CHALMERS

Improved Resource Utilization at a Kraft Pulp Mill

A case study of Södra Cell Värö

Master's Thesis within the Sustainable Energy Systems program

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Division of Industrial Energy Systems and Technologies
CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS

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Cover:
The recovery boiler at the Södra Cell Värö pulp mill.

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ABSTRACT

The Södra Cell Värö kraft pulp mill will during 2015 and 2016 be expanded to increase the pulp production capacity. The increased pulp production will generate an even larger amount of by-products and excess heat from the process, thus likely to increase the amount of unused resources compared with the current situation.

This master thesis work is an investigation of different alternative solutions to increase the resource utilization at Värö, and by that increase the mill's economic profitability and environmental performance. A base case of the expanded pulp mill's energy system was modelled and used as a reference case for the alternative solutions. The following alternatives for increased resource utilization were examined: bark burning, lignin extraction, increased district heating deliveries to Varberg and Kungsbacka, and increased bark drying to use as fuel in the lime kiln. The evaluation was done with respect to energy and mass balances and by using three key performance indicators; resource efficiency, economic performance and CO_2 emissions. Furthermore, a description of other possible solutions, which for different reasons were discarded earlier in the work, was made. Several of these solutions showed great potential for further studies.

With respect to the economic performance all the alternatives, except increased bark drying, which was not included in the economic analysis; and bark burning, showed better results than the base case. With respect to resource efficiency lignin extraction generally showed the best results. The CO_2 emission balances differed a lot for the different alternatives depending on assumptions regarding the surrounding energy system.

The investigation showed that all alternatives, except for bark burning, overall gave better results than the base case and implementing anyone of these alternatives would result in increased resource utilization at the Södra Cell Värö pulp mill.

Key words: Kraft pulp mill, bark, lignin extraction, district heating, resource efficiency, economic performance, CO_2 emissions

Ökat resursutnyttjande på ett sulfatmassabruk
En fallstudie av Södra Cell Värö
Examensarbete inom masterprogrammet *Sustainable Energy Systems*
JOEL HEDLUND
WILLIAM ULLGREN
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SAMMANFATTNING

Södra Cells sulfatmassabruk i Värö kommer under 2015 och 2016 att byggas ut för att öka produktionskapaciteten av pappersmassa. En ökning av pappersmassa-produktionen genererar även en större mängd biprodukter och överskottsvärme, vilket riskerar att öka mängden outnyttjade resurser jämfört med dagens situation.

Detta examensarbete är en utredning av olika alternativa lösningar för att kunna effektivisera Södra Cell Värös resursutnyttjande och därmed öka brukets ekonomiska lönsamhet och miljöprestanda. Ett basfall över sulfatmassabrukets energisystem har modellerats för det planerade utökade sulfatmassabruket, och basfallet har använts som referensfall för de alternativa lösningarna. De alternativ som har undersökts mer i detalj är eldning av bark, ligninextraktion, ökad fjärrvärmeleverans till Varberg och Kungsbacka och torkning av bark för användning som bränsle i mesaugnen. Utvärderingen har gjorts med avseende på energi- och massbalanser över sulfatmassabruket efter den planerade produktionsökningen och med hjälp av tre nyckeltal; resurseffektivitet, ekonomisk lönsamhet samt påverkan på globala koldioxidutsläpp. Vidare har en analys genomförts av andra möjliga lösningar, som av olika anledningar föll bort i en gallringsprocess, men där många av dessa alternativ visade stor potential för vidare studier.

Med avseende på ekonomisk lönsamhet fick alla alternativen, förutom barktorkningen, som inte ingick i den ekonomiska analysen, och eldning av bark, bättre utfall än basfallet. Resultaten avseende resurseffektivitet varierade, men genomgående uppvisade fallet med ligninextraktion det bästa resultatet. Koldioxidbalanserna för de olika alternativen skiljde sig mycket åt beroende på antagande om det omgivande energisystemet.

Undersökningen visade att alla alternativen, förutom eldning av bark, på det hela taget var bättre än basfallet och att implementera något av dessa alternativ skulle medföra ett förbättrat resursutnyttjande på Södra Cell Värös sulfatmassabruk.

Nyckelord: Sulfatmassabruk, bark, lignin extraktion, fjärrvärme, resurseffektivitet, ekonomisk lönsamhet, koldioxidutsläpp

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Preface

In this project an investigation of alternatives for increased resource utilization of the future expanded Södra Cell Värö pulp mill has been conducted. The suggested alternatives have been compared to a base case and evaluated using three key performance indicators; economic performance, resource efficiency and CO_2 emissions. The thesis work was carried out from September 2014 to June 2015 and is the final part of the studies at the master program Sustainable Energy Systems. This master thesis was carried out at the Division of Industrial Energy Systems and Technologies within the Department of Energy and Environment at Chalmers University of Technology, in collaboration with Södra.

Our first expression of gratitude is to our supervisors Roine Morin, Södra, and Elin Svensson and Karin Pettersson, Chalmers, for all the valuable help during this master thesis work. Without your help this would not have been possible. Also huge thanks to Linda Rudén and Per Olowson, Södra, for answering all of our questions and listening to our thoughts.

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Finally, we would like to thank all employees and master thesis students at the division of Industrial Energy Systems and Technologies and the personnel at Södra Cell Värö for all the help and for all intriguing discussions during our lunches and fikas. You have made our time both at Chalmers and Värö very delightful, and we will really miss you all.

Göteborg, June 2015

Joel Hedlund

William Ullgren

Notations

Abbreviations

ADt	Air dried ton
BLG	Black liquor gasification
CHP	Combined heat and power
Coal PP	Coal power plant
C_p	Specific heating value
DH	District heating
DME	Dimethyl ether
DS	Dry substance
ECF	Elemental chlorine free
HOB	Heat only boiler
HP	Heat pump
HW	Hot water
HX	Heat exchanger
LP	Low pressure (steam)
LW	Lukewarm water
MP1	Medium pressure 1 (steam)
MP2	Medium pressure 2 (steam)
O&M	Operation and maintenance (costs)
PCM	Phase change material
PM	Intermediate pressure (steam)
TCF	Totally chlorine free
WW	Warm water
tDS	Ton dry substance
ΔCO_2	Difference in global CO_2 emissions
ΔNAP	Difference in net annual profit
ΔT_{min}	Minimum temperature difference
η	Efficiency
η_{is}	Isentropic efficiency
$\eta_{resource}$	Resource efficiency

Chemical symbols

CaO	Calcium oxide
CO_2	Carbon dioxide
H_2O_2	Hydrogen peroxide
O_2	Oxygen
Na_2CO_3	Sodium carbonate
Na_2S	Sodium sulfide

1 Introduction

This master thesis covers an investigation of different alternatives for improved resource utilization at the Södra Cell Värö pulp mill. The investigated alternatives are modelled and compared to a base case with respect to different key performance indicators.

1.1 The forest industry

The forest industry is a vital part of the Swedish economy as well as the social and environmental structure. It includes companies within all process stages from growing and harvesting the raw material to producing e.g. sawn timber, pulp and paper. (Sandberg et al., 2014, The Swedish Forest Industries, 2014)

Figure 1 presents a comparison of pulp, paper and sawn timber export among the world's leading exporters, where Sweden is the third largest. The exported products account for about 10% of Sweden's total export, approximately 100 Billion SEK/year, making it the biggest net exporter of all Swedish industries. (The Swedish Forest Industries, 2014)

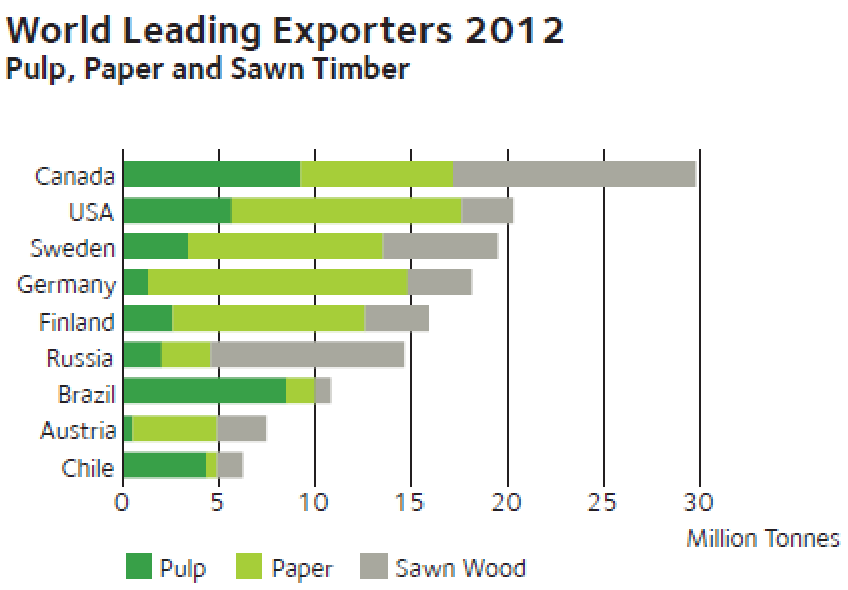

Figure 1. Comparison of pulp, paper and sawn timber exports of the world's leading exporters. (The Swedish Forest Industries, 2014)

The forest, which covers 70% of the Swedish land area, is not only of economic interest for Sweden but also includes some social and environmental factors of great importance. These factors include providing job opportunities and environmentally function as carbon sinks and providing home and shelter for a huge part of Sweden's biodiversity. About 60,000 jobs are provided that directly work within the forest industry and up to 200,000 jobs if including subcontractors. (The Swedish Forest Industries, 2014)

Traditionally, the forest provides the forest industry with biomass materials. The biomass materials are converted into products such as sawn wood products, timber and paper, but also into fuels, such as solid wood fuels. These products are provided to society, including different energy companies, and other industries. (The Swedish Forest Industries, 2014)

Biomass could also be used in various unconventional ways, e.g. in industrial products that can replace fossil-based materials, such as plastics, but also for renewable transportation fuels. (Leung et al., 2013, The Swedish Forest Industries, 2014)

Within the Swedish forest industry there are some large companies. This master thesis is conducted in collaboration with one of these companies, Södra.

1.2 Södra

Södra consists of more than 50,000 private forest owners and together they own more than half of the privately owned forest in southern Sweden. Today Södra is a world leading producer of paper pulp, dissolving pulp and Durapulp[1]. The company's turnover is 17 Billion SEK/year and about 3,500 employees works for Södra. The company manufactures just over 1.5 million tons pulp/year, which is sold and processed into products such as graphic papers, paperbacks, paper towels and toilet paper. Other business areas include sawn and planed timber goods, interior products, wood fuel and electricity. (Södra, 2014c, Södra, 2015b)

Södra has within the business area of pulp, called Södra Cell, three pulp mills in Sweden, located in Mönsterås, Mörrum and Värö. Previously, two mills in Norway, Tofte and Folla, was also included, but they have now been closed down or sold (Södra, 2013). In this master thesis, the focus will be on the Värö pulp mill. (Södra, 2014c)

1.2.1 Södra Cell Värö

The Värö pulp mill was built in 1972 and is located north of Varberg on the west coast of Sweden. It is a kraft pulp mill with an annual production of about 425,000 tons of pulp. Approximately 90% of the pulp that is produced at the pulp mill is exported to Europe. The Värö mill produces pulp, heat, electricity and dried bark using wood as raw material. Together with the sawmill, Värö also produces pellets from sawdust. Because of the high energy efficiency of the kraft pulp mill, the recovery boiler is able to satisfy the amount of steam normally needed in the mill processes. Hence, Värö does not need to burn bark for steam production. (Södra, 2014c, The Swedish Forest Industries, 2014)

Figure 2 shows an energy balance over the Värö pulp mill for the current production capacity.

[1] Durapulp is a bio-composite material that completely consists of renewable and biologically degradable components. Some of its properties are high folding strength, high tear strength and high bending stiffness. SÖDRA. 2014b. *DuraPulp* [Online]. Available: http://www.sodra.com/sv/Massa/Vara-massaprodukter/Kompositmaterial/DuraPulp/ [Accessed 11 Nov 2014].

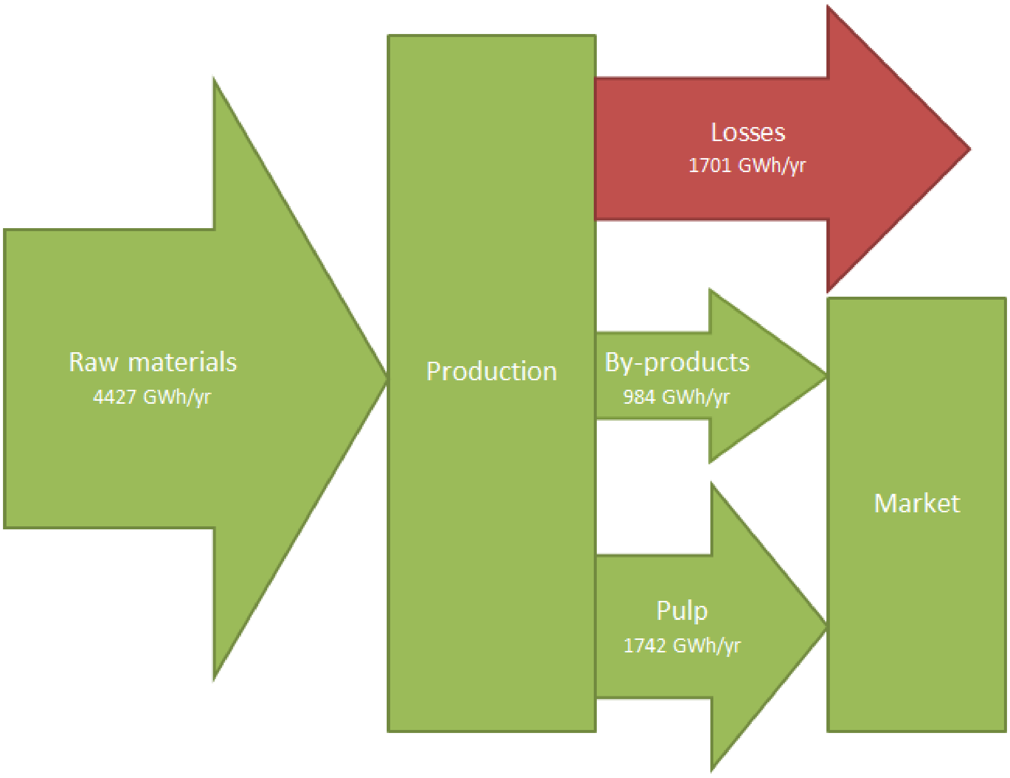

Figure 2. Schematic picture of the energy balance at Södra Cell Värö. (Rudén, 2014, Morin, 2014)

According to Figure 2, more than 60% of the input leaves the process as by-products or losses, primarily as heat losses. The by-products account for 984 GWh/year, further reading about the by-products can be found in Section 1.2.1.2. (Morin, 2014, Rudén, 2014)

1.2.1.1 The Södra Cell Värö Expansion

The board of Södra has in February 2014 decided to invest 4 Billion SEK in a rebuilding project where the objective is to expand the Värö pulp mill. The objective of the expansion is to increase the annual production capacity from today's 425,000 tons to 700,000 tons of pulp, which is an increase of the plant size to approximately 1.6 times its current size. This means that the Värö pulp mill will be one of the largest mills in Europe for production of softwood kraft pulp. The new construction is planned to be finished during the third quarter of 2016. (Södra, 2014c)

The increased production of pulp from the expanded Värö will increase the pulp mill's profitability. The expansion will also increase the production of renewable electricity, which Södra receives renewable electricity certificates for. However, the expansion of the pulp mill will also cause increased losses, which leads to the objective of this master thesis: to find solutions to make use of the excess thermal energy and bark. (Morin, 2014, Rudén, 2014, Varberg Energi, 2014a)

1.2.1.2 Products and by-products of Södra Cell Värö

The main products of Södra Cell are pulp, tissue and specialty product, and dissolving pulp. Dissolving pulp is produced at the Mörrum pulp mill. During pulp production there are some by-products created, e.g. bark, turpentine, tall oil, electricity and excess heat from water and steam. The by-products are mainly sold at the fuel, electricity and district heating markets.

Bark can be challenging to sell as a fuel since the market is limited and the heating value of moist bark is low, which makes bark less competitive on the biomass market compared to other biomass materials. This is why Värö already uses a bark dryer to increase the dryness of the bark, and thereby the bark's competitiveness. The amount of bark that will be available after the expansion of the mill is approximately 900,000 m^3 in total from the pulp mill and sawmill at Värö. The market price of bark is subject to seasonal variations due to the change in demand; it is high during the winter when the demand of e.g. district heating increases. Today, during the winter period; October to March, the bark is sold as fuel to different consumers, e.g. energy companies. However, during the summer period; April to September, the demand of bark on the market is declining, and the bark is than piled up and stored at the pulp mill site. Due to limitations in storage area and the risk of spontaneous self-ignition of the bark piles, it is crucial to make use of the bark; either to sell it or to produce electricity and heat depending on the price of bark. The large amount of bark being produced at the mill site and the limited market for bark makes it interesting to investigate the potential of producing more high value products from bark. (Lyckehed, 2014, Rudén, 2014, Tärneberg, 2014)

Today, Södra Cell Värö delivers some of its excess heat to the district heating network of Varberg, operated by Varberg Energi. Together with Varberg Hospital, Varberg Energi has six boilers for heat delivery to the district heating network. These boilers use solid wood fuel, bio-oil and natural gas to operate. (Lyckehed, 2014, Sundquist, 2014, Varberg Energi, 2014b, Varberg Energi, 2014a)

The expansion of the pulp mill will also increase the production of excess heat, which will increase the pulp mill's possibility to deliver more district heating. The transmission line from Värö to Varberg is built for 50 MW; however the current agreement between the two parts permits only a delivery of 28 MW during the winter period and 10 MW during the summer period. (Varberg Energi, 2014b, Sundquist, 2014)

1.3 Objective

The aim of this master thesis is to present different technical ideas and solutions for improved resource utilization at the expanded Södra Cell Värö pulp mill. The suggested alternatives are evaluated and compared to a base case with respect to economic performance, resource efficiency and CO_2 emissions. Excess heat and bark are the main focus of this thesis work; however, the possibility of extracting lignin is also included.

1.4 System boundaries

The pulp mill together with the by-products from the sawmill shapes the system boundaries of this master thesis project. This means that costs for transportation and construction outside the mill are not considered. Figure 3 presents the system boundaries for the models considered in this thesis work.

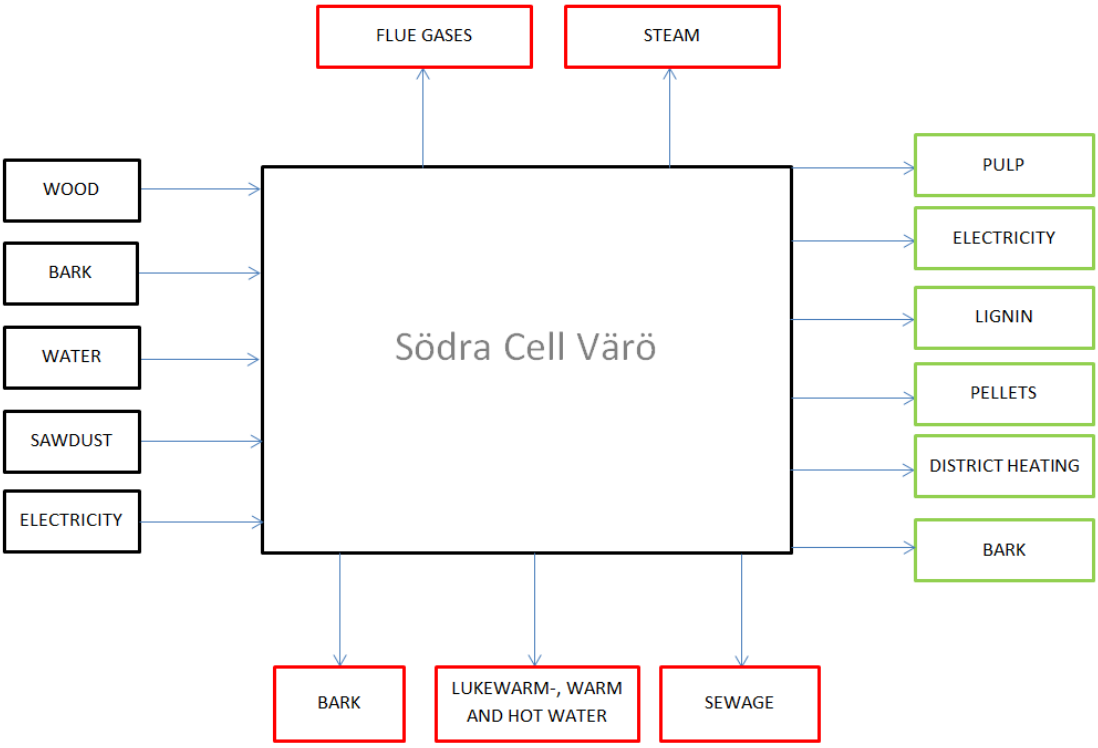

Figure 3. A schematic picture of the system boundaries of this master thesis. The black boxes are input products into the system, the green boxes indicate products that potentially can be sold on the market and the red boxes indicate potential system losses.

As can be seen in Figure 3, wood, bark, water, sawdust and electricity enters the system. Bark and sawdust comes from the sawmill, water from the river Viskan, electricity from the electricity grid and the majority of the wood from the southern parts of Sweden. The red noted products are potential losses, which includes flue gases, blown-off steam, bark, water of varying temperatures and sewage. The products that potentially can be sold on the market, the green noted products; are pulp, electricity, lignin, pellets, district heating and bark.

1.5 Report Outline

Chapter 2 includes a description of the raw materials used in the process and a presentation of the process. The chapter ends with a detailed description of the energy system at the pulp mill.

Chapter 3 presents different alternatives for increased resource utilization. The alternatives are divided into three groups; first group includes alternatives that were immediately discarded, the second group includes interesting alternatives that was discarded and the third group the investigated alternatives.

Chapter 4 presents the methodology of this thesis; the creation of the models of the investigated alternatives and the base case, how the different alternatives vary compared to the base case and the key performance indicators used for evaluation are defined. This chapter also presents the different input data and assumptions made.

Chapter 5 presents the results and a discussion about the energy balances and the key performance indicators results. A discussion about the possibility of combining the different alternatives is also presented and finally why the chosen key performance indicators were selected.

Chapter 6 presents the conclusions of this thesis.

Chapter 7 presents suggestions for further studies.

2 Process description

2.1 The main components of the wood raw material

Wood is the base resource used at the pulp mill at Södra Cell Värö. Since Värö is a softwood kraft pulp mill, mostly the softwood species spruce and pine are used in the kraft pulp process. (Södra, 2014c, Hedberg, 2014, Morin, 2014, Rudén, 2014)

The main components of wood are cellulose, hemicellulose and lignin. Spruce and pine are composed by approximately 42% cellulose, 27% hemicellulose and 28% lignin. The desired components in kraft pulp are cellulose and hemicellulose. The lignin is separated from the pulp since it ties the cellulose fibers together, and makes the paper go yellow and brittle. Ideally, removal of all lignin is preferable, however, there will always be some lignin residues left in the pulp after the delignification, since it is too expensive economically and in terms of yield and energy use to separate the lignin completely. (Theliander et al., 2002, Södra, 2014c)

Bark works as a protecting coating layer around the wood stem, and the main components of bark are the same as for softwood, but in other quantities. As already mentioned in Section 1.2.1, normally the Värö mill only uses the recovery boiler to satisfy the steam needed in the process, which results in unutilized bark as a by-product. Because of the large amount of unutilized bark from the process it is interesting to find alternatives for increased utilization of bark. (Theliander et al., 2002, Södra, 2014c, Lyckehed, 2014, Tärneberg, 2014)

2.2 Process overview

Figure 4 presents an overview of the Södra Cell Värö kraft pulp process.

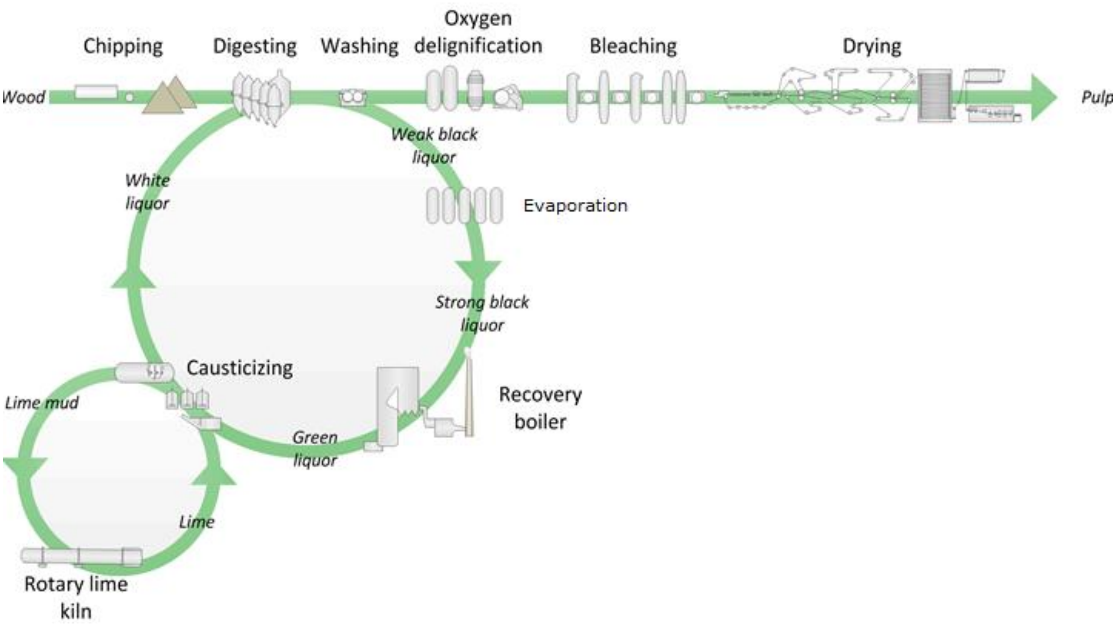

Figure 4. Process overview (Svensson, 2012).

The process starts with the wood being debarked and the logs being chipped. The chips are stored in large stacks before being transported to the digester where they are cooked at a high temperature together with the cooking liquor, called white liquor. It is in the digester the lignin is dissolved and the pulp is created. (Hedberg, 2014, Theliander et al., 2002)

Following the fiber line, the upper line of Figure 4, the pulp is separated from the black liquor by displacement washing and screening. Thereafter the pulp is bleached in the bleaching stage. Pulp bleaching at the extended Värö will be carried out using O_2 and H_2O_2 and possibly other chemicals in either one of two different types of bleaching: ECF bleaching or TCF bleaching. Elemental chlorine free bleaching, ECF, means that the process does not use chlorine gas but can use chlorine oxides for bleaching. Totally chlorine free bleaching, TCF, means that the process is not using any chlorine at all, neither elemental chlorine nor chlorine oxides. The bleached pulp is then dried and cut into sheets or flash dried and packed in bales before transported and sold. (Theliander et al., 2002, Rudén, 2014)

Connected to the fiber line after the digester is the recovery cycle for cooking chemicals, the circle in Figure 4 connected to the fiber line. The liquor from the cooking stage is called thin black liquor. Black liquor consists of water, chemicals and dissolved wood residues, and thin black liquor is black liquor with high water content. The thin black liquor is heated in the evaporators so the amount of water is decreased by evaporation, i.e., the thin black liquor is thickened into thick black liquor, and is further sent to the recovery boiler. In the recovery boiler the organic compounds are combusted to produce heat, which generates high pressure steam, while the inorganic residues are reduced and forms a "smelt". The high pressure steam is expanded in a turbine to generate electricity and steam with lower pressure, to be used as heating utility in the process. The major part of the "smelt" consists of sodium carbonate, Na_2CO_3, and sodium sulfide, Na_2S. The "smelt" is dissolved in the dissolving tank and green liquor is formed. The green liquor flows to the slaker where it is mixed with lime, CaO, and then to the causticizing reactors. The mixture is then filtered to remove the lime mud. The lime mud goes to the lime kiln where the lime mud is washed, heated and burned in the lime kiln to form burnt lime. The filtrated liquor is white liquor, which is sent back to the digester and the process starts over again. (Bood and Nilsson, 2013, Fritzson, 2002, Theliander et al., 2002, Rudén, 2014)

A large part of the wood residue in the liquor is lignin which has a high heating value. The lignin can be extracted from the black liquor and thereby lower the heating value of the black liquor, which lowers the amount of heat produced in the recovery boiler. This means that if the need for heat in the process is decreased, or can be satisfied in another way, there is a possibility to use lignin for other purposes. (Wallmo et al., 2009)

2.3 Overview of the energy system of the kraft pulp mill

Energy and mass balances have already been estimated for the expanded mill (Ivarsson, 2014, Törmälä, 2014), for both winter and summer conditions combined with ECF or TCF, and also for summer with or without bark burning for bark destruction purposes (Rudén, 2014). The resulting incoming and outgoing energy and material flows from these balances are used for understanding and modelling the energy system in this thesis.

