***25%***	***50%***
Electricity production [kWh]	30 768 724	29 925 656	28 661 053	26 553 382
Yearly payments incl certificates	9 538 000	9 277 000	8 885 000	8 232 000
Yearly maintenance cost	615 000	599 000	573 000	531 000
Annual savings from decreased usage of bark [kr]	0	453 000	1 133 000	2 266 000
Payback	8	7,7	7,3	6,6
Internal interest rate	18%	19%	19%	21%
NPV year 10 [kkr]	7 170	8 662	10 899	14 628

Table 4.5: The financial key values obtained when varying the electricity price.

Price	***+10 %***	***+25%***	***+50%***	***-10%***	***-25%***	***-40%***
Electricity	0,264	0,3	0,36	0,216	0,18	0,144
Payback	7	5,8	4,5	9,4	12,4	16,5
Internal interest rate	20%	23%	28%	16%	14%	12%
NPV year 10 [kkr]	12 446	20 360	33 550	1 894	-6 020	-13 934

Table 4.6: The financial key values obtained when varying the certificate price.

Price	***+50 %***	***+100%***	***+200%***	***-10%***	***-25%***	***-40%***
Certificate	0,105	0,14	0,21	0,063	0,0525	0,042
Payback	6,6	5,6	4,2	8,4	9	9,7
Internal interest rate	21%	24%	30%	17%	17%	16%
NPV year 10 [kkr]	14 864	22 558	37 946	5 631	3 323	1 015

4.2 Saved emissions

The yearly production can, according to the analysis above, vary from 13 992 500 kWh, *Table 4.2*, to 42 251 600 kWh, *Table 4.1*. *Table 4.6* will summarize how much emissions of CO_2 the investment can save compared to the average electricity production in Sweden, EU and the Nordic countries, not including Norway and Iceland. The comparison is assuming that the investment generates completely fossil free emissions of CO_2 and no life cycle perspective is considered. The emissions of CO_2 from SCM's turbine is therefore 0 g / kWh.

Table 4.7: Presents the saved emissions of CO_2 with regards to presented countries emissions of CO_2 originating from electricity generation.

	13 992 500 kWh	***42 251 600 kWh***
Sweden (13,3 g CO_2/kWh)	186,1 ton	562 ton
Sweden, Denmark and Finland (97,4 g CO_2/kWh)	1362,9 ton	4115,3 ton
EU (310 g CO_2/kWh)	4337,7 ton	13098 ton

4.3 Electricity production

Table 4.8 presents the minimum and maximum yearly electricity production from the potential turbine compared to the annual production and consumption of electricity at Södra, SCM and the Swedish paper mill industry.

Table 4.8: The corresponding potential electricity production with respect to Södra, SCM and the Swedish paper mill industry.

	Minimum (13 992 500 kWh)	***Maximum (42 251 600 kWh)***
Percentage of the paper mill industry's electricity production	0,24%	0,74%
Percentage of Södra's electricity production	0,8%	2,46%
Percentage of SCM's electricity production	4,5%	13,5%
Percentage of the paper mill industry's electricity consumption	0,07 %	0,21%
Percentage of Södra's electricity consumption	0,99%	3%
Percentage of SCM's electricity consumption	4,4%	13,4%

5. Discussion

The results in this study were based on multiple assumptions, both in regards to the potential electricity production, as well as for the solution for the identified critical processes. No heat losses were considered for the VKK flow whilst being transported at the factory. Furthermore, the synergies, among other values obtained, were based on historical values from a limited amount of months. All values were obtained from data collected over the months of February to August, 2018, with data from colder winter months not available. Winter months would potentially change both the amount of VKK and the amount of excess steam. As temperatures differ drastically each year over the winter months, it was too complex to consider the different scenarios within this study.

The design of the potential heat exchangers were also based on historical values. Factors such as seasons, as aforementioned, with extreme weather, may result in insufficient heat exchange. The calculated synergies will also vary with such weather variations.

To obtain an estimated outcome of the future profitability of the potential turbine, this study has made such simplifications based on the above reasoning. The estimated outcome will be discussed below.

