THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Analysing different technology pathways for the pulp and paper industry in a European energy systems perspective

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This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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ABSTRACT

For the pulp and paper industry (PPI), earlier research has shown that there are many technology pathways, proven and new, available for improvement of energy efficiency and additional sales of (new) products. Some pathways can only be implemented in kraft mills, e.g. black liquor gasification (BLG), but some can be implemented industry-wide, e.g. carbon capture and storage (CCS). From a future perspective it is not clear which pathway is the most profitable one or which pathway gives the lowest emissions of CO_2 due to uncertainties in both the future value of different products and the future development of energy infrastructure. This can lead to decision anxiety, both for the PPI regarding the choice of pathways and for decision-makers creating new policy schemes.

The overall aim of this thesis is to analyse six technology pathways for the European PPI: increased electricity production, export of bark, extraction of lignin, CCS, BLG and export of heat for district heating purposes. To elucidate the potential for, and effects of, implementation of these pathways, three themes of research questions are addressed:

1. General integration opportunities in different types of existing mills.
2. Economic performance and global CO_2 emissions assuming different future developments of the European energy market.
3. Factors influencing the potential for industry-wide implementation.

The results show that for kraft pulp mills, proven pathways, such as increased electricity production and district heat production, are economically robust, i.e. they are profitable for varying energy market conditions. The new and emerging technology pathways studied, CCS, BLG and lignin extraction, hold a larger potential for reduction of global CO_2 emissions, but their economic performance is more dependent on the development of the energy market. Further, the thesis shows how earlier, detailed research can be lifted to a higher system level in order to be put in context and to answer research questions on a more aggregated industry level. The thesis also shows that improving the availability (and accuracy) of public data and statistics is a key factor if good industry level analyses are to be performed.

Keywords: pulp and paper industry, kraft pulp mill, biorefinery, technology pathways, global CO_2 emission, energy market scenarios

To my parents

Once you've gone tech, you ain't ever going back

~ Robyn, Fembot

Ring the bells that still can ring
Forget your perfect offering
There is a crack in everything
That 's how the light gets in.

~ Leonard Cohen, Anthem

List of appended papers

This thesis is based on the papers listed below, referred to by Roman numerals in the text:

I. Svensson, I.-L., Jönsson, J., Berntsson, T., Moshfegh, B., 2008. Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden – Part 1: Methodology. Energy Policy 36(11): 4178-4185.

II. Jönsson, J., Svensson, I.-L., Berntsson, T., Moshfegh, B., 2008. Excess heat from kraft pulp mills: Trade-offs between internal and external use in the case of Sweden – Part 2: Results for future energy market scenarios. Energy Policy 36(11): 4186-4197.

III. Jönsson, J., Algehed, J., 2008. Economic trade-offs between internal and external use of excess heat from kraft pulp mills in Sweden. Proceedings of the 21st International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, Krakow, Poland, 24-27 June 2008, pp. 965-972.

IV. Jönsson, J., Algehed, J., 2009. A systematic approach for assessing potentials for energy efficiency at chemical pulp mills. Proceedings of the 22nd International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, 2009, Foz do Iguaçu, Paraná, Brazil, August 31 - September 3, pp. 1559-1568.

V. Jönsson, J., Algehed, J., 2010. Pathways to a sustainable European kraft pulp industry: Trade-offs between economy and CO_2 emissions for different technologies and system solutions. Applied Thermal Engineering 30(16): 2315-2325.

VI. Jönsson, J., Ruohonen, P., Michel, G., Berntsson, T., 2011. The potential for steam savings and implementation of different biorefinery concepts in Scandinavian integrated TMP and paper mills. Applied Thermal Engineering 31(13): 2107-2114.

VII. Jönsson, J., Pettersson, K., Berntsson, T., Harvey, S. Comparison of options for utilization of a potential steam surplus at kraft pulp mills –Economic performance and CO_2 emissions. Submitted to International Journal of Energy Research.

VIII. Jönsson, J., Berntsson, T. Analysing the Potential for implementation of CCS within the European Pulp and Paper Industry. Submitted to Energy

IX. Jönsson, J., Pettersson, K., Berntsson, T., Harvey, S. Comparison of options for debottlenecking the recovery boiler at kraft pulp mills – Economic performance and CO_2 emissions. Manuscript for the 25th International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, 2012.

Co-authorship statement

Jönsson is the main author of Papers III-V and VIII. Papers I and II are a joint effort by Jönsson and Svensson (Linköping University of Technology, Sweden). Jönsson was responsible for the input data and calculations related to the pulp mill whereas Svensson was responsible for the input data and calculations for the district heating system. The system modelling and optimization in the energy system modelling tool reMIND was a joint effort by Jönsson and Svensson. Paper VI is a joint effort by Jönsson and Ruohonen (Aalto University, Finland) based partly on the master thesis work performed by Michel (Chalmers University of Technology, Sweden), supervised by Jönsson and Ruohonen. Ruohonen was responsible for the supervision of the modelling whereas Jönsson was responsible for the supervision of the data gathering and analysis of the results. Papers VII and IX are a joint effort by Jönsson and Pettersson (Chalmers University of Technology) where Pettersson was responsible for the calculations regarding black liquor gasification with downstream production of electricity and motor fuels whereas Jönsson conducted the system modelling and optimization using the reMIND tool.

Professor Thore Berntsson supervised the work for Papers I-II (together with Professor Bahram Moshfegh) and Papers VI-IX (Papers VII and IX were co-supervised by Professor Simon Harvey). Jessica Algehed, PhD, supervised the work for Papers III-V.