The recovery boiler constitutes the central point of the energy system and is the main producer of steam. The high pressure steam produced from the recovery boiler goes to the turbines; one back-pressure turbine and one condensing turbine. The back-pressure turbine is a part of the existing mill while the condensing turbine will be built for the new expanded mill. Both turbines will be connected to separate electricity generators. Steam is, both in the current and in the expanded mill, extracted at different pressure levels; high pressure steam, HP, at 86.9 bar, medium pressure steam 2, MP2, at 27-27.5

bar, medium pressure steam 1, MP1, at 11.4-13.5 bar, intermediate steam, PM, at 9.3 bar, and low pressure steam, LP, at 4.3-4.5 bar. There is also a condensing extraction that is simply called condensate at 0.026-0.072 bar. The steam flows to different parts within the system, such as the dryers, the digester, the bleaching plant and the evaporation plant. Steam is also used for heating the sawmill and the pellets factory connected to the pulp mill. (Lyckehed, 2014, Rudén, 2014)

Figure 5 shows the steam system and how the different components are interconnected.

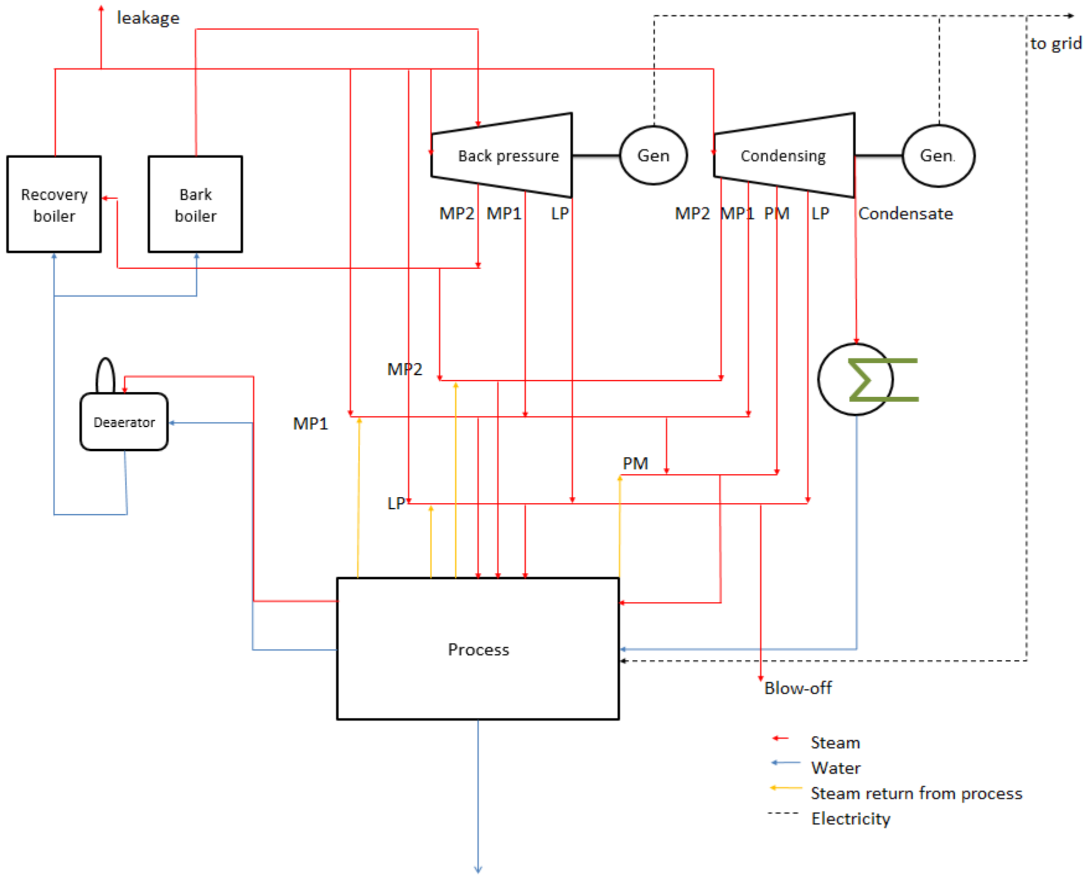

Figure 5. The energy system of the Södra Cell Värö pulp mill.

As can be seen in Figure 5, the Värö mill also has a bark boiler, which can be used for extra steam generation when there is a steam deficit in the mill or when the steam demand of other consumers are greater than the steam produced by the recovery boiler. Hence, under such conditions, the bark is not sold but burned to generate electricity and process heat (Lyckehed, 2014). As presented in Figure 5, the bark boiler is only connected to the back-pressure turbine, which means that when the bark boiler is operating some of the steam from the recovery boiler is redirected to the condensing turbine. It is also notable that the steam from the bark boiler is entering the back-pressure turbine at lower pressure than the steam from the recovery boiler, which is indicated by the red arrow from the bark boiler to the back-pressure turbine.

The secondary heating system is used to recover some of the heat by using it for preheating different streams in the mill. Some water used in the secondary heating system is also heat exchanged with black liquor and LP steam to be used to heat the sawmill and the pellets factory. Water from the lukewarm, warm and hot water system is reused by being cooled in the cooling towers and thereafter used as cooling water in different parts of the system. This is done in order to reduce the freshwater intake to the mill. The water that is not recovered nor reused in the secondary heating system is released to the sea after being handled in the waste water treatment facility. During the summer period the excess heat from the water system are foremost hot and lukewarm water and during the winter period it is warm and lukewarm water that are available. The secondary heating system balances are presented in Appendix A: Secondary Heating System. (Hedberg, 2014, Rudén, 2014)

The black liquor stream that is separated from the pulp in the digester is used to heat the district heating and the hot water, before it enters the evaporation plant. The cooling of the thin black liquor is necessary to prevent the liquor from boiling in the pipes. The evaporation of black liquor demands large amounts of live steam. Some of the condensate from this steam is extracted and used to heat the water stream to the sawmill and the pellet factory. By doing that the primary heat demand in the sawmill and pellet factory is reduced. (Rudén, 2014)

Figure 6 shows the amount and temperature of the available excess heat from the secondary heating system. In Table 3 in Section 4.1.1, the different temperature levels and flows are presented.

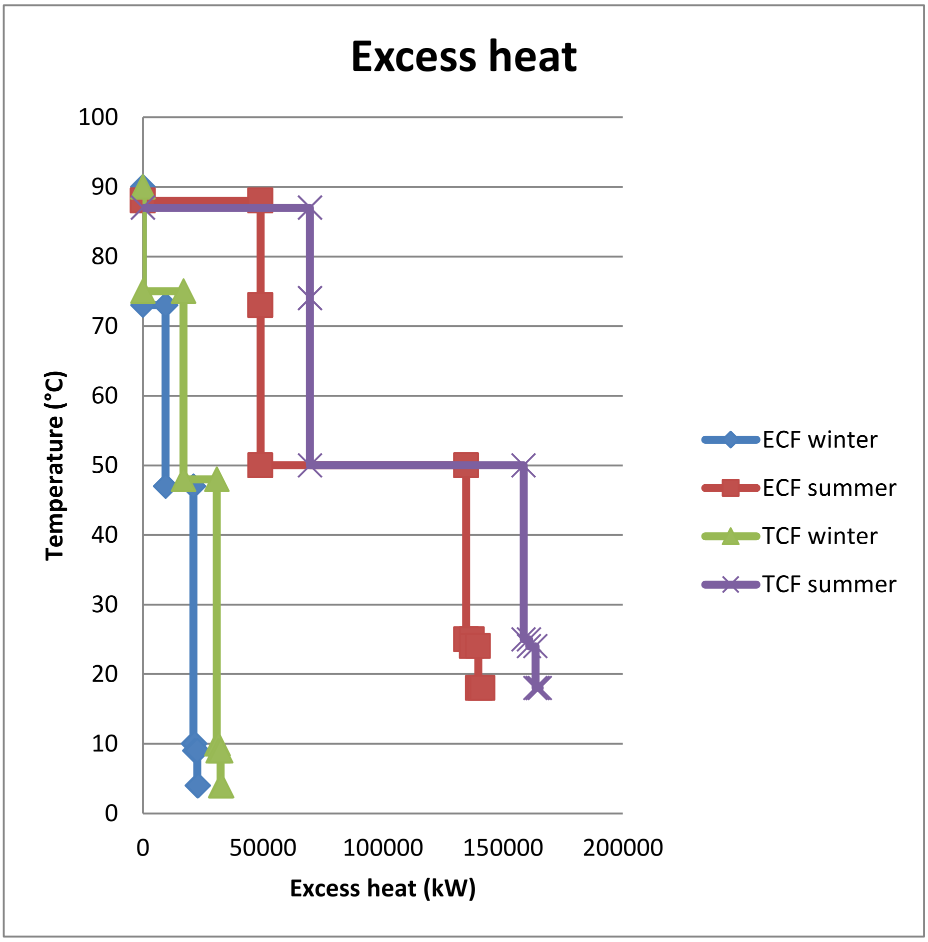

Figure 6. Available excess heat for the winter and the summer periods for ECF and TCF.

The excess heat that can be seen in Figure 6 is stored in different tanks before it is sent to the cooling towers and cooling turbines, or to the waste water treatment plant. This is why the temperature is levelled and not decreasing.

To co-locate a sawmill and a pulp mill has several advantages; the pulp mill provides heat and electricity to the sawmill, and the sawmill provides chips, bark and sawdust to the pulp mill. The sawdust sent from the sawmill is used to produce pellets, and is also used as fuel in the pulp mill's lime kiln, which is a powder burner. (Hedberg, 2014, Lyckehed, 2014, Morin, 2014, Rudén, 2014)

3 Alternatives for increased resource utilization

For this master thesis work a thorough investigation of different alternatives for improved resource utilization at the Södra Cell Värö pulp mill was prepared, however due to time limitation only a few of them were studied more in detail. In this chapter, all the alternatives considered in this project are presented and divided into three groups. The first group consists of the alternatives that were discarded at an early stage, the second group consists of the alternatives that where more comprehensively evaluated, but later on discarded, and the final group is the alternatives that were selected for further investigation.

3.1 Early stage discarded alternatives

3.1.1 Bark bread

Using bark to produce bread is an option created by "thinking outside the box". This is a type of bread that has been used and is still used in small regions of, especially, the northern parts of Europe. However, with todays commercialized bread the bark bread would not have a competing chance to break into the market and with the quantity of bark that exist, this option is not an alternative. (Mental_floss, 2009)

3.1.2 Bark in combi pellets

Combi pellets are a combination of bark and normal pellets. Södra has produced combi pellets before, and also pure bark pellets. Since Södra already have experiences about combi pellets and due to time limitation this alternative was discarded in an early stage by Södra. (Södra, 2014a)

3.1.3 Excess heat for drying forest residues

Using excess heat for drying forest residues is an alternative that has already been studied by Södra, and since they had problems with drying enough of the bark, there would not be enough excess heat to also dry forest residues. This is why drying forest residues were discarded in an early stage.

3.1.4 Excess heat for drying sawdust

An alternative to use the excess heat would be to dry sawdust. However, at the moment, there exists a sawdust dryer with enough capacity to dry all the existing sawdust and that is why there is no need to investigate this alternative any further. An exception would be if an expansion of the timber production at the sawmill occurs or if an investment in a more energy efficient dryer is considered.

3.2 The interesting but discarded alternatives

3.2.1 Algae cultivation

Algae cultivation is a topic that is growing and becoming more interesting for the market and the industry sector. There is research on algae batteries and algae for biomass and biofuel production (Hardwick, 2015, Industry, 2012, Johansson, 2009, Rosén, 2009). The research is still on a developing stage; however it has been shown that microalgae cultivation in waste water treatment plants can be an interesting opportunity. The reason for this is that microalgae can both be beneficial for the waste water treatment and be utilized for biofuel production. This is an interesting alternative, but according to what has been seen so far it would not directly increase the resource utilization at the mill, and therefore it was not further studied. (Chinnasamy et al., 2014, Rajkumar et al., 2014, Steele et al., 2014, Trentacoste et al., 2014)

3.2.2 Bark as insulation material

Bark has very good insulating properties, not because of its thermal conductivity, which is quite high, but for its comparatively low thermal diffusivity. Because of this property, bark is suited for heat storage-optimized insulation materials in e.g. buildings. Processing and compression of the bark is needed to make bark an insulating material, and a question would be whether the revenue from selling the product will be higher than the processing costs. (Kain et al., 2012)

With the large amount of bark available at the Värö site, refining of the bark for creating insulation material would be an interesting option. A problem with this is that it would require more research, which is why this alternative was not further investigated.

3.2.3 Fish farming

With increased fish consumption during the last 30 years and increased awareness of the origin of the fish cultivation, there might be an interest in fish farming (Johansen, 2013, Jordbruksverket, 2015). There has been a fish farm in connection to the nuclear power plant Ringhals, which is located near Värö (Vattenfall, 2013). With the heat from an industrial plant, a fish farm could work all year around, and according to Svenskt vattenbruk (2014), the heating cost is not a large part of the total cost, if a well isolated building is used and water is recirculated. One problem with recirculating fish farms is that the owners need to be trained and have high knowledge about the business. (Svenskt vattenbruk, 2014)

Fish farming would likely require an external company since it is not within Södras' present business area. Together with the uncertainty regarding whether there would be any benefits at all from co-localization with the pulp mill, this puts the fish farming alternative on the list of options that are not further investigated.

3.2.4 Gasification of black liquor and biomass

Technologies for black liquor gasification and solid biomass gasification are currently under development. The two different gasification options are presented below. These alternatives were discarded by Södra, so no further investigation of the below presented alternatives was done.

3.2.4.1 Black liquor gasification

As presented in Section 2.2, black liquor is produced during the pulp process in a kraft pulp mill. In the digester, wood chips together with white liquor are cooked and pulp and thin black liquor are created. The thin black liquor is thickened in the evaporation plant, since the water content in the liquor is decreasing through evaporation, and thick black liquor is made. As it is today at the Södra Cell Värö pulp mill, thick black liquor is fired in the recovery boiler to produce steam, which is used to generate electricity and steam, and can be further used in the pulp mill processes. (Bioenergy, 2007, Mistra, 2012, Pettersson, 2011)

An alternative for the energy and chemical recovery at the mill is using black liquor gasification, BLG, instead. The purpose of the black liquor gasification is to generate a synthesis gas, syngas, and use the syngas for efficient electricity and heat production, or as a feedstock for biofuel for the transport sector, e.g. methanol, DME or synthetic natural gas. In addition, the chemicals are recovered as in the case of using a recovery boiler. (Biogasportalen, 2014, Lindmark, 2013b, Lindmark, 2013a, SGC, 2011, Bioenergy, 2007, Isaksson, 2015, Mistra, 2012, Pettersson, 2011)

3.2.4.2 Solid biomass gasification

Since the possibility of selling bark varies during the year the option of producing other qualities of wood-based fuels for the fuel sectors are of interest for Södra. Materials such as bark, but also shavings and chips, which cannot be used for pulp and timber production, may be converted into biofuels through biomass gasification. Looking at bark, which is one of the pulp mill's major by-products when producing pulp and paper, it has a similar structure as wood and may therefore be an interesting raw material for biofuels production. (Södra, 2008, Södra, 2014a, Westerberg, 2013)

A biomass gasifier can be implemented in the process instead of a bark boiler. The process for producing syngas works in a similar way as for black liquor gasification. (Jönsson, 2012, Pettersson, 2011, Stern et al., 2012)

3.2.5 Increased bark boiler capacity

By increasing the capacity of the bark boiler there will be an opportunity for increasing the generation of steam, and thereby enhance the possibility to generate more electricity that could be sold on the electricity market. In addition, it will improve the pulp mill's situation of handling more bark for destruction burning. This is for preventing self-ignition of bark during the summer period. However, currently, increased capacity in the bark boiler would require a completely new bark boiler, adding a high investment cost for Södra. The requirements to make increased capacity for the bark boiler an interesting alternative would be if there occurs a need for increased steam demand at the mill.

Currently, it is possible for the turbines to manage more steam for electricity generation, especially increasing the usage of the condensing turbine. As mentioned in Section 2.3, the bark boiler is only connected to the back-pressure turbine making the condensing turbine better utilized when the bark boiler is operating. This is because the steam from the recovery boiler will be redirected from the back-pressure turbine to the condensing turbine.

This alternative was postponed until having the knowledge whether or not either of the presented needs in this section existed.

3.2.6 Low temperature electricity generation

PCM, which stands for phase change material, is one possible technology for low temperature electricity generation, which is based on a phase change material engine system. The technology is based on the principle of volume change when changing state of the material, in this case from solid to liquid when heated and from liquid to solid when cooled. (Johansson and Söderström, 2014)

Södra has already evaluated this alternative and realized that it is not profitable. This is because of the required pump effects in order to pump all the streams needed for the PCM would be too large and consume any electricity generated. Thereby the profit would be marginable. (Andersson, 2014)

3.2.7 Polyurethane foams made from liquefied bark-based polyols

During recent years technologies producing polyurethane foams from liquefied bark-based polyols have been developed. Polyurethane foam can be used for a variety of different applications; some examples are packaging, vibration dampening and filling materials. It has recently been proved that it is possible to mix bark with the polyurethane foam without affecting the properties in any significant way. The research has also managed to produce bark-based foams with several similar properties to polyethylene glycol. (D'Souza et al., 2014, D'Souza and Yan, 2013)

Biomass-based polyurethane would be a huge environmental improvement since today polyurethane is largely petroleum derived. An advantage would be the biodegradability, which has been shown for the bio-based material, but which is negligible for the petroleum-based one. (Hu et al., 2014)

With further research and progress in the area this is likely to become an interesting alternative for bark usage. However, since these technologies are still under development at laboratory stage and outside the normal business area of Södra, it was chosen to not further investigate this alternative.

3.2.8 Wood residues for producing plastic composites

It has been shown that kraft mill sludge could be used to produce superior wood-plastic composites. However, due to time limitation it was decided not to further investigate this alternative. (Migneault et al., 2014)

3.3 The investigated alternatives

Included in the third group are the alternatives that were investigated and these are bark burning, lignin extraction, district heating and drying bark. The alternatives presented will now on be called scenarios, since it will be easier to distinguish them and separate them from the base case.

3.3.1 Burning bark

Bark burning is here defined as a process where bark is burned in a bark boiler in order to produce superheated steam. The steam is thereafter used in the back-pressure turbine to generate electricity, see further Figure 5, and extracted at different pressure levels for use as a heating medium in the process. As mentioned in Section 2.3 and presented in Figure 5, the bark boiler is only connected to the back-pressure turbine, meaning that some of the steam produced in the recovery boiler will be redirected to the condensing turbine when the bark boiler is operating. As stated in Section 3.2.5, it is possible to increase the steam production since the turbines are able to manage an increase of steam.

For Södra this alternative is of interest foremost during the summer period when the demand of bark is lower on the biomass market and the stacked amount of bark increases on the mill site. This alternative is modelled in Scenario 1, Section 4.2.2, to see if it is beneficial to burn bark, and during which periods of the year it is most profitable. (Lyckehed, 2014)

3.3.2 Lignin extraction

An interesting alternative is extraction of lignin from the black liquor. Lignin can be a renewable alternative feedstock to otherwise oil-based products, since lignin has a chemical structure similar to oil. In addition, lignin extraction can enable increased pulp production. (Tomani, 2010, Wallmo et al., 2009, Macdonald, 2011)

Lignin extraction would lead to a reduction of the organic content in the black liquor, leading to less thermal energy in the recovery boiler, and thereby decreasing the load on the equipment/material. If thermal energy is the limiting factor for the load of the recovery boiler, the possibility to increase the liquor flow rises if lignin is extracted. Thus, this enables an increased amount of wood to be delignified in the digester. (Tomani, 2010, Wallmo et al., 2009, Zhu et al., 2014)

Currently, the leading commercially available alternative for lignin extraction is the LignoBoost process. A schematic overview of the LignoBoost process can be seen in Figure 7. The liquor is extracted from the evaporators at about 40% DS. Then, in a precipitation step, CO_2 is added, reducing the pH, making it possible to separate lignin from the liquor in filtration step 1. The liquor is resent to the evaporators to the next evaporator step with lowered lignin content. The lignin is dissolved in a re-suspension step with spent wash water, and then acidified to lower the pH. Thereafter it is possible to filtrate and wash out impurities in filtration step 2. This is done with acid wash water. The filtrate from the filtration is sent back and enters the evaporators together with the thin black liquor, while the spent wash water is sent to the re-suspension step and the lignin is extracted. (Tomani, 2010, Wallmo et al., 2009, Zhu et al., 2014)

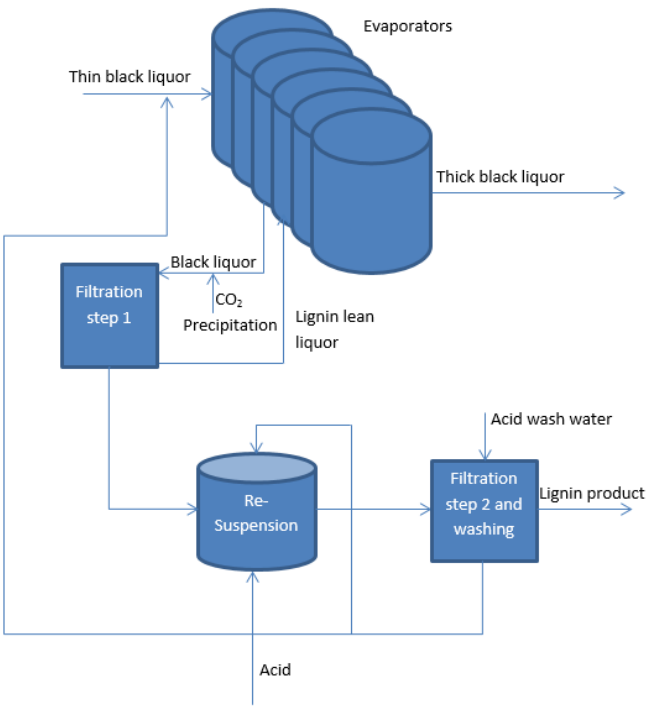

Figure 7. Schematic overview of the LignoBoost process for lignin extraction.

The extracted lignin can be used in several different types of applications and a few different promising future applications are carbon fiber, dispersant and asphalt emulsions. Currently, the main option is to use the lignin as a fuel. (Innventia, 2012, Innventia, 2014, Macdonald, 2011, Tomani, 2010, Wallmo et al., 2009)

This alternative is modelled in Scenario 2, Section 4.2.3.

3.3.3 District heating

Figure 8 shows a schematic picture of a district heating network. The red lines present the delivered district heating to the buildings and the blue lines shows the water that is returned back to the heating facility.

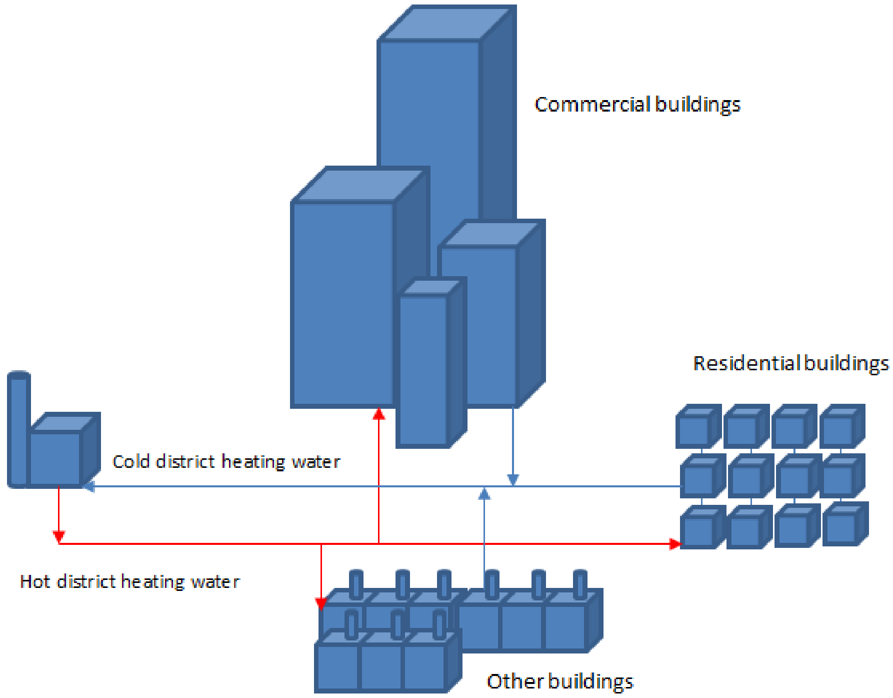

Figure 8. Schematic picture of a district heating network.

As mentioned in Section 1.2.1.2, the amount of district heating delivered to Varberg from Södra is set to 28 MW during the winter period and 10 MW during the summer period. The transmission line from Värö to Varberg is built for 50 MW; however, there is an uncertainty from Varberg Energi if the district heating capacity can be further increased from 28 MW respectively 10 MW to Varberg. If Södra cannot increase its deliveries to Varberg there exists the possibility to expand the district heating network to Kungsbacka to make use of the mill's excess heat.

The option of increasing the district heating capacity to Varberg is of interest for Södra due to the large amount of excess heat that will be available from the expanded mill. By recover the increased amount of excess heat produced, the possibility to utilize more of the transmission line to Varberg will increase, and it might even be possible to supply both Varberg and Kungsbacka with district heating. That is why this alternative is interesting and is modelled in Scenario 3, Section 4.2.4.

3.3.4 Drying bark to use as fuel in the lime kiln

By increasing the dryness of bark to 93% DS, the bark may be used as a replacement fuel for sawdust in the lime kiln. Today the lime kiln is supplied with sawdust as fuel, but if instead bark could be used as fuel, the more valuable sawdust could be sold at the biomass market to a higher price than bark.

The bark dryer is designed to remove water by evaporating moisture from the bark. The function is to utilize various heat sources, e.g. excess heat from water and steam, to heat air that will dry the bark. As the dried and heated outdoor air is in contact with the bark, the bark will get dryer. The evaporated water from the bark will lower the temperature in the surrounding air until the air is either saturated or has left the drying zone. The higher the temperature is the more water can be carried out from the drying zone by the saturated air. After the drying sequence, the dried bark is used as a fuel, either at the drying site or sold for further use somewhere else. By drying the bark the heating value of the bark will increase and provide a more competitive fuel on the biomass market. (Biomass, 2010, Holmberg and Stenström, 2014, Holmberg and Ahtila, 2005, Johansson et al., 2004)

The reason why bark cannot simply be sold on the market is that the amount of bark available from all Swedish paper and pulp mill sites would force the price on bark and other wood fuels to drop because of the high supply compared with the current market demand.

This alternative is interesting both in a resource perspective but also in an economic perspective for Södra. Because of the limited amount of information regarding costs for low temperature bark drying, the economic performance will not be calculated for this scenario. However, it is obvious that the economic performance will increase if the less attractive bark substitutes the more attractive sawdust as fuel and the sawdust is sold at the biomass market. This alternative is modelled in Scenario 4, see Section 4.2.5, and will hereon only be called bark drying.

3.3.5 Investigated scenarios

Table 1 presents a summary of the investigated scenarios. Each scenario is divided into several sub scenarios, which is presented in Section 4.2.

Table 1. A summary of the scenarios investigated.

Scenario	
Scenario 1	Burning bark
Scenario 2	Lignin extraction
Scenario 3	District heating
Scenario 4	Bark drying

4 Methodology and input data

An introductory study was carried out to get familiar with the Värö pulp mill as it is today and for the future planned expansion of the mill. Included in the introductory study were literature studies of the mill, interviews with personnel and study visits to the pulp mill. Based on the acquired knowledge a model of the energy system was made.

The alternatives for how to use the excess heat and bark as presented in Chapter 3, was identified in the literature study. Of these a few alternatives were chosen for further investigation, modelled and then evaluated using three key performance indicators; economic performance, resource efficiency and CO_2 emissions. All the investigated alternatives where evaluated and compared to a base case, see further Section 4.2.1.

4.1 Modelling approach

Since the main interest of this thesis is to make use of the excess heat and bark available and not to modify the process, the process is modelled as a black box, see Figure 9. The black box only works as an energy user and a source of excess heat in the models.

For the different scenarios, as well as the base case, the energy and mass balances is determined by building models over the expanded mill.

4.1.1 Data and assumptions for the base case and the scenarios

Some key data for this master thesis work are presented in Table 2. More data can be found in Appendix B: Input and process data.

Table 2. Summary of some key data.