5.1 Electricity production

The purpose of the financial analysis was to illustrate the great variation of the profitability whilst changing different values. The purpose was further to gain a better understanding of the boundaries in which the potential profitability would be obtained. As previously mentioned, many simplifications were made in order to conduct this study. Outcomes from the most significant simplifications are presented below.

A linear correlation between the varying bark usage and that of the electricity production has been assumed in the model that is based on the budget offer from Company W. If the available steam increases with 37,7%, as a result of 0% bark usage, it is assumed that the electricity production also increases to 37,7%, which in reality would be lower.

The Excel model was used to illustrate how the profitability is dependent on the VKK flow and the steam flow, and furthermore, how these depend on one another. To reach a maximum production, both of these flows must be available at the same time. This is assumed in the Excel model, which partly explains why the model has a higher output in the reference scenario. In reality, these values might not be reached simultaneously and the output will therefore be lower.

The difference between the 2 models discussed in the reference scenario is partly due to the fact that not all losses were considered in the Excel model. The constant, K in *Equation 2.9*, calculated by Excel is meant to compensate for as much of these losses as possible. It is however, not 100% correct. This is also partly why the Excel model has a higher output in the reference scenario. The Excel model is considering deviations such as pressure drops and heat losses but is based on the calculations of the constant K. The reference model based on company W's budget offer considers the correct losses. It does, however, only consider the correct losses in the reference scenario in *Table 3.12*, that is with 7,04 kg of steam per second, since a linear relation is assumed for the additional steam flow. The efficiency of the turbine may potentially change with this increase. All analyses with additional steam flow and those based on the Excel model can therefore be assumed not to have taken full consideration of these losses.

5.1.1 Varying VKK flow

Company W's budget offer was based on a VKK flow where 50 liters per second and per month was removed from the average measured flow. If the measured flow of VKK was the same as the actual flow during the considered months, the output of the turbine would have been different. A higher amount of available VKK would increase the turbine output and a lower amount of available VKK would decrease it.

The increase in production, based on an increase of steam, assumes that the required amount of VKK is available. Firstly, this might not be the case, and secondly, the potential increase in costs that appears due to this was not considered. Such costs can develop due to more erosion, as described in *Section 2.6.2.2.2*, and hence higher annual maintenance costs. Additionally, costs originating from the VKK production were not considered. With a higher amount of VKK required, such costs would increase, which would decrease the profitability.

5.1.2 Potential increase in excess steam

An attempt was made to approximate the increase in excess steam that will reach the turbine as a result of the increased temperature of VKK. All calculations were based on historical flows and temperatures during a limited period, with actual values potentially varying in the future. In addition to this, the calculation of the synergy and its effect on the profitability was based on a few simplifications. Some of these are presented below.

As a result of further steam, that is 37,7 %, the demand for cooling would increase. This is partly understood by comparing the Excel model based VKK demand at 9,69 kg steam per second with the model based on Company W's suggested turbine. The demand of VKK between the 2 models is increasing by 34%, approximately just as much as the steam flow of 37,7 %. This was not considered in the profitability analysis conducted for the different bark usage scenarios. It is thus not certain that the reference scenario of yearly production can be reached when the production has increased linearly with the steam increase. No consideration has been taken to the VKK flow that is assumed to be available. This is regarding both models. The required flow of VKK would, in reality, also increase and if the required flow is not available, the output will decrease. The financial key values obtained were therefore based on the fact that the required amount of VKK is available, as well as that the additional flow will not result in further costs. With an insufficient flow of VKK available, the profitability will decrease.

Regarding the model based on Company W's budget offer, additional electricity production was also assumed to increase linearly along with the increase in steam flow, that is a further 37,7%. In reality, this increase would be lower than this percentage due to losses among other factors. An alternative calculation to estimate the further production with additional steam is via Excel and linear regression, which would be based on the available data in *Table 3.10*. This method was used when estimating the further flow needed for the mechanical seals. This calculation was, however, not used for this matter due to the lack of data regarding the effect. The effect was based only on the average historical monthly steam flows and was not the instantaneous effect. There is, therefore, only 5 available values for the effect and an estimation based on this would have been misleading.