Papers based on the same work but not included

Jönsson, J., Algehed, J., 2009. Pathways to a sustainable European pulp and paper industry: Trade-offs between different technologies and system solutions for kraft pulp mills, Chemical Engineering Transactions 18, pp. 917-922. *(Early version of paper V)*

Jönsson, J., Ruohonen, P., Michel, G., Berntsson, T., 2010. Increased thermal efficiency in Scandinavian integrated TMP and paper mills – Analysing the potential for steam savings using the Heat Load Model for Pulp and Paper. Chemical Engineering Transactions 21, pp. 535-540. *(Early version of paper VI)*

Jönsson, J., Berntsson, T., 2010. Analysing the potential for CSS within the European pulp and paper industry. Proceedings of the 23rd International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, 2010, Lausanne, Switzerland, June 14-17, pp. 676-683. *(Early version of paper VIII)*

Other work by the author not included

Jönsson, J., Ottosson, M., Svensson, I.-L., 2007. Överskottsvärme från kemiska massabruk – En socioteknisk analys av interna och externa användningspotentialer. Arbetsnotat Nr 38, Program Energisystem, Linköping, Sweden. *(In Swedish)*

Svensson, I.-L., Ottosson, M., Jönsson, J., Moshfegh, B., Anshelm, J., Berntsson, T., 2009. Socio-technical aspects of potential future use of excess heat from kraft pulp mills. Proceedings of the 22nd International Conference of Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, 2009, Foz do Iguaçu, Paraná, Brazil, August 31 - September 3, pp. 995-1004.

Algehed, J., Wirsenius, S., Jönsson, J., 2009. Modelling energy efficiency and carbon dioxide emissions in energy-intensive industry under stringent CO_2 policies: Comparison of top-down and bottom-up approaches and evaluation of usefulness to policy makers. Proceedings of the ECEEE 2009 summer study, La Colle sur Loup, France, June 1-6, pp. 1181-1191.

Berntsson, T., Jönsson, J., 2010. Towards a sustainable European energy system – The role of the pulp and paper industry. Chemical Engineering Transactions 21, pp. 529-534.

Table of Contents

1 Introduction

This chapter gives a short background to the thesis work and presents the aim of the thesis together with the research questions addressed. Lastly, the chapter provides an overview of the appended papers.

1.1 Background

Today, the challenge of curbing global climate change is high on the agenda in many countries. In Europe, the EU has defined the goal of achieving 20% reduction of greenhouse gas emissions[1], 20% share of renewable in the energy mix, and 20% improvement of energy efficiency on a European level by the year 2020 (EC 2010). Further, Sweden has set a national target to reach a reduction of emissions of greenhouse gas emissions[2] of 40% by the year 2020.

In Europe, the industrial sector is responsible for about 30% of the total energy use and about 20% of the emissions of fossil CO_2[3] (Eurostat 2009). The pulp and paper industry (PPI) is the sixth largest industrial energy user in Europe and the single largest industrial user of biomass, using approximately 102 TWh of electricity and 330 TWh of thermal energy annually, out of which 55% originates from biomass, during 2009 (CEPI 2011). In Europe, roughly, the energy used in the PPI corresponds to 4% of the total energy use and 14% of the industrial energy use (Eurostat 2009). In Sweden and Finland, two of the main pulp and paper producers in Europe, the PPI stands for ~50% of the industrial energy use (SEA 2010; SF 2011). As for other energy-intensive industry sectors as well as the power and heat sector, the energy use, and thus on-site emissions of CO_2, in the PPI are associated with only a few geographical sites, i.e. mills. Due to this fact, making changes in the energy system at only a limited amount of mills can have significant impact on the European energy system as a whole and consequently also on the emissions of CO_2. It should be noted that within the energy-intensive industry, the energy use is mainly related to the production processes rather than the support processes and thus the process of changing the energy use demands strategic decisions rather than operative decisions. For the European PPI, a large share of the CO_2 emissions are biogenic (~62%), and consequently if carbon capture and

[1] Compared to the greenhouse gas emissions emitted in 1990.

[2] To be reached by reductions in Sweden as well as by investments in other EU countries or by applying flexible measures such as CDM.

[3] This figure refers only to the actual on-site emissions and not the emissions related to e.g. electricity imported from the grid or transport of raw materials and finished products, which are allocated to the power and the transport sector respectively.

storage (CCS) is implemented in the PPI, the levels of CO_2 in the atmosphere can be further reduced in comparison to implementing CCS only for fossil-based emission sources. Thus the PPI can play a significant role when striving to reach both European climate targets and national climate goals in Sweden and Finland.

In the climate-conscious Europe of today, with increasing energy prices, the threat of depletion of fossil fuels and the introduction of new policy instruments, not least for reduction of greenhouse gas emissions, large changeovers are to be expected for the energy systems within the European PPI in the near future. Already today, the PPI is approaching a transitional situation – where it is no longer only producing pulp and/or paper but also producing additional products which can increase both the mill profitability and the overall mill energy efficiency – thereby transforming mills into so-called biorefineries. These additional products can be electricity, district heating, wood pellets, dried bark chemicals, materials, biofuels etc. Another alternative is to integrate CCS, something which can be done also in combination with integration of other new technologies such as black liquor gasification (BLG). The above-mentioned technologies and system solutions, aiming at transforming a mill into different types of biorefineries, are hereafter collectively denoted *technology pathways*.