Data			
Components			**Unit**
Bark		900,000	m^3/year
Bark 40% DS		313	GWh/year
Bark 60% DS		320	GWh/year
Specific heating value black liquor	$C_{p,black\ liquor}$	3.65	kJ/kg°C
Specific heating value water	$C_{p,water}$	4.19	kJ/kg°C
Fuel effect lime kiln		46.2	MW
Back-pressure turbine effect		63	MW
Condensing turbine effect		63.7	MW
Efficiency Recovery boiler	η	0.85	-
Efficiency Bark boiler	η	0.78	-
Isentropic efficiency Back-pressure turbine	η_{is}	0.87	-
Isentropic efficiency Condensing turbine	η_{is}	0.86	-
Efficiency Generators	η	0.98	-

As mentioned earlier in Section 1.2.1.2, the amount of bark available at the mill after the expansion is approximately 900,000 m^3/year (Lyckehed, 2014), which is equal to the total energy amount of 633 GWh/year (Lyckehed, 2014). Bark with 40% DS, which is the dryness of the bark after the logs being debarked, has an energy content of 313 GWh/year and bark with 60% DS, which is the dryness of the bark after being dried in the current bark dryer, has an energy content of 320 GWh/year. The efficiency of the bark boiler is 0.78 (Rudén, 2014), and the amount of bark that the bark boiler has the capacity to handle is approximately 340,000 m^3/year. An assumption for the bark is that all bark that cannot be used within the pulp mill is considered to be sold at the biomass market to winter price. More about prices can be found in Section 4.3.1.

Table 3 presents the excess heat from the secondary heating system for the different bleaching alternatives. As mentioned in Section 2.3, during the summer period the excess heat from the secondary heating system are foremost hot and lukewarm water and during the winter period it is warm and lukewarm water that are available.

Table 3. Amount of excess heat from the secondary heating system (Rudén and Olowson, 2014).

Excess heat	Unit	ECF summer	ECF winter	TCF summer	TCF winter
Lukewarm water	kg/s	409	59	425	69
	ºC	50	47	50	48
Warm water	kg/s	0	31	0	54
	ºC	73	73	74	75
Hot water	kg/s	133	0	191	0
	ºC	88	90	87	90

The steam used in the process, which can be seen in Table 4 is produced in the recovery boiler and in the bark boiler, when burning black liquor and bark. As presented earlier in Section 2.3, the mill has two turbines, a back-pressure turbine and a condensing turbine; where the recovery boiler is connected to both of the turbines, but the bark boiler is only connected to the back-pressure turbine. The extraction pressure levels of the turbines can be seen in Table 5 when the turbines operate normally.

Table 4. Steam demand in for the process [MW] (Ivarsson, 2014).

Steam demand	ECF summer	ECF winter	TCF summer	TCF winter
MP2	28.8	29.4	28.8	29.4
MP1	29.7	32.6	36.5	39.0
PM	30.8	33.1	29.8	31.2
LP	183.6	211.7	188.5	214.0

Table 5. Steam table regarding output pressures from the back-pressure and the condensing turbines (Ivarsson, 2014).

Steam type	Pressure	Unit
MP2	27-27.5	Bar
MP1	11.4-13.7	Bar
PM	9.3	Bar
LP	4.3-4.5	Bar
Condensate	0.028-0.072	Bar

It is assumed that both turbines have the same efficiency independent of load, even though in reality the efficiency will drop if the turbines are only operating at part load. The recovery boiler has the same efficiency, same temperature and pressure delivery, both while operating at full and part load. For the bark boiler it is assumed that it is either operating at maximum capacity or not operating at all, no part load is assumed.

These assumptions will reduce the complexity of the model. There is already a need for both a summer and a winter model. This is due to the steam needed in the process differs depending on season, see Table 4. In addition, there are also the two different alternatives for bleaching, ECF and TCF, that have different requirements as well.

For more information regarding the data and assumptions made see Appendix B: Input and process data and Appendix C: Assumptions.

4.2 Description of the used models

This section describes the used models. First the base case is described and thereafter the different scenarios are presented, and also differences compared with the base case are highlighted.

4.2.1 Base case

4.2.1.1 Steam system presentation

Figure 9 presents the steam system for the base case, which is used as a reference for the studied scenarios. Since there will be two different bleaching alternatives, ECF and TCF, with different steam demands at the mill, there are actually two base cases; however, they are built in the same way. Hereafter, base case will refer to both base cases except when the bleaching type is specified. The base case's steam system includes a recovery boiler, a bark boiler, a back-pressure steam turbine, a condensing steam turbine and generators connected to each of the turbines and the process, which is represented as a black box in Figure 9.

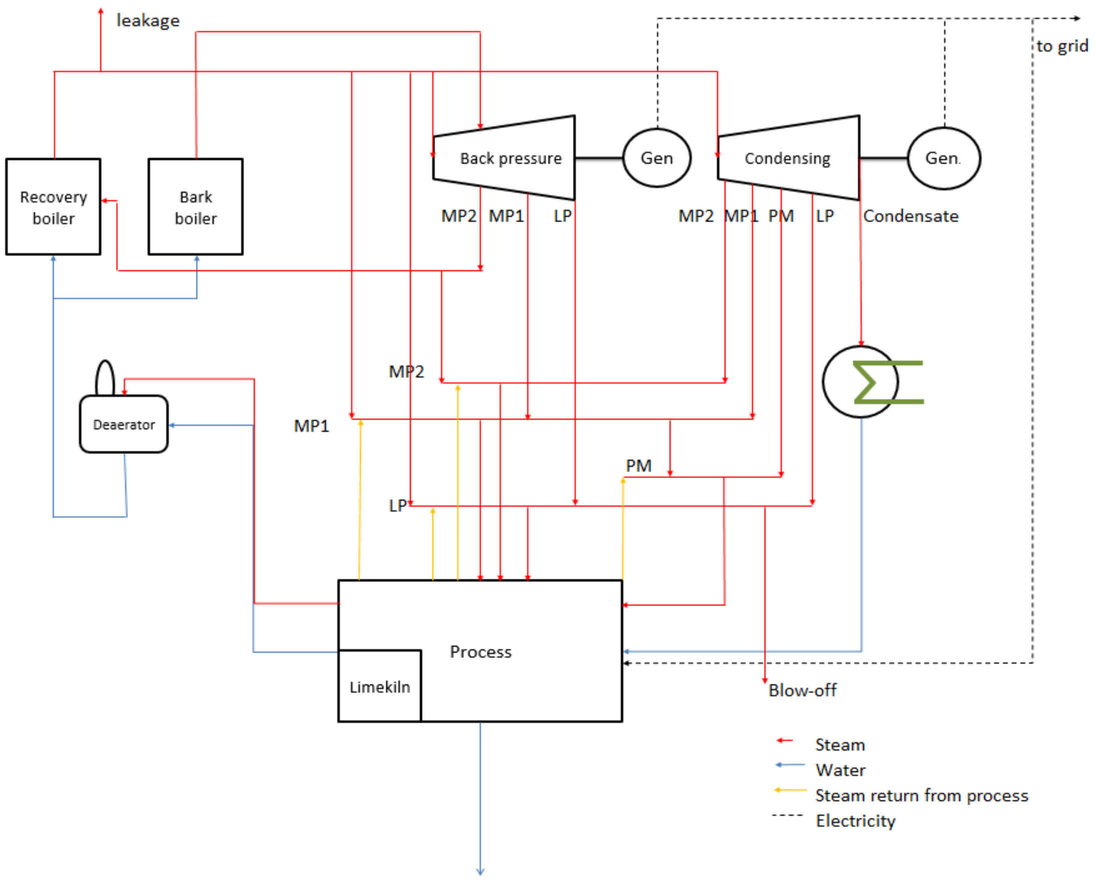

Figure 9. A simplified schematic picture of the steam system for the base case.

The steam from the recovery boiler is divided into two streams; one that enters the back-pressure turbine and one entering the condensing turbine. The amount of steam that is entering the two turbines varies and depends on whether the bark boiler is operating or not. There also exist bypass flows, however, these are not used during normal operation and therefore not modelled. The steam from the bark boiler enters the back-pressure turbine at a lower pressure and temperature level compared to the steam from the recovery boiler.

When the bark boiler is not operational, steam from the recovery boiler supplies both the turbines. However, when the bark boiler is operating, more steam is redirected from the recovery boiler to supply the condensing turbine, since all the steam from the bark boiler is delivered to the back-pressure turbine.

As already mentioned in Section 4.1.1, Table 5 presents the different steam pressures from the turbines and these deliveries are dependent on the process. The turbine output of LP steam is the same as the process demand, until the condensate part of the condensing turbine reaches its maximum capacity of 150 ton/h. At that point, if there are more steam then the process needs the steam will be extracted as LP, since that delivers the most work to the generators. If there is no need for the extra LP steam, the steam is blown-off.

In the base case, the bark boiler operates during half of the summer period, April-September, i.e. for three months, since it is assumed that it is not possible to sell all bark produced during the summer period. This is a precaution made by the mill to avoid the piles becoming too big and to reduce the risk for the bark piles to self-ignite.

4.2.1.2 The district heating system

Connected to the steam network is a network of heat exchangers with the purpose of heating the district heating water. Figure 10 shows a schematic picture of how the heat exchanger network for district heating is planned to be built for the expanded pulp mill.

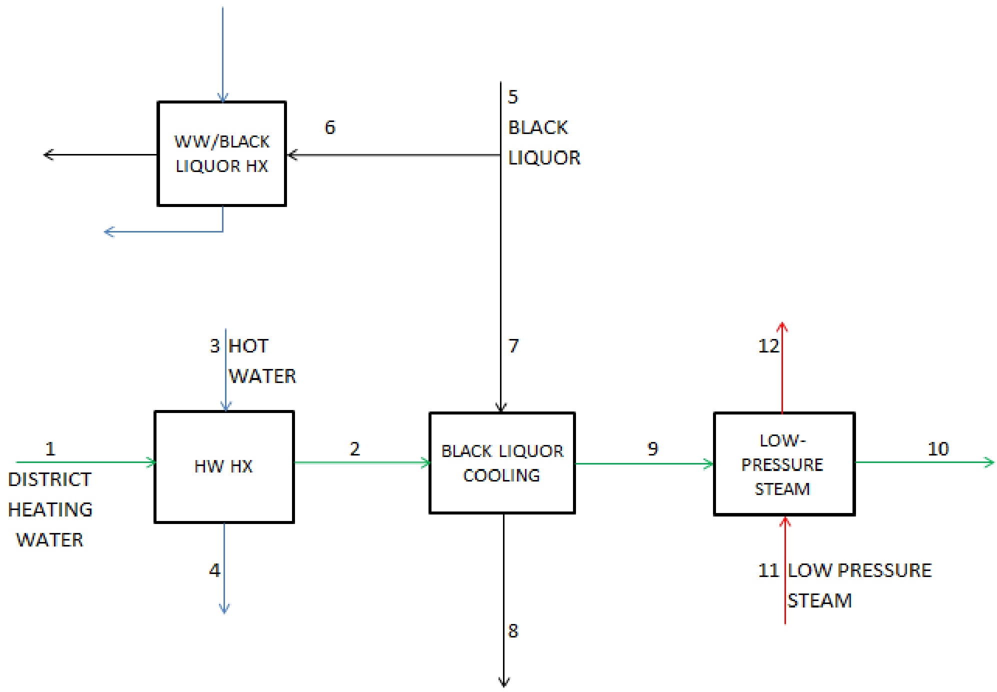

Figure 10. Schematic picture of the heat exchanger network for the planned district heating system.

The heat exchanger network consists of three heat exchangers; a hot water heat exchanger, a black liquor cooling heat exchanger and a low-pressure steam heat exchanger, all with the purpose of heating the district heating water to the required temperature of 84^{0}C during summer and 93^{0}C during winter.

The temperature of the black liquor out from the black liquor cooling heat exchanger, location 8, is limited to 85^{0}C, which is set as a limit for all the sub scenarios involving the black liquor cooling.

From the digester, location 5, the black liquor will be divided into two flows. The black liquor at location 5 has a fixed mass flow of 259 kg/s independent of season, however, depending on season the black liquor is split differently between location 6 and 7. The warm water and black liquor heat exchanger shows where the black liquor flows, if not used in the district heating heat exchanger network.

As mentioned in Section 1.2.1.2, the district heating capacities to Varberg is set for the base case to 28 MW during the winter period and 10 MW during the summer period.

4.2.2 Scenario 1: Bark Burning

The bark burning scenario consists of four different sub scenarios that are demonstrating how much bark that is burned, and during what part of the year the burning occurs.

The modelled sub scenarios in the bark burning scenario are:

- Scenario 1a: Burning bark only during the summer period,
- Scenario 1b: Burning bark all year,
- Scenario 1c: Burning bark as in the base case during the summer period and the entire winter period,
- Scenario 1d: Not burning any bark at all

By varying the amount of bark burnt in the process the amount of steam being produced is changed. The produced steam will be utilized in the turbines and after that any excess steam is blown-off. Figure 11 shows the part of the system where the modifications for the different sub scenarios are done.

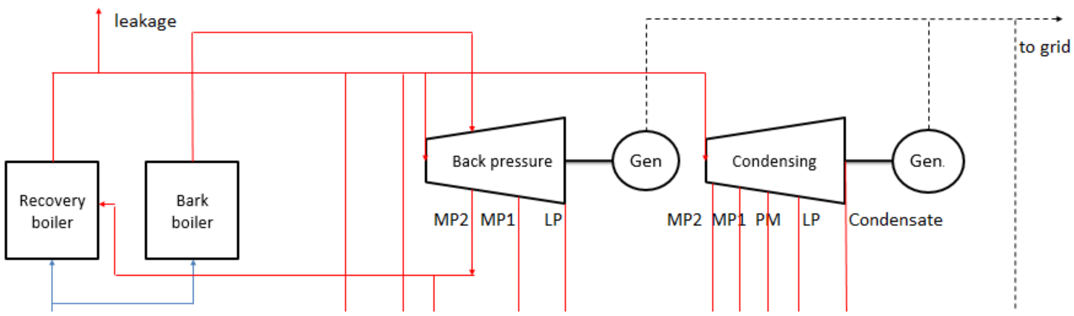

Figure 11. Schematic picture of the parts of the system used in Scenario 1: Bark Burning.

Table 6 presents a clarification when bark is burned during the year in the different sub scenarios of the bark burning scenario.

Table 6. Explanation when bark is burned for the different sub scenarios in the bark burning scenario.

Sub Scenario	Duration of bark burning for the different sub scenarios
Scenario 1a	Summer period, i.e. April – September (6 months)
Scenario 1b	All year (12 months)
Scenario 1c	Half the summer period (3 months, base case) and entire winter period (6 months), i.e. 9 months in total
Scenario 1d	No bark burning

4.2.2.1 Scenario 1a: Burning bark only during the summer period

With the expansion of the mill, there will be an increased amount of bark residue. As mentioned earlier in the base case, to avoid self-ignition in the bark piles the bark is burned during approximately half of the summer period.

Scenario 1a evaluates the situation of burning bark the entire summer period, i.e. for six months, instead of half the summer period, as in the base case. As described in Section 4.2.1 and seen in Figure 9, when the bark boiler is in operation it will affect the steam flow and how much of the recovery boiler's steam that is distributed to the condensing turbine instead of to the back-pressure turbine. This sub scenario means that some of the steam from the recovery boiler will be delivered to the condensing turbine instead of the back-pressure turbine, since the steam from the bark boiler is sent to the back-pressure turbine.

4.2.2.2 Scenario 1b: Burning bark all year

Scenario 1b shows the effect of burning bark the entire year. By burning bark all year the results will be increased electricity generation and a decreased amount of bark piled up at the mill site; since primarily the 40% DS bark is used as fuel in the bark boiler and the 60% DS bark is used when there is a deficit of 40% DS bark. As in the previous sub scenario, Scenario 1a, some of the steam from the recovery boiler will be delivered to the condensing turbine instead of the back-pressure turbine, since the back-pressure turbine will be supplied with steam from the bark boiler.

4.2.2.3 Scenario 1c: Burning bark as in the base case during the summer period and the entire winter period

This sub scenario focuses on burning bark during the winter period instead of selling the bark, and still burn bark during approximately half the summer period to avoid self-ignition of the bark, as in the base case. The effect of burning bark during the winter period will be increased electricity production for sale, and this at the expense of selling that amount of bark on the biomass market as fuel for e.g. heat production. As in the previous sub scenarios, the amount of steam produced in the bark boiler will be delivered to the back-pressure turbine, and force some of the steam from the recovery boiler to be redistributed to the condensing turbine. Still there will be dried bark with 60% DS for sale at the biomass market.

4.2.2.4 Scenario 1d: Not burning any bark at all

Ideally it would be possible to sell the bark all-year, avoiding any need for storage and risk for self-ignition, which is the assumption this sub scenario is based on. In this sub scenario the bark boiler is never used, only the recovery boiler, and in normal operation the recovery boiler can cover all the steam needed by the process by itself, as mentioned in Section 2.1.

4.2.3 Scenario 2: Lignin extraction

The lignin extraction sub scenarios are based on the LignoBoost process, presented in Section 3.3.2. The amount of extracted lignin is set so the steam production is sufficient to satisfy the mill steam demand and no condensing power is produced. This was applied in the eight sub scenarios for lignin extraction, which are:

- Scenario 2a: Same production of pulp, without bark burning,
- Scenario 2b: Same production of pulp, with bark burning,
- Scenario 2c 2%: Increased pulp production 2%, without bark burning,
- Scenario 2d 2%: Increased pulp production 2%, with bark burning,
- Scenario 2c 5%: Increased pulp production 5%, without bark burning,
- Scenario 2d 5%: Increased pulp production 5%, with bark burning,
- Scenario 2c 10%: Increased pulp production 10%, without bark burning,
- Scenario 2d 10%: Increased pulp production 10%, with bark burning

As already stated in Section 3.3.2, if the recovery boiler is the process' bottleneck and the rest of the process, especially the evaporation plant, could handle a production increase, then lignin extraction enables higher pulp production. As also mentioned in Section 2.2, pulp bleaching at the extended Värö will be carried out using O_2 and H_2O_2, and possibly other chemicals in either one of two different types of bleaching: ECF or TCF. The lignin extraction sub scenarios are all based on the ECF base case, and the sub scenarios with increased pulp production will be explained in 2c and 2d.

4.2.3.1 Scenario 2a: Same production of pulp, without bark burning

In this sub scenario, lignin is extracted but with the same amount of pulp production. That would, as mentioned in Section 3.3.2, lead to a lower fuel effect in the recovery boiler, and thus lower the electricity production. The bark boiler is not used.

4.2.3.2 Scenario 2b: Same production of pulp, with bark burning

This sub scenario is the same sub scenario as 2a, but now it is assumed that the bark boiler is operating the entire time, making it possible to extract even more lignin and still satisfy the steam demand of the process.

4.2.3.3 Scenario 2c: Increased pulp production, without bark burning

All the increased pulp production sub scenarios only differ in the amount of pulp produced. If the pulp production is increased, naturally the need for steam, electricity and wood will also increase. These increases are modelled linearly and follow the pulp production. The increase in black liquor flow, which follows from the production increase, is calculated to control that it does not exceed any limitations. With the increased black liquor flow it is now possible to extract more lignin and still deliver enough heat from the recovery boiler to satisfy the process steam demand.

In this sub scenario the pulp production is increased with 2%, 5% and 10%, and the bark boiler is not used.

4.2.3.4 Scenario 2d: Increased pulp production, with bark burning

Scenario 2d is the same as Scenario 2c, but with the bark boiler operating during the entire year. The bark burning makes it possible to extract even more lignin since the steam from the bark boiler helps satisfy some of the process demand of steam.

In this sub scenario the pulp production is increased with 2%, 5% and 10%, and the bark boiler is operational.

4.2.4 Scenario 3: District heating

For the objective to increase the district heating capacity the following sub scenarios were studied:

- Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger,
- Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump,
- Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump,
- Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg,
- Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka

The different sub scenarios have their root in the base case's heat exchanger network for district heating, and for the respective sub scenarios different components are added. The added components are heat exchangers and heat pumps. More information about how these two components work can be found in Appendix D: Component descriptions.

4.2.4.1 Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger.

Figure 12 shows a schematic picture of the heat exchanger network for Scenario 3a.

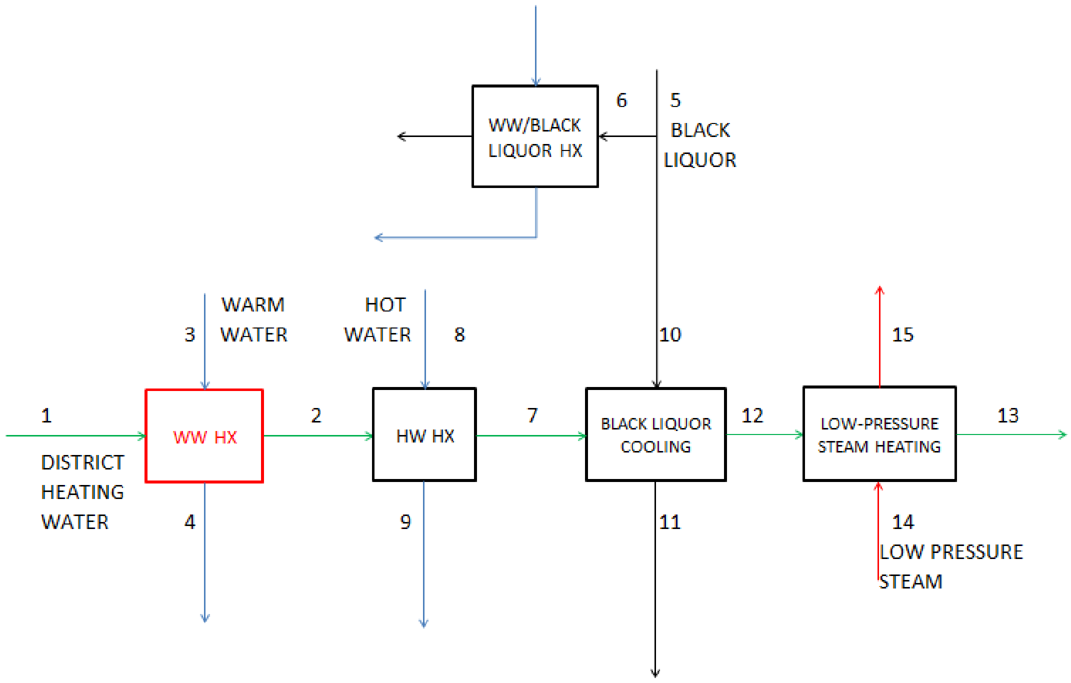

Figure 12. Schematic picture of the heat exchanger network for Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger.

Scenario 3a differs from the base case by an addition of a warm water heat exchanger, the red box in Figure 12, which was placed prior to the hot water heat exchanger. The warm water heat exchanger will improve how the other heat sources in the network can be utilized, and thereby increase the district heating network's capacity.

The amount of warm and hot water available can be seen in Table 3 in Section 4.1.1. Appendix E: District heating flow data presents at which temperatures and mass flows the different water and black liquor flows enter and leave the heat exchanger network, which is showed in Figure 12.

4.2.4.2 Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump.

Figure 13 presents a schematic picture of the heat exchanger network for Scenario 3b.

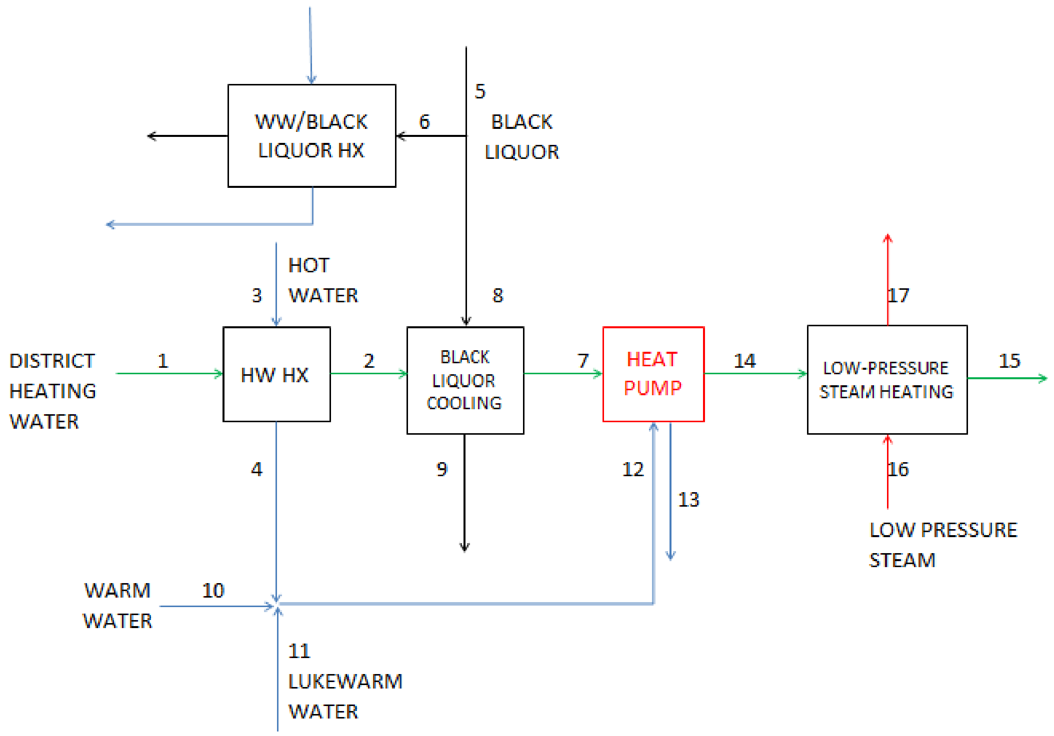

Figure 13. Schematic picture of the heat exchanger network for Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump.

In Scenario 3b a heat pump is added to the base case's heat exchanger network, instead of a heat exchanger as in Scenario 3a. Notation is that the heat pump used in the sub scenario is actually several heat pumps parallel connected, but in this thesis work the parallel connected heat pumps are referred to as a heat pump. This was the technical and economically solution that was recommended by the heat pump manufacturer. Even though there are other possible places to locate the heat pump, it is placed after the black liquor cooling heat exchanger. A discussion about alternative places to put the heat pump in the heat exchanger network is discussed in Chapter 7: Future study suggestions.

The choice of placing the heat pump after the black liquor cooling is based on two reasons. As mention in Section 4.2.1.2, since the black liquor out from the black liquor cooling heat exchanger is fixed to 85°C, the heat pump will cause violation of the minimum temperature difference, ΔT_{min}, if it is placed before the black liquor cooling heat exchanger. The second reason is based on the fact that by placing the heat pump before the black liquor cooling, the amount of heat exchanged between the black liquor and the district heating water will decrease and thereby reduce the heat exchanger's utilization. This is because the black liquor temperature out from the black liquor cooling is fixed. A following problem will be that the low-pressure steam heat exchanger after the black liquor cooling heat exchanger will be the only heating source available that can heat the district heating to its required temperature.

Before entering the heat pump, the water streams are mixed in a mixing point. In this sub scenario all three water streams, lukewarm, warm and hot water; are used to deliver heat to the heat pump. These streams can be more thoroughly viewed in Table 3 in Section 4.1.1. After the heat pump the water streams are delivered to the cooling towers in the mill.

A summary of the different water flows and temperatures for each location in Figure 13 are presented in Appendix E: District heating flow data.

4.2.4.3 Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump.

Figure 14 presents a schematic picture of the heat exchanger network for Scenario 3c.

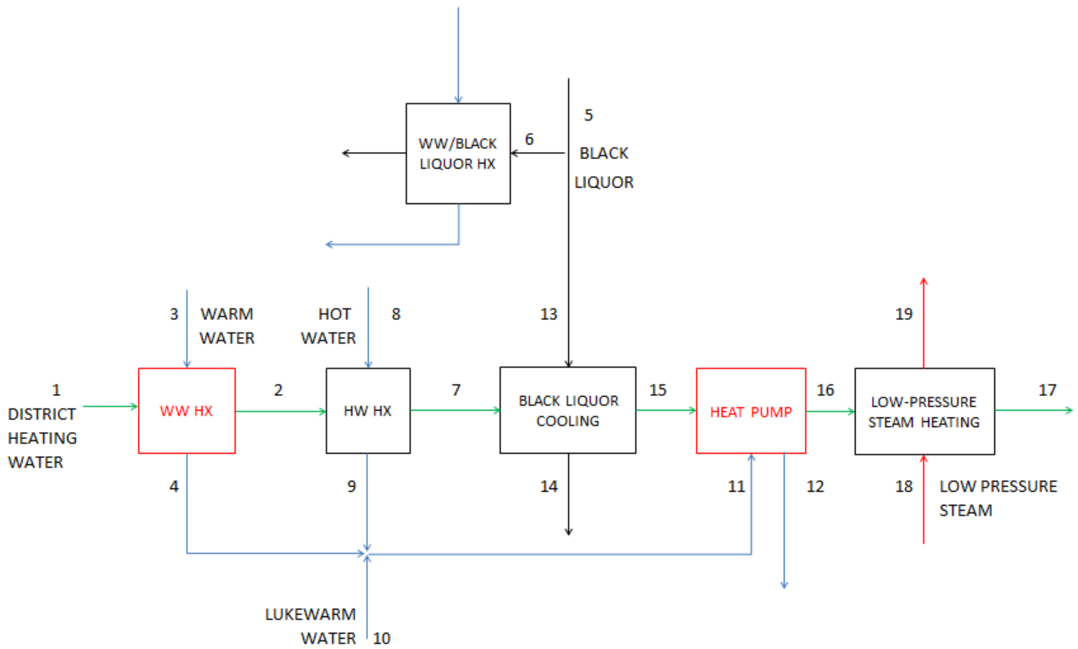

Figure 14. Schematic picture of the heat exchanger network for Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump.

