CHALMERS

Opportunities for improved heat integration in average Scandinavian kraftliner mills: A pinch analysis of a model mill

Master's Thesis within the Sustainable Energy Systems programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS

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Abstract

Energy savings and increased efficiency is important to a large energy consuming industry such as the pulp and paper industry. To give industries incentives to do something about their energy consumption, policy instruments are used and research in the pulp and paper field show that large savings can be achieved. One way to save steam is process integration and a tool to find steam saving opportunities is pinch analysis. The method is used in this thesis where a pinch analysis of a modelled average Scandinavian Kraftliner mill has been done. The mill is modelled within the national research program FRAM (Future Resource Adapted Pulp Mill) and the results in this thesis might act as a guideline for possible steam saving opportunities for a mill of this size and type.

The pinch analysis shows that theoretically, 20 MW of steam can be saved through improved heat exchanging, which is about 11% of today's steam demand. By making a retrofit analysis, two steam saving proposals with possibility to save 13.7 and 19.6 MW of low pressure steam were worked out.

Other investigated steam saving alternatives were flue gas heat recovery, upgrading of the evaporation plant, and energy savings in the paper machine. The steam saving opportunities were put together to eight different investment alternatives with steam savings between 120 and 420 GWh/yr. The economic evaluation of those alternatives shows an investment cost in the range 1–15 M€, depending on the investment. The largest investment cost is an upgrade of the evaporation plant, 10.4 M€.

The steam surplus can be used for fuel savings and thereby achieve annual earnings. To analyze this, two levels of bark and electricity prices were used and the resulting earnings lie between 2.5–10 M€/yr depending on investment alternative, bark and electricity prices.

An interesting concept within process integration and the biorefinery field is lignin separation. In this thesis it is investigated what lignin price is required for lignin to be equally profitable as saving fuel. The same levels of fuel and electricity prices as for the fuel savings were used and consequently two lignin price levels were achieved. The achieved lignin prices vary between 30 and 51 €/MWh. Depending on the investment alternative and thereby achieved lignin price, this is comparable to the price of high-grade biofuels as well as the oil price.

Conclusions that can be drawn are; considerable savings can be achieved in the mill, it is clearly profitable to save fuel and the estimated lignin price implies that lignin separation can be an interesting alternative to fuel saving.

Key words: pinch analysis, steam savings, retrofit, lignin separation, kraft pulp mill, fuel savings

Contents

Notations

a	Annuity factor
ADt	Air dry tonne (90% dryness)
BDt	Bone dry tonne (100% dryness)
FG	Flue gases
FGHR	Flue Gas Heat Recovery
FRAM	Future Resource Adapted Pulp Mill, Swedish national research program
GCC	Grand Composite Curve
HW	Hot Water (production)
HP	High Pressure steam
i	Interest rate
LP	Low Pressure steam
MP	Medium Pressure steam
NCG	Non Condensable Gas
NOx	Nitrogen Oxides
STFI	STFI - Packforsk which is Innventia since 2003

1 Introduction

1.1 Background

The energy usage is a topic with high priority for the political agenda and therefore also the media coverage. With this in mind, energy savings in industries become more and more important since industrial processes are large energy consumers. Policy instruments and environmental regulations are also used to stimulate a lowered environmental impact. Therefore, it is important to analyze the current energy system and consider the future, to be prepared for what might come and increase efficiency, to avoid high costs in the future.

The pulp and paper industry is a large energy consumer and the importance of efficient process integration is high. Research with purpose to make the industry less energy consuming is an ongoing process. The Future Recourse Adapted Pulp Mill, FRAM, is a national Swedish research program with the aim to investigate how the pulp and paper industry can have less environmental impact. Several pulp and paper mills have been modelled within FRAM and a central part in the research has been to investigate the energy saving potentials in those theoretical mills [1] [2] [3]. This thesis contains an investigation of the energy system of one of those modelled mills, the Kraftliner mill, which is the only type that has not been investigated before. The energy saving potential is individual for each real mill but the energy savings found in the study of this modelled mill may act as a guideline for possible energy saving potentials.

An interesting concept within process integration and the biorefinery field is lignin separation. A lot of research has been done during the last years and several methods to separate the lignin from the black liquor have been developed. One efficient method to separate lignin is the LignoBoost process where the lignin is separated from the evaporation plant. The lignin can be utilized as fuel or as raw material for high-grade chemicals [4].

One objective for this thesis is a pinch analysis of an integrated pulp and paper kraftliner mill. A pinch analysis is an analysis of the processes in order to save energy. Since not many pinch studies have been made on this type of mill, it is of interest to find the energy saving potential. Compared to a market pulp kraft mill, this integrated mill does not have the same possibility to become a net energy exporter or to be self-sufficient in energy supply from the wood. In this thesis it is also investigated how the energy savings can be used. What are the benefits of decreasing the import of wood waste or alternatively what lignin price is required for lignin separation to be equally profitable as saving fuel?

1.2 Objectives

The main purpose of the thesis is to identify possible steam saving opportunities in a modelled average Scandinavian kraftliner mill. A secondary purpose is to economically evaluate possible investment alternatives, based on the possible steam saving opportunities. An important part of this economic evaluation is to identify the price for lignin which makes lignin separation equally profitable as saving fuel.

2 Scope and Delimitations

2.1 Scope

This thesis addresses the possible steam saving potential of a modelled kraftliner mill, which represents an average Scandinavian mill of that type.

The study covers the production process in an integrated pulp and paper mill, though the focus is on the pulping process. Since the model represents an average Scandinavian mill, the results in this thesis are not applicable on any specific Scandinavian site. However, the level of the steam saving potential indicates the possible steam savings for a typical mill of this size and type. The optimal solutions for each mill are naturally individual for each site.

To make a relevant analysis of the economy of the proposed measures, two levels of energy prices are taken into account.

2.2 Delimitations

The modelled FRAM mill is based on a large amount of information but some data is not known; for example distances between streams. This can lead to that a possible retrofit of a system cannot be viable while the distance between the streams are too far and too much heat would be lost or the costs too high. Further, as the distances are unknown, an exact piping cost calculation is impossible, which in turn, makes the economic calculations/evaluations rough estimations. Pumps have been held intact and supposed to work at the same capacity; consequently costs for those are neglected.

The investigation of the heat integration potential at the mill is originally divided in two parts; the paper machine and the pulp process. This is because the liner machine has to work independently of the pulp process and the liner machine was modelled as a black box and no information about the energy recovery system was known. Probably, the distances also make the piping costs too high for integration.

A further delimitation lie in the rough economic investment calculation for an upgrade of the evaporation plant, where the calculation is based on scaling and assumptions.

The focus has been to find heat integration opportunities and increase the energy efficiency in that way. Therefore, no attention has been put into other energy saving options such as electricity saving possibilities. The standpoint has also been to keep as much existing equipment as possible instead of buying new and thereby increase investment costs. An exception is the evaporation plant which is one of the major steam consumers in the mill.

3 Theory

In this section, the basic in pinch analysis and lignin separation is presented. All information in section 3.1 is from the course material in the course Industrial Energy Systems [5].

3.1 Basic pinch analysis

Pinch technology is a useful method to analyze an industrial process in order to save energy and money. The system analysis is done by answering the questions: How much heat must be added? How much heat must be removed or extracted? How much heat can be heat exchanged internally and how should the heat exchanger network be designed to maximize the heat recovery? To answer these questions the process streams are divided into hot and cold streams where hot streams are streams with a cooling demand and cold streams represent a heating demand.

A minimum temperature difference for heat exchange is set to each individual stream. The minimum temperature difference is chosen, for example, with regards to heat transfer characteristics and purpose of the stream.

The heat content in all hot streams is calculated and combined together they represent the hot composite curve. A cold composite curve is calculated correspondingly. After plotting those with Q on the x-axis and the temperature on the y-axis, the minimum hot and cold utility demands can be read. The composite curves are show in Figure 1 below. Where the curves overlap, internal heat exchange is possible. The pinch point appears where the curves meet with the minimum temperature difference, usually at one point only.

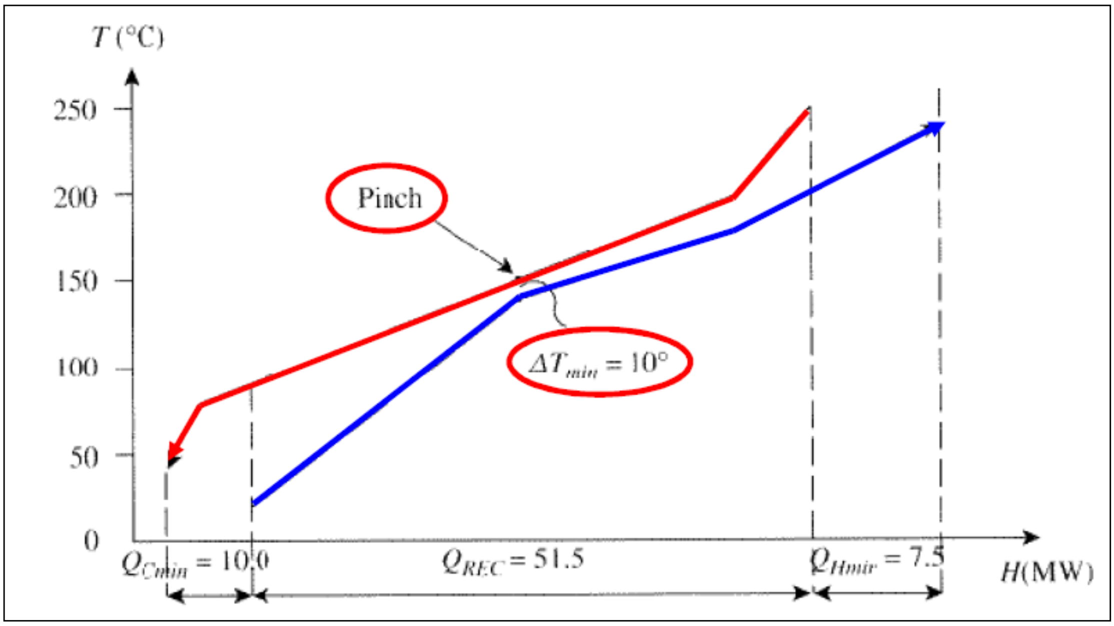

Figure 1 *The hot and cold composite curves. The pinch appears at the minimum temperature difference, usually at one point. Minimum hot and cold utility demand can be read where the curves do not overlap,* Q_{Cmin} *and* Q_{Hmin}.