For energy-efficient implementation of different technology pathways, it is an advantage if the mill has a surplus of steam and/or heat which can be utilized for thermal integration of the new biorefinery processes, or a heating demand at such a temperature level so that it can be supplied with heat from the biorefinery processes. Depending on the development of the energy markets, the implementation of different technology pathways can also contribute to a reduction of the global CO_2 emissions.

The potential for energy-efficient introduction of new technologies and production of additional value-adding products depends both on mill-specific conditions, such as the type of pulping process and potential for thermal integration, and on geographical conditions, such as the proximity to other large industries and important energy infrastructure (e.g. natural gas grids and/or district heating grids). Research and development projects have identified potentials for energy efficiency and implementation of specific biorefinery concepts within the pulp and paper industry. However, most previous studies are either detailed – considering only mill-specific conditions for one mill, not stating anything about the overall potential on a national or European level – or very aggregated, not considering important mill-specific conditions. Consequently, in order to make the fast-approaching transition of the European PPI as smooth as possible from both an environmental and a business-competitiveness point of view, the knowledge concerning techno-economic potentials within the field needs to increase and new approaches, connecting the results from detailed studies to the actual European PPI stock, are necessary.

None of the earlier performed, aggregated industry level studies includes technology pathways which lead to new products. Instead, they mainly focus on increased energy efficiency and fuel switching. As mentioned above, on the other hand, many studies regarding technical aspects of such pathways have been performed at mill level. These studies, however, have not been extended to incorporate the whole industry and the infrastructure level influencing the potential for large-scale implementation of the individual pathways. Thus, the European PPI's progress towards energy-efficient implementation of different technology pathways, and how these pathways will influence the global CO_2 emissions and the energy systems, on both mill and industry level, need to be studied. This study aims at acting as a building block in filling this research space by evaluating the potential for, and effect of, implementation of selected technology pathways for utilisation of excess heat[4] within the European PPI – as is further description in the next section.

1.2 Aim

The overall aim of this thesis is to identify and analyse selected future technology pathways for the European PPI which, for different assumptions regarding policy instruments and the development of the energy market, will:

- Strengthen the competitiveness of the pulp and paper industry
- Reduce the global emissions of CO_2
- Interact with the expected development of the rest of the European energy system in an efficient way.

In this thesis, the term 'technology pathway' refers to combinations of technical solutions, both well-tried and emerging, that have been proved to have a large technical, economic and/or CO_2 emissions reduction potential and are at least at pilot scale, indicating a possible implementation within a near future. The pathways are strategic and will, if implemented, have a significant effect on a mill's energy system. Examples of pathways are production of the second generation of biofuels and CCS. The pathways were selected based on their fulfilment of the following two criteria:

1. Identified as interesting from an economic and/or CO_2 reduction potential point of view
2. Enough technical and economic data available at the start of the thesis work

The focus is on thermal energy efficiency and thermal integration of selected pathways based on the characteristics of different mills. Increasing the thermal energy efficiency and implementing these pathways will alter the whole mill's energy balance, not only the thermal energy balance, and these changes are evaluated using a European energy systems perspective (for further descriptions see Chapter 3 on delimitations and Section 5.2 on the system levels studied). The selected technology pathways, their resulting

[4] Here, the term excess heat refers to heat (in excess) at different temperature levels, ranging from lukewarm water to steam.

energy balance changes, and how these changes are valued from both an economic and CO_2 emissions point of view, are further described in Chapter 3, Section 4.2 and Section 6.3.2. The analysis is made with an overall systems perspective with Europe as system boundary but with input data based on earlier, detailed (mill level) research for the individual technology pathways analysed, see Chapter 6; Input data.

1.2.1 Research themes and research questions

To elucidate the potential for, and effects of, implementation of selected technology pathways within the PPI as stated in the aim, three themes of research questions are addressed:

1. **General integration opportunities in different types of existing mills.** What are the characteristics of the mills' existing energy systems and how do they influence the potential for thermal integration of new processes? How large is the potential for process steam savings for different types of mills? At what temperature(s) can excess heat be made available? Are there ways to draw general conclusions for different types of mills?
2. **Economic performance and global CO_2 emissions assuming different future developments of the European energy market.** How do assumptions regarding different energy market parameters influence the economic performance and CO_2 emissions for the pathways? Are any of the studied pathways "robust"[5] given the uncertainty of the future energy market and parameters such as policy instruments and investment costs?
3. **Factors influencing the potential for industry-wide implementation.** Which process characteristics and external, geographical and infrastructural, factors influence the potential for large-scale implementation of the pathways? In what way do these characteristics and factors influence the potential?

The work performed in order to answer the research questions in theme 2 is based on previous, detailed work regarding each individual technology and its characteristics. Using this earlier research as a basis, together with the methodological developments performed to answer research questions 1 and 3, the aim of this thesis can be reached.

The three themes and their research questions are addressed in Chapters 7, 8 and 9 respectively and the main conclusions are summarised in Chapter 11.

[5] Here, the term robust is used to describe the state when a pathway shows a stable economic performance and/or a stable reduction potential for global CO_2 emissions for multiple changes of different parameters such as the energy market prices.

1.3 List and short summary of appended papers

This thesis is based on nine papers. A graphic overview of the papers is given in Fig. 1. The figure shows that the papers address different issues and cover different parts of the European pulp and paper industry. It can also be seen that the papers analyse the PPI on different system levels. Papers I-III, V, VII and IX analyse a single kraft pulp mill based on data from a model mill depicting a typical Scandinavian pulp mill. As an addition, Papers IV, VI and VIII are based on data from existing European pulp and paper mills and cover a broader spectrum of the industry. Below, the papers are presented in brief.