Since the temperature of all considered processes are monitored, there may be situations, such as winter, where the allowed temperature of VKK potentially can increase above 35 °C. As the outside temperature is colder, the required cooling of the Nash pumps and the mechanical seals can potentially be reached with VKK warmer than 35°C. Additionally, the VKM, used as the cooling medium in the suggested new heat exchangers, will be colder and therefore will enable a better cooling of VKK. As a result, the output from the turbine can potentially be higher during these circumstances due to the potential further cooling taking place as VKK is heated. The further heating of VKK results in a further excess of steam available for the turbine, that is an even larger synergy. The potential output can hence increase. However, since the excess steam is used as direct heat, prior to being used in the turbine, the amount of excess steam may be lower during colder periods compared to warmer. It would therefore be complex to approximate the actual steam available for electricity production after a balance has occurred during winter, that is, when the flows and temperatures have stabilized. However, the reasoning is valid and the profitability will be affected by the varying seasons.

It is further assumed that the synergies calculated from a warmer VKK will not result in any heat losses. The 10°C increase was hence assumed for all considered waters, that is VKK, VKT and VHA. No temperature losses were assumed to occur before these waters reach the feedwater tanks or when being produced at the water treatment plant. The waters would realistically lose some of the heat and a smaller synergy, that is the additional steam flow of 2,65 kg/s, would hence be obtained than that of 37,7%. This reasoning can also be considered in regards to the potential critical processes since the the actual consequence of the turbine might be milder than considered in this study.

5.2 Profitability

5.2.1 Spot and certificate price

In the analysis, a changed certificate price has proven to change the profitability significantly. The actual future price will be decided by the market and is hence unknown. The analysis has taken consideration to an increase with up to 300%, even though the historical values over the last 10 years have been larger than 300%, as illustrated in *Figure 2.23*. The certificate price's effect on the profitability may therefore be larger in reality than what has been considered in this study.

The spot price affects the profitability even more but has not varied as much historically (Bixia 2018). The considered reference value of 0,24 kr/kWh is believed to be rather low compared to the historical values illustrated in *Figure 2.22.* A higher price is a realistic assumption for the future. With a higher spot price for electricity and a higher certificate price, the profitability of this investment will increase.

It can further be noted that a greater profitability can occur when the synergy can save bark in the bark heater compared to if the synergy can be taken advantage of for electricity production. The saved heat is therefore more valuable than the electricity production. An increased spot price and certificate price can however change this.

The electricity can, in addition to being fossil free, be considered sustainable since it originates from residual steam and initially from trees. The farming of trees can further also be considered as sustainable since the annual plantation exceeds the annual harvesting. Of further note, is that the electricity generation from the potential turbine at SCM will produce less intermittent and more reliable electricity than many other sources of sustainable electricity generations. From a broader perspective, that is the need for reliable sustainable electricity, a source such as the potential turbine at SCM, will therefore be important.

5.2.2 Non-considered Costs

The profitability was based on an additional cost of 15%, which is believed to cover non-considered costs and problems that may appear throughout the installations. Examples of non-considered costs are:

- The VKM filters prior to the cooling of the compressors and the Sulzer pumps.
- The pump that provides the mixbeds with condensed steam that may have to be exchanged.
- Consequences of more frequent cleaning of pipes were not considered, however, can potentially result in production losses and also further costs.

This 15% might also differ, which will affect the profitability in all considered scenarios.
A further consequence not considered in the financial analysis, however mentioned in this study, is erosion appearing in the case of a higher VKK flow and thus more moisture in the steam. This would result in higher annual maintenance cost.

The design of the turbine is suggested by Company W as ideal for the initial flow of 7,04 kg/s. If a higher steam flow is probable, a different turbine might be advantageous. All scenarios considering a higher steam flow might therefore require a larger, and hence more expensive, turbine.

5.3 Critical processes

As a general starting point to estimate the potential outcomes of a warmer VKK, the assumptions were based on historical values from a limited period. Thus, maximum values considered might be higher in the future and the suggested solution’s designs might therefore be insufficient. The historical values have, however, been considered to decrease the chances for such an outcome.