The pinch decomposes the process in two separate parts. Above the pinch there is a heat deficit and below the pinch there is a heat surplus. To reach as efficient internal heat exchange as possible the following rules shall be followed;

- Do not transfer heat through the pinch.
- Do not heat below the pinch.
- Do not cool above the pinch.

The energy system is analyzed by checking whether these rules are obeyed or not and at the same time looking for improvements in the heat exchange. A retrofit of the existing system can be done to solve violations to the above rules – so called pinch violations – and improve the internal heat exchange, whereby substantial energy savings can be achieved.

3.2 Lignin separation

In the field of process integration and biorefineries, lignin separation is of interest. Lignin is part of the raw material in the wood and is separated from the fibres in the cooking process. Usually, it is then burned in the recovery boiler together with other cooking chemicals and thereby satisfying the mill's steam demand. If the steam demand is reduced, lignin separation is possible.

The separated lignin is promising for use as a fuel since it has a higher heating value than for example bark, which is a common fuel in mills. The heating value for bark lies between 7 and 10 MJ/kg [6] depending on the fuel whereas it for lignin lies around 23.7 MJ/kg. Though, the sulfur content of lignin is about 1–3% [7]. Lignin also has the possibility of being used as a raw material for high-grade chemicals. Separation of lignin affects the energy balance of the mill and the possible separation rate is restricted to the recovery boilers need of a certain amount of fuel. A decreased steam demand is a way to reduce the fuel demand in the recovery boiler. The separation of lignin also increases the steam demand of the evaporation plant, which has to be accounted for.

One efficient method to separate the lignin is the LignoBoost technology [20] in which a black liquor flow is extracted from the evaporation plant and to precipitate the lignin, the pH is lowered by injecting CO_2. This makes the lignin molecules agglomerate and thereby possible to separate and wash. Consequently, the next step is a filtration process followed by washing. The washing is done with condensate from the evaporation plant where H_2SO_4 has been added. The final product is a separated lignin cake of 70% solids content. The filtrates from the washing and filtration are recycled back to the evaporation plant. This increases the load on the evaporation plant which has to be taken into account when evaluating the amount of extracted lignin [8]. A process scheme can be seen in Figure 2.

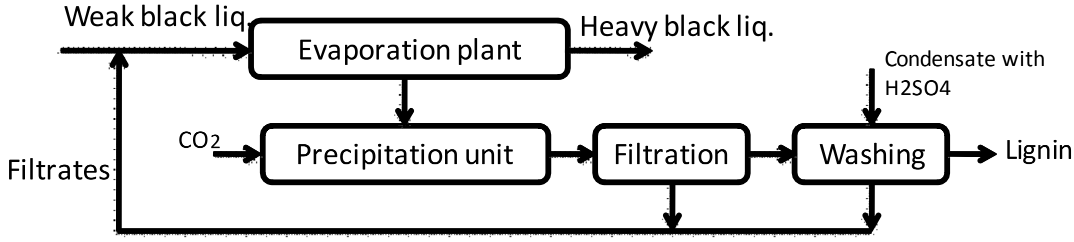

Figure 2 Lignin separation plant.

4 Processes and the studied mill

Below is a description of the kraft process and paper production in general terms presented, followed by a more detailed description of the studied mill.

4.1 The kraft process and paper production in general

The logs are debarked and chopped into small pieces, chips. This is followed by a steaming of the chips with the purpose to heat them and to force air out. The pre-steamed chips enter the digester where the delignification process takes place. Two main streams leave the digester; one stream with the delignificated chips for further processing and one with the cooking chemicals, the lignin, and so on – the so called black liquor – to the evaporation plant.

In the evaporation plant, the dry solid content of the weak black liquor is increased. The strong black liquor leaves the evaporation plant to be burned in the recovery boiler.

The recovery boiler produces the steam that is used in the plant. Usually high pressure steam of around 60–80 bar, medium pressure steam of ~ 10 bar and low pressure steam of ~4.5 bar is produced. The steam pressure is reduced in a back pressure turbine to suitable levels. The electricity produced in the turbine is used in the mill and reduces the purchased power demand.

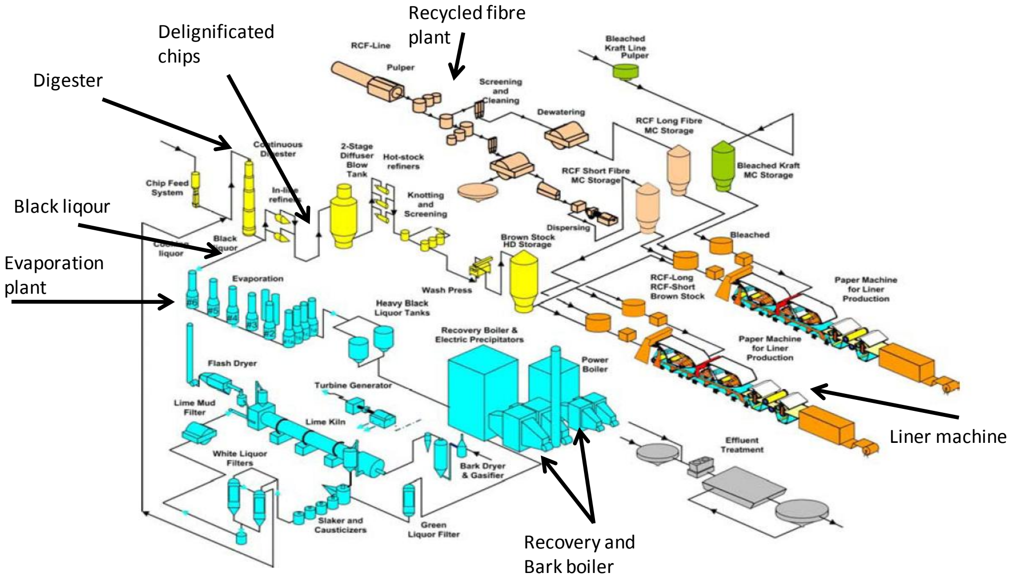

Figure 3 *A picture of the mill. To simplify the understanding, some parts are marked with arrows.*

Liner is a certain paper quality that is used, for example, in cardboard. In the paper mill, this liner is produced, which is a large energy consumer in the mill. Generally, a paper machine consists of a head box where the pulp is spread out, a press section and a drying section. The head box is pressurized, letting water disappear and in the press section, a more efficient water removal appears by letting the pulp pass between pressing rolls. The liner is then dried in the drying section, where a large amount of heat is needed [9]. A simplified picture of the liner machine can be found below. As the liner does not have to be white, recycled fibres are commonly used in the kraft process. The recycled paper is mechanically treated and then further processed to become pulp again. This is then mixed with the pulp from the pulp mill before entering the liner machine.

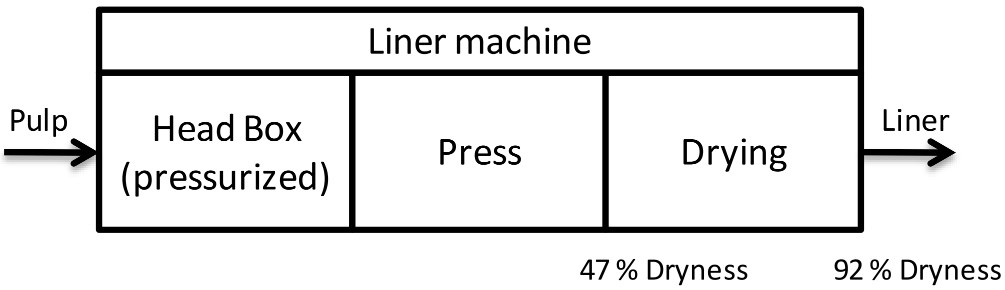

Figure 4 *A simplified picture of the liner machine. Pulp is distributed in the pressurized head box where part of the water disappears. Further water removal is performed in the press section followed by drying in the drying section.*

4.2 The studied mill

A more detailed description of the mill is represented below. Those parts of the mill that is of interest from an energy perspective are emphasized. If not referred to something else all information in this is section is from the report ‘’Kraftliner Mill’’ which is written within the research program FRAM [10].

4.2.1 Kraftliner mill FRAM 11

The Kraftliner mill is modeled within the FRAM project. The FRAM program was a Swedish national research program between 2003 and 2005. The main focus in the project was to reduce process disturbing chemicals and become less resource demanding. The model of the mill is developed by STFI (now Innventia) and modeled in WinGEMS. All data is representing steady state conditions. To represent an average Scandinavian mill of today all processes and technologies chosen are based on configurations and technologies of today. A more deltailed description follows below.

4.2.2 Fibre line

After the logs have been debarked and cut to chips these are fed to the chip bin to be presteamed. The presteaming of the chips is done with steam from the black liquor flash and LP steam. Cooking and delignification then takes place in a continuous digester with a conventional two flash system.