In **Papers I-II**, a kraft pulp mill and a utility (producing district heating) are modelled within the same system boundary in order to analyse the competitiveness of using pulp mill excess heat as district heating compared with other production techniques for district heating and alternative utilization options for the excess heat. Paper I presents the methodology used, and Paper II presents the results and shows how the competitiveness of using excess heat as district heating depends on future energy market conditions (energy market scenarios), the sizes of the district heating demand, and the type of existing heat production.

Paper III uses the model from Papers I and II and expands the methodology to address also the question of pricing of pulp mill excess heat. In the paper, supply and demand curves are constructed which show the magnitude of excess heat that the mill and the utility are willing to sell or buy (in MW) depending on the excess heat price (in €/MWh). The analysis is made for four different scenarios concerning the future energy market.

In **Paper IV**, a systematic approach for assessing a mill's steam balance, assuming only a limited amount of data, is developed and applied to a case study. It is investigated which energy-related data are publicly and/or easily accessible for the European kraft pulp industry. Assuming this limited amount of data, a model is developed which assesses the existing steam balance of a kraft pulp mill in terms of total steam production and steam consumption at different pressure levels. As an example of how the model can be used, a case study is made showing the potential for improved energy efficiency through increased electricity production within the Swedish kraft pulp industry.

Paper V investigates the annual net profit and global CO_2 emissions for different energy-related technology options for utilizing excess heat at a kraft pulp mill depicting a typical Scandinavian mill. The methodology used is based on the methodology presented in Papers I-III. The options studied are: Increased electricity production, selling of bark, production of district heating, extraction of lignin and capturing of CO_2. The analysis is performed using four different scenarios for energy prices and emissions on the future energy market.

In **Paper VI**, the potential for steam savings and temperature levels of excess heat are identified for four Scandinavian thermo-mechanical (TMP) pulp and paper mills using the Heat Load Model for Pulp and Paper (HLMPP). The results are compared with similar results for two other TMP mills in order to draw some more general conclusions. Based on the data for the six mills, an analysis is made regarding the relationship between the steam consumption and temperature levels of excess heat and mill-specific characteristics such as production rate and fresh warm water usage. Based on the results, the potential for implementation of different biorefinery concepts at a TMP mill is discussed.

Paper VII builds on the work presented in Paper V and compares selected technology options for utilization of potential surplus steam at a kraft pulp mill depicting a typical Scandinavian mill. The technology options studied include lignin extraction, electricity production, capturing of CO_2 and black liquor gasification with production of electricity or dimethyl ether (DME). The methodology and model used are based on the work presented in Paper V, and the technology options are compared with respect to annual net profit and global CO_2 emissions for four different scenarios concerning the future energy market. The paper also includes a sensitivity analysis on different parameters.

Paper VIII presents an approach for analysing the potential for reduction of global CO_2 emissions by introduction of selected technology pathways in the European pulp and paper industry. The approach is based on bottom-up thinking whilst still estimating the potential on a European level, considering both technical and geographical data for the mills. The usefulness of the approach is exemplified by a case study of the potential for reduction of global CO_2 emissions by introduction of CCS within the European Pulp and Paper industry.

Paper IX builds on the work presented in Paper VII and compares three selected technology options for debottlenecking the recovery boiler and utilizing a potential steam surplus at a kraft pulp mill depicting a typical Scandinavian mill. The technology options compared are extraction of lignin, black liquor gasification (as a booster) and an upgrading of the existing recovery boiler.