Some assumptions were also based on the ’worst case scenario’. Since this is a theoretical study, some of these assumptions may not be realistic to consider in reality. Some of the suggested solutions may therefore be neglected in reality when experienced employees decide what a realistic scenario potentially can be. A potential scenario is therefore that some of the processes will remain unchanged and that the output of the turbine instead will be decreased at such extreme scenarios so that a process is affected. Consequently, the cost for a solution may outweigh the losses in payments that will occur in such situations. Such a conclusion is complex and therefore requires experienced employees to evaluate. This was therefore not considered in this study.

An example of such a potential process is the heat exchanger suggested for the mixbeds. A safety margine of 45 °C, that is 5 °C below the maximum temperature of 50 °C, was set as a requirement. The condensed steam was assumed to reach 47 °C, which is believed to justify the suggested heat exchanger due to the safety margine. However, the safety margine might be unnecessarily large, with 47 °C potentially adequate. The 47 °C further assumes no heat losses after the VKK has been heated by 10 °C. In reality, the condensed steam may actually peak below the safety margine of 45 °C due to these heat losses and therefore a heat exchanger may actually not be needed.

5.3.1 VKM

The estimated maximum temperature of VKM is also uncertain since its value can differ from one year to another. 23 °C has been the considered maximum temperature, even though temperatures of up to 26 °C were reached during the summer of 2018. Consequences of a 26 °C temperature would have been too complex to consider in this study. However, during the majority of the year, the VKM temperature would be much lower. A potential increase in cooling capability would hence be obtained but was not considered since it would likewise be too complex to estimate.

It was further assumed that the sum of the VKM flows required by all processes using VKM as a result of the potential installation of a turbine, will be available from the water treatment plant. If this cannot be ensured, the output of the turbine will have to be decreased due to insufficient cooling of VKK after the turbine.

ClO_2 production

While the maximum temperature of VKK was set to 25 °C, it may reach higher temperatures during warm summers with warmer VKM. The outgoing temperature of VKK and the concentration of ClO_2 in the residual gas tower is monitored. If the outgoing concentration is too high, meaning a high yield loss, the output of the turbine must be decreased due to too warm VKK. During extreme summer temperatures, a warm VKK might result in a need for such a decreased output of the turbine. However, the limit of 25 °C was set with the intention that sufficient absorption will function at warmer temperatures. The yield loss might therefore not be significant during warmer VKK. This is partly illustrated in *Figure 3.6*, where the incoming concentration is illustrated as affecting the yield loss more than that of the temperature.

6. Conclusion

The Rankine Cycle steam turbine was chosen because of its advantageous performance compared to the ORC turbine. One of the reasons for the lower performance of the ORC turbine, see *Table 3.14*, is believed to be due to heat losses occuring in the heat exchange between the steam and the organic fluid. This was further illustrated in *Figure 2.20* as the shaded area. Since the steam is already produced, it is better to expand it directly compared to using it to heat the organic medium in an ORC turbine.

The financial analysis illustrates the great variation of the profitability whilst changing different values. This analysis resulted in a margin in which the potential profitability was obtained. Additionally, the synergies from a warmer VKK will either generate more electricity or enable a larger amount of bark available to sell. A mix between the 2 will most likely occur in the future.

The maximum increase in steam obtained due to the synergy is estimated at 37,7 %, which is reached when 0 % of the steam is provided from burning bark and no heat losses considered. This, however, requires an increased average available flow of VKK. It can further be concluded that profitability is greater when the synergy, that is the further 2,65 kilos of steam per second, can save bark in the bark heater, compared to if the 2,65 kg/s can be taken advantage of for electricity production. The saved heat is hence more valuable than the electricity production. An increased spot price and certificate price can however change this.