4.2.3 Chemical recovery

Evaporation

The evaporation plant is a 6-effect plant, though it is assumed to have an average efficiency of 5.5 effects. The effects are of the falling film type and operate with counter current flow. LP steam is fed to the first effect and weak liquor to the sixth effect. The dry solids content of the strong black liquor is 72% after the evaporation and the plant is designed with a separate stripper.

Lime Kiln

The lime kiln is fired with oil and the lime mud has a dryness of 70%.

4.2.4 Energy system

Recovery and bark boiler

The energy system consists of a recovery boiler and a bark boiler. The **recovery boiler** is designed to burn black liquor and thereby produce 105.8 MW of high pressure steam at 60 bar, 450°C. The black liquor has a dry solids content of 72% when it is distributed at a low level in the boiler house.

The **bark boiler** is designed with a bubbling fluid bed and produces 65.8 MW high pressure steam. The bark is fired at 38% dryness and to cover the steam demand supplementary bark is purchased.

4.2.5 Steam system

Steam is produced in the recovery boiler and the bark boiler. Due to increased production over the years the turbine has become too small and part of the produced high pressure steam is directly reduced. The produced HP steam is 60 bar/450°C, MP is 10 bar/200°C and LP steam 4.5 bar/150°C. An overview of the steam production system can be seen in Figure 5.

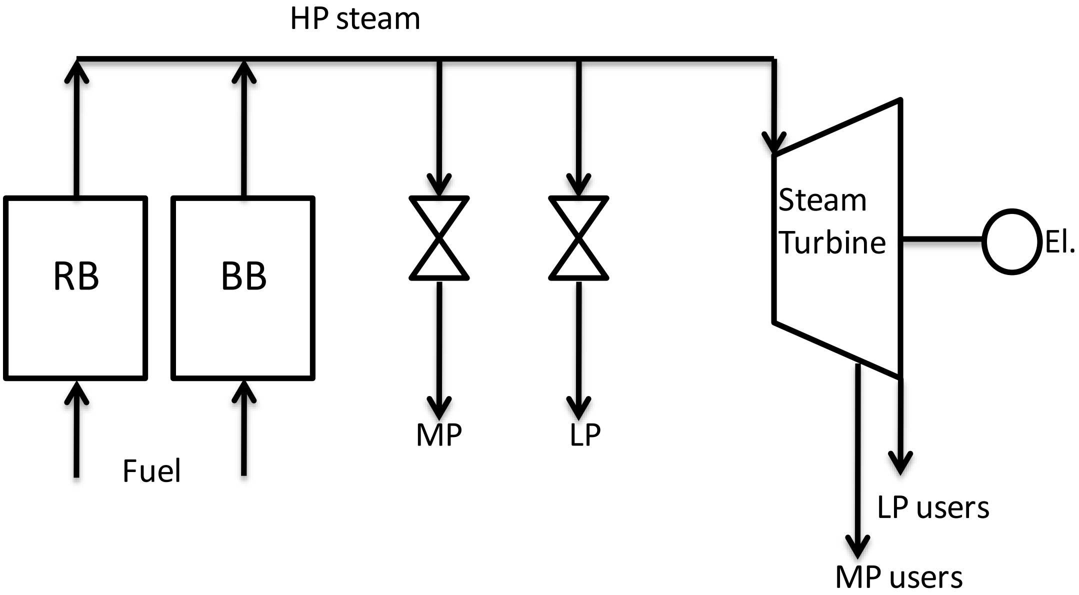

Figure 5 *The steam production system at the mill. High pressure steam is produced in the recovery boiler (RB) as well as in the bark boiler (BB). The steam turbine has become too small, therefore part of the steam is directly reduced to medium and low pressure steam.*

The steam consumption at the mill is 174.5 MW and the direct reduction is 18.1 t/h HP to MP steam and 18.1 t/h HP to LP steam. A table of the steam consumption can be found in Appendix I – Steam consumption.

4.2.6 Liner machine

The liner machine has a production capacity of 417 000 t/a and an operating speed of maximum 1070 m/min. The paper machine is equipped with only one shoe press which gives a final dryness of 47% before the dryer. After the drying section the dryness is 92%. As the liner machine is modeled as a black box, this is not included in the main investigation for energy savings. In this report, either it is assumed that the paper machine is represented by the one studied in a previous thesis work done in 1990 [11] or that no integration possibilities are possible. See also section 6.1.4.

5 Methodology

A literature study was done to increase the knowledge and reach a higher understanding within the field of the work. This was followed by the procedure below; pick the right stream data, make a pinch analysis, find steam saving opportunities, followed by calculation of possible fuels savings and separation of lignin.

5.1 Stream data

Stream data was given in an Excel file and the processes was represented on a flow sheet. The streams of interest were picked with regard to their heat content and purpose of the stream. The selected streams were compiled in an Excel file, see Appendix II – Stream Data.

5.2 Pinch analysis

Start and target temperatures and heat loads were put into Pro-PI, an Excel software for pinch analysis. The streams were given individual ΔT_{min} with regards to their heat transfer capability. The ΔT_{min} values were chosen to be the same as those used in the work ''Energy Export Opportunities from Kraft Pulp and Paper Mills and Resulting Reductions in Global CO_2 emissions'' [12]. After construction of the hot and cold composite curves, the minimum hot and cold utility demand could be read and compared with today's demand. The construction of the Grand Composite Curve gave the information about possible process integration opportunities. Due to lack of information about the paper machine this is not included in the pinch analysis, just the pulp mill.

5.3 Steam saving opportunities

To save steam and to use available heat in an efficient way, a retrofit was done of the existing network. Two different approaches in the retrofit were used 1) to solve pinch violations practically and 2) to solve the pinch violations as far as possible.

Moreover, the following opportunities were evaluated; flue gas heat recovery, energy recovery in the paper machine, and evaporation plant upgrade. The proposals were then mixed into eight investment alternatives.

5.4 Fuel savings

The power boiler is supposed to work at full load and the steam savings could result in a decreased fuel demand in the bark boiler. The quantity of saved fuel was calculated from an energy balance over the bark boiler and the steam system.

5.5 Lignin separation

Each investment alternative corresponds to a possible lignin separation rate. This requires extra investments and reduces electricity production. However, it could become more valuable than bark if lignin prices are high enough.

5.6 Economic evaluation of the investment alternatives

The steam savings were compiled into eight investment alternatives, each corresponding to a certain amount of saved steam. The investment costs for the different alternatives were calculated as well as the annual earnings from fuel savings, i.e. saved money from not burning the fuel. Furthermore, the investment costs for a lignin separation plant were calculated as well as the required price for lignin in order to make lignin separation profitable.

The annual earnings from fuel savings will depend on future costs for bark and electricity prices. This means that the earnings for each investment will vary depending on the future prices. An illustration of this can be seen in Figure 6 below. Also, the needed minimum lignin prices follow this behaviour.

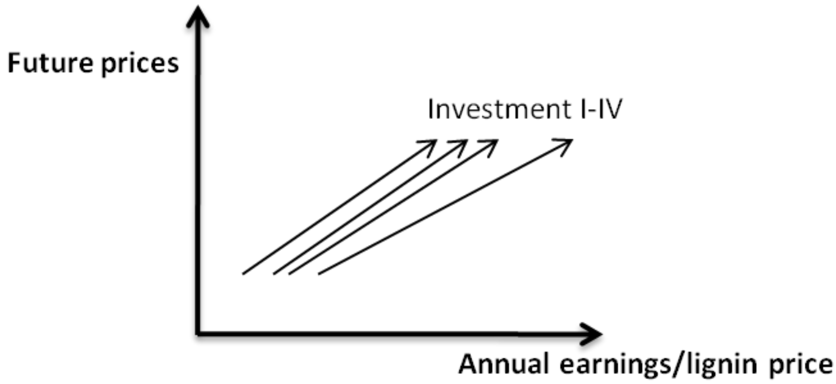

Figure 6 *An illustration of the annual earnings from saving fuel. The different investments lead to certain annual earnings, which in turn depend on future bark and electricity prices.*

6 Results Kraftliner mill

In this section the results from the pinch analysis are presented as well as the other steam saving opportunities. A summation of the investment alternatives is followed by fuel saving and lignin separation evaluation. Furthermore, the economic evaluation of the investment alternatives is presented in Section 6.5.

6.1 Steam saving opportunities

The major work in this project has been to analyze the energy system of the mill and primarily to make the pinch analysis of the heat exchanger system. The results from the energy system analysis are presented in the next sections. Below the grand composite curve is presented.