Scenario 3c is a combination of the two previous sub scenarios, Scenario 3a and 3b, placing a warm water heat exchanger and a heat pump into the heat exchanger network. The warm water heat exchanger is placed prior the heat exchanger network, as in Scenario 3a, and the heat pump is placed, as in the previous sub scenario, after the black liquor cooling heat exchanger.

As can be seen in Figure 14, both warm and hot water are heat exchanged before they are mixed with the lukewarm water for further use in the heat pump. A summary of the different water flows and temperatures for each location in Figure 14 are presented in Appendix E: District heating flow data.

4.2.4.4 Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg.

Instead of increasing the capacity to Varberg, compared to the base case, there is an option to expand the district heating grid to Kungsbacka while maintaining planned deliveries to Varberg.

The planned temperature for the delivered water to Kungsbacka is 95°C during the winter period and 86°C during the summer period, and the delivered water back to the mill has a temperature of 42°C during the winter period and 48°C during the summer period. The temperature will drop by 2°C each way to and from Kungsbacka, i.e. in total a temperature drop of 4°C. The planned capacities to Kungsbacka are 23 MW during the winter period and 10 MW during the summer period. These are assumed capacities for the different seasons.

Figure 15 presents a schematic picture of the heat exchanger network for Scenario 3d. The figure only shows the heat exchanger network to Kungsbacka. The heat exchangers connected to the district heating production for Varberg is the same as in Figure 10.

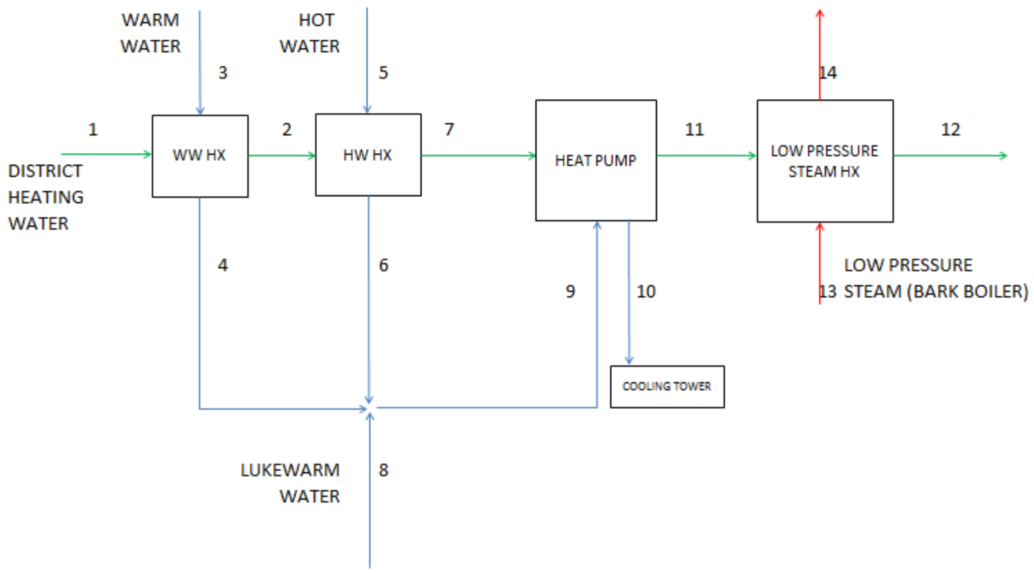

Figure 15. Schematic picture of the heat exchanger network for Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg. The figure only shows the heat exchanger network to Kungsbacka, however the Varberg heat exchanger network is the same as in Figure 10.

The heat exchanger network, Figure 15, works in the same way for Kungsbacka as it does for Varberg. The district heating water passes four heat exchangers in the heat exchanger network; these are a warm water heat exchanger, a hot water heat exchanger, a heat pump and a low-pressure steam heat exchanger. The difference compared to the base case's heat exchanging network are that no black liquor cooling heat exchanger is used and that the hot steam in the low-pressure heat exchanger comes from the bark boiler and not from the recovery boiler.

For this sub scenario, all excess water in Table 3 in Section 4.1.1 are used to heat the district heating water. Bark burning will also be used since the excess heat from the secondary heating system will not be enough to satisfy the district heating demand.

Appendix E: District heating flow data presents a summary of the different water flows and temperatures for each location in Figure 15.

4.2.4.5 Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka.

Scenario 3e is a combined sub scenario of district heating deliveries to Varberg and Kungsbacka, with implemented heat exchangers, heat pumps and heat exchangers with steam from the bark boiler and the recovery boiler in the heat exchanger networks. This sub scenario studies if it is possible to deliver the required capacities of 50 MW to Varberg, and 23 MW during the winter period and 10 MW during the summer period to Kungsbacka.

Figure 16 presents a schematic picture of the heat exchanger network for Scenario 3e.

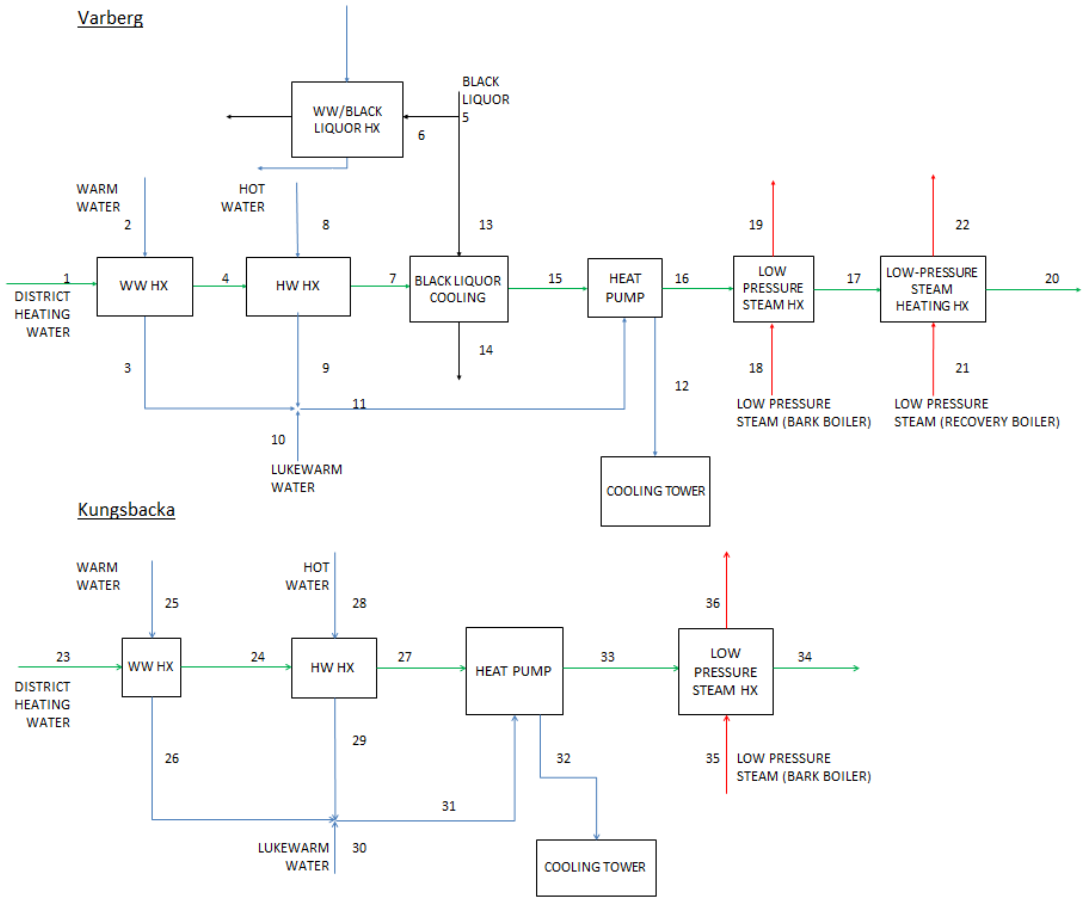

Figure 16. Schematic picture of the heat exchanger network for Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka.

To be able to reach the desired capacities for Varberg and Kungsbacka, all excess water in Table 3 in Section 4.1.1, are used to heat the district heating water. Besides using all excess heat from the secondary heating system, which will not completely satisfy the district heating demand, additional steam from the bark boiler is also used. Appendix E: District heating flow data presents a summary of the different water flows and temperatures for each location in Figure 16.

4.2.5 Scenario 4: Bark drying

Scenario 4 studies the possibility of drying bark to 93% DS and use the bark, instead of sawdust, as fuel in the lime kiln. That is why this new bark dryer will be placed near the lime kiln. As mentioned in Section 3.3.4, by implementing the bark dryer, the current used fuel sawdust can instead be used to produce wood pellets or sold at the biomass market.

For this scenario, a new bark dryer is implemented to manage to dry as much bark as possible with all the excess heat of warm and hot water available from the secondary heating system. By drying the bark, the effective heating value of the bark will increase which makes it better suited for burning. The lukewarm water cannot be used due to its low temperature and that is why only warm and hot water will be used to heat the drying air into the bark dryer.

Figure 17 shows a scheamtic picture of the modelled bark dryer.

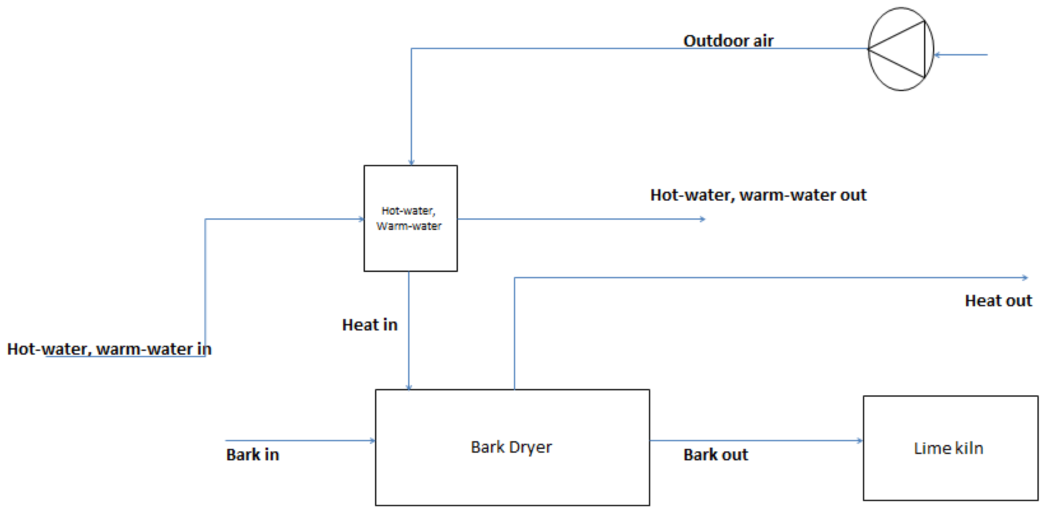

Figure 17. Schematic picture of the modelled bark dryer.

As can be seen in Figure 17, the drying sequence starts with outdoor air entering the fan. The air is then heated by warm and hot water. Thereafter the heated air enters the bark dryer, where the bark is dried. The bark is delivered to the lime kiln and the air is released into the environment.

The models for this scenario are based on two assumptions. First it is based on how much of the excess heat from the secondary heating system that can be used to heat the incoming outdoor air. The second assumption is based on how much bark that can be dried from 40% to 93% DS with the amount of heated air from the warm and hot water heat exchanger. Table 17 in Appendix C: Assumptions shows the assumed data that is used for the calculations of the bark drying scenario. The sub scenarios studied are:

- Scenario 4a: Constant dryer size,
- Scenario 4b: Varied dryer size

4.2.5.1 Scenario 4a: Bark drying – Constant dryer size

In this sub scenario, the dryer has a constant dryer volume independent of how much excess heat that are available or how much bark that will be dried.

4.2.5.2 Scenario 4b: Bark drying – Varied dryer size

This sub scenario is modelled with a dryer that can vary in size after the amount of excess heat available and how much fuel, in the form of bark, that is needed in the lime kiln.

4.2.6 Summary of the investigated scenarios

Table 7 presents the different sub scenarios investigated and includes the abbreviation used in the results tables for Table 11, Table 12, Table 13 and Table 14 in Chapter 5.

Table 7. Explanation of what the different sub scenarios will be called in the result tables, i.e. Table 11, Table 12, Table 13 and Table 14.

Abbrev.	*Sub scenario*
Base case	Base case
1a	Scenario 1a: Burning bark only during the summer period
1b	Scenario 1b: Burning bark all year
1c	Scenario 1c: Burning bark as in base case during the summer period and the entire winter period
1d	Scenario 1d: Not burning any bark at all
2a	Scenario 2a: Same production of pulp, without bark burning
2b	Scenario 2b: Same production of pulp, with bark burning
2c 2%	Scenario 2c: Increased pulp production 2%, without bark burning
2d 2%	Scenario 2d: Increased pulp production 2%, with bark burning
2c 5%	Scenario 2c: Increased pulp production 5%, without bark burning
2d 5%	Scenario 2d: Increased pulp production 5%, with bark burning
2c 10%	Scenario 2c: Increased pulp production 10%, without bark burning
2d 10%	Scenario 2d: Increased pulp production 10%, with bark burning
3a	Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger
3b	Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump
3c	Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump
3d	Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg
3e	Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka
4a	Scenario 4a: Constant dryer size
4b	Scenario 4b: Varied dryer size

4.3 Key performance indicators

Evaluation of the different sub scenarios is performed by comparing them with respect to economic performance, resource efficiency and CO_2 emissions.

Figure 18 presents the different input and output used to calculate the key performance indicators.

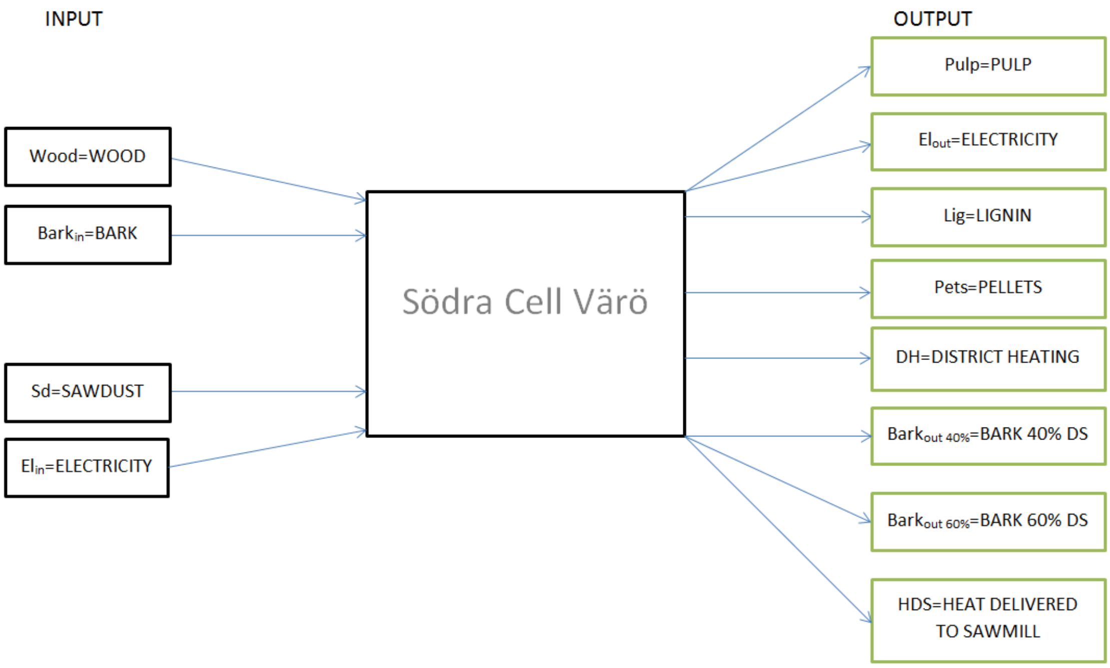

Figure 18. Schematic pictures of calculated flows across system boundaries.

4.3.1 Economic performance

The economic performance of the different sub scenarios is evaluated by calculating the net annual profit, NAP. The difference in net annual profit between a sub scenario and the base case is calculated according to the following equation:

$$\Delta NAP = (\Delta El_{out} - \Delta El_{in}) * P_{el} + \Delta Pulp * \left(P_{pulp} - O\&M_{pulp}\right) + \Delta Bark_{out\ 40\%} * P_{Bark\ 40\%} + \Delta Bark_{out\ 60\%} * P_{Bark\ 60\%} + \Delta DH * P_{DH} + \Delta Lig * \left(P_{lig} - O\&M_{lig}\right) - \Delta Wood * P_{wood} - IC * a \quad \text{[MSEK/year]} \quad (1)$$

The variables used in Equation 1 are:

a: The annuity factor,

IC: The investment cost, [MSEK],

O&M: The operation and maintenance costs, [MSEK/GWh],

P: Price, [MSEK/GWh],

$\Delta Bark_{out\ 40\%}$: The difference between the evaluated sub scenario and base case in amount of bark with 40% DS out from the system, [GWh/year],

$\Delta Bark_{out\ 60\%}$: The difference between the evaluated sub scenario and base case in amount of bark with 60% DS out from the system, [GWh/year],

ΔDH: The difference between the evaluated sub scenario and base case in amount of district heating produced, [GWh/year],

ΔEl_{in}: The difference between the evaluated sub scenario and base case in amount of electricity used, [GWh/year],

ΔEl_{out}: The difference between the evaluated sub scenario and base case in amount of electricity produced, [GWh/year],

ΔLig: The difference between the evaluated sub scenario and base case in amount of lignin extracted, [GWh/year],

ΔPulp: The difference between the evaluated sub scenario and base case in amount of pulp produced, [GWh/year],

ΔWood: The difference between the evaluated sub scenario and base case in amount of wood used, [GWh/year]

Sawdust is not included in the NAP since the amount of sawdust input only varies for the bark drying scenario, Scenario 4, and NAP is not calculated for that scenario. $Bark_{in}$, Pets and HDS are also not included in Equation 1 because these parameters are constant through all the sub scenarios and the base case.

The different prices, costs and O&M costs used in the calculation of the economic performance indicator are presented in Table 8.

Table 8. Summary of prices and costs.

P	Value	Unit	O&M	Value	Unit
P_{DH}	0.362[2]	MSEK/GWh	$O\&M_{Lig}$[3]	0.077	MSEK/GWh
P_{el}	0.304[4]	MSEK/GWh	$O\&M_{Pulp}$[5]	0.856	MSEK/GWh
P_{lig}	0.180[6]	MSEK/GWh			
P_{pulp}	2.14[7]	MSEK/GWh			
P_{wood}	0.171[8]	MSEK/GWh			

The electricity price is an average based on the last three years prices from the Nord Pool spot market. It is assumed that all bark is sold during the winter period according to winter prices. The price of bark can be found in Appendix G: Confidential data. Appendix G: Confidential data also includes all the investment costs used in the different scenarios.

An annuity factor of 0.16 is used since the investments are considered to be a relatively long term strategic investments.

Sensitivity analyses has also been conducted for the electricity and district heating prices, see Appendix F: Sensitivity Analysis.

[2] The prices are half of the one from SVENSK FJÄRRVÄRME 2010. Prisvärd fjärrvärme. *En fördjupad rapport om fjärrvärmepriser.* Stockholm. Since that is the average consumer price and not producer price.
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[8] SÖDRA. 2015a. *Massaved* [Online]. Available: https://skog.sodra.com/Documents/Prislistor/Virke/069%205%20M2%20%283%29%20Massaved.pdf [Accessed 27 Apr 2015].

4.3.2 Resource efficiency

The resource efficiency is calculated according to:

$$\eta_{resource} = \frac{\frac{GWh_{out}}{year}}{\frac{GWh_{in}}{year}} = \frac{Pulp+El_{out}+Lig+Pets+DH+Bark_{out\,40\%}+Bark_{out\,60\%}+HDS}{Wood+Bark_{in}+Sd+El_{in}} \quad [-] \quad (2)$$

$$[0 \leq \eta_{resource} \leq 1]$$

Where the variables not already defined for Equation 1 are:

HDS: Heat delivered to the sawmill, [GWh/year],

Pets: Amount of pellets produced, [GWh/year],

Sd: Amount of sawdust used in the lime kiln, [GWh/year],

$Bark_{in}$: Amount of bark delivered from the sawmill to the pulp mill, [GWh/year]

The resource efficiency is used to compare how well the different sub scenarios utilize the resources. A resource efficiency of 1 would mean that the energy input is equal to the energy output, i.e. no losses.

A sensitivity analysis for the resource efficiency can be seen in Appendix F: Sensitivity Analysis.

4.3.3 CO_2 emissions

The difference in global CO_2 emissions between a sub scenario and the base case is calculated according to:

$$\Delta CO_2 = -((\Delta Bark_{out\,40\%} + \Delta Bark_{out\,60\%} - \Delta Sd) * e_{Bark\,\&\,sawdust} + (\Delta El_{out} - \Delta El_{in}) * e_{Electricity} + \Delta Lig * e_{Lignin} + \Delta DH * e_{DH}) \quad [\text{kton } CO_2/\text{year}] \quad (3)$$

Where the variable that have not already been explained for Equation 1 and 2 is:

e: Emission factor, [ton CO_2/GWh]

Table 9 presents two cases, C1 and C2, with different assumptions regarding how a change in net export of different energy products influence the surrounding energy system. The cases are further presented in Figure 19 and Figure 20.

Table 9. Cases, C1 and C2, with different assumptions regarding how a change in net export of different energy products influence the surrounding energy system.

Case	$e_{Bark\,\&\,sawdust}$	$e_{Electricity}$	e_{Lignin}	e_{DH}
C1	Bio	Coal PP	Bio	Bio
C2	Coal	Coal PP	Coal	NG

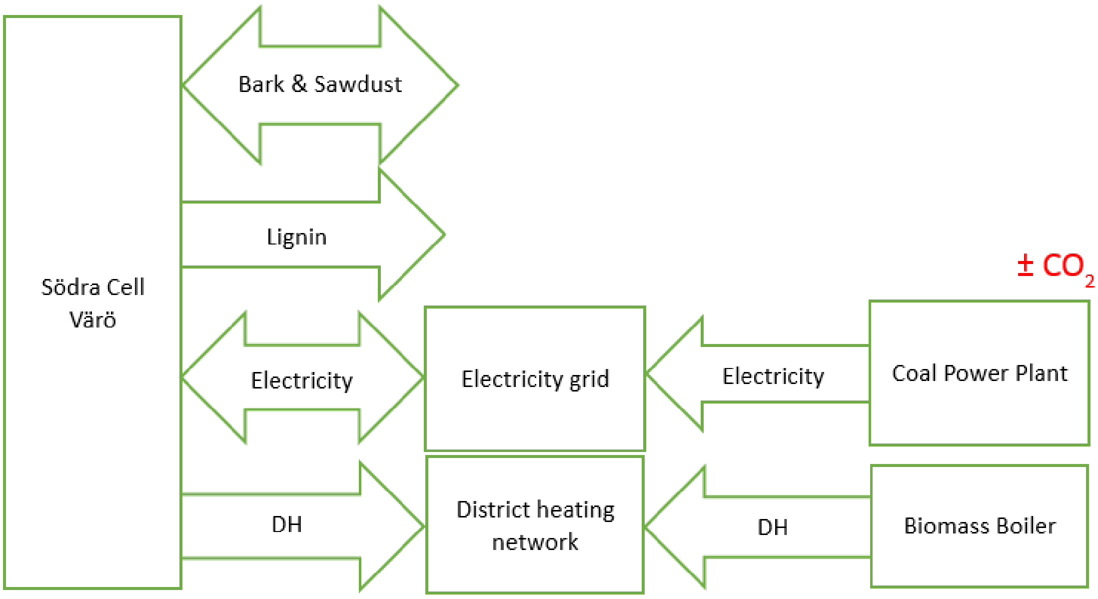

Figure 19. A schematic picture showing the assumptions regarding how a change in net export of different energy products from Södra Cell Värö influence the surrounding energy system in Case C1.

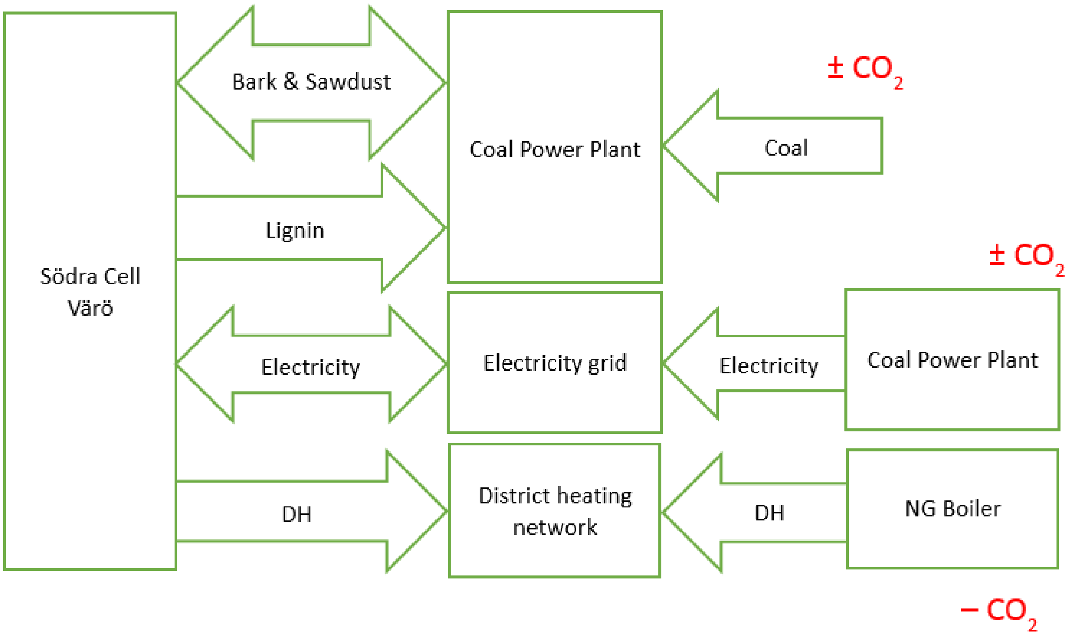

Figure 20. A schematic picture showing the assumptions regarding how a change in net export of different energy products from Södra Cell Värö influence the surrounding energy system in Case C2.

For C1 (Figure 19), a net change of the export of bark & sawdust and lignin are assumed to influence the usage of other biomass fuels. Since biomass is considered a renewable fuel, as long as the biomass growth is higher than the usage, no change of emission is assumed to be associated with this. When district heating from the mill is replacing district heating from a biomass boiler, this is also assumed to have no effect on the emissions. Both for C1 and C2 (Figure 20), a net change of sold electricity from the mill is assumed to influence the production of electricity from coal-fired power plants, Coal PP, with an emission factor of 855.6 ton $CO_2/GWh_{Electricity}$. The difference in C2,

Figure 20, compared to C1, is that the biomass, i.e. bark & sawdust and lignin, is now replacing or is replaced by coal as fuel, and that the district heating is now replacing district heating from a natural gas, NG boiler. Only CO_2 emissions related to the combustion of fuels is included. The emissions from transportation and extraction are not considered. For coal an emission factor of 349.2 ton CO_2/GWh_{fuel} is used and for natural gas an emission factor of 204.5 ton CO_2/GWh_{fuel} is used. The different emission factors used is summarized in Table 10. The reason why both replacement of a biomass boiler and a natural gas boiler is considered is because Varberg has both these two types of boilers and they are representing minimum and maximum emissions for Varberg's district heating production.

Table 10. Emission factors used for evaluation of the difference in global CO_2 emissions.

		Unit
Bio	0	ton CO_2/GWh_{fuel}
Coal	349.2	ton CO_2/GWh_{fuel}
Coal PP	855.6	ton $CO_2/GWh_{electricity}$
NG	204.5	ton CO_2/GWh_{fuel}

There is a sensitivity analysis presented in Appendix F: Sensitivity Analysis where different combinations, compared to C1 and C2, of the emission factors are used.

5 Results and discussion

Chapter 5 is divided in two parts where the first part covers the resulting energy balances and where the second part includes the comparison of the key performance indicators between the base case and the scenarios.

5.1 Resulting energy balances

Table 11 and Table 12 present the resulting energy balances for the entire year, including both the summer and winter periods, for the ECF and TCF base cases and sub scenarios. The results from the tables also form the basis for the key performance indicators evaluation.

Table 11. Energy balance results, ECF.