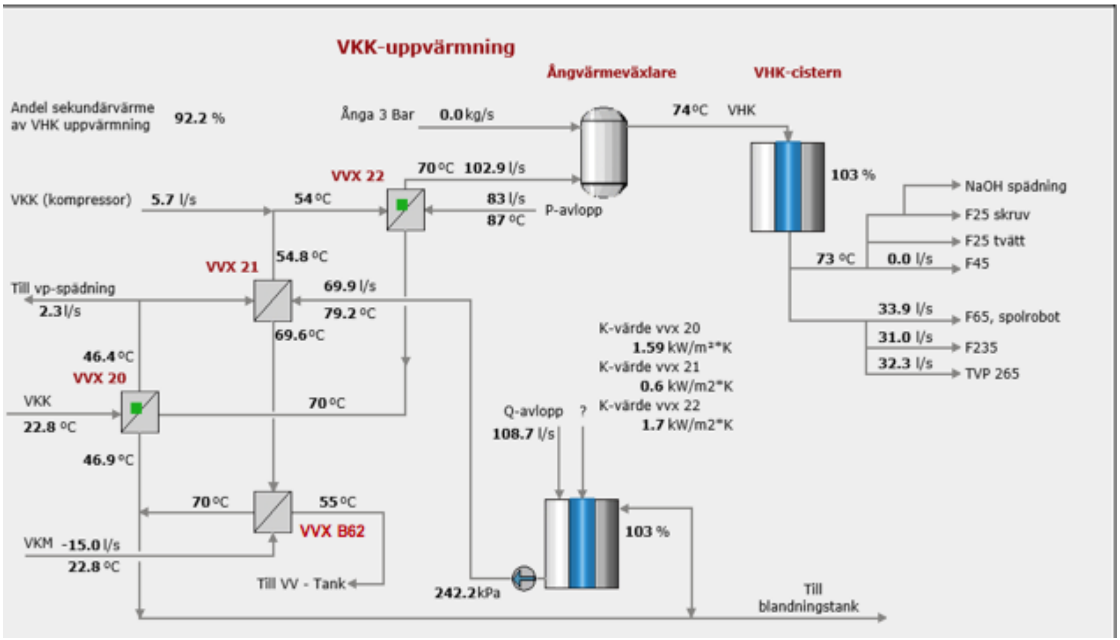
After the affected critical processes were identified, the cost for solutions were estimated. Along with the turbine and other building associated costs, the cost for the entire investment will be approximately 56 580 442 kronor. The annual production will likely vary from 13 992 500 kWh to 42 251 600 kWh. The PB will vary from 4,2 years to 18 years, however the majority of the analysis result in a PB below 9 years. The NPV will, after 10 years, vary from -13 934 000 to 37 946 000 kronor but the majority of the analyses resulted in a positive NPV. The IRR will vary from 11% to 30%, however, the majority of the analyses resulted in an IRR around 19%. Since the discount rate was set to 10%, all scenarios resulted in a profitable investment according to the IRR method and *Equation 2.23*.

A significant amount of CO_2 emissions can be prevented if the investment is carried out. With considerations taken to the European electricity mix, which is most relevant in the future with a joint power grid, the prevented emissions varies between 4337,7 tons to 13 098 tons.