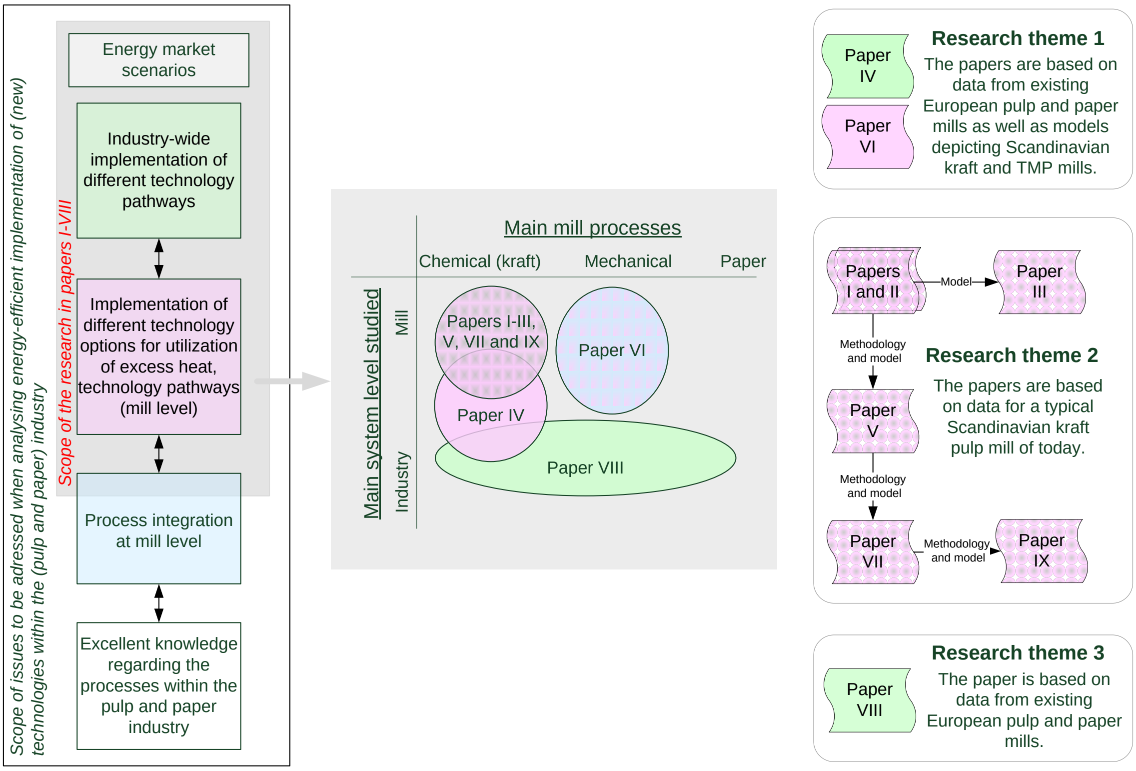


Figure 1. *Positioning of the appended papers in relation to (1) the scope of issues to be addressed when analysing energy-efficient implementation of (new) technologies within the PPI (left), (2) type of mill and system level studied (middle), and (3) each other (right). The colouring shows the scope of the papers.*

1.4 Short comments to facilitate the reading

This thesis uses a systems approach to address the questions stated in the three research themes defined above. The systems approach and the system levels used are further described in Section 5.2. Further, the work is based on the assumption that "biomass is a limited resource" and also, when discussing CCS this thesis assumes that "all CO_2 are equal". These two assumptions are further described and motivated in Section 5.1. Chapter 13 presents all abbreviations used, and Chapter 3 presents the scope and delimitation of the thesis together with a short description of some terms frequently used in the text such as 'utilization of excess heat'. Chapter 2 gives a short presentation of the European PPI and its key energy system characteristics.

2 Overview of key energy system characteristics for the European PPI

This chapter briefly introduces the European PPI from an energy systems perspective. The PPI is divided into three different sub-sectors, described and presented with respect to their energy use and CO_2 emissions. It is also described how the type of production processes influences the potential for implementation of new technology pathways.

In this thesis, the European pulp and paper industry is defined as the mills located in the countries that are included in the confederation of European paper industries, CEPI (CEPI, 2008), i.e. the countries in Europe with the highest density of pulp and paper industry. Relative to the world production, the 19 CEPI countries are responsible for about 20% of the total pulp production and 24% of the total paper and board production, producing 36 million tonnes of pulp and 89 million tonnes of paper and board in 2009 (CEPI 2011). Within CEPI, a majority of the pulp, >60%, is produced in Scandinavia, mainly in Sweden and Finland, whereas the paper production is more evenly geographically distributed although Germany, Sweden and Finland collectively are responsible for ~48% (CEPI 2011). With respect to energy use, the PPI is the sixth largest industrial energy user in Europe and the single largest industrial user of biomass, using approximately 102 TWh of electricity and 330 TWh of thermal energy annually (55% biomass) during 2009 (CEPI 2011). Relative to the total energy use in Europe, the energy use within the PPI corresponds, roughly, to 4% of the total energy use and 14% of the total industrial energy use (Eurostat 2009).

With respect to energy use and CO_2 emissions the PPI can be divided into three sub-sectors: chemical/kraft pulp[6] (and paper) mills, mechanical pulp (and paper) mills, and pure paper mills without any virgin pulp production. Depending on sub-sector, the amount and type of energy sources and raw material used, and consequently the on-site emissions of CO_2, differ; see Fig. 2 and Table 1.

Considering CO_2 emissions, generally, kraft mills have the largest on-site emissions out of the three sub-sectors. These emissions are, however, mainly biogenic, originating from the recovery boiler and (for an integrated kraft mill) the bark boiler. A mechanical mill, using large amounts of electricity in the mechanical pulping process, has lower on-site emissions of CO_2 than a kraft mill of the same size. A paper mill using imported kraft or mechanical pulp and/or de-inked paper has a lower energy demand than a mechanical or kraft pulp and paper mill and, due to the lower energy use, lower on-site

[6] The kraft (sulphate) process is not the only chemical pulping process. It is, however, by far the largest in terms of production volume both within CEPI and in the world.

emissions of CO_2. In some cases, paper mills buy steam from another industry or heat and power plant to cover their steam demand, and for those cases the on-site emissions are shifted to that production site instead, just as for the emissions related to the electricity used in the mechanical mills. For mechanical mills and pure paper mills, the type of on-site emitted CO_2 depends on the type of fuel used in the on-site boilers.