ECF	Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a	4b
Pulp produced	3115	3115	3115	3115	3115	3115	3115	3177	3177	3271	3271	3427	3427	3115	3115	3115	3115	3115	3115	3115
Electricity produced	975	996	1044	1023	954	714	690	748	708	760	726	788	761	975	975	975	1023	1023	954	954
Bark 40% DS sold	206	100	0	0	313	206	0	216	0	230	0	253	0	206	206	206	0	0	104	44
Bark 60% DS sold	319	319	190	311	319	319	190	319	201	319	216	319	243	319	319	319	311	311	319	319
District heating sold	166	166	166	166	166	166	166	166	166	166	166	166	166	167	263	263	311	389	166	166
Pellets sold	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129
Heat delivered to the sawmill	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215
Lignin sold	0	0	0	0	0	821	1008	828	1018	871	1051	907	1097	0	0	0	0	0	0	0
Raw wood material (incl. bark) used	7255	7255	7255	7255	7255	7255	7255	7400	7400	7618	7618	7981	7981	7255	7255	7255	7255	7255	7255	7255
Electricity used	499	499	499	499	499	499	499	509	509	524	524	549	549	499	528	526	510	527	499	499
Bark delivered from the sawmill	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132
Sawdust delivered from the sawmill	403	403	403	403	403	403	403	411	411	423	423	443	443	403	403	403	403	403	148	74
Bark burnt	107	213	427	320	0	107	427	107	427	107	427	107	427	107	107	107	320	320	362	436

All numbers are in the unit of GWh/year

Table 12. Energy balance results, TCF.

TCF	Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a
Pulp produced	3130	3130	3130	3130	3130	3115	3115	3177	3177	3271	3271	3427	3427	3130	3130	3130	3130	3130	3130
Electricity produced	962	986	1034	1010	938	714	690	748	708	760	726	788	761	962	962	962	1010	1010	938
Bark 40% DS sold	206	100	0	0	313	206	0	216	0	230	0	253	0	206	206	206	0	0	0
Bark 60% DS sold	319	319	190	311	319	319	190	319	201	319	216	319	243	319	319	319	311	311	298
District heating sold	166	166	166	166	166	166	166	166	166	166	166	166	166	168	263	263	311	407	166
Pellets sold	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129
Heat delivered to the sawmill	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215
Lignin sold	0	0	0	0	0	821	1008	828	1018	871	1051	907	1097	0	0	0	0	0	0
Raw wood material (incl. bark) used	7316	7316	7316	7316	7316	7255	7255	7400	7400	7618	7618	7981	7981	7316	7316	7316	7316	7316	7316
Electricity used	499	499	499	499	499	499	499	509	509	524	524	549	549	499	528	524	514	532	499
Bark delivered from the sawmill	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132	132
Sawdust delivered from the sawmill	405	405	405	405	405	403	403	411	411	423	423	443	443	405	405	405	405	405	0
Bark burnt	107	213	427	320	0	107	427	107	427	107	427	107	427	107	107	107	320	320	512

All numbers are in the unit of GWh/year

5.1.1 Base case

The first difference between ECF and TCF, except for the difference in bleaching procedure, is that TCF has a higher pulp production capacity compared to ECF. This is shown when looking at Table 11 and Table 12 and therefore it is no surprise that TCF uses more input of raw wood materials. Since the amount of bark at the mill site is assumed, as mentioned in Section 4.1.1, to 900,000 m^3, there is no difference in bark between the two bleaching alternatives even though TCF uses more raw wood materials than ECF.

In general, the data is similar between the two bleaching alternatives except for the electricity production and the already mentioned pulp production. The explanation for the difference in the electricity production is found in the different bleaching alternatives need for steam for their processes to work properly, which is shown in Table 4. Since TCF needs more steam to work, less electricity is produced for TCF compared to ECF, which can also be seen in Table 4.

All numbers in Table 11 and Table 12 are presented on a yearly basis; but the tables are actually a summary of data performed on a seasonal basis, i.e. data collected during the summer and winter period respectively and then summed up. For instance, the electricity production is increased during the summer period due to two reasons: the process needs less steam during the summer period and the mill is forced to burn bark for preventing the bark from self-combust. These two actions increase the steam supply to the turbines and thereby more electricity is generated.

5.1.2 Scenario 1: Bark burning

A reminder of the modelled sub scenarios for the bark burning scenario, Scenario 1:

- Scenario 1a: Burning bark only during the summer period,
- Scenario 1b: Burning bark all year,
- Scenario 1c: Burning bark as in the base case during the summer period and the entire winter period,
- Scenario 1d: Not burning any bark at all

The results from the bark burning scenario, Scenario 1, are in many ways similar to the results according to the base case. The main differences are found in the bark sold; both for bark 40% DS and bark 60% DS, for the bark burnt, and for the electricity produced.

Viewing Table 11 and Table 12, an increase in the amount of bark burnt is implemented in Scenario 1a compared to the base case. The difference between the sub scenario and the base case is 213 GWh/year compared to 107 GWh/year according to bark burnt. The increased use of bark results in a boost of steam generated in the bark boiler, and is used to increase the electricity production with approximately 20 GWh/year. The result shows that increasing the electricity production with 20 GWh/year will be on the expense of approximately 100 GWh/year of bark. As mentioned in 4.2.2.2, the bark category contributing to the increased bark burning is bark with 40% DS. The amount of 40% DS bark that is sold is reduced by half the amount from the base case.

Scenario 1b, burning bark all year, will generate even more electricity; approximately 70 GWh/year more than the base case. The production will be achieved at the expense of even more bark, approximately 320 GWh/year, which includes that all the total sales of bark with DS content of 40% and almost half of the sales of 60% DS bark will be burnt instead of sold compared to the base case. Note that, in this sub scenario, large amount of LP steam are blown-off to the atmosphere since the steam produced from the combustion of the bark will not be needed within the system or for the pulp process. The condensing turbine cannot extract more work since the condensing part already works at its maximum, and the back-pressure turbine do not have a condensing part, which means that it is already extracting the maximum amount of steam. The blown-off steam has high energy content and this sub scenario of bark burning is therefore inefficient even though some electricity is generated, since a lot of heat will be wasted with the blown-off steam.

When comparing Scenario 1c to the base case, the results will differ approximately as much as the results for the previous sub scenario, with the exception that less bark is burnt during the summer period, i.e. 320 GWh/year instead of 427 GWh/year. This is due to that bark burning is only performed during half of the summer period instead of the entire summer period. Compared to the base case, all the 40% DS bark but only a small amount of the 60% DS bark is used, leaving more of the 60% DS bark available, i.e. approximately 311 GWh/year of the bark for ECF and TCF. By burning bark during the winter period, the outcome will be increased electricity production during the winter period compared to the base case, but more bark available during the summer period.

Scenario 1d, not burning any bark at all, shows that less electricity will be generated compared to the base case, i.e. approximately 954 GWh/year for ECF and 938 GWh/year for TCF is generated, which is about 20 GWh/year less than the base case. This is due to that no bark is burnt at all, and both categories of bark, bark with 40% DS and 60% DS; are available for trading at the biomass market. The difference between Scenario 1d and the base case according to electricity production is not that huge since, as mentioned in Section 1.2.1.2, the transformation from bark to electricity has quite low efficiency. This is why the option of selling bark may be a better choice than burn it.

5.1.3 Scenario 2: Lignin extraction

A reminder of the modelled sub scenarios for the lignin extraction scenario, Scenario 2:

- Scenario 2a: Same production of pulp, without bark burning,
- Scenario 2b: Same production of pulp, with bark burning,
- Scenario 2c 2%: Increased pulp production 2%, without bark burning,
- Scenario 2d 2%: Increased pulp production 2%, with bark burning,
- Scenario 2c 5%: Increased pulp production 5%, without bark burning,
- Scenario 2d 5%: Increased pulp production 5%, with bark burning,
- Scenario 2c 10%: Increased pulp production 10%, without bark burning,
- Scenario 2d 10%: Increased pulp production 10%, with bark burning

As mentioned in Section 4.2.3, this scenario is only based on ECF. The main difference for Scenario 2 compared to the base case is, as the name of the scenario implies, the extraction of lignin. From Table 11 and Table 12, it can be seen that the extracted lignin is at the expense of electricity production. This is no surprise considering that as much lignin as possible is extracted from the black liquor while still maintaining the rest of the process intact, resulting in a lower amount of heat produced in the recovery boiler. Therefore a larger part of the heat produced needs to go to the process instead of being used for electricity production. This applies to all sub scenarios.

Besides the electricity production decrease, from 975 GWh/year to 714 GWh/year, and the lignin extraction rates increase, from 0 to 821 GWh/year, there are not any other significant differences between the base case and Scenario 2a. Scenario 2b does not have any more significant differences either, except for the ones that are to be expected, like the decreased amount of bark left for sales. In Scenario 2a the bark is left available, since the bark boiler is operating in the same way as for the base case. However, in Scenario 2b the bark boiler is operating and uses all the bark of 40% DS and approximately half of the bark of 60% DS, leaving 190 GWh/year still available for selling on the biomass market. This results in an increase of 187 GWh/year of lignin extracted and a decrease of electricity produced with 24 GWh/year. Värö would still be a net producer of electricity but it is a significant decrease of electricity.

The increased pulp production sub scenarios, Scenario 2c and 2d, have more differences compared to the base case than the sub scenarios with the same pulp production, which is to be expected. The amount of wood, electricity, and sawdust used increases, as well as the pulp produced. The increase in sawdust should not be any problem considering that the sawmill have more sawdust as it is and could increase its production of sawn timber by approximately 16% (Rudén, 2014). Since the amount of wood used increases, the amount of bark available at the mill site will also increase. For Scenario 2c, this means that there will now exist even more bark available compared to the base case. For Scenario 2d with a 10% pulp production increase, even more pulp is produced. For this scenario no bark with 40% DS and 243 GWh/year of 60% bark is left for sale.

5.1.4 Scenario 3: District heating

A reminder of the modelled sub scenarios for the district heating scenario, Scenario 3:

- Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger,
- Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump,
- Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump,
- Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg,
- Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka

The main difference between the district heating scenario and the base case is how much of the excess heat from the secondary heating system that is used for heating the district heating water sent to Varberg and Kungsbacka.

As mentioned in Section 4.2.4.1, a heat exchanger is added to the heat exchanger network for Scenario 3a. By doing that, the heat exchanger network manages a slight increase of district heating delivery compared to the base case, 168 GWh/year compared to 166 GWh/year; which is the only difference compared to the base case. It is no surprise that the increase of district heating is not larger since the amount of warm water added is not that much.

Scenario 3b reaches the maximum district heating transmission line capacity of 50 MW, and also a district heating delivery of approximately 260 GWh/year to Varberg, compared to 166 GWh/year for the base case. Because of the heat pump, the electricity use increases with approximately 30 GWh/year, but the amount of district heating delivered to Varberg increases with approximately 100 GWh/year. For this sub scenario, contributions from all of the excess heat streams are used as heating mediums to the heat pump.

Scenario 3c will also reach 50 MW of district heating since both a new heat exchanger and a heat pump are implemented. The only difference compared to Scenario 3b is that a smaller heat pump is needed for this sub scenario and thereby less electricity is required for heating the district heating water. This means that the electricity used between the sub scenarios are 525.7 GWh/year instead of 527.5 GWh/year for ECF and 524 GWh/year instead of 527.8 GWh/year for TCF. For Scenario 3c in comparison to the base case the district heating delivery increases from approximately 166 GWh/year to 263 GWh/year.

In Scenario 3d, where deliveries also to Kungsbacka is assumed possible, it can be seen that the district heating capacity is increased even more, 311 GWh/year for ECF and TCF compared to 166 GWh/year for the base case. The assumed demands for Kungsbacka of 23 MW during the winter period and 10 MW during the summer period are reached for both TCF and ECF, and the district heating delivery to Varberg, as in the base case, is still managed. As mentioned in Section 4.2.4.4, for this sub scenario both a heat exchanger for the warm water and a heat pump are added to the heat exchanger network. This sub scenario also requires steam from the bark boiler to generate the required heat for heating the district heating water. Since the bark boiler is operating, the electricity generation compared to the base case is enhanced, but all bark with 40% DS and some with 60% DS is used. Even though the bark boiler is operational, there still exists approximately 311 GWh/year of bark with 60% DS to be sold at the biomass market. Because a heat pump also is needed for the Kungsbacka heat exchanger network to work properly, there is an increased electricity usage for this sub scenario. However, the increased production of heat is much larger, i.e. 10 GWh/year electricity for 145 GWh/year of district heating, compared to base case.

Scenario 3e reaches the demand for the TCF operation but not for ECF during the winter period. ECF winter can fully satisfy the Kungsbacka demand and a demand of 45.8 MW to Varberg. As presented in Section 3.3.3, the transmission line to Varberg is capable of delivering 50 MW, making the ECF winter scenario deliver 4.2 MW less than what the Varberg transmission line may handle. The district heating annual delivery is increased to 389 GWh/year compared to the base case's 166 GWh/year, on the expense of all water from the secondary heating system and the bark boiler steam. Even though the bark boiler is operating at maximum there still exists bark, approximately 311 GWh/year, to be sold at the biomass market. Since the bark boiler is used to its maximum the electricity production is also increased to the same level as in Scenario 3d, and can be sold at the electricity market.

5.1.5 Scenario 4: Bark drying

A reminder of the modelled sub scenarios for Scenario 4 that are studied:

- Scenario 4a: Constant dryer size,
- Scenario 4b: Varied dryer size

The main difference between the base case and Scenario 4 is the amount of bark burnt and the amount of sawdust delivered from the sawmill to the pulp mill. As mentioned in Sections 3.3.4 and 4.2.5, the sawdust from the sawmill is used as fuel in the lime kiln and by drying bark to 93% DS the bark can replace sawdust as fuel in the lime kiln. If replacing sawdust with bark as fuel, the more valuable sawdust can be sold at the biomass market to a higher price than bark, and that is why the imported sawdust to the mill is decreased since less of it is used as fuel in the lime kiln.

A result of drying the bark and let it be used in the lime kiln instead of in the bark boiler is the decreased generation of electricity compared to the base case. Looking at Table 11 and Table 12, the 'bark burnt' is indicating the bark burnt in the lime kiln and not in the bark boiler, as the other scenarios does. And that is also an explanation why the electricity production is decreasing instead of increasing.

The warm and hot water from the secondary heating system are insufficient for ECF to dry all bark with 40% DS. Because of this insufficiency, there will still be bark with 40% DS available to be sold at the biomass market or be burned in the bark boiler after the drying sequence.

5.2 Resulting key performance indicators

As mentioned in Section 4.3, the economic performance results, ΔNAP, and the CO_2 emissions results, ΔCO_2, are presented in comparison to the base case. If the difference in net annual profit, ΔNAP, shows a negative value for a sub scenario, then that sub scenario has a worse economic performance than the base case and the company will lose money by implementing that sub scenario. If ΔNAP is positive, the sub scenario has a better economic performance than the base case and the company will earn money by implementing that sub scenario. The CO_2 emission indicator works in the opposite way of the net annual profit; if it is positive it means that the emissions are higher than for the base case and if it is negative, the emissions are lower than for the base case. As mentioned in Section 4.3.2, the resource efficiency, $\eta_{resource}$, is a number which presents the energy out over the energy in. If that number is higher for a sub scenario then the base case, the sub scenario has a better resource efficiency.

Figure 21 and Figure 22 presents the economic performance indicator for the different scenarios with ECF respectively TCF bleaching.

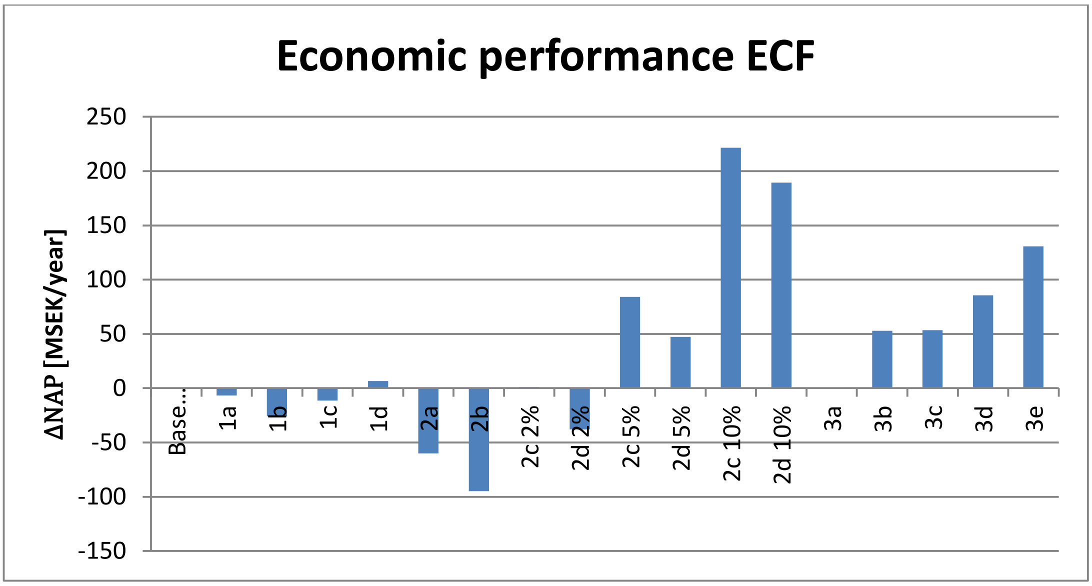

Figure 21. Economic performance, ΔNAP, for the different scenarios with ECF bleaching.

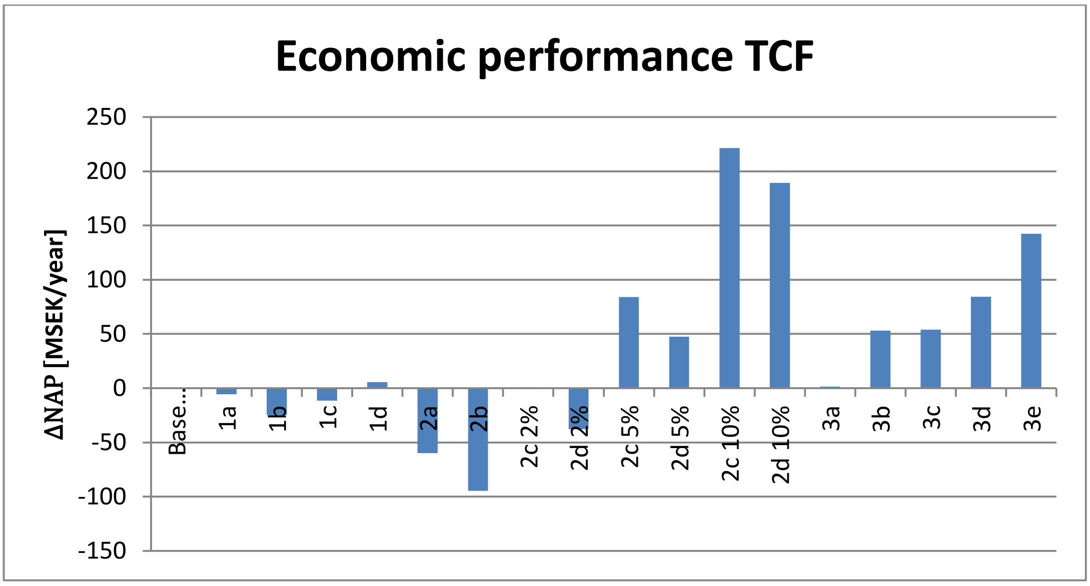

Figure 22. Economic performance, ΔNAP, for the different scenarios with TCF bleaching.

Figure 23 and Figure 24 shows the resource efficiencies for the base case and all the scenarios, for ECF respectively TCF bleaching.

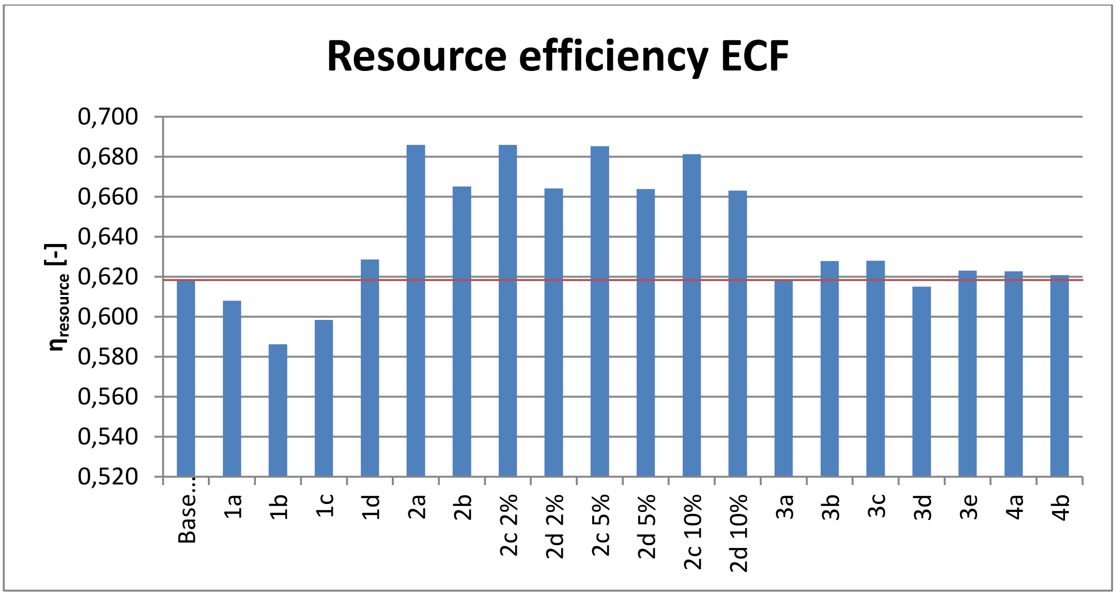

Figure 23. Resource efficiency, $\eta_{resource}$, for the base case and the different scenarios with ECF bleaching.

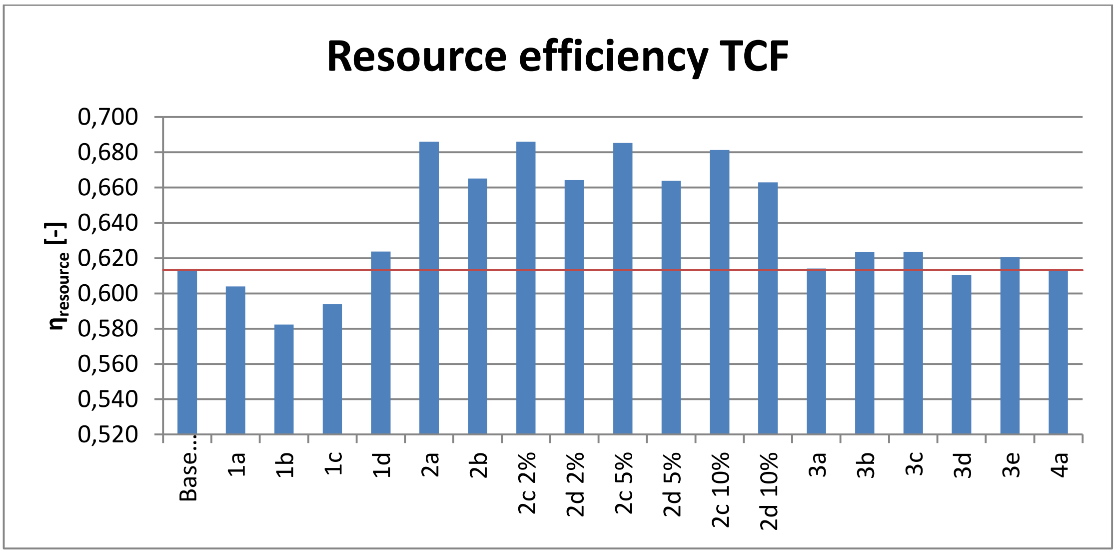

Figure 24. Resource efficiency, $\eta_{resource}$, for the base case and different scenarios with TCF bleaching.

In Figure 23 and Figure 24 it can be seen that all sub scenarios does not lead to increased resource utilization. Since the aim of this master thesis is to find alternatives for increased resource utilization these sub scenarios might seem like a bad idea, but that might not be the actual case. The reason for this is the different qualities of the energy, e.g. electricity is in a useful form that could be used directly, while bark would have efficiency losses in the transformation phase to useful energy. Since the resource efficiency key performance indicator values all energy qualities the same, one need to study what is behind the numbers as well, i.e. the resulting energy balances presented in Section 5.1. An example of this is Scenario 3d where this sub scenario has a lower $\eta_{resource}$ than the base case, but behind those numbers there is an increased net production of electricity and of district heating which is almost as big as the lowered amount of energy in the form of bark available. If the differences in energy quality would be considered, this would have changed the results for Scenario 3d.

Figure 25 and Figure 26 present the change in global CO_2 emissions for the scenarios with ECF respectively TCF bleaching.

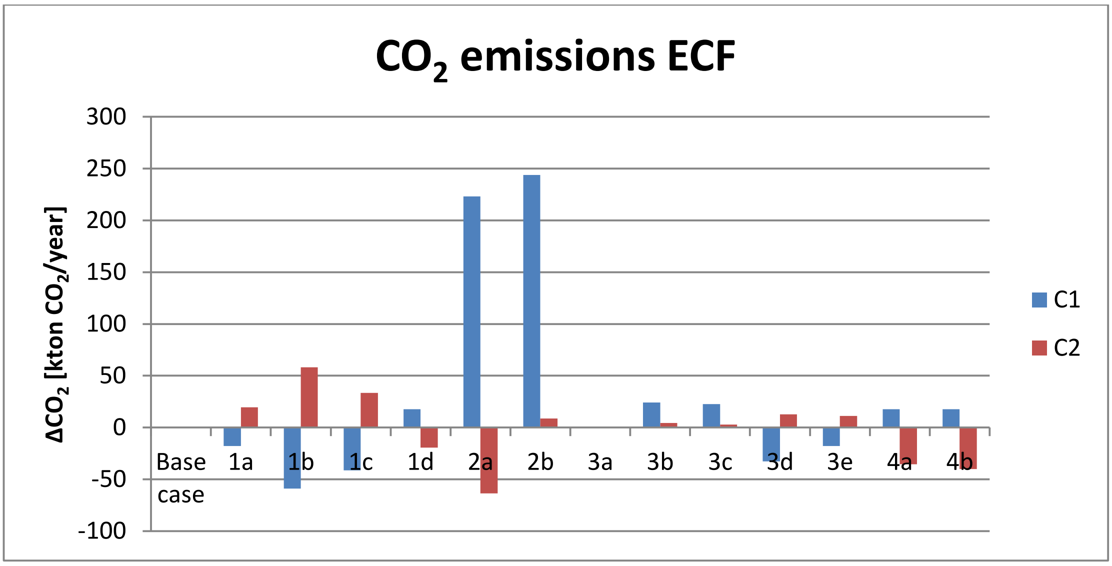

Figure 25. Change in global CO_2 emissions, ΔCO_2, for the different scenarios with ECF bleaching.

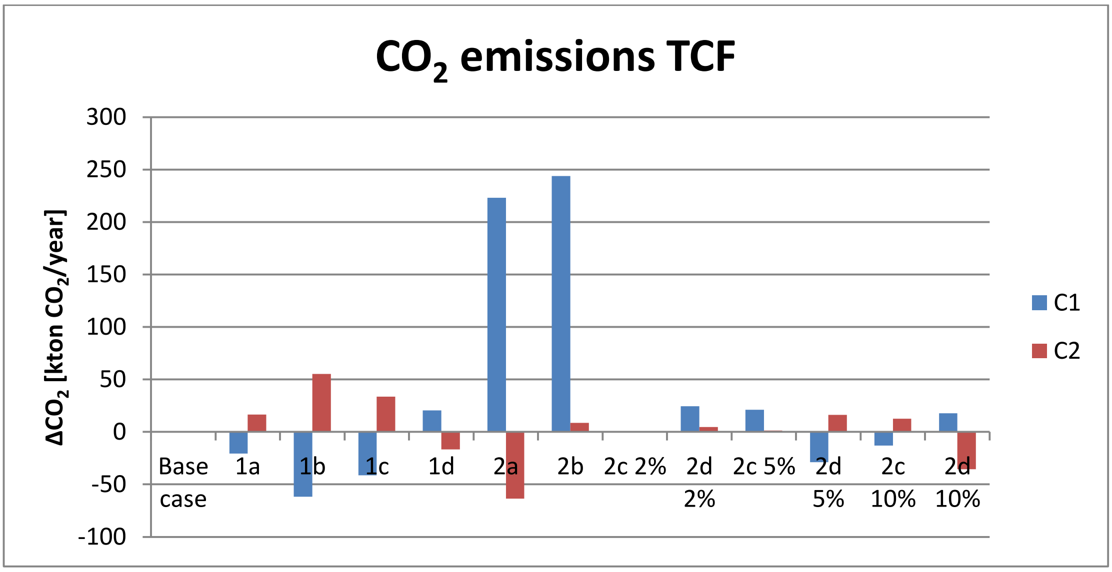

Figure 26. Change in global CO_2 emissions, ΔCO_2, for the different scenarios with TCF bleaching.