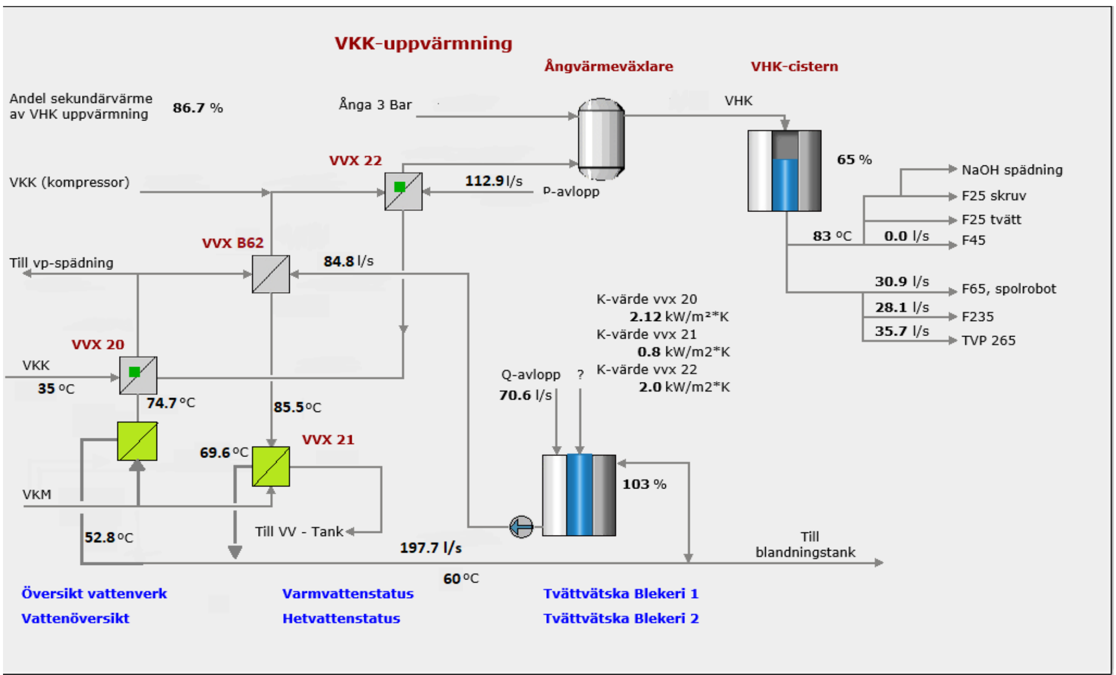
The potential electricity generation corresponds to 4,5 - 13,5% of SCM's current electricity production and 4,4 - 13,4% of SCM's current electricity consumption.

Realistic and uncomplicated solutions can be installed for the critical processes affected by the installation. An exact value of the profitability was, however, complex to obtain due to many reasons such as external prices and costs, as well as internal temperatures and flows which depend on external temperatures, among other factors. In situations with abnormal outside temperatures, the output of the turbine might have to be decreased in the case of too warm VKK. Sadly, it is during these circumstances that the amount of excess steam is high due to a low demand of direct heating. Irregardless of these circumstances, the average values of that of the flow of steam and VKK is believed to result in a profitable investment.