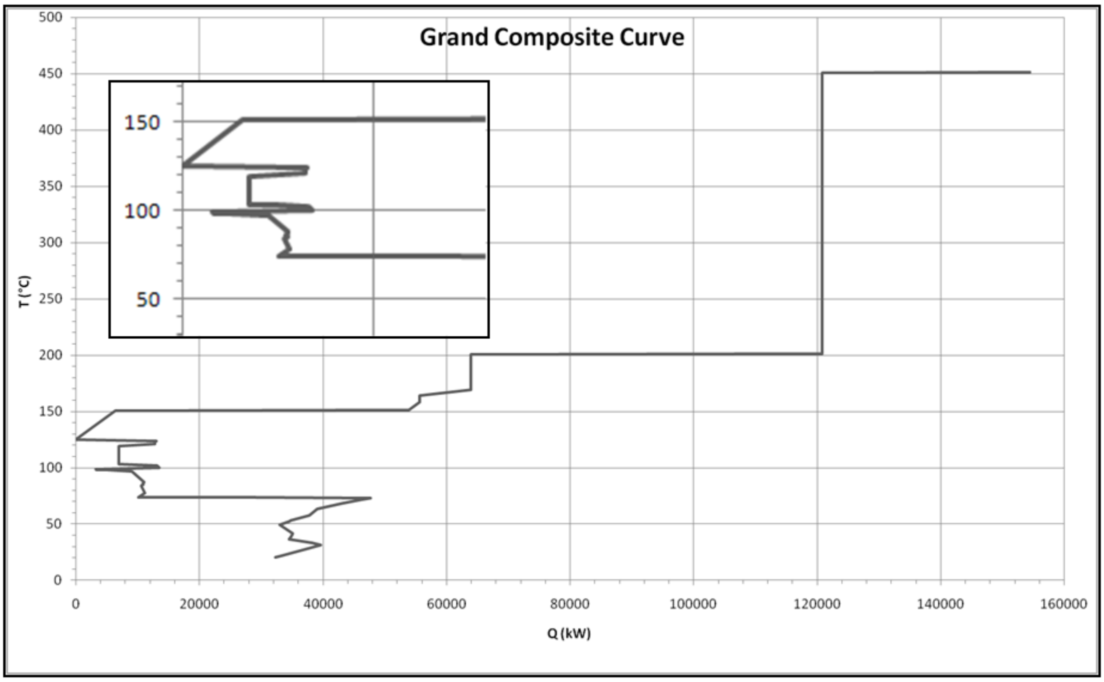

Figure 7 *The grand composite curve (with individual ∆Tmin) for the mill. The minimum hot utility demand is 154.3 MW which is 20.2 MW less than today's usage. The Pinch temperature is 125°C.*

Today's hot utility demand is 174.5 MW (see Appendix I – Steam consumption). The GCC shows a minimum hot utility demand of 154.3 MW and a cold utility demand of 32.3 MW. Theoretically is it possible to save 20.2 MW.

6.1.1 New heat exchanger networks

The sum of the pinch violations was 20.1 MW (see Table 1 below) and all was of the character ‘heating below pinch’. All of this heating is LP steam except 0.5 MW which is MP steam.

Table 1 *Pinch violations*

Pinch violations	[MW]
Hot water production	3.4
Causticising	0.5
Chip steaming	5.9
Heating etc	1.8
Wood yard	1.4
White water	6.6
Digester hi-heat zone	0.5
Total	20.1

The major sources among the pinch violations were the chip steaming that accounts for 5.9 MW, almost 30% of the pinch violations, and the white water 6.6 MW accounting for 31%. The white water is used to keep the temperature in the liner machine. Only by reducing those two one could achieve more than 60% less pinch violation.

The retrofit of the existing network ended up in two steam saving proposals, NN1 and NN2. Those are represented in Table 2 and Table 3. Even though the chip steaming is a large part of the pinch violations, it is not included in the first proposal. The reason for this is that a change in the way of presteaming the chips also includes additional investments such as a new chip bin in addition to the new heat exchanger network. The table below shows the solved pinch violation for proposal NN1.

Table 2 *Solved pinch violations in proposal 1, NN1.*

NN1				
Stream with heat demand	**Heated with**	**Replaced by**	**Load [MW]**	**Steam saving [kg/s]**
Wood yard	LP	Effl RCF plant	1.4	0.5
Whitewater	LP	Surf cond	6.6	2.83
Office heating	LP	Surf cond	1.8	0.69
Hot water production	LP	Surf cond	3.4	1.56
Causticising	LP	Surf cond	0.5	0.19
			13.7	5.78

In NN1, 68% of the pinch violations are solved. As too large amounts of hot water are produced, the production was reduced to the amount actually needed. Thereby the black liquor heat exchanger could be used in another way. Further, by changing the hot water production together with the caustisicing, pinch violations were reduced by 3.4 MW and 0.5 MW respectively. The water to the wood yard is heat exchanged with the effluent from the recycled fibre plant instead of with LP steam. The heat from the surface condenser is used to heat the white water for the liner machine, for office heating and for hot water production as well as for the water used in the causticising process. The existing network and the proposed retrofit are represented in Appendix VII – existing network and Appendix VIII – Retrofit proposal NN1.

In NN2, the changes in the chip steaming are added and the LP steam is replaced by flash steam that earlier was used for producing hot water. In this proposal 98% of the pinch violations are solved. A figure of the network can be found in Appendix IX – Retrofit proposal NN2.

Table 3 *Solved pinch violations in proposal 2, NN2.*

NN2				
Stream with heat demand	**Heated with**	**Replaced by**	**Load [MW]**	**Steam saving [kg/s]**
Presteaming of chips	LP	Flash steam	5.9	2.22
Wood yard	LP	Effl RCF plant	1.4	0.5
Whitewater	LP	Surf cond	6.6	2.83
Office heating	LP	Surf cond	1.8	0.69
Hot water production	LP	Surf cond	3.4	1.56
Causticising	LP	Surf cond	0.5	0.19
			19.6	8

A striking result is that large energy savings can be achieved in the mill, though it requires some changes in the heat exchanger system.

The differences between the two proposed retrofits of the heat exchanger systems are small. In proposal NN2 98% of the pinch violations are solved. The only further modification compared to NN1 is the chip presteaming. Before, LP steam was used which is now replaced by a flash steam of a lower temperature. Thereby a new chip bin is required and an investment in such is needed.

In both proposals above, the condensation temperature in the surface condenser is supposed to be 76°C. This is according to a six effect evaporation plant and if the plant is upgraded with one effect the temperature will probably have to be lower. For a more profound discussion about this, see section 7.1.3.

6.1.2 Evaporation plant

The calculated steam savings in the evaporation plant are approximations. By adding one extra effect the steam requirement is lowered. It is also assumed that the dry solids content in the black liquor stream will increase 3%, from 72% to 75%, which increases the steam production. This has been taken into account in the calculations.

The evaporation plant was modelled as a black box and no information was given about the streams within the plant. Therefore, to make a rough steam saving approximation, the heat demand was supposed not to change between the effects and boiling point changes was not taken into consideration.

With more information this calculation could be more exact.

Today the live steam demand is 38.8 MW. With an upgrade to a 7-effect plant this is changed to 23 MW. This results in a steam saving potential of 15.8 MW, see Appendix IV – Evaporation plant upgrade. Since an upgrade of an evaporation plant is a quite large investment, the option not to take this investment was also considered.

6.1.3 Flue gas heat recovery

The hot flue gases from the recovery boiler are an unused but potential heat source. The flue gas heat recovery is approximated for the flue gases from the recovery boiler and the steam saving potential was found to be 4.3 MW. Other flue gas heat recovery options such as heat exchanging the flue gases from the limekiln are possible, but not as large as those of the recovery boiler.

6.1.4 Paper machine

In FRAM, the paper machine was modeled as a black box and no details were given about its energy recovery. A potential increase in the energy efficiency is therefore approximated with the help of a previous thesis work done on the same type of liner machine [11].

An upper estimate of the possible energy savings in the paper machine is approximated to 9.6 MW. This is the largest amount that can be saved and is based on a scaling from the thesis work mentioned above. The purpose in that work was to reduce the steam demand for the heating of ventilation air in the paper machine and at the same time decrease the mills waste water temperature. The steam use in the paper machines energy saving system was 6 MW whereof all could be saved.

A lower estimate is that no steam savings are possible in the paper machine, assuming that several efficiency measures have already been implemented. The savings probably lie somewhere in between 0 and 9.6 MW. Of course, the investment costs for the liner machine will differ in the same way.

6.2 Investment alternatives

The steam saving opportunities were compiled into eight different investment options, see Table 4 below. The options are assorted so that you choose to invest in either of the two heat exchanger network proposals together with a heat exchanger for the flue gases and upgrading of the evaporation plant in one 'package', alternative I and II. In alternatives III and IV the upper energy saving estimation in the paper machine is added. In alternative V-VIII the evaporation plant upgrade is excluded; i.e. the same first four investment alternatives but the evaporation plant upgrade investment is omitted.

Table 4 *Investment alternatives for the mill and total amount saved steam. NN1 and NN2 are the two new proposed heat exchanger networks.*

Investment alternatives		Saved HP steam	Saved LP steam		
No.		[kg/s]	[kg/s]	[MW]	[GWh/yr]
I	NN1, Evap, FGHR	11.6	14.9	33.8	288
II	NN2, Evap, FGHR	14.4	17.2	39.7	340
III	NN1, Evap, FGHR,Paperm	14.7	19.1	43.4	370
IV	NN2, Evap, FGHR,Paperm	17.5	21.3	49.3	420
V	NN1, FGHR	5.0	7.6	14.1	120
VI	NN2, FGHR	7.8	9.9	21.8	186
VII	NN1, FGHR,Paperm	8.1	11.8	22.7	193
VIII	NN2, FGHR,Paperm	10.9	14	30.4	259

6.3 Fuel savings

The reduced steam demand makes it possible to decrease the fuel consumption and thereby decrease the steam production in the bark boiler. It is assumed that the bark boiler works at full load and has an efficiency of 0.9. In Table 5 below, the fuel savings are presented for each investment alternative. A consequence of the reduced steam flow to the turbine is a decrease in electricity production. This is also included in the table below.

Table 5 *Fuel saved according to each investment option.*

	Fuel savings		Reduced electricity prod
No.	[MW]	[GWh/yr]	[MW]
I	35.7	287	0.4
II	44.2	360	1.4
III	45.3	370	1.5
IV	53.8	442	2.6
V	15.7	134	0.0
VI	24.2	206	0.2
VII	25.2	215	0.2
VIII	33.8	288	0.7

The bark savings can reduce the fuel costs in the mill. The economical aspects of the bark savings are treated in section 6.5.3.