In Figure 25 and Figure 26, Scenario 2 is dominating in a way that makes it hard to compare the other sub scenarios properly and that is why Figure 27 and Figure 28 present the CO_2 emissions without Scenario 2.

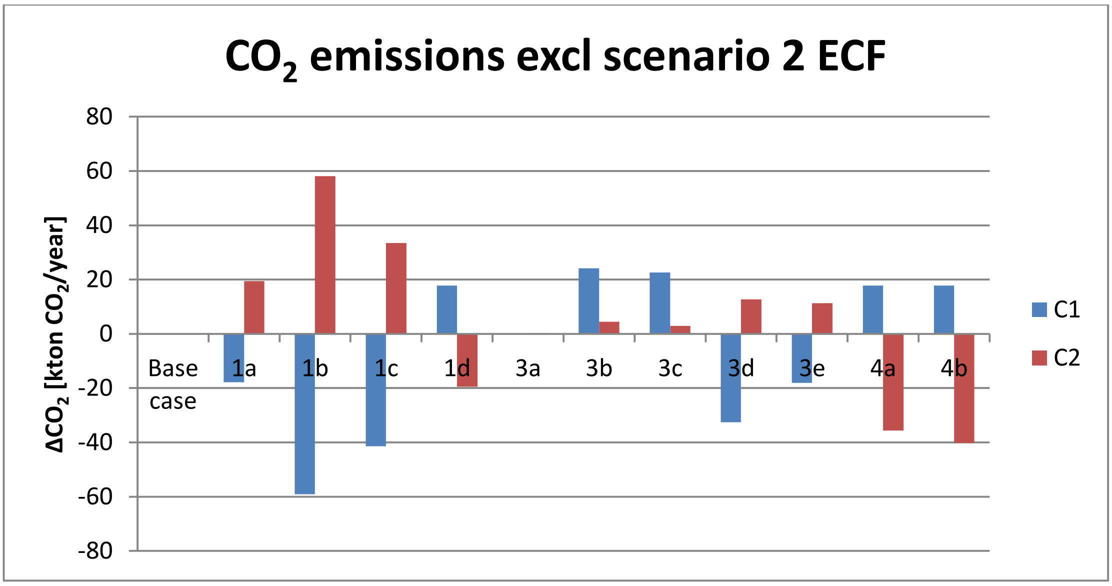

Figure 27. Change in global CO_2 emissions, ΔCO_2, for the different scenarios with ECF bleaching excl. Scenario 2.

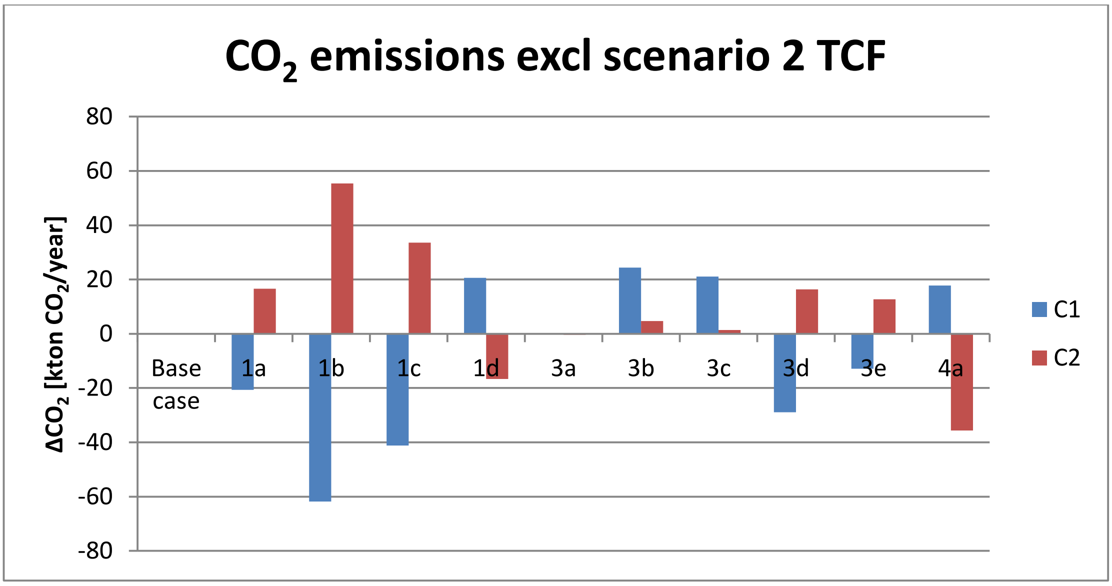

Figure 28. Change in global CO_2 emissions, ΔCO_2, for the different scenarios with TCF bleaching excl. Scenario 2.

Table 13 and Table 14 show the results for the key performance indicators for the different sub scenarios.

Table 13. Resulting key performance indicators. ECF.

		Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a	4b
ΔNAP (MSEK/year)	**E1**	0	-7	-26	-11	7	-60	-95	1	-38	84	47	222	189	1	53	54	86	131		
$\eta_{resource}$ **(GWh_{out}/GWh_{in})**	**R1**	0.618	0.608	0.586	0.598	0.629	0.686	0.665	0.686	0.664	0.685	0.664	0.681	0.663	0.619	0.628	0.628	0.615	0.623	0.623	0.621
ΔCO_2	**C1**	0	-18	-59	-41	18	223	244							0	24	23	-33	-18	18	18
(kton CO_2/year)	**C2**	0	19	58	33	-19	-64	9							0	4	3	13	11	-36	-40
Legend color code		Worse than base case			Relatively close to base case				Better than base case												

Table 14. Resulting key performance indicators. TCF.

TCF		Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a
ΔNAP (MSEK/year)	**E1**	0	-5	-25	-11	5	-60	-95	1	-38	84	47	222	189	1	53	54	84	142	
$\eta_{resource}$ **(GWh_{out}/GWh_{in})**	**R1**	0.614	0.604	0.582	0.594	0.624	0.686	0.665	0.686	0.664	0.685	0.664	0.681	0.663	0.614	0.623	0.624	0.610	0.620	0.614
ΔCO_2	**C1**	0	-21	-62	-41	21	223	244							0	24	21	-29	-13	18
(kton CO_2/year)	**C2**	0	17	55	34	-17	-64	9							0	5	1	16	13	-36
Legend color code		Worse than base case			Relatively close to base case				Better than base case											

5.2.1 Base case

Both the economic performance indicator, ΔNAP, and the emissions performance indicator, ΔCO_2, are naturally zero for the base case, since both these indicators are defined as a comparison to the base case. The resource efficiency, however, is not defined in that way. Looking at the resource efficiency for the base cases, these are 0.618 for ECF bleaching and 0.614 for TCF bleaching.

5.2.2 Scenario 1: Bark burning

A reminder of the modelled sub scenarios for the bark burning scenario, Scenario 1:

- Scenario 1a: Burning bark only during the summer period,
- Scenario 1b: Burning bark all year,
- Scenario 1c: Burning bark as in the base case during the summer period and the entire winter period,
- Scenario 1d: Not burning any bark at all

As mentioned in Section 3.3.1, since the bark boiler is only connected to the back-pressure turbine more steam from the recovery boiler will be redirected to the condensing turbine if the bark boiler is in operation, making the condensing turbine produce more electricity. Because of the large thermodynamic losses when burning bark in the bark boiler for electricity generation only, the electricity output from the system will be much smaller than the energy content of the bark, that instead of being burnt could have been sold at the biomass market. That is why the economic and resource efficiency performance indicators are decreased when bark burning is applied. Since the output of bark, i.e. 40% DS and 60% DS bark, from the system decreases and the electricity output from the system increases, there are variations concerning the emission performance indicator depending on the assumed scenario considered. Generally if the usage of bark is assumed not to be associated with an increase of the CO_2 emission in the surrounding system, these scenarios will lead to decreased global CO_2 emissions. However, if the usage of bark is assumed to lead to increased usage of coal in the surrounding system, the global CO_2 emissions are increased.

Looking at the bark burning scenarios, the best sub scenario both in respect to economic performance and resource efficiency is the sub scenario without any bark burning at all, Scenario 1d. This is no surprise considering the price levels assumed for bark and the thermodynamic losses when burning bark for electricity generation only.

The problem with Scenario 1d is, as already mentioned in Section 4.2.2.4, the fact that it is based on the assumption that there is no problem to store the bark during the summer period and no difficulties to sell all bark during the winter period to winter prices. The reason for this sub scenario being the worst with respect to CO_2 emissions of the bark burning scenarios for case C1, is that no emission reduction is assumed to be associated with the increased export of bark and at the same time less renewable electricity is produced at the mill, increasing the production of electricity in coal power plants. The opposite occurs when the bark is assumed to replace coal.

The opposite extreme sub scenario is burning bark the entire year, Scenario 1b. This sub scenario is not the most probable and reasonable either, unless the steam generated is needed somewhere in the system. As shown in Table 13 and Table 14, this sub scenario is the best bark burning scenario from a CO_2 emissions point of view for case C1, but the worst for case C2. From an economic and resource point of view, this is not a preferred scenario. A trend that can be seen from the results is that with the electricity and bark prices used in this thesis, it is economically more profitable not to burn bark for electricity generation, which means that there need to be other reasons for burning bark. The same goes for the resource efficiency, which decreases as the bark burning increases. However, it is important to always compare the current electricity price with the current bark price to see if it is better to generate electricity or sell bark.

5.2.3 Scenario 2: Lignin extraction

A reminder of the modelled sub scenarios for the lignin extraction scenario, Scenario 2:

- Scenario 2a: Same production of pulp, without bark burning,
- Scenario 2b: Same production of pulp, with bark burning,
- Scenario 2c 2%: Increased pulp production 2%, without bark burning,
- Scenario 2d 2%: Increased pulp production 2%, with bark burning,
- Scenario 2c 5%: Increased pulp production 5%, without bark burning,
- Scenario 2d 5%: Increased pulp production 5%, with bark burning,
- Scenario 2c 10%: Increased pulp production 10%, without bark burning,
- Scenario 2d 10%: Increased pulp production 10%, with bark burning

For the lignin extraction scenarios the economic performance and CO_2 emissions contains both the best and the worst results among all scenarios. However among all scenarios, the ones including lignin extraction generally have the best resource efficiency. However, as already mentioned in Section 5.2, it is important to emphasize that the quality of the energy flows have not been considered here. With a wider system perspective than what has been applied in this study, the resource efficiency also depends on what e.g. the lignin is used for. If the purpose of extracting lignin is to use it as a fuel, than the efficiency of the process in which the lignin is burnt will be the main deciding factor for the resource efficiency.

Scenarios 2a and 2b are currently not economically feasible, assuming lignin is priced as a biomass fuel, because the investments of the equipment and the operation and maintenance costs are high. However, there is research going on about usage of lignin in other applications, which would lead to a higher lignin value and thereby increased lignin price. This might open the possibility for lignin extraction to become economically feasible in the future without pulp production increase.

Scenarios 2c and 2d, 5% respectively 10% production increase, are very good investments from an economic point of view. The reason why these alternatives has very good economic performance is foremost for the increased pulp that could be sold.

It should be noted that for the lignin extraction sub scenarios with increased pulp production, i.e. Scenarios 2c and 2d, it is assumed that the bottleneck for increased pulp production is the recovery boiler. This means that a more relevant comparison for Scenarios 2c and 2d is with other investment options for increased pulp production, instead of to the base case. However, this has been outside the scope of this master thesis. Since the alternatives would either be a new recovery boiler or another extension of the existing one, which currently is impossible since the recovery boiler already is extended to its maximum capacity, the LignoBoost investment would probably be significantly smaller in comparison.

In Table 13 and Table 14 the CO_2 emission performance indicator is not included for Scenarios 2c and 2d. The reason for this is that those sub scenarios includes pulp production increase and Eq. 3 in Section 4.3.3 does not include the wood that is used or the pulp produced which makes the numbers for these sub scenarios invalid.

Overall the results for lignin extractions give a divided picture. If a production increase of 5% or 10% is possible, it would be positive from an economic and resource efficiency perspective.

5.2.4 Scenario 3: District heating

A reminder of the modelled sub scenarios for the district heating scenario, Scenario 3:

- Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger,
- Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump,
- Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump,
- Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg,
- Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka

Out of Scenarios 3a-c, in which only district heating delivery to Varberg is considered, Scenario 3c, with a combination of a heat pump and a heat exchanger added, is the best considering the economic performance and resource efficiency. This is due to that it uses more of the excess heat from the secondary heating system compared to Scenarios 3a and 3b, and also less electricity is needed for the heat pump to produce the same total amount of district heating compared to Scenario 3b. This means that more electricity could be sold at the electricity market. However, the capital cost for both Scenarios 3b and 3c is higher than for Scenario 3a due to investments in both a heat exchanger and a heat pump. In this master thesis, both Scenarios 3b and 3c uses a heat pump of the same size; the difference in the effect needed in the two sub scenarios is not big enough to allow a reduction of the size of the heat pump. However, since the heat pump in Scenario 3c delivers less heat and also uses less electricity, the operation cost is lower for Scenario 3c. The global CO_2 emissions for Scenario 3a is either unchanged or decreased, depending on how much district heating that is sold to Varberg Energi and also if the district heating from the mill replaces a biomass boiler or a natural gas boiler. For Scenarios 3b and 3c, the only differences in global CO_2 emissions are the amount of electricity used. Within these sub scenarios the difference between Case C1 and C2 are the emission factors of bark & sawdust and district heating.

If the district heating delivery is extended to also include Kungsbacka, Scenario 3d, in addition to the current delivery to Varberg, it results in an increased economic performance compared to the base case and Scenarios 3a-c. The increased profit for this sub scenario is because more district heating and electricity can be sold. The increased district heating is due to the fact that more excess heat from the secondary heating system is utilized but also steam from the bark boiler is used to heat the district heating water. Since the bark boiler is operating in this sub scenario more steam is produced and thereby more electricity can be generated from the turbines. Because both excess heat from the secondary heating system and bark are currently unutilized resources at the mill, the utilization of these will increase the economic performance at the mill. The resource efficiency drops somewhat because of the need for bark burning to deliver the final heat needed to match the assumed district heating demand, and also because all steam is not used and blown-off. The reason for the blown-off steam is as mentioned in Section 4.1.1 that the bark boiler is either operating at maximum capacity or not operating at all. From a CO_2 emission perspective, the Kungsbacka sub scenario is better for Case C1 but worse for Case C2 compared to the base case and the other previously mentioned sub scenarios. This is due to the fact that bark is burnt in the bark boiler which results in less sellable bark for the market. The positive key performance indicator values for this district heating sub scenario are due to the fact that heat deliveries from the mill to the district heating system opens the possibility to use more of the low temperature excess heat available, which can be considered to have zero cost (from an economic, emissions and resource perspective), and would otherwise go to waste.

Scenario 3e, the sub scenario which combines district heating delivery to Kungsbacka with maximized delivery to Varberg, has an even better economic performance than the other district heating sub scenarios since more district heating can be sold. In this sub scenario all of the excess heat available and steam from the bark boiler is used to produce district heating. The resource efficiency for Scenario 3e is not as good as the Varberg combined heat exchanger and heat pump sub scenario, Scenario 3c, but it is better than the base case and Scenario 3d. For this sub scenario, the bark boiler is still operating but no steam is blown-off, which makes the resource efficiency better than for Scenario 3d. For CO_2 emissions the results is similar for Scenario 3e and Scenario 3d, with the exception that it is, for Scenario 3e, a little bit worse for C1 and better for C2.

5.2.5 Scenario 4: Bark drying

A reminder of the modelled sub scenarios for Scenario 4 that are studied:

- Scenario 4a: Constant dryer size,
- Scenario 4b: Varied dryer size

The economic performance has not been calculated for the bark drying scenarios. The reasons are that the used model is simplified and reliable economic data for the dryers could not be obtained. There are research projects being carried out on low-temperature bark dryers (Holmberg and Stenström, 2014, Stenström, 2014), however data for drying with lukewarm water to a dry content of 93% DS is not yet available.

For ECF there are two sub scenarios for bark drying, 4a and 4b, while there is only one for TCF, 4a. The reason for this is that there is enough excess heat in the WW and HW to dry all the bark needed to replace the sawdust in the lime kiln for TCF, while ECF do not have enough heat.

The ECF results for bark drying show increased resource efficiencies, but also increased CO_2 emissions for C1 compared to the base case. The reason for the increased emissions for Case C1 can be found in the lowered electricity production, since the bark boiler is not in operation. For Case C2 there is a decrease of emissions and the reason for this can be found in the change in emission factor for bark & sawdust.

For TCF the resource efficiencies are actually the same as in the base case, due to the fact that TCF has enough excess heat to dry enough bark to replace all the sawdust in the lime kiln. There is not enough bark with 40% DS to replace all the sawdust, which means that bark with 60% DS is also used. This actually lowers the heat demand for the process, since it is counted as if the bark where dried from 40% to 93% DS not from

60% to 93% DS. It is the same reasoning behind the numbers for TCF as for ECF concerning the CO_2 emissions.

5.3 Possibility of combining different scenarios

This thesis has focused on separately investigating and comparing different scenarios for improved resource utilization at the Södra Cell Värö pulp mill. However, some of the investigated scenarios have the possibility of being combined since they do not use the same resources. Possible combinations of scenarios, that in some sub scenarios already been implemented, are:

- Bark burning with lignin extraction,
- Bark burning with district heating,
- Bark burning with lignin extraction and district heating,
- Lignin extraction with district heating,
- Lignin extraction with bark drying,
- District heating and bark drying

In Scenario 2b and 2d, bark burning and lignin extraction are already combined. However, there are more possibilities for combinations of these two alternatives, e.g. bark burning only during parts of the year instead of the entire year. As already presented, a combination of these two allows a higher extraction of lignin while still satisfying the process steam demand.

Since the bark boiler is used in two of the district heating sub scenarios, Scenarios 3d and 3e, this combination has already been investigated.

There are ways of combining bark burning, lignin extraction and district heating since they use different resources. The extreme scenarios of lignin extraction, Scenario 2d, and of district heating, Scenario 3e, might not be possible to combine since they both need the steam from the bark boiler. However, it is possible to have some steam used both for district heating and for the process enabling lignin extraction.

Bark drying and lignin extraction can be combined, since even with lignin extraction there will be excess heat in the form of HW and WW that could be used for drying bark.

The district heating and bark drying scenarios cannot be fully combined since they both are utilizing the mill’s bark and excess heat, i.e. the water from the secondary heating system. A combination that is possible between bark drying and district heating would be to use the lukewarm water to the heat pumps for the district heating and the rest of the excess heat, i.e. WW and HW, for bark drying.

5.4 The choice of key performance indicators

The three key performance indicators used in this work have been chosen because they together cover a large spectrum of impacts, both from a company perspective and from a society perspective.

The economic performance indicator is needed in order to know if it is feasible for a company to implement a certain scenario. It also presents a cost for increased resource efficiency and a decrease of the CO_2 emissions.

The resource efficiency is of great interest, because it shows how more products can be produced from the same or less resources. The important thing is that resources are not unlimited and also has an economic value.

CO_2 emissions are a hot topic on the environmental agenda today, and it is expected that the regulations regarding CO_2 emissions will become increasingly stringent over time. For that reason it is important for companies to reduce their CO_2 emissions and thereby reduce the risk of being punished. For companies, this key performance indicator is of interest from an environmental perspective but also from a regulatory and economic perspective, since better environmental thinking will reduce the economic punishment of emitting CO_2. Looking in a system perspective, it is not enough that one company makes a contribution to reduce the CO_2 emissions, even though it has some effects since a pulp mill is a part of a huge industry with large flows. Instead, if all companies make a contribution to reduce the CO_2 emissions an effect will be seen and accomplished, and thereby the CO_2 level can be counteracted.

From the results gathered in Section 5.2, no clear connections can be demonstrated between the different key performance indications. For instance, it is possible to have good or bad resource efficiency combined with either good or bad economic performance and CO_2 emissions as well as the opposite.

6 Conclusions

This master thesis has compared different options for improved resource utilization at the expanded Södra Cell Värö pulp mill. The options were compared to each other and a defined base case from an economic performance, resource efficiency and CO_2 emission perspective. The following scenarios were considered:

- Bark burning
- Lignin extraction
- District heating
- Drying of bark for use in the lime kiln

From the results, no unanimous answers could be given and all of the scenarios have their advantages and disadvantages. However, all scenarios, except the bark burning scenario, shows an improvement compared to the base case with respect to resource efficiency, and all of these the scenarios should be studied further.

The results show that lignin extraction could be a really good option, but further studies are needed to see if it is possible to increase the pulp production and if the lignin could be sold to a higher price. With the current price of lignin and if no pulp increase is possible the economic performance will be worse than the base case. A further investigation of great interest could be to burn bark combined with lignin extraction during part of the year as a way of handling the bark.

For district heating, the required district heating capacities in the studied scenarios are possible to achieve. This is why contacts should be made with both Varberg Energi and the city of Kungsbacka to see if there is any interest for an expansion of the district heating capacities.

A lot of questions about the drying of bark for use in the lime kiln still remain. Even though bark drying shows some good results, for instance it increases the resource efficiency in case of ECF bleaching; it must be more thoroughly investigated in order for any definite conclusions to be drawn. Bark drying might be a way of handling the large amount of unutilized bark and, if possible, the lime kiln should be supplied with a combination of bark and sawdust as fuel.

The results do not show any reasons for increased bark burning unless extra steam and heat is needed in the system, i.e. if more district heat is needed or if more bark needs to be dried, or alternately, if larger amounts of bark need to be combusted to avoid self-ignition in storage. Burning bark is neither good from an economical nor a resource efficiency point of view, and thereby it is not reasonable to invest in a larger and more modern bark boiler.

7 Future study suggestions

This chapter presents some suggestions for further studies.

The lignin extraction could be better studied with another base case model where the effects on the evaporation plant as well as the pulp process limitations are included. This is to be able to better quantify the potential of the pulp production increase and identify the different bottlenecks of the pulp process.

Within the existing district heating models the location of the heat pump could be changed to better utilize the excess heat and the heat pump's properties. During the thesis work it was realized that this placement of the heat pump is not optimal. The problem is that the heat pump is working with very high temperatures, forcing the system to use a non-standard heat pump that is suited to work with high temperatures which makes the heat pump more expensive. A suggestion would be to have heat pumps both prior and after the black liquor cooling. This is possible and would mean that heat pumps of standard types could be used. By doing this, the costs, both for investments and operation, will be lowered. Another opportunity is to combine the heat pump and using the black liquor flow after the black liquor cooling to heat the inlet flow on the evaporating side of the heat pump. This would enable a more efficient overall use of the excess heat from the mill.

Before investigating the low-temperature bark drying further it is suggested to wait for the results from ongoing research about low temperature bark drying. (Holmberg and Stenström, 2014, Stenström, 2014)

There are also some alternatives that were not investigated in detail in this thesis that still are recommended for deeper investigation:

- Bark as an insulation material is interesting because of the isolating properties of bark. With the huge amount of bark that will be available after the expansion of the mill, this could be a solution to increase the bark value on the market. The amount of bark at the mill site is not only a problem for Värö, but a problem for pulp mills in general.
- Gasification might be an interesting alternative for usage of the large amount of bark that for the expanded pulp mill may not be utilized.
- Fish farming is another suggestion to be deeper investigated. The reason for this is that the fish market is getting more and more aware of where the fish comes from and how environmentally friendly it is. The conditions for fish farming are promising around pulp mills if, for instance, the heat needed in the fish farm could be satisfied with excess heat from the pulp mill.
- Algae culture, with its growing market, is very interesting. Especially if it could be combined with the waste water treatment facilities and not only the excess heat.
- Polyurethane foams made from liquefied bark-based polyols might become an interesting alternative when the research of this environmentally friendly alternative to fossil-based polyurethane foams has been developed further.

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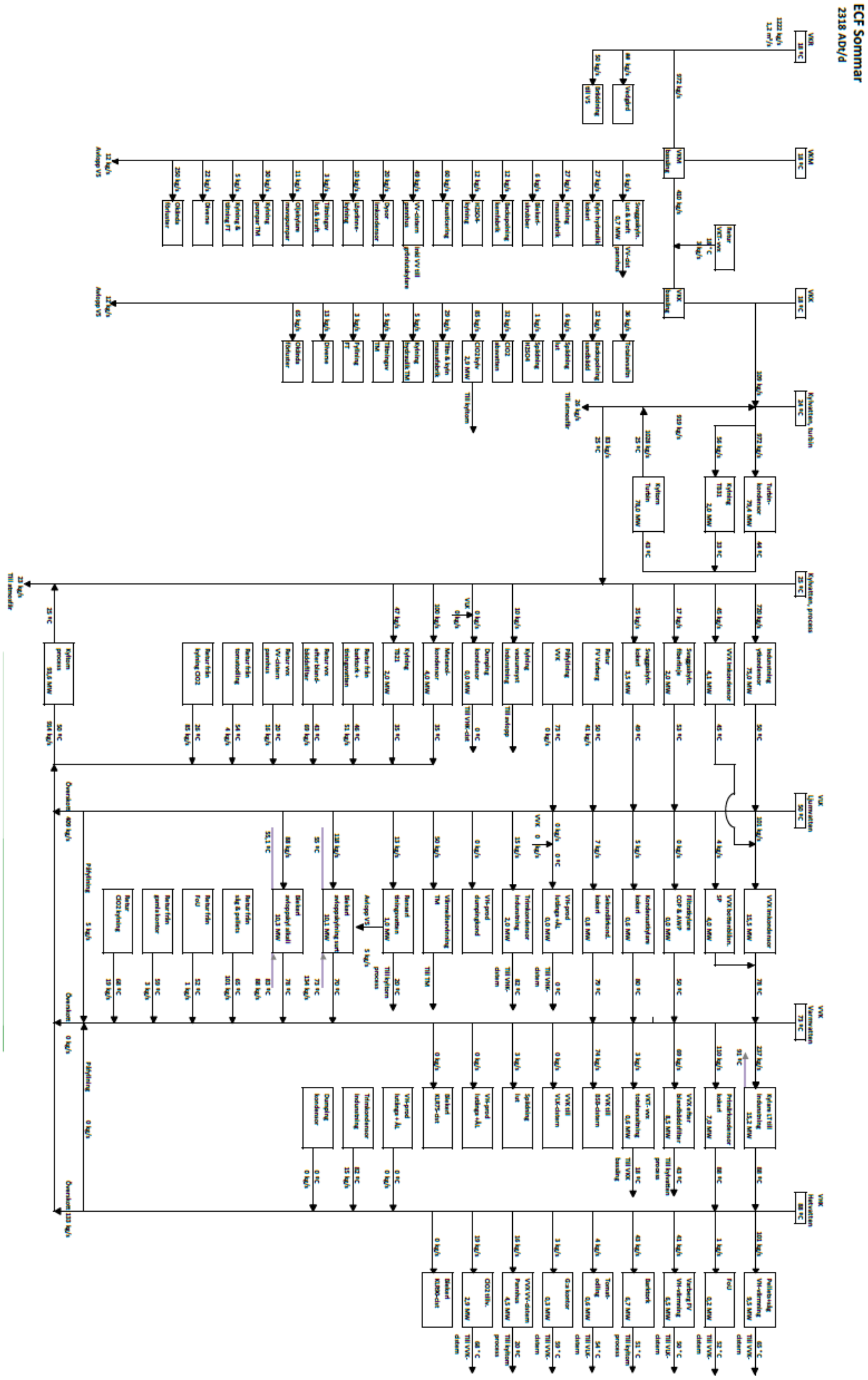
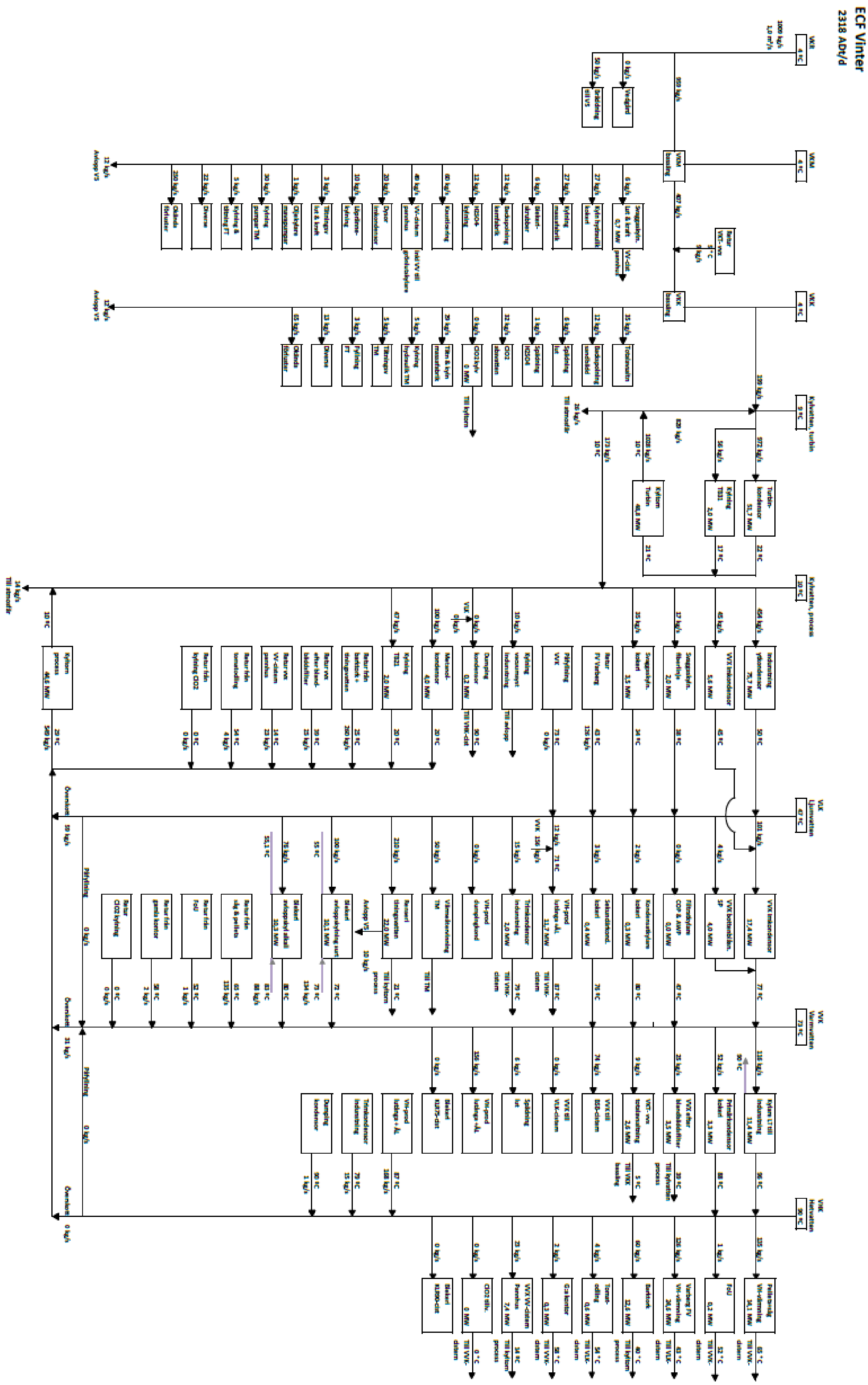
Appendix A: Secondary Heating System