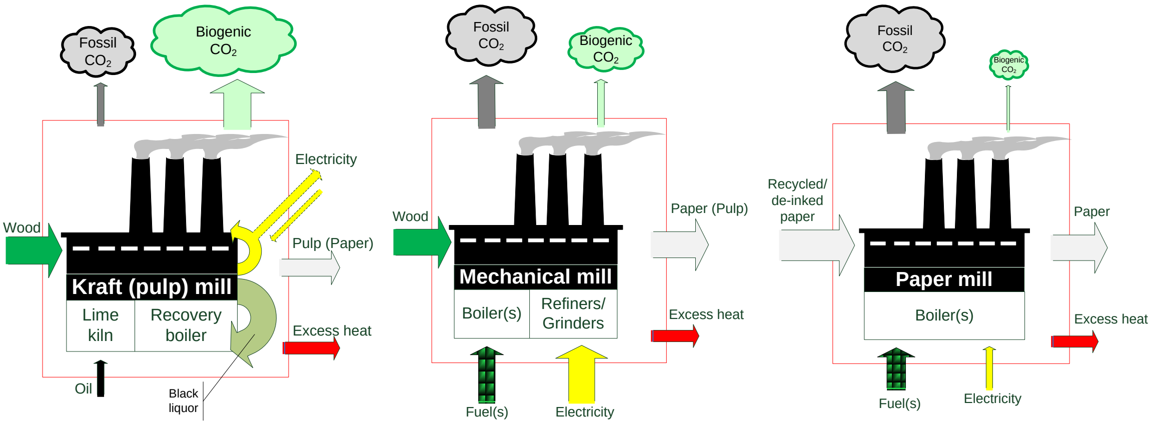


Figure 2. *A schematic overview of the flows of energy, raw material and on-site emissions of CO_2 for different types of mills. The thickness of the arrows gives a rough estimate of the size of the flows. The red line shows the system boundary for the mill energy system.*

Table 1. *Use of energy and wood raw material for paper based on different types of pulp. The numbers are relative with paper based on kraft pulp as a basis for the comparison. Thus, the energy and wood raw material use for paper based on kraft pulp is set to 1 (100%) and the energy and wood raw material use for paper based on mechanical pulp or recycled/de-inked paper is shown in relation to the use of energy and wood raw material for paper based on kraft pulp.* (Wiberg 2001)

Use of energy and wood raw material for paper based on…	Kraft pulp	Mechanical pulp	Recycled/ de-inked paper
...total fuel	1	0.2	
...fossil fuel	1		2
...electricity	1	2	0.5
...wood raw material	1	0.5	

As can be seen in Fig. 2 and Table 1, the type of pulp production largely influences the energy balance of a mill and thus also the potential for, and effect of, implementation of new technologies.

Out of the three sub-sectors, the kraft PPI holds the largest potential for implementation of new technologies which produce (new) biomass-based, value-added products[7] in addition to the pulp and paper. This is because in the chemical/kraft pulping process the wood fibres are separated from the rest of the wood components. The fibres are used for production of pulp (or paper), and the rest of the wood components – lignin and parts of the hemicelluloses – are dissolved in the black liquor. Today, the black liquor is burned

[7] Even though the captured CO_2 is not a product of the same character as biofuels or electricity, captured CO_2 is here regarded as a value-added product, since biogenic CO_2 is assumed to be entitled to the same economic compensation as fossil CO_2: see Section 5.1 on fundamental assumptions.

in a recovery boiler producing steam and recovering the process chemicals. Consequently, the kraft PPI holds a large potential for implementation of new technologies which utilize the lignin and hemicelluloses in the black liquor in more efficient ways compared to just burning it for steam production purposes, e.g. extracting the lignin or producing product gas through gasification.

Further, a market kraft pulp mill (producing only pulp, not paper), having a lower steam demand than an integrated kraft pulp and paper mill (producing both pulp and paper), can be self-sufficient on thermal energy based on the wood raw material alone and, if energy-efficient, can even have a steam surplus. This characteristic makes the kraft PPI especially interesting when considering the implementation of new technologies, since different biomass streams (lignin, hemicelluloses and bark) are present and, at the same time, there is a potential for an energy surplus which can be utilized to cover the energy demand of new processes. Fig. 3 presents the grand composite curve[8] for a typical[9] Scandinavian market kraft pulp mill. As can be seen in the figure, some of the excess heat has a rather high temperature, ~100°C, although the majority of the excess heat has a lower temperature, ~40°C. For kraft pulp mills, it has been shown that if the water use is reduced, the amount of excess heat at ~100°C can be increased (Bengtsson 2004; Wising, Berntsson et al. 2005; Axelsson, Olsson et al. 2006).

Contrary to the chemical process, in the mechanical pulping process all of the cellulose, hemicelluloses and the lignin are used for the pulp production, and thus the only biomass stream available is the falling bark. Consequently, the mechanical PPI cannot produce value-added products from the lignin and hemicelluloses in the same way as the kraft PPI can. However, thermal integration[10] of new technology processes is still an option. This is also true for a paper mill without virgin pulp production (having neither bark nor any other biomass streams available).

Bearing the above-described characteristics in mind, it can be concluded that when analysing the potential for implementation of new technology pathways producing value-added products based on more efficient utilization of the wood raw material, the kraft PPI, especially kraft market pulp mills, is of particular interest. However, when analysing the potential for thermal integration of new processes or utilization of excess

[8] The grand composite curve displays the net heat-flow characteristics of a process, or a sum of processes, versus the temperature of the flows. For a further description see for example Kemp (2007) or Klemeš et al. (2010).

[9] This is an example of a grand composite curve. In reality all mills are different and thus grand composite curves for different mills do not necessarily look exactly the same.

[10] However, as mentioned in Section 4.1, process integration studies mapping the thermal characteristics of mechanical mills are not as frequently performed as process integration studies of kraft mills. As a part of the results of this thesis, the grand composite curves for four thermo-mechanical mills are presented in Section 7.2.

heat for e.g. district heating, mechanical mills and pure paper mills can also be of interest.