The electricity production is not largely affected in any of the investment options. This is because of the small turbine, which cannot swallow all the produced steam. Hence, 10 kg steam/s reaches suitable steam levels by direct reduction. Naturally, the steam savings are mainly withdrawn from the direct reduction leaving the turbine unaffected as far as possible.

6.4 Lignin separation

The steam savings in the investment alternatives in Section 6.2 above can be used for lignin separation and the result for each investment option is represented in Table 6 below.

When lignin is separated with the LignoBoost technology, a black liquor stream is extracted from the evaporation. The separation process is assumed to increase the steam demand of the evaporation plant with 0.45 x 3 MJ/(kg separated lignin) [13]. Therefore, a certain amount of steam was saved in the investment alternatives but at the same time an increased steam demand appears with the separation that has to be satisfied. The results from the calculations can be seen in the table below. A decrease in electricity production follows from the reduced steam flow to the turbine.

Table 6 *Lignin separation and reduced electricity production for the investment alternatives.*

	Lignin separation rate		Reduced electricity production	
No.	**[kg/s]**	**[t/ADt]**	**[MW]**	**[GWh/yr]**
I	1.39	0.14	0.4	3.2
II	1.73	0.17	1.1	9.7
III	1.77	0.18	1.3	10.7
IV	2.11	0.21	2.2	19.1
V	0.61	0.06	0.0	0.0
VI	0.95	0.09	0.2	1.8
VII	0.98	0.10	0.2	2.0
VIII	1.32	0.13	0.7	6.0

6.5 Economic evaluation

The investment costs for the steam saving opportunities, the different investment alternatives, and the lignin separation plant are represented in this section. Furthermore, the annual earnings from fuel savings are compiled to make the different options more comparable. Moreover, the lignin price required to make lignin separation profitable is evaluated in Section 6.5.4.

6.5.1 Costs for the investment alternatives

The equipment costs for each steam saving alternative were calculated and can be found in Table 7. The piping cost for a new heat exchanger network was approximated to fifty percent of the cost for the network. The price for a new chip bin was approximated from the equations used in the work of Marcus Olsson and Erik Axelsson [1] and has been updated with the Chemical Engineering Plant Cost Index. The PhD work of Marcus Olsson has been used to approximate the evaporation plant upgrade [14], see Appendix V. The cost of the paper machine retrofit was in the thesis work from 1990 found to be 1.5 MSEK. This cost was updated with the Chemical Plant Cost Index and piping was added.

Table 7 *Investment costs for the steam savings opportunities.*

Investment costs [M€]	NN1	NN2	FGHR	Paper machine	Evaporation plant upgrade
Heat exchangers	0.38	0.43	0.29	0.25	
Piping	0.19	0.22	0.15	0.13	
Chip bin		2.85			
7 effect upgrade					10.4
Sum inv.costs [M€]	0.57	3.5	0.44	0.38	10.4

The major investment is the evaporation plant upgrade. This was expected as an upgrade of this kind is expensive but large savings can be gained. The cost for the chip bin is also relatively large compared to the networks.

The steam saving opportunities was compiled into different investment packages (see Section 6.2) and the investment costs for those alternatives are presented in Table 8 below.

Table 8 *Investment costs for the investment options.*

No.	Package Savings	Investment cost [M€]	Saved steam [MW]
I	NN1, Evap, FGHR	11.4	33.8
II	NN2, Evap, FGHR	14.3	39.7
III	NN1, Evap, FGHR, Paperm	11.8	43.4
IV	NN2, Evap, FGHR, Paperm	14.7	49.3
V	NN1, FGHR	1.0	14.1
VI	NN2, FGHR	3.9	21.8
VII	NN1, FGHR, Paperm	1.4	22.7
VIII	NN2, FGHR, Paperm	4.3	30.4

To make the different alternatives more clear and comparable, the saved steam is included in the table.

6.5.2 Investment costs for lignin separation

Lignin separation requires an investment in a separation plant. The cost for the plant depends on the lignin separation rate. The investment costs are approximated with the cost equation below [8] and can be found in Table 9.

$$Cost\ Lign.sep\ plant\ [M€] = 7.74 \times LR^{0.6}$$ LR is the separation rate [kg/s]

Lignin separation also requires rebuilding of the evaporation plant. In alternative V-VIII, no steam savings are made but smaller changes to allow lignin separation, see Appendix V. In alternative I-IV an evaporation plant upgrade is already included in the steam savings investment. No additional investment is assumed to be necessary to enable lignin separation.

Table 9 *Investment costs for the separation plant and the extra costs needed to allow lignin separation in alternative V-VIII.*

No.	Lignin separation [t/ADt]	Investment cost Separation plant [M€]	Investment cost evaporation plant[M€]	Operational cost [M€/yr]
I	0.14	9.4	-	1.6
II	0.17	10.8	-	2.0
III	0.18	10.9	-	2.1
IV	0.21	12.1	-	2.5
V	0.1	5.7	4.4	0.7
VI	0.1	7.5	4.4	1.1
VII	0.1	7.7	4.4	1.2
VIII	0.1	9.1	4.4	1.6

6.5.3 Annual earnings from saving fuel

The annual earnings from saving fuel are represented below. The results are divided into two cases; one based on low bark and electricity prices and the other based on high bark and electricity prices [15]. Case I is calculated for a bark price of 20 €/MWh and 66 €/MWh electricity price. Case II is based on a bark price of 34 €/MWh and an electricity price of 94 €/MWh. Both cases include a cost for electricity certificates of 20 €/MWh and an annuity factor of 0.1.

Table 10 *Annual earnings from fuel savings. Case I calculated with a bark price of 20€/MWh and electricity price of 66 €/MWh and Case II calculated with a bark price of 34 €/MWh and electricity price 94 €/MWh.*

No.	Fuel savings [GWh/yr]	Annual earnings Case I [M€/yr]	Case I [€/MWh]	Case II [M€/yr]	Case II [€/MWh]	Investment cost [M€]
I	287	2.9	10	6.8	24	11.4
II	360	3.5	10	8.2	23	14.3
III	370	3.9	11	8.7	24	11.8
IV	442	4.5	10	10	23	14.7
V	134	2.6	19	4.4	33	1.0
VI	206	3.6	18	6.4	31	3.9
VII	215	4.0	19	7.0	32	1.4
VIII	288	4.9	17	8.8	31	4.3

It is clearly profitable to save fuel. Comparing the two cases in €/MWh the largest gains can be found for the lowest investment costs, i.e. alternatives V-VIII in which the evaporation plant is omitted. The most obvious reason for that is the annualized investment cost. Consequently the investment for the evaporation plant upgrade has a large influence on the annual earnings.

6.5.4 Lignin price

The aim was to locate the breakeven point where the lignin separation becomes equally profitable as saving fuel. This was done by setting the annual fuel earnings equal to the earnings for lignin. Like in Section 6.5.3 above, both low and high bark and electricity prices were used for the calculations giving two cases. Further, an investment in a lignin separation plant is seen as a strategic investment with an annuity factor of 0.1. The resulting lignin prices follow in the table below.

Table 11 *Resulting required lignin prices for the investments based on low and high bark and electricity prices.*

No.	Lignin separation [t/ADt]	Lignin price Case I [€/t.Lignin]	Lignin price Case I [€/MWh]	Lignin price Case II [€/t.Lignin]	Lignin price Case II [€/MWh]
II	0.14	200	30	297	45
II	0.17	196	30	292	44
III	0.18	197	30	293	45
IV	0.21	196	30	292	44
V	0.06	234	36	333	51
VI	0.09	213	32	313	48
VII	0.10	221	34	324	49
VIII	0.13	209	32	311	47

For case I the required lignin price vary between 30–36 €/MWh and in case II between 44-51 €/MWh. The results are discussed in Section 7.2.2.

7 Discussion

7.1 Steam savings

The theoretical steam savings from the pinch analysis were found to be ~ 20 MW. This is in the same range as the saving potential Axelsson has found [1] and correspond to ~ 12% of today's steam demand in the mills.

7.1.1 The GCC

The construction of the GCC is done with regard to how the system is constructed today but also with a thought of how one would like to make changes. For example, today a too large amount of hot water is produced and therefore reduced in the curve, making the GCC a little bit different.

The GCC below shows today's minimum hot utility demand without any changes except for the hot and warm water consumption. The minimum hot utility demand is 160 MW and the cold utility demand 38 MW.