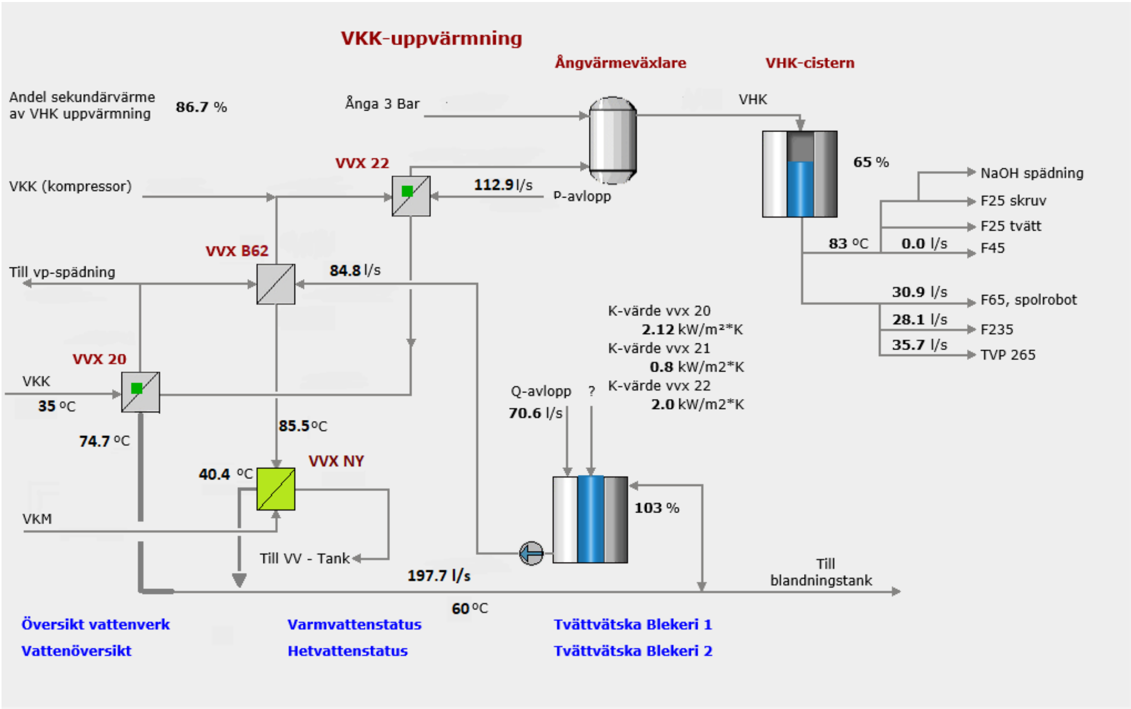
Appendix



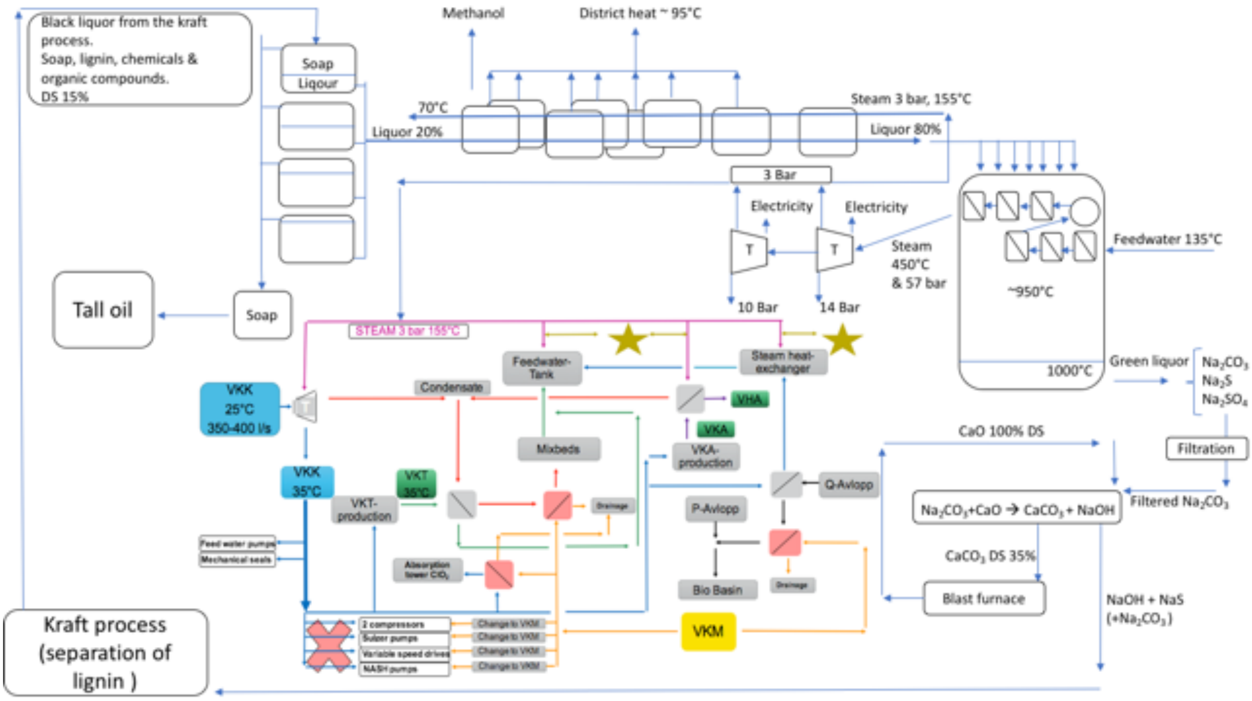
Appendix 1: A photo of the layout of heat exchangers prior to the modification where VVX B62 replaced VVX 21 that was removed. The picture originates from SCM's internal monitoring system.



Appendix 2: Illustrates the option of having two new heat exchangers installed. See yellow for the new heat exchangers. The picture originates from SCM's internal monitoring system.



Appendix 3: Illustrates the option of having one new heat exchanger installed. See yellow for the new heat exchanger. The picture originates from SCM's internal monitoring system.



Appendix 4: Illustrates an overview of Figure 2.2 and 3.13 put together.

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