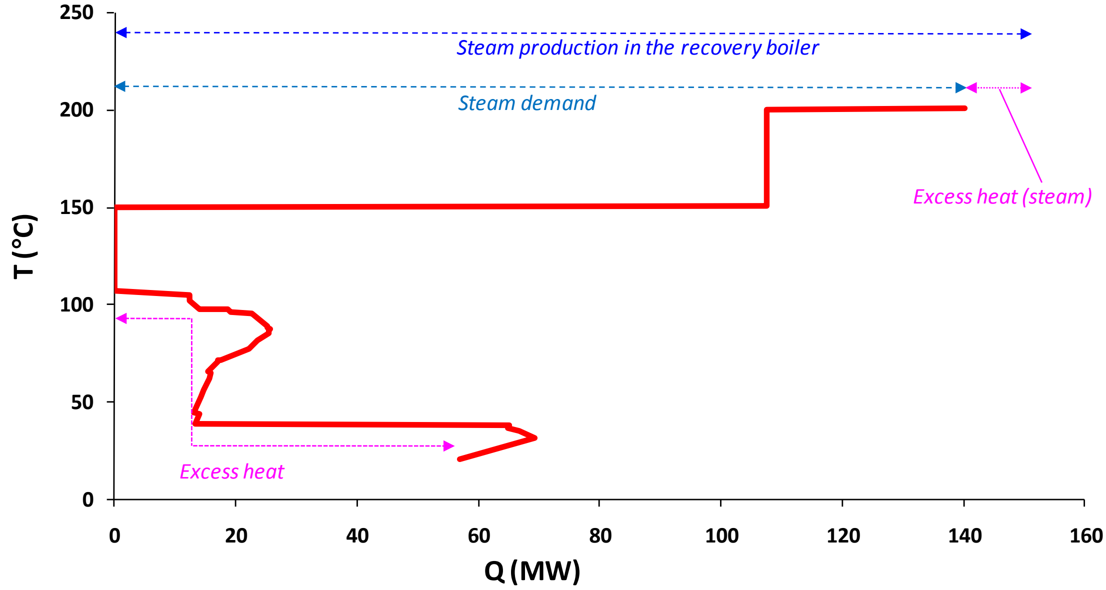


Figure 3. *Grand composite curve for a typical Scandinavian kraft pulp mill with high water usage (based on Axelsson et al. 2006). The demand for high-pressure steam has been omitted in the figure, as has the corresponding amount of steam produced in the recovery boiler. The blue dotted lines show the steam demand and steam production. The mill is self-sufficient in thermal energy from the wood raw material alone and has a small steam surplus (pink line). The pinch temperature is ~105°C and the mill has ~8MW of excess heat at LP steam level, ~10 MW of excess heat at a temperature >100°C, and ~20 MW of excess heat at ~40°C (pink line).*

3 Scope, delimitations and definitions

This chapter briefly presents the delimitations for this thesis and the appended papers on which it is based. Some frequently used terms are also presented and described.

Based on bottom-up models and thinking, this thesis performs energy systems analyses of the European PPI on different system levels (for further description see Section 5.2). As described in the previous section, the energy systems of different types of mills differ significantly. In this thesis, thermal energy-efficiency measures which enable energy-efficient implementation of selected technology pathways are studied. Consequently, the kraft PPI, especially the kraft market pulp mills (having potential for a steam surplus), is of particular interest. This is due to the large thermal flows in the kraft PPI (compared to the mechanical and paper PPI, see Fig. 2), along with the fact that a kraft mill, due to the lignin content in the black liquor, can implement a larger variety of biorefinery concepts.

The European PPI is a large user of both thermal energy and electricity. However, as stated above, the focus in this thesis is on thermal energy efficiency and implementation of selected new concepts based on the thermal characteristics of different mills. Thus, electrical energy efficiency and measures aiming at reducing the electricity consumption – such as double disc refiners, pre-treatment of chips to ease refining, and variable speed drives on pumps – are not within the scope of this thesis. Further, increased energy efficiency in support processes such as space heating, ventilation and compressed air systems has not been analysed. It should be noted, though, that systems aspects regarding electricity use and production are included, such as combined heat and power production, steam recovery from electricity use in the refiners, etc.

As for energy efficiency, the concept of biorefinery is by nature wider than the scope of this thesis. Consequently, a limited number of technology pathways, leading the PPI towards becoming biorefineries, have been studied. These technology pathways are:

1. Increased electricity production
2. Export of bark
3. Extraction of lignin
4. Carbon capture and storage[11] (CCS)
5. Black liquor gasification (BLG)
6. Export of heat for district heating

[11] CCS is sometimes not considered as a biorefinery technology. However, since CO_2 can be a valuable product it is a competing option for utilization of pulp mill excess heat which has the potential to contribute to substantial reduction of CO_2 emissions.

The studied pathways range from proven to emerging technologies, and from technologies which can be implemented at all mills to technologies which require certain process and infrastructural conditions, as described in Table 2. As stated in the aim, the pathways have been selected based on judged potential for sound economic performance and/or large potential for reduction of global CO_2 emissions, together with good availability of data. The data used for pathways 1-5 in the list above are based on previous, in-depth research projects for each technology focusing on technology characteristics and thermal process integration.