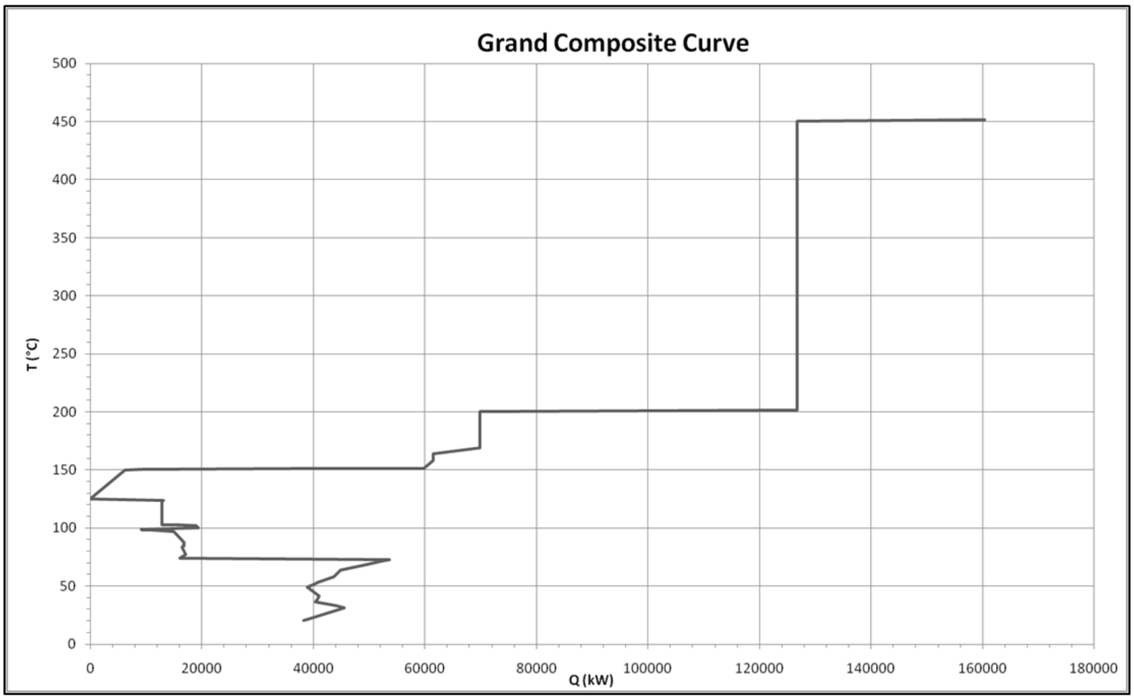

Figure 8 *The grand composite curve without changes except for the hot and warm water consumption. Minimum hot utility demand 160 MW and cold utility demand is 38 MW.*

However, the focus is to make changes to achieve better energy efficiency. A large pinch violation is the chip steaming that uses LP steam for pre-steaming the chips. As the chips can be seen as a cold stream that needs to be heated to a certain temperature (120°C) it is not necessary to heat it with LP steam as it is in the GCC above. Therefore, the pre steaming is not a steam demand at 150°C and can instead be represented as a cold stream at ~ 120°C. This lowers the hot and cold utility demand with 6 MW respectively in the GCC, see GCC below. Constructing the curve this way requires a change in the pre steaming (which would be desirable) which in turn requires an investment in a new chip bin. LP steam entered the old chip bin and a change means a change in chip bin construction if steam of a lower temperature is used, flash steam for example. The new GCC below shows the same pinch temperature (125°C) but a reduced hot and cold utility demand. The new demands are 154 MW and 32 MW respectively.

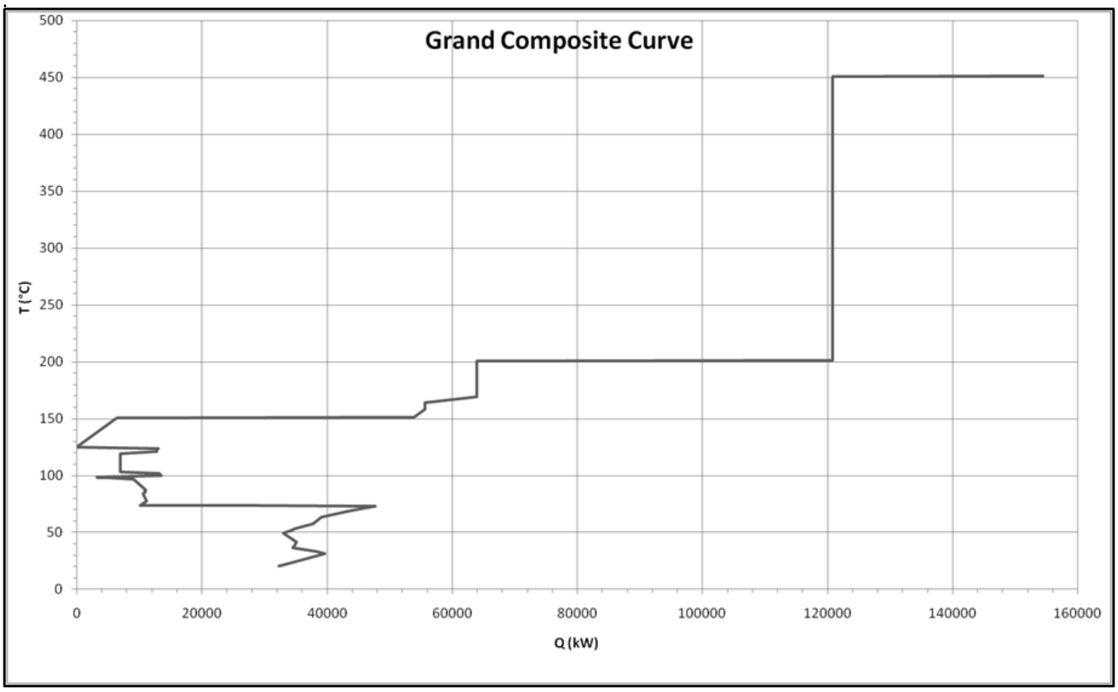

Figure 9 *The grand composite curve with a hot utility demand of 154 MW and a cold utility demand 32 MW. In GCC it is planned to make a change in the chip steaming, therefore the hot utility demand is 6MW less than in* Figure 8.

7.1.2 Turbine

Another investment option not considered would be a condensing turbine which could produce electricity from the saved steam. This is neglected as quick calculations, not presented here, show small gains. One could also invest in a larger back pressure turbine and reach higher electricity production which in turn would reduce the purchased electricity.

7.1.3 The evaporation plant upgrade and retrofits

I the evaporation plant, 15.8 MW could be saved by adding one effect. In the pinch analysis, the surface condenser is represented as a hot stream with a condensation temperature of 76ºC. As the evaporation plant was modelled as a black box, the possible savings were calculated after the retrofit. Therefore, the retrofits have been done on a six effect basis.

By adding an extra effect, the condensation temperature in the surface condenser would be lower. The minimum temperature difference between the effects and the boiling point increase has to be handled whereby the total ΔT over the plant increases.

This results in a lower temperature in the surface condenser, which might affect the retrofit and it is possible that those would change. With a temperature of 60ºC in the surface condenser, the same theoretical savings can be achieved. Though, with a lower temperature (50ºC), the theoretical savings also decreases.

7.2 The economic investigation

In this section, the annual earnings from fuel savings are commented and the required lignin price is compared with the annual earnings from saving fuel.

7.2.1 Lignin price and annual earnings from bark savings

To analyze this part, two levels of electricity and bark prices were used. The prices are picked from ‘’Scenarios for assessing profitability and carbon balances of energy investments in industry’’ [15]. The prices are based on a future energy scenario for the year 2020 and the results can therefore not be seen as valid today.

The annual earnings from bark savings vary between 134–440 GWh/yr whereas the earnings do not differ that much; 2.6–4.9 M€/yr for the lower electricity and bark prices and 4.4–10 M€ for the higher, see Section 6.3 and 6.5.3. These annual earnings can be compared with those found by Olsson et al.[8] where investments in new turbines are proposed and thereby the electricity production is increased. The annual earnings in their paper lie in the range of 2–4 M€ for an electricity price of 40 to 60 €/MWh. The results in this thesis, where an electricity price of 46 and 74 €/MWh is used (the electricity certificates withdrawn), are in the same magnitude or even higher. Another positive aspect by saving fuel is that no further investments than those for the steam savings are required.

For the lignin separation to be profitable, the lignin price has to be equal or higher than the required value of lignin. In alternative I-IV, the required lignin price is between 1.3 and 1.5 times the bark price, which is comparable with the price of lignin as a biofuel accordning to Erik Axelsson and Berntsson [12] where the lignin price is ~30% higher than the bark price. For the alternatives V-VIII and low bark prices, the required lignin price vary between 1.6 and 1.8 times the bark price making it less suitable as biofuel. However, for high bark prices, the lignin price vary between 1.4 and 1.5 times the bark price and might thereby be interesting for use as a biofuel. The required value is also interesting to compare with the oil price since one possible way to use the lignin is to replace oil as fuel. The heavy oil price in the future scenario report mentioned above is 27 €/MWh, representing the same level as the low electricity and bark prices whereas the higher heavy oil price is 51 €/MWh.

With low bark, electricity and oil prices, the required lignin value for alternatives I-IV, VI and VIII (30–32 €/MWh) is comparable with the oil price. Though, the 3–5 €/MWh price difference suggests to save bark and not to extract lignin to replace the oil in the mill. Still, to replace oil by lignin might be profitable in this case depending on for example taxes not considered here. For alternative V and VII, the required lignin price is far too high to suggest lignin separation as an interesting option if lignin is priced relative to the oil price.

For the higher price level, the required lignin value for investment I-IV is lower than the oil price, which promotes lignin as a replacement for oil as fuel. To burn lignin instead of oil lowers the spending with 51 €/MWh minus the lignin production cost. The required lignin price in alternative V-VIII (47–51 €/MWh) is a less clear case as the price approaches the oil price.

The lignin separation requires a larger investment than the bark savings but on the other hand it is more adaptable to future demands then the bark savings. If one believes in lignin as a raw material for chemicals or materials in the future, it is of interest to invest in a separation plant.

8 Conclusions

Large energy savings, between 14 and 49 MW, can be achieved in the mill. This corresponds to 8–28% of today's steam demand. The savings will of course be individual for each mill and will probably lie somewhere in between.

The investment costs for the different investment alternatives vary between 1–15 M€ depending on chosen investment. The largest investment is the evaporation plant upgrade, 10.4 M€.

The results show that it is clearly profitable to save fuel. From the investment alternatives it is possible to make an annual profit of 2.5–10 M€/yr depending on the bark and electricity prices.