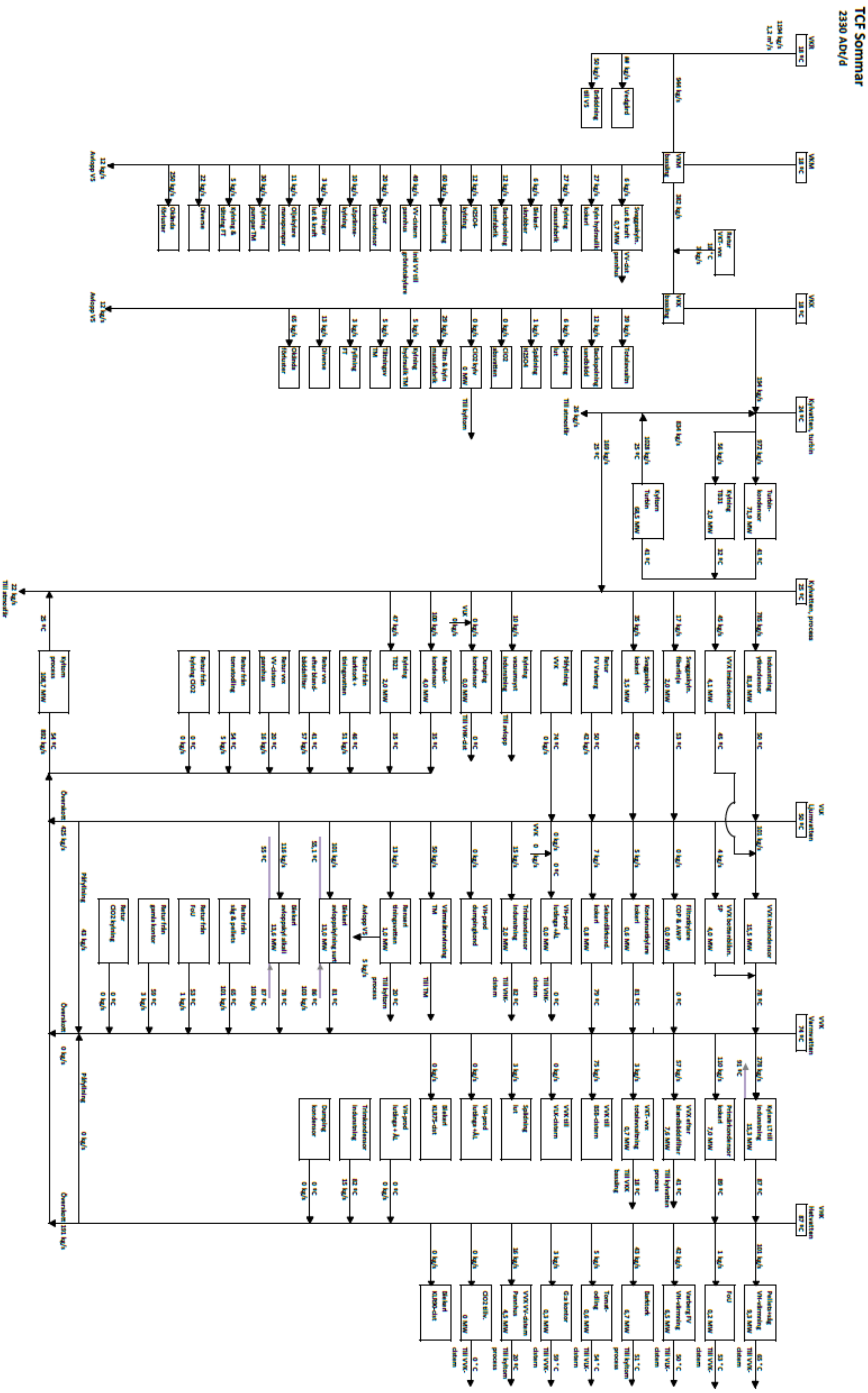
VHK Vatten, hetvatten, kemiskt renat

VLK Vatten, ljumvatten, kemiskt renat

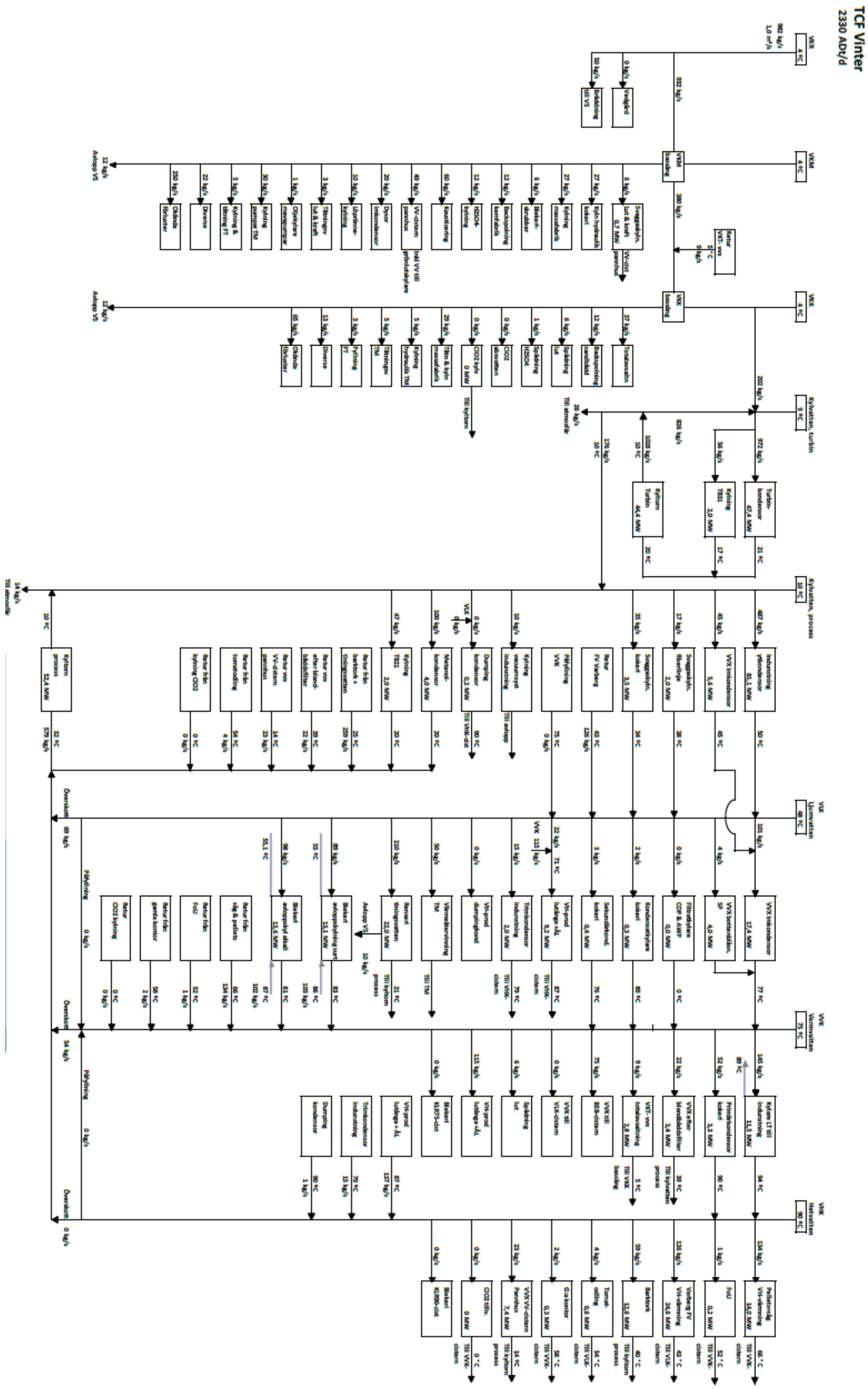
VVK Vatten, varmvatten, kemiskt renat




ECF Vinter
2318 Adt/d


TCF Sommar
2330 ADt/d

TCF Vinter
2330 ADt/d



Appendix B: Input and process data

Specific heat for water and black liquor

For the district heating scenarios, assumptions of constant C_p for water and black liquor are used. The constant values are:

Water: $C_{p,water} = 4.19 \left[\frac{kJ}{kg^0C}\right]$

Black liquor: $C_{p,black\ liquor} = 3.65 \left[\frac{kJ}{kg^0C}\right]$

The following equation is used to calculate the C_p for black liquor:

Black liquor: $$\mathrm{C_p} = \left(0.96 - 0.45 * \mathrm{DS_{black\ liquor}}\right) * \mathrm{C_{p,water}} \left[\frac{kJ}{kg^0C}\right] \quad (4)$$

Bark

Energy content 40% DS bark: 0.66 MWh/m^3

Energy content 60% DS bark: 0.75 MWh/m^3

Prices

Prices for district heating and electricity are used as follows.

The price for district heating is set to 724,000 SEK/GWh (72.4 öre/kWh), and the assumed price Södra receives for its district heating is half of that price, i.e. 362,000 SEK/GWh (36.2 öre/kWh). (Svensk Fjärrvärme, 2010)

The price for electricity is taken from Nord Pool spot market (Nord Pool Spot, 2015) and the prices are presented in Table 15.

Table 15. Electricity prices.

Prices from Nord Pool				
Year	2012	2013	2014	
Average price	281.9	340.8	287.8	SEK/MWh
Average sum			303.5	SEK/MWh

Appendix C: Assumptions

Components

Table 16 presents the assumed efficiencies for different components that are implemented in the process models. For the two turbines an isentropic efficiency is used and for the other three components their input-to-output efficiencies are used.

Table 16. Data for the major equipment in the pulp mill energy system.

Component		
Recovery boiler	η	0.85
Bark boiler	η	0.78
Back pressure turbine	η_{is}	0.87
Condensate turbine	η_{is}	0.86
Generators	η	0.98

Bark drying

Table 17. Data assumed for the bark dryer.

Assumed data		Unit
Average annual temperature	7	°C
ΔT	15	°C
Used temperature	22	°C

Appendix D: Component descriptions

Heat exchanger

Figure 29 shows a simplified model of a heat exchanger. There are different types of heat exchangers; however the type that is used in the district heating and bark drying scenarios is of a closed-type. A closed-type heat exchanger means that no mixture of the two entering fluids are done just heat exchanging.

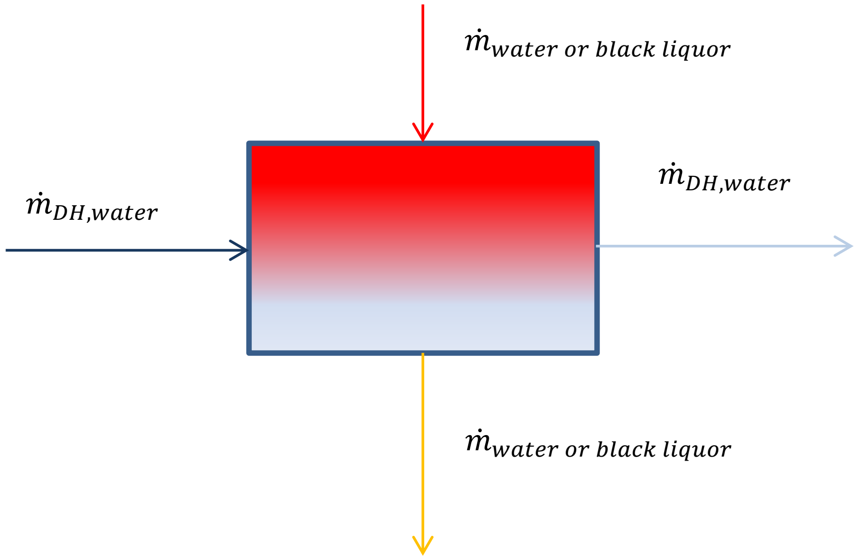


Figure 29. A schematic picture of a heat exchanger.

The following equations are used when calculating heat exchanging between two fluids, in this case the fluids are water and black liquor:

$$Q_{Heat} = \dot{m}_{water} * C_{p,water} * \Delta T_{water} = \dot{m}_{black\ liquor} * C_{p,black\ liquor} * \Delta T_{black\ liquor} \quad (5)$$

The overall equation for heat exchanging through the heat exchangers, both between water and water, water and black liquor, and between water and steam are:

$$\dot{m}_{DH,water} * C_{p,water} * \Delta T_{DH,water} = \dot{m}_{water} * C_{p,water} * \Delta T_{water} \quad (6)$$

$$\dot{m}_{DH,water} * C_{p,water} * \Delta T_{DH,water} = \dot{m}_{black\ liquor} * C_{p,black\ liquor} * \Delta T_{black\ liquor} \quad (7)$$

When studying heat exchangers there are some limits that are important to maintain, e.g. the heat exchanger's cost depends on price. A too large heat exchanger will be very expensive. An important parameter to check is the minimum temperature difference, ΔT_{min}. This is a parameter that describes what the difference between the two interacting streams shall have after the heat exchanger. This means that incoming colder stream shall have a specific temperature compared to the hot streams leaving temperature.

Figure 30 shows a heat pump and how the heat pump works. At position 1 the mixture of lukewarm, warm- and hot-water will enter and work as a heating medium. In position 2 the heat exchange will be carried out. Position 3 will compress the fluid medium within the heat pump, and thereby the temperature will increase. At position 4 the heat exchange to the other fluid will be carried out and it is at this position the district heating water will be heated and increased in temperature. In position 5 the intern fluid will be expanded through an expansion throttle and the temperature will drop. And after that the procedure is repeated.

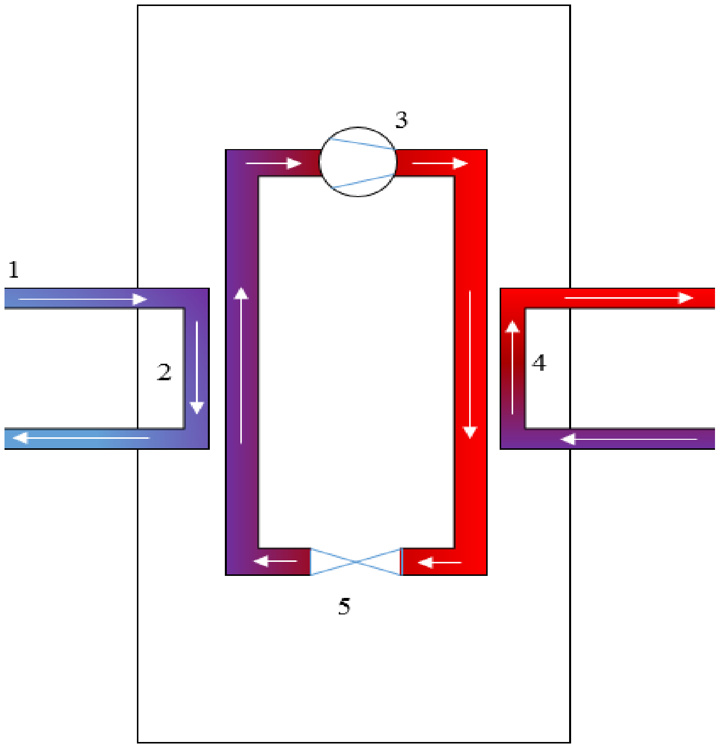


Figure 30. Schematic picture of a heat pump.

The heat pump that is used for this evaluation is based on the specifications for a Grasso MX SO 800 built by Francks Kylindustrier.

Appendix E: District heating flow data

Table 18. Base case district heating.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^{0}C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	46.0	140.0	46.0	140.0
2	Temp	^{0}C	84.0	84.0	84.0	84.0
	Mass flow	kg/s	46.0	140.0	46.0	140.0
3	Temp	^{0}C	88.0	90.0	88.0	90.0
	Mass flow	kg/s	42.0	126.0	42.0	125.0
4	Temp	^{0}C	50.0	43.0	50.0	43.0
	Mass flow	kg/s	42.0	126.0	42.0	126.0
5	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	259.0	259.0	259.0
6	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	194.0	259.0	194.0
7	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
8	Temp	^{0}C	84.0	85.0	84.0	85.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
9	Temp	^{0}C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	46.0	140.0	46.0	140.0
10	Temp	^{0}C	84.0	93.1.0	84.0	93.1.0
	Mass flow	kg/s	46.0	140.0	46.0	140.0
11	Temp	^{0}C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	-	-	-	-
12	Temp	^{0}C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	-	-	-	-

Table 19. Scenario 3a: Increased district heating capacity to Varberg by implementing a warm water heat exchanger.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^0C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	170.0	131.9	219.0	132.8
2	Temp	^0C	50.0	48.1	50.0	52.6
	Mass flow	kg/s	170.0	131.7	219.0	132.8
3	Temp	^0C	73.0	73.0	73.0	73.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
4	Temp	^0C	50.0	47.0	50.0	47.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
5	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	259.0	259.0	259.0
6	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	194.0	259.0	194.0
7	Temp	^0C	50.0	48.1	50.0	56.6
	Mass flow	kg/s	170.0	131.9	219.0	132.8
8	Temp	^0C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	175.0	126.0	233.0	126.0
9	Temp	^0C	55.0	53.1	55.0	57.5
	Mass flow	kg/s	175.0	126.0	233.0	126.0
10	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
11	Temp	^0C	85.0	85.0	85.0	85.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
12	Temp	^0C	84.0	92.8	84.0	92.8
	Mass flow	kg/s	170.0	131.9	219.0	132.8
13	Temp	^0C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	170.0	131.9	219.0	132.8
14	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
15	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

Table 20. Scenario 3b: Increased district heating capacity to Varberg by implementing a heat pump.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^{0}C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	622.0	239.0	735.0	269.0
2	Temp	^{0}C	59.3	64.7	60.1	62.0
	Mass flow	kg/s	622.0	239.0	735.0	269.0
3	Temp	^{0}C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	175.0	126.0	233.0	125.0
4	Temp	^{0}C	55.0	47.0	55.0	47.0
	Mass flow	kg/s	175.0	126.0	233.0	125.0
5	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	259.0	259.0	259.0
6	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	194.0	259.0	194.0
7	Temp	^{0}C	59.3	69.9	60.1	66.6
	Mass flow	kg/s	622.0	239	735.0	269.0
8	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
9	Temp	^{0}C	59.0	85.0	60.1	85.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
10	Temp	^{0}C	73.0	73.0	74.0	75.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
11	Temp	^{0}C	50.0	47.0	50.0	48.0
	Mass flow	kg/s	409.0	59.0	425.0	69.0
12	Temp	^{0}C	51.5	50.7	51.8	53.4
	Mass flow	kg/s	584.0	216.0	658.0	248.0
13	Temp	^{0}C	29.0	29.0	29.0	29.0
	Mass flow	kg/s	584.0	216.0	658.0	248.0
14	Temp	^{0}C	84.0	92.9	84.0	92.9
	Mass flow	kg/s	622.0	239.0	735.0	269.0
15	Temp	^{0}C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	622.0	239.0	735.0	269.0
16	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
17	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

Table 21. Scenario 3c: Increased district heating capacity to Varberg by implementing a warm water heat exchanger and a heat pump.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^0C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	622.0	213.4	735.0	247.0
2	Temp	^0C	50.0	45.8	50.0	47.7
	Mass flow	kg/s	622.0	213.4	735.0	247.0
3	Temp	^0C	73.0	73.0	73.0	73.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
4	Temp	^0C	50.0	47.0	50.0	47.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
5	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	259.0	259.0	259.0
6	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	194.0	259.0	194.0
7	Temp	^0C	59.3	68.9	60.1	66.6
	Mass flow	kg/s	622.0	213.4	735.0	247.0
8	Temp	^0C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	175.0	126.0	233.0	125.0
9	Temp	^0C	55.0	50.8	55.0	52.7
	Mass flow	kg/s	175.0	126.0	233.0	125.0
10	Temp	^0C	50.0	47.0	50.0	48.0
	Mass flow	kg/s	409.0	59.0	425.0	69.0
11	Temp	^0C	51.5	49.2	51.8	51.4
	Mass flow	kg/s	584.0	216.0	658.0	248.0
12	Temp	^0C	29.0	29.0	29.0	29.0
	Mass flow	kg/s	584.0	216.0	658.0	248.0
13	Temp	^0C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
14	Temp	^0C	59.0	85.0	60.1	85.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
15	Temp	^0C	53.9	74.8	60.1	71.6
	Mass flow	kg/s	622.0	213.4	735.0	247.0
16	Temp	^0C	84.0	92.9	84.0	92.9
	Mass flow	kg/s	622.0	213.4	735.0	247.0
17	Temp	^0C	84.0	93.0	84.0	93.0
	Mass flow	kg/s	622.0	213.4	735.0	247.0
18	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
19	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

Table 22. Scenario 3d: Expanding the district heating network to Kungsbacka while maintaining planned deliveries to Varberg.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^0C	48.0	40.0	48.0	40.0
	Mass flow	kg/s	59.7	96.3	59.7	96.3
2	Temp	^0C	48.0	48.4	48.0	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
3	Temp	^0C	73.0	73.0	73.0	75.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
4	Temp	^0C	50.0	47.0	50	47.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
5	Temp	^0C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	62.8	0.0	64.5	0.0
6	Temp	^0C	55.0	54.8	55.0	61.6
	Mass flow	kg/s	62.8	0.0	64.5	0.0
7	Temp	^0C	82.7	48.4	82.6	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
8	Temp	^0C	50.0	47.0	50.0	48.0
	Mass flow	kg/s	12.8	59.0	13.0	69.0
9	Temp	^0C	50.0	47.0	50.0	47.6
	Mass flow	kg/s	12.8	90.0	13.0	123
10	Temp	^0C	29.0	29.0	29.0	29.0
	Mass flow	kg/s	12.8	90.0	13.0	123.0
11	Temp	^0C	82.7	48.4	82.6	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
12	Temp	^0C	88.0	68.1	88.0	83.5
	Mass flow	kg/s	59.7	96.3	59.7	96.3
13	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
14	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

Table 23. Scenario 3e: Maximum district heating capacity to Varberg and deliveries to Kungsbacka.

Location/ period		Unit	ECF Summer	ECF Winter	TCF Summer	TCF Winter
1	Temp	^{0}C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	740.0	214.0	852.0	242.9
2	Temp	^{0}C	73.0	73.0	73.0	75.0
	Mass flow	kg/s	0.0	0.0	0.0	0.0
3	Temp	^{0}C	50.0	47.0	50.0	47.0
	Mass flow	kg/s	0.0	0.0	0.0	0.0
4	Temp	^{0}C	50.0	42.0	50.0	42.0
	Mass flow	kg/s	740.0	214.0	852.0	242.9
5	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	259.0	259.0	259.0
6	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	259.0	194.0	259.0	194.0
7	Temp	^{0}C	57.8	65.3	58.8	61.2
	Mass flow	kg/s	740.0	214.0	852.0	242.9
8	Temp	^{0}C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	175.0	126.0	233.0	125.0
9	Temp	^{0}C	55.0	50.5	55.0	52.7
	Mass flow	kg/s	175.0	126.0	233.0	125.0
10	Temp	^{0}C	50.0	47.0	50.0	48.0
	Mass flow	kg/s	396.2	0.0	412.0	0.0
11	Temp	^{0}C	51.5	50.5	51.8	52.7
	Mass flow	kg/s	571.2	126.0	645.0	125.0
12	Temp	^{0}C	29.0	29.0	29.0	29.0
	Mass flow	kg/s	571.2	126.0	645.0	125.0
13	Temp	^{0}C	107.0	107.0	107.0	107.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
14	Temp	^{0}C	85.0	85.0	85.0	85.0
	Mass flow	kg/s	0.0	65.0	0.0	65.0
15	Temp	^{0}C	57.8	71.1	58.8	66.3
	Mass flow	kg/s	740.0	214.0	852.0	242.9
16	Temp	^{0}C	78.2	85.9	79.0	78.8
	Mass flow	kg/s	740.0	214.0	852.0	242.9
17	Temp	^{0}C	84.0	93.0	84.0	91.2
	Mass flow	kg/s	740.0	214.0	852.0	242.9
18	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	7.5	2.6	7.5	5.2
19	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	7.5	2.6	7.5	5.2
20	Temp	^{0}C	84.0	93.1	84.0	93.1
	Mass flow	kg/s	740.0	214.0	852.0	242.9
21	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
22	Temp	^{0}C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

23	Temp	^0C	48.0	40.0	48.0	40.0
	Mass flow	kg/s	59.7	96.3	59.7	96.3
24	Temp	^0C	48.0	48.4	48.0	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
25	Temp	^0C	73.0	73.0	73.0	75.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
26	Temp	^0C	50.0	47.0	50.0	47.0
	Mass flow	kg/s	0.0	31.0	0.0	54.0
27	Temp	^0C	88.0	90.0	87.0	90.0
	Mass flow	kg/s	62.8	0.0	64.5	0.0
28	Temp	^0C	55.0	54.8	55.0	61.6
	Mass flow	kg/s	62.8	0.0	64.5	0.0
29	Temp	^0C	82.7	48.4	82.6	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
30	Temp	^0C	50.0	47.0	50.0	48.0
	Mass flow	kg/s	12.8	59.0	13.0	69.0
31	Temp	^0C	50.0	47.0	50.0	47.6
	Mass flow	kg/s	12.8	90.0	13.0	123.0
32	Temp	^0C	29.0	29.0	29.0	29.0
	Mass flow	kg/s	12.8	90.0	13.0	123.0
33	Temp	^0C	82.7	48.4	82.6	55.7
	Mass flow	kg/s	59.7	96.3	59.7	96.3
34	Temp	^0C	88.0	68.1	88.0	83.5
	Mass flow	kg/s	59.7	96.3	59.7	96.3
35	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-
36	Temp	^0C	-	-	-	-
	Mass flow	kg/s	-	-	-	-

Appendix F: Sensitivity Analysis

A sensitivity analysis for the economic performance, resource efficiency and CO_2 emission key performance indicators were performed due to the variables of electricity price, district heating price, electricity certificates, O&M_{Lig} cost, pulp production, recovery boiler efficiency, bark boiler efficiency, generator efficiency, the efficiency of both turbines and different cases of CO_2. It is performed both for ECF bleaching and TCF bleaching, that is why the scenario names appear twice.