Table 2. *A short list of some characteristics for the selected technology pathways, including in which type of mills they are technically possible to implement and in which of the appended papers they are studied.*

Technology pathway[a]	**Increased electricity production**	**Export of bark**	**Extraction of lignin**	**CCS**	**BLG**	**Export of heat for district heating**
Technically possible to implement in...	All types of mills	All mills with virgin pulp production	Kraft mills	All types of mills	Kraft mills	All types of mills
Temperature level of excess heat that can be utilized when implementing the pathways[b]	High temperature (steam)	High temperature (steam)	High temperature (steam) and medium temperature[c] (~70°C)	High temperature (steam) and medium temperature (~100°C)	High temperature (steam)	All temperature levels[d]
Potential for industry-wide implementation limited by infrastructural conditions?	NO	NO	NO	YES	NO	YES
Proven or emerging	Proven	Proven	Emerging	Emerging	Emerging	Proven
Included in Paper(s)...	I-V, VII and IX	I-III, V, VII and IX	V, VII and IX	V, VII-IX	VII and IX	I-III, V, VII and IX

[a] *The technology pathways are further described in Chapter 4, Section 4.2.*
[b] *How implementation of the different pathways affects a mill's energy balance is described in Table 3.*
[c] *Warm water at ~70°C can be used to satisfy the heat demand of the lignin washing process.*
[d] *Assuming that low temperature excess is upgraded using a heat pump.*

In this thesis it is assumed that implementing energy-efficiency measures decreases the process steam demand. Further, the thesis assumes that, for a kraft pulp mill, if the process steam demand is reduced there are two different ways to benefit from this through production of additional products that generate additional revenues[12]:

[12] For this to be true, the mill must be self-sufficient on thermal energy from the wood raw material alone. If the mill imports large amounts of external fuel, one alternative when implementing energy-efficiency measures would be to decrease the import of external fuels corresponding to the steam saved.

1. Use the steam surplus to cover the heat demand of the production processes for the additional products (such as electricity production or capture of CO_2).
2. Assuming that no additional, external fuel is to be imported to the mill, the decreased steam demand allows introduction of new processes which reduce the steam production whilst producing new products (such as extraction of lignin or black liquor gasification where the product gas is used to produce motor fuels or electricity).

Throughout this thesis, these two options are collectively referred to as “utilization of excess heat” or “utilization of a potential steam surplus”. For the selected pathways, Table 3 gives a short description of how the implementation of the pathways affects a mill’s energy balance. The table also describes how energy-efficiency measures, reducing the process steam demand and generating a potential steam surplus, affect the potential for implementation assuming that no external fuel is to be added (in relation to the two different ways to benefit from this through production of additional products, mentioned in the bullet list above).

Table 3. *A description of how implementation of the different pathways affects the energy balance of a kraft pulp mill and how the potential for energy-efficient implementation is influenced by investments in energy-efficiency measures reducing the process steam demand.*

Technology pathway[a]	**Effect on the energy balance of a mill if implemented and a description of how energy-efficiency measures, reducing the process steam demand and generating a potential steam surplus, affect the potential for implementation assuming that no external fuel is to be added.**
Increased electricity production	Any potential steam surplus can be used to generate additional electricity in back-pressure or condensing turbines (depending on the pressure level of the steam).
Export of bark	Falling bark can be either exported or burned in the bark boiler. If burned, steam is produced and thereby more electricity can be produced or the steam can be used to cover the heat demand of new processes.
Extraction of lignin	If lignin is extracted from the black liquor, the heat content will be reduced and consequently the steam production will be reduced. If no external fuel is to be added, energy-efficiency measures need to be implemented in order to reduce the steam demand so that the (lower) amount of steam produced is enough to cover the steam demand.
CCS	The CCS processes have a (large) heat demand. If no additional fuel is to be added, energy-efficiency measures need to be implemented in order to reduce the steam demand and thereby generate a steam surplus large enough to cover the process steam demand of the capture process.
BLG[b]	The black liquor gasification process is exothermal, i.e. steam is produced. The amount of steam produced is, however, lower than the amount produced if the same quantity of black liquor is burned in a recovery boiler. If no external fuel is to be added, energy-efficiency measures need to be implemented in order to reduce the steam demand so that the (lower) amount of steam produced is enough to cover the steam demand.
Export of heat for district heating	Both high-temperature excess heat (steam), medium-temperature excess heat (~90°C) and low-temperature excess heat (<70°C) can be used to produce heat for district heating purposes (although the temperature of the low-temperature excess heat needs to be lifted by a heat pump first). If energy-efficiency measures are implemented, this increases the amount of high-temperature excess heat (steam) but, generally, decreases the amount (and temperature) of excess heat at lower temperature levels.

[a] *The technology pathways are further described in Chapter 4, Section 4.2.*
[b] *It should be noted that in this thesis BLG is assumed to be implemented as a booster, i.e. in parallel to the recovery boiler. See further description in Papers VII and IX.*

For the papers analysing the kraft PPI – Papers I-V, VII and IX – the majority of the papers, Papers I-III, V, VII and IX, are based on data for a model mill depicting a typical Scandinavian kraft pulp mill. Paper IV, on the other hand, is based on data from several existing Swedish kraft pulp mills as well as data for model mills. For the thermo-mechanical (TMP) mills more extensively studied in Paper VI, they all have different characteristics and have been chosen in order to show the steam-saving potential for different types of TMP-based pulp and paper mills. The reason for choosing mills with TMP lines is that amongst the mechanical pulp and paper processes, TMP is the most promising process to convert to a biorefinery due to the possibility to recover steam from the high-pressure refiners. The majority of the European TMP production is located in Scandinavia (>70%), as is also a majority of the chemical pulp production. This is mainly due to the abundance of wood raw material and historically low electricity prices. Thus, the mills included for the work in Paper VI were all Scandinavian. The total number of mills in the CEPI countries decreased by 25% between the years 2000 and 2010 (CEPI 2011). When looking at the “whole” European PPI, as in Paper VIII, this change of the industry structure is taken into consideration by including only a selection of mills in the study. The selection was done together with PPI consultants from Pöyry. Thereby 176 mills were selected and included, based on their competitive strength and size; see Section 6.2.

4 Main concepts and related work

This chapter presents main concepts and earlier work within