By an investment in a lignin separation plant, it is possible to extract lignin for use either as a fuel or as a high-grade chemical depending on the future situation. The mill will be adaptable to future demands. The results show that a lignin price span of 30–51 €/MWh will be required to make lignin profitable depending on chosen investment and the bark and electricity prices. This is, for low bark and electricity prices and alternatives I-IV, comparable with the price assumed in other studies where the price for lignin as biofuel is ~ 30% higher than the bark price or equal to the oil price. This is also true for alternatives V-VIII for high bark and oil prices.

With a bark price of 20 €/MWh and an oil price of 27 €/MWh, the required lignin price in the investment alternatives is 30–36 €/MWh. With this price needed for the lignin it is not beneficial to extract lignin for use as fuel. This mill would rather choose not to separate the lignin but to save bark. Though, if other taxes for fossil fuels than those considered here were in place lignin extraction could be interesting for the required lignin price of 30 €/MWh. Another possibility is to sell lignin as a high-grade chemical. It all depends on the future situation.

On the other hand, with an oil price of 51 €/MWh, the required lignin price vary in the investment alternatives between 44–51 €/MWh depending on investment alternative and lignin could thereby be interesting as a replacement for oil.

9 Future Work

A more exact analysis of the lignin price would be preferable. In this thesis the bark and electricity prices are supposed to follow each other. If one goes up, the other also does. It would be an interesting object to separate the bark and electricity prices and make a deeper sensitivity analysis of the lignin price; to which of those, or other parameters included, is the lignin price most sensitive.

Also, extreme bark and electricity prices are used in this thesis, and to analyze what happens in between them would be of interest, e.g. how is the lignin price affected between these values?

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Appendix I – Steam consumption

HP steam	MW
Back pressure turbine	21.9
Blow down recovery boiler	0.2
Blow down bark boiler	0.1
Soot blowing recovery boiler	10.4
Soot blowing bark boiler	1.0
Total HP steam	33.6
MP steam	**MW**
Digesting	17.2
Linerboard	51.4
RCF	1.9
Miscellaneous, losses	3.6
Total MP steam	74.1
LP steam	**MW**
Woodyard	1.4
Stripper	5.4
Causticising	0.5
Linerboard	6.6
Hot water prod	3.4
Heating etc	1.8
Digesting-chip steaming	5.9
Evaporation	38.8
Miscellaneous, losses	3.1
Total LP steam	**66.8**
Sum steam consumption	**174.5**

Appendix II – Stream Data

Stream nr.	Hot streams	Tstart [° C]	Ttarget [° C]	Load [MW]
2	General cooling	40	35	7.1
3	Cooling in recycled fibre plant	52.9	45	6.4
4	Smelt dissolver condensor	100	99.9	1.8
5	Digester bottom	87.3	81	2.4
6	Black liquor	105.5	90	4.2
7	Flash steam 191	105	104	6.2
8	Flash steam 302 - hx with chip steaming	127	126	10.6
9	Excess steam	127	126	2.8
10	Stripper condenser	100	99	3.7
11	Stripper sec. cond.	90	89	0.4
12	Effluent recycled fibre plant	45	37	3.6
13	Effluent pulpwashing	71.8	37	1.3
14	Effluent liq steam condensate (evap.plant)	75	37	0.9
15	Surface condensor	76	75	38.3
	Cold streams	**Tstart [° C]**	**Ttarget [° C]**	**Load [MW]**
18	WW production 50	18	50	16.9
19	HW production 85	50	85	7.9
22	Digester top (MP 8bar)	160.7	165.6	8.3
23	Digester down (MP 8bar)	119.5	155	8.8
	LP to evaporation	150	151	38.8
	LP to stripper	150	151	5.4
26	Chip steaming (flash 302)	99	100	10.6
27	Chip steaming (LP-str 305)	119	121	5.9
	MP to recycled fibre plant	200	201	1.9
	MP to linerboard	200	201	51.4
	HP blow down recovery boiler	450	451	0.2
	HP blow down bark boiler	450	451	0.1
	HP soot blowing recovery boiler	450	451	10.4
	HP soot blowing bark boiler	450	451	1
34	Make up water to boiler	18	100	5.6
35	Wood yard (LP)	18	35	1.4
36	Office heating	45	50	1.8
37	White water/pick up water (LP)	60	70	6.6
	Turbine	450	451	21.9
	Miscellaneous,losses MP	200	201	3.6
	Miscellaneous,losses LP	150	151	3.1

Appendix III – Paper machine savings

The steam savings in the paper machine are scaled from a thesis work written 1990 by Per Swärd for Smurfit Kappa in Piteå [4].

In 1989 the liner production in the investigated liner machine was 257 871 t/yr and the steam saving potential was found to be 6 MW.

For the FRAM 11 type mill, the liner production is 417 000 t/yr.

The possible savings in the paper machine were therefore scaled with a factor of 1.62 (= 257 871/417 000).

This represents a maximum steam saving potential of 9.6 MW.

Appendix IV – Evaporation plant upgrade

The existing plant is a 6-effect evaporation plant but today the efficiency is equivalent to 5.5 effects. A natural choice would be to add one more effect and thereby reduce the live steam demand.

The dry solids content is supposed to increase from 72% to 75% which increases the heating value and thereby also the steam production. The dry solids content before the evaporation is 12.6%.

The evaporation plant is modeled as a black box and no information is given about the streams within the plant. To make a steam saving approximation the change in total steam demand is estimated according to the following calculations:

$$\dot{m}_{BL\,in} = 89\ \frac{kg}{s}$$

$$\dot{m}_{BL\,out} = 14.9\ \frac{kg}{s}$$

$\Delta h_{vap,w} = 2200\ \frac{kJ}{kg}$ for water in the temperature span 90 – 130ºC.

$$Q_{tot} = [\dot{m}_{BLin}\,(1 - 0{,}126) - \dot{m}_{BLout}(1 - 0{,}72)] * \Delta h_{vap,w}$$

The expression within brackets is the water separated from the black liquor stream

This gives $Q_{tot} = 161\ MW$

$$Q_{sep} = \frac{Q_{tot}}{N_{effects}} = \frac{161}{7} = 23\ MW$$

This result is to be compared with today's 38.8 MW. The potential savings are

$$38.8 - 23\ MW = 15.8\ MW$$

Appendix V – Investment costs for the evaporation plant

Evaporation plant upgrade, investment alternative I-IV

The calculations are approximated from Marcus Olssons PhD work, ’’Simulations of Evaporation Plants in Kraft Pulp Mills’’ [14] and based on keeping 4 old effects and investing in 3 new effects. The net increase is therefore from 6 to 7 effects.

The capacity in the pulp mill is 359 ton water per hour [18] and for the mill in this thesis 293 ton water per hour [10]. The area of the 7-effect evaporation plant is 26 300 m^2 [19] and to fit this mill, the area was scaled: 26300 m^2*(293/359) = 21465 m^2 ~ 21500 m^2. The area per effect was approximated to 21500/7.

To calculate the investment cost, the equation $I_{evap} = C_1(1.3\ n_1 + n_{2\text{-}6}) + C_2\ (1.3A_1 + A_{2\text{-}6})$ was used where C_1 = 1.82 M€ and C_2= 17.3*10^-3 M€/m^2 whereas n_1 is the first effect (n_1=1) and $n_{2\text{-}6}$ is the new effects 2 and 3 ($n_{2\text{-}6}$=2) [14]. The approximated investment cost is 10.4 M€, which is included in alternative I-IV.

Least cost to allow lignin separation, investment alternative V-VIII

In investment alternatives V – VIII, steam savings in the evaporation plant are omitted, though, to allow lignin separation an area extension is needed in the evaporation plant. Below, the basis of calculations is presented:

According to Olsson and Berntsson, an area extension of 39% is needed to allow lignin separation and the separation rate in his work is 0.292 t/ADt [18]. For investment alternative V-VIII in this mill, the separation rate is around 0.1 t/ADt.

To allow lignin separation, the area extension was scaled to fit this mill:

$A_{extension}$ = 0.1/0.292*0.39 = 0.134 giving an area increase in %. The total area of the mill was scaled: A_{tot} = 20200 m^2 * (293/359) = 16 486 m^2. Consequently, the final area extension for the evaporation plant is approximately A_{tot}*$A_{extension}$=16490*0.134=2210 m^2.

To calculate the cost for the area extension, the equation

$I_{evap} = C_1(1.3\ n_1 + n_{2\text{-}6}) + C_2\ (1.3A_1 + A_{2\text{-}6})$ has been used [14]. The cost for the area extension was thereby approximated to 4,4 M€.

Appendix VI – Steam savings from FGHR

The hot flue gases are supposed to be cooled from 175ºC to 100ºC without any acid precipitation [13]. A heat exchanger is placed in the chimney and a closed circulating water system transfer the heat from the flue gases to preheat the air to the recovery boiler.

$$(\dot{m}\ C_p)_{FG} = 57.6\ \frac{kJ}{s°C}$$

$$Q_{FG} = 57.6(\ 175 - 100) = \ 4320\ kW$$

$$Q_{air} = \ Q_{H_2O}$$

By heat exchanging this way is 4.3 MW saved.

The air to the boiler requires a ΔT_{min} of 18 K and the temperature of the air to the heat exchanger is 35ºC. Thereby, the water temperature leaving the heat exchanger needs to be 53ºC. This gives $\dot{m}\ C_p\ = 41.6\ \frac{kJ}{s\ °C}$ for the water.

An illustration of the system can be seen in the figure below.