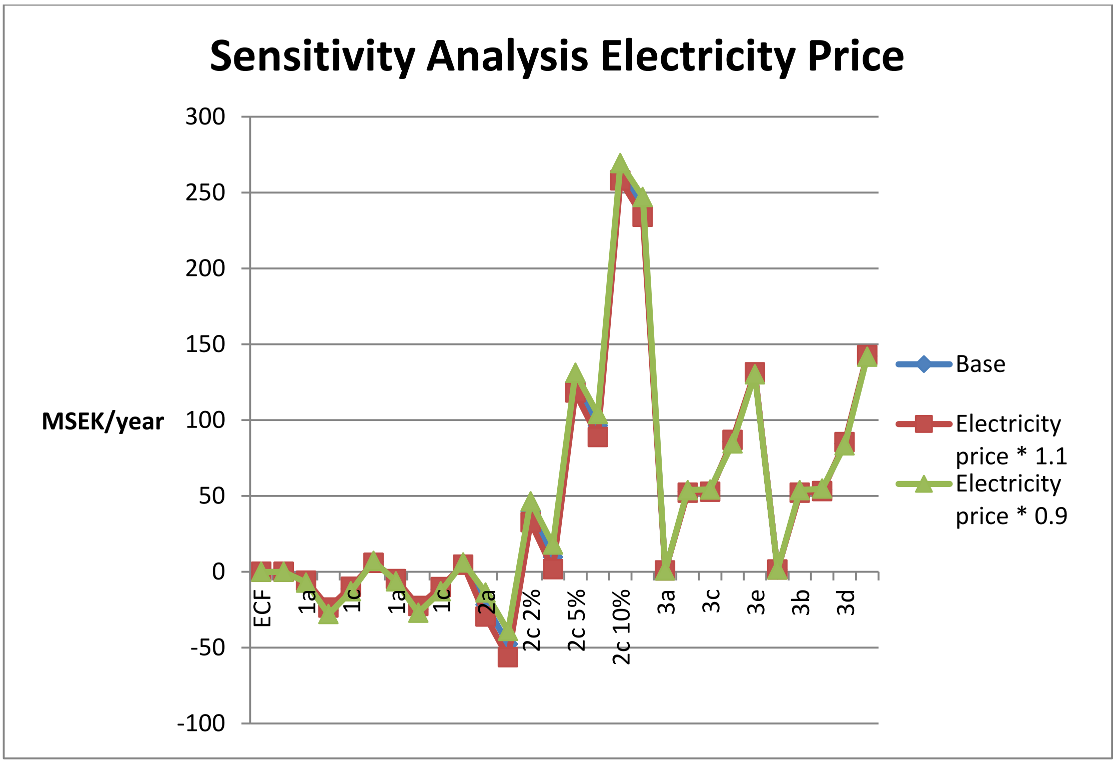


Figure 31. Sensitivity Analysis Electricity Price.

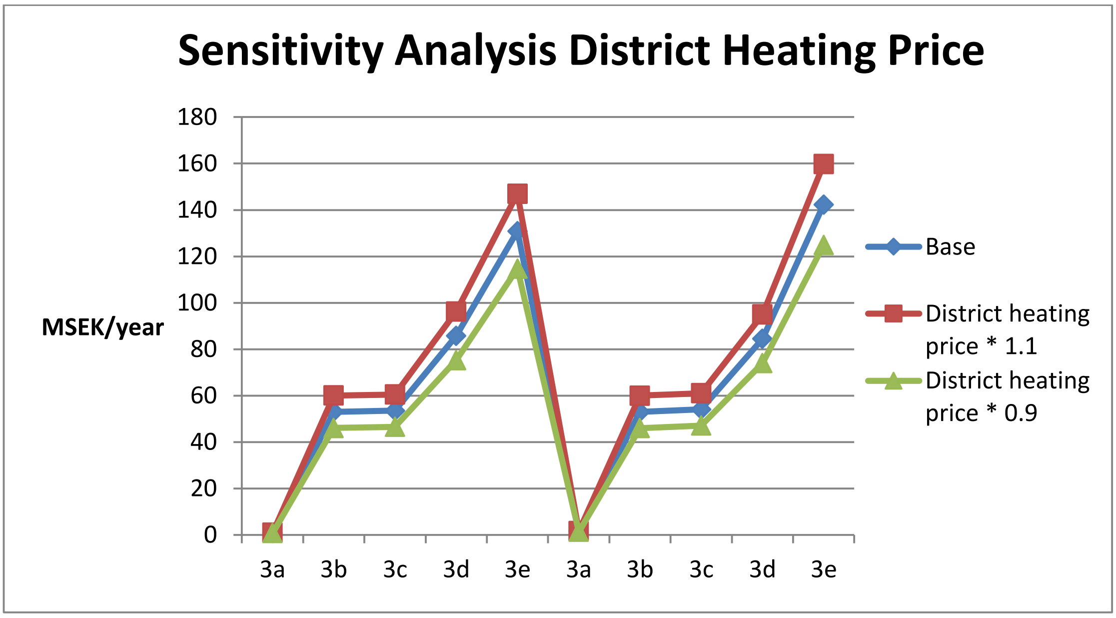


Figure 32. Sensitivity Analysis District Heating Price.

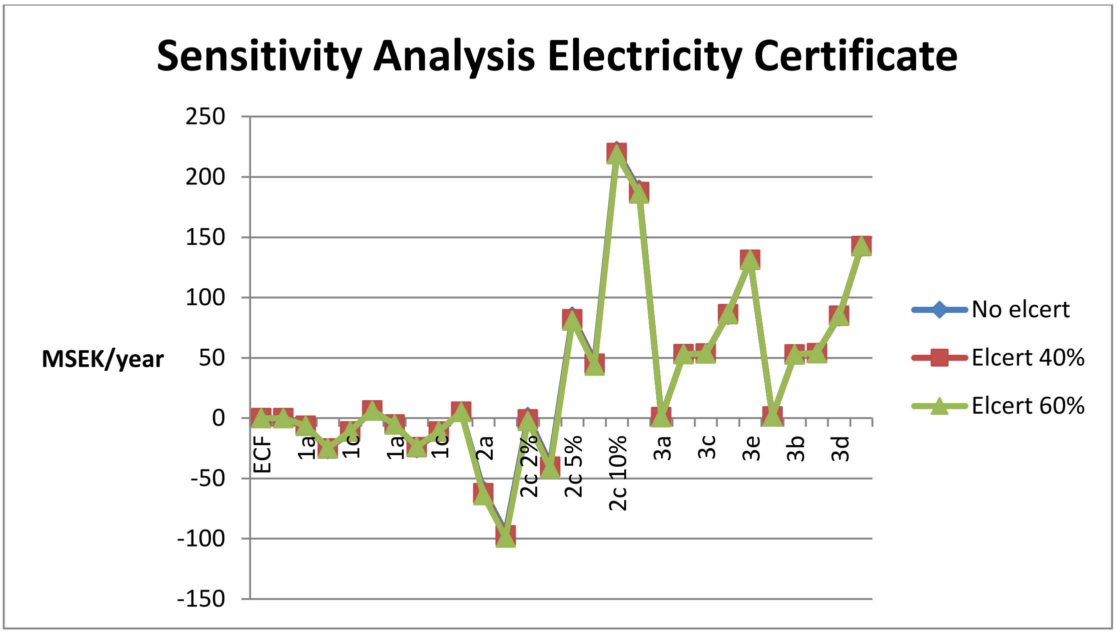


Figure 33. Sensitivity Analysis Electricity Certificate. The electricity certificate price is the average for 2014. (Cesar, 2015)

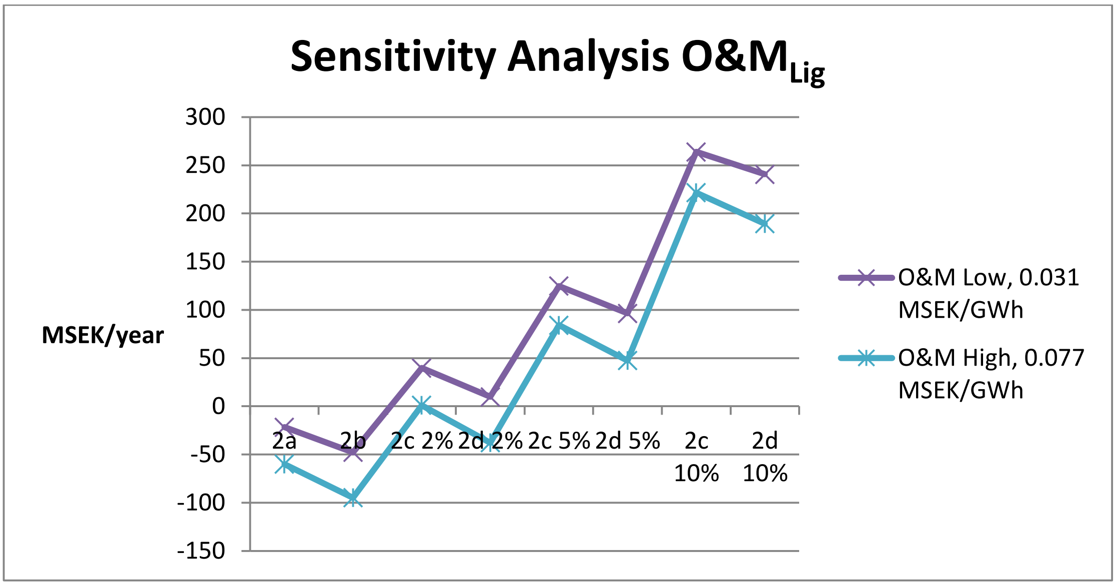


Figure 34. Sensitivity Analysis O&M$_{Lig}$.

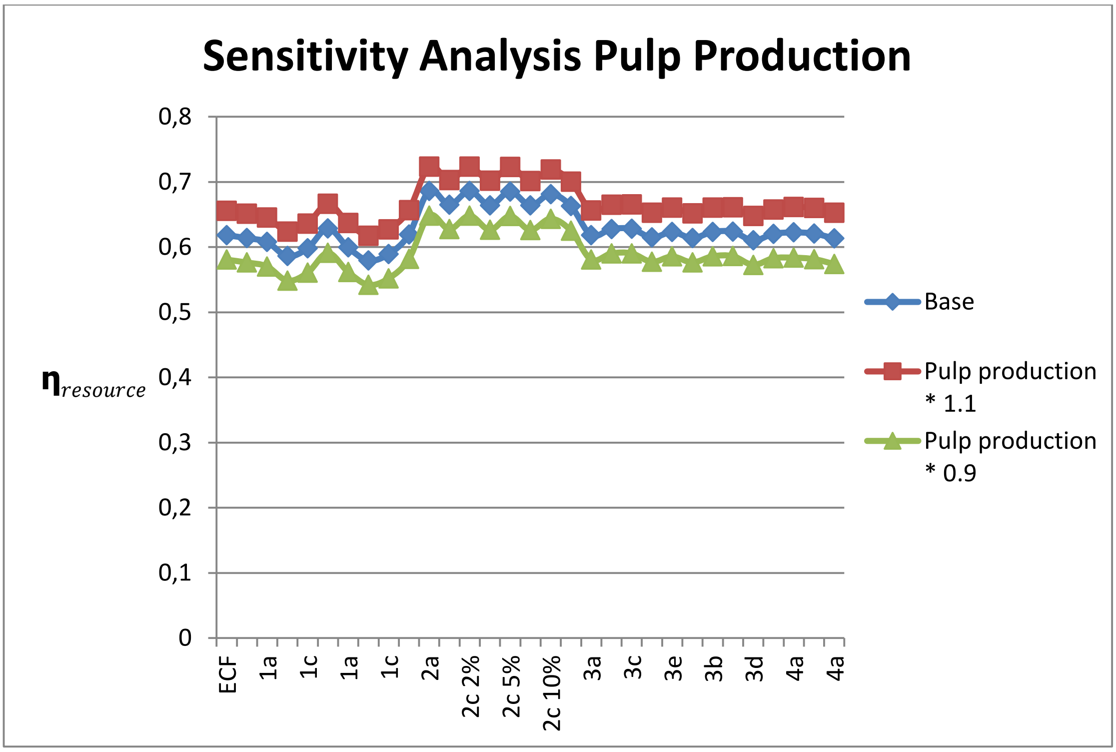


Figure 35. Sensitivity Analysis Pulp Production.

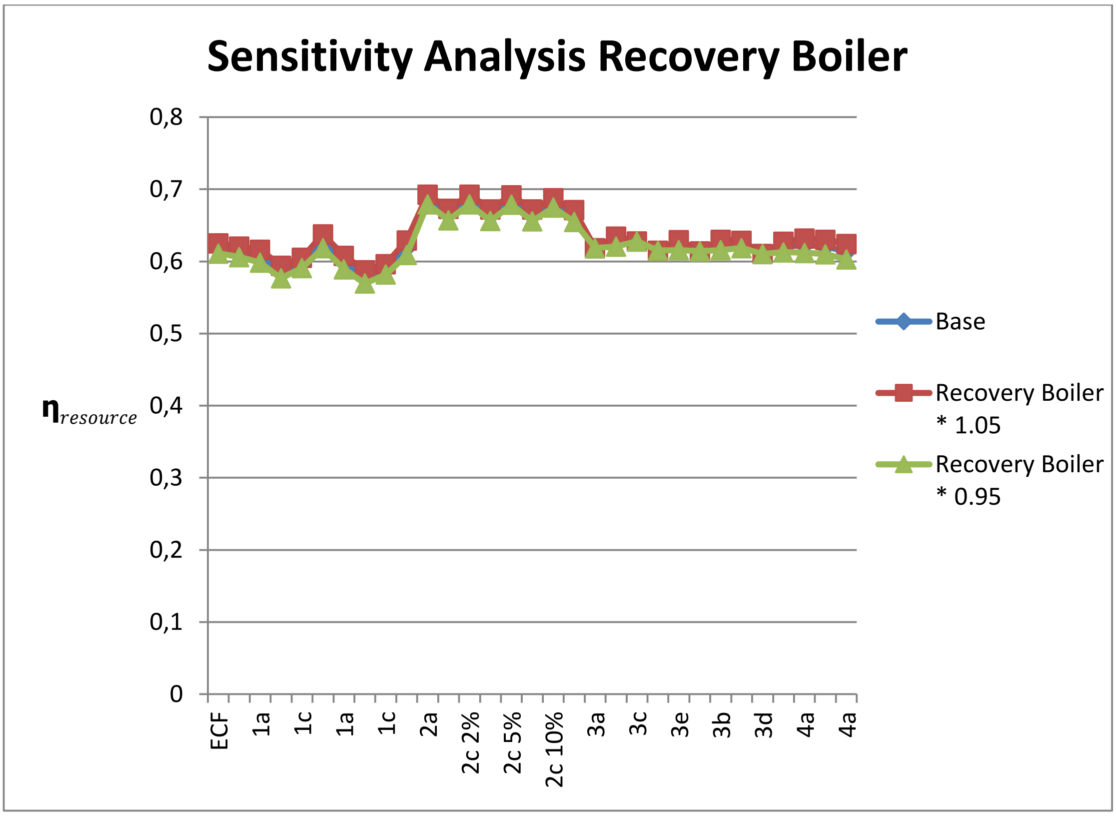


Figure 36. Sensitivity Analysis Recovery Boiler.

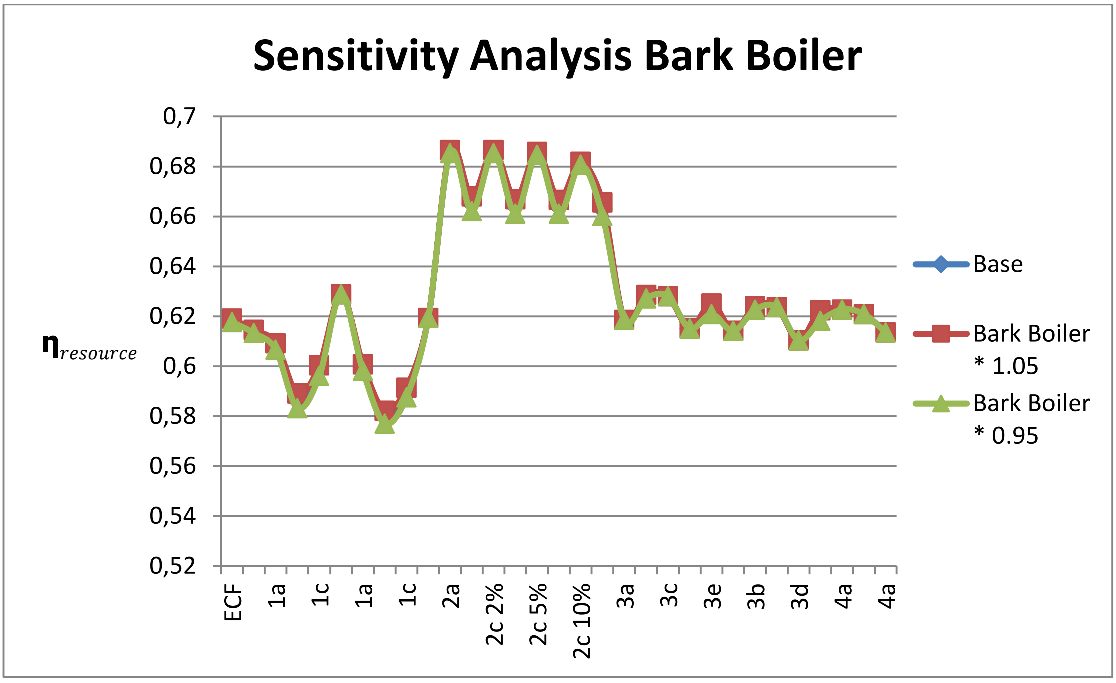


Figure 37. Sensitivity Analysis Bark Boiler.

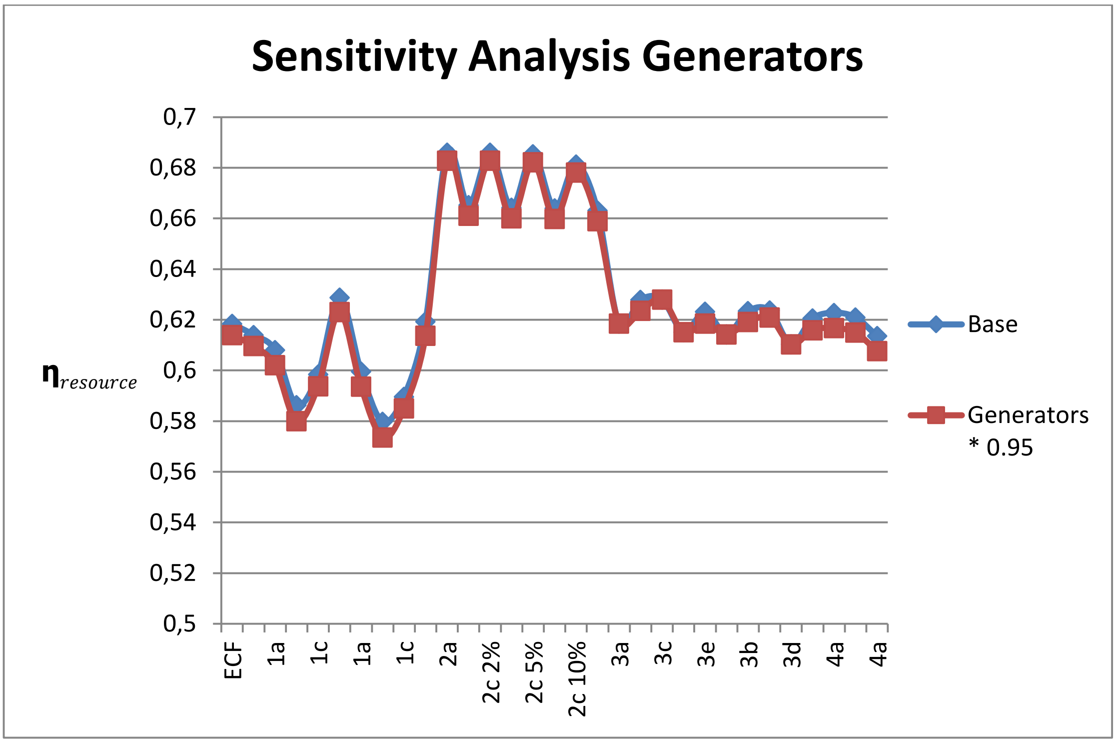


Figure 38. Sensitivity Analysis Generators.

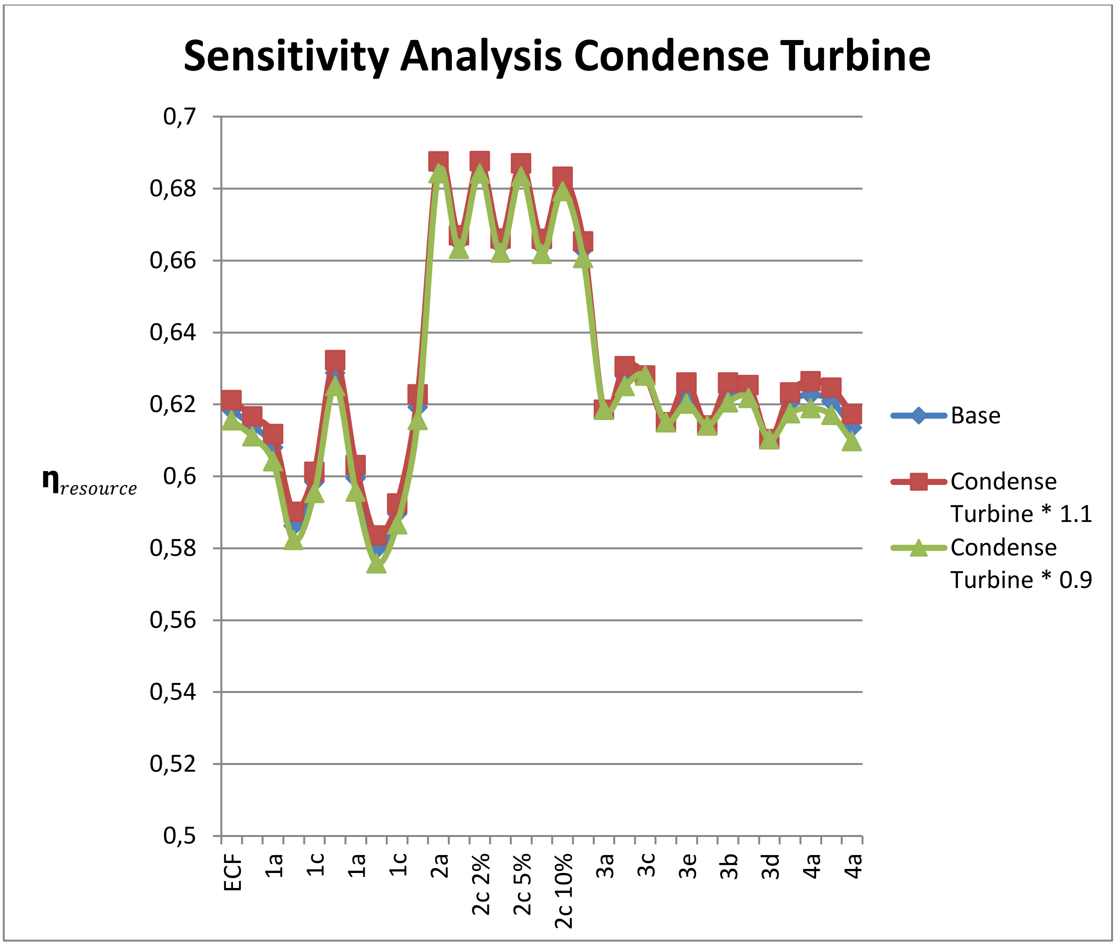


Figure 39. Sensitivity Analysis Condense Turbine.

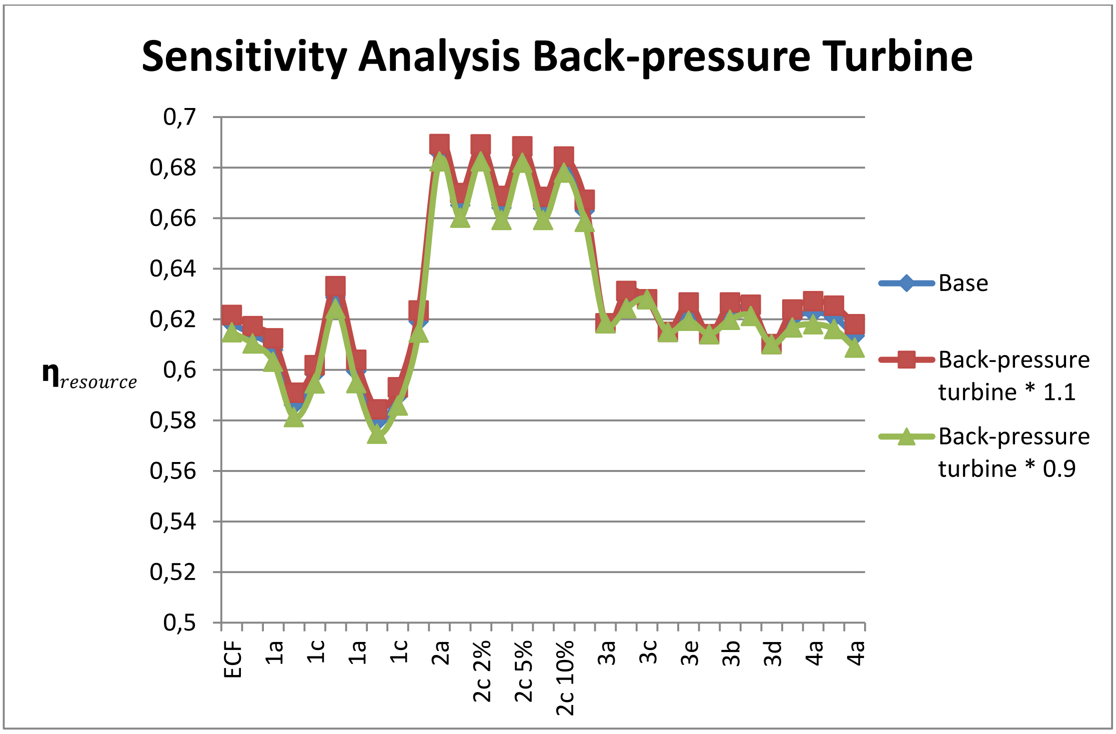


Figure 40. Sensitivity Analysis Back-pressure Turbine.

Table 24. Explanation table to Table 25 and Table 26.

CO_2-emissions	C1	Bio=0, el coal=855.6, Bio=0, Bio=0
	C2	Coal=349.2, el coal=855.6, Coal=349.2, NG=204.48
	C3	Bio=0, el coal=855.6, Coal=349.2, Bio=0
	C4	Bio=0, el coal=855.6, Coal=349.2, NG=204.48
	C5	Bio=0, el coal=855.6, Bio=0, NG=204.48
	C6	Coal=349.2, el coal=855.6, Bio=0, Bio=0
	C7	Coal=349.2, el coal=855.6, Coal=349.2, Bio=0
	C8	Coal=349.2, el coal=855.6, Bio=0, NG=204.48

Table 25. Sensitivity Analysis ΔCO2 ECF.

ECF		Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a	4b
ΔCO_2	C1	0	-18	-59	-41	18	223	244	203	238	206	234	203	226	0	24	23	-33	-18	18	18
(kton CO_2/year)	C2	0	-18	-59	-41	18	-64	-108	-86	-118	-98	-133	-114	-157	0	24	23	-33	-18	18	18
	C3	0	-18	-59	-41	18	-64	-108	-86	-118	-98	-133	-114	-157	0	4	3	-62	-64	18	18
	C4	0	-18	-59	-41	18	223	244	203	238	206	234	203	226	0	4	3	-62	-64	18	18
	C5	0	19	58	33	-19	223	361	203	354	205	349	201	339	0	24	23	42	57	-36	-40
	C6	0	19	58	33	-19	-64	9	-87	-2	-99	-18	-116	-44	0	24	23	42	57	-36	-40
	C7	0	19	58	33	-19	-64	9	-87	-2	-99	-18	-116	-44	0	4	3	13	11	-36	-40
	C8	0	19	58	33	-19	223	361	203	354	205	349	201	339	0	4	3	13	11	-36	-40

Table 26. Sensitivity Analysis ΔCO2 TCF.

TCF		Base case	1a	1b	1c	1d	2a	2b	2c 2%	2d 2%	2c 5%	2d 5%	2c 10%	2d 10%	3a	3b	3c	3d	3e	4a
ΔCO_2	C1	0	-21	-62	-41	21	223	244	203	238	206	234	203	226	0	24	21	-29	-13	18
(kton CO_2/year)	C2	0	-21	-62	-41	21	-64	-108	-86	-118	-98	-133	-114	-157	0	24	21	-29	-13	18
	C3	0	-21	-62	-41	21	-64	-108	-86	-118	-98	-133	-114	-157	0	5	1	-58	-62	18
	C4	0	-21	-62	-41	21	223	244	203	238	206	234	203	226	0	5	1	-58	-62	18
	C5	0	17	55	34	-17	223	361	203	354	205	349	201	339	0	24	21	46	62	-36
	C6	0	17	55	34	-17	-64	9	-87	-2	-99	-18	-116	-44	0	24	21	46	62	-36
	C7	0	17	55	34	-17	-64	9	-87	-2	-99	-18	-116	-44	0	5	1	16	13	-36
	C8	0	17	55	34	-17	223	361	203	354	205	349	201	339	0	5	1	16	13	-36