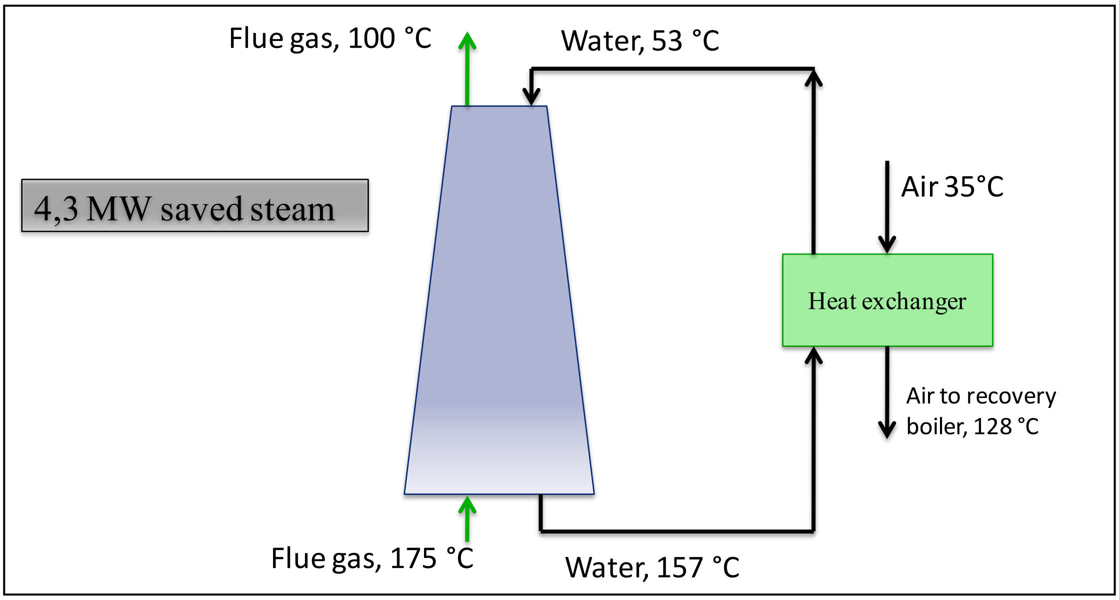
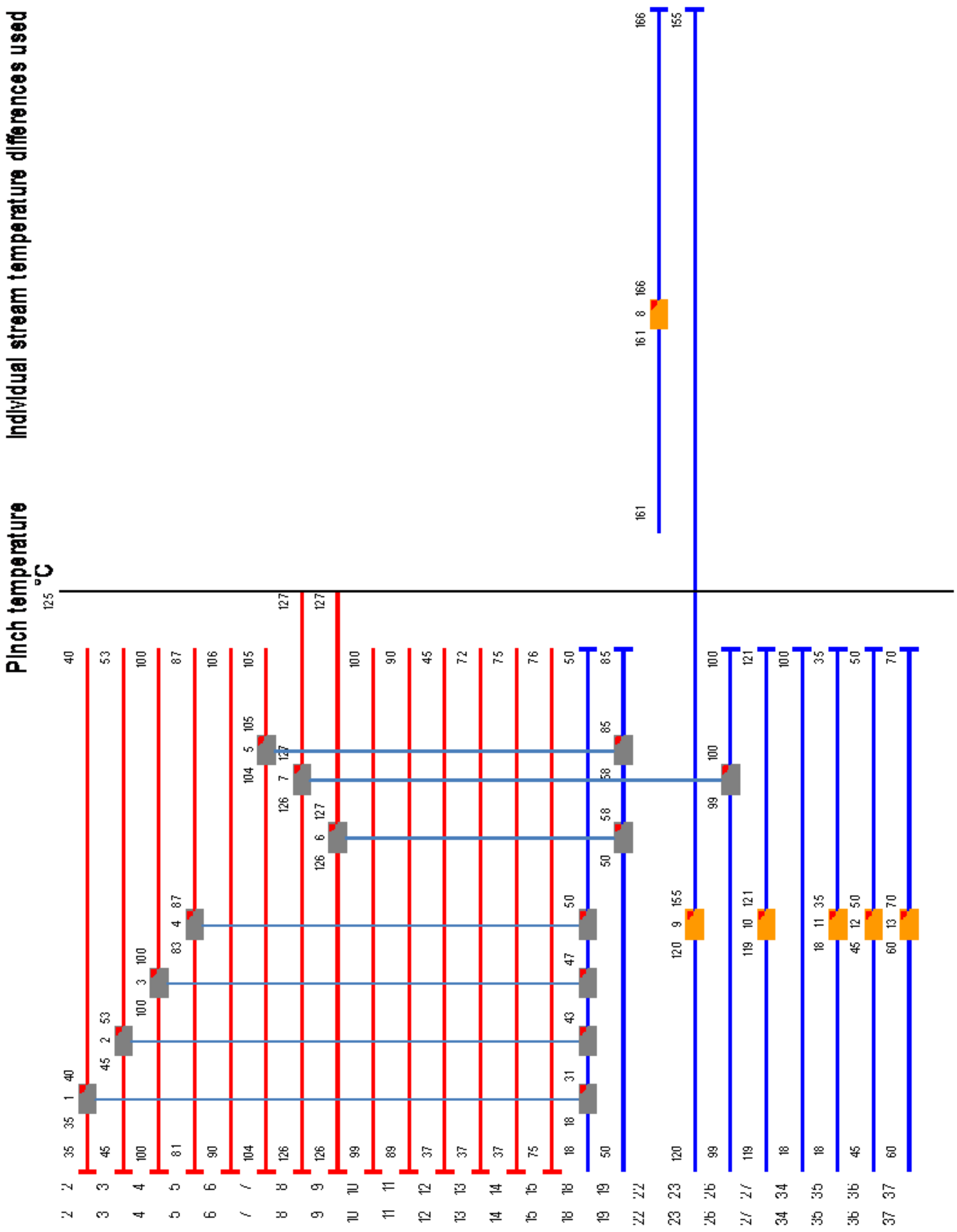
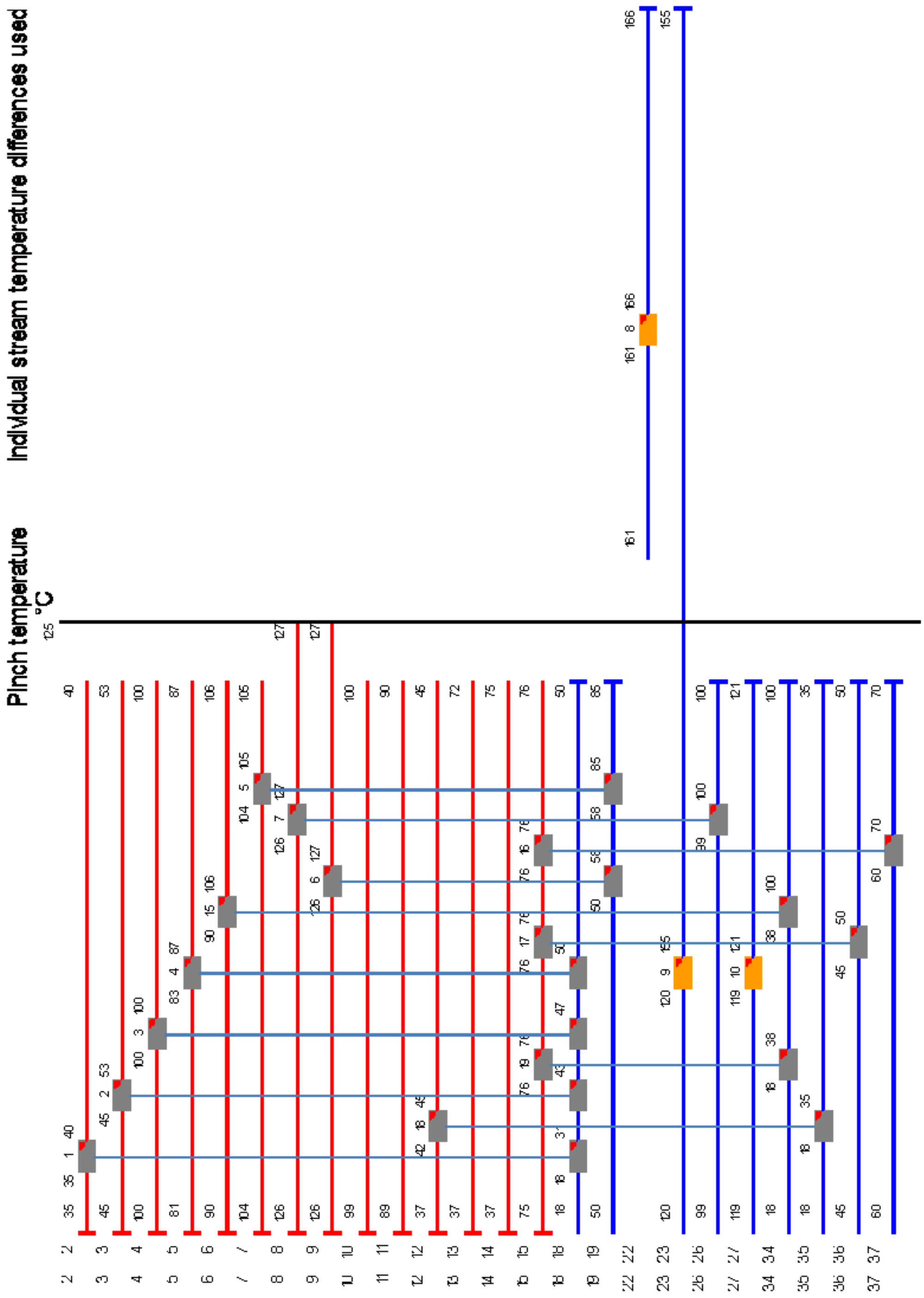


Figure VI 1 *An illustration of the FGHR. Possible savings are 4.3 MW.*

Appendix VII – Existing network



Appendix VIII – Retrofit proposal NN1



Appendix IX – Retrofit proposal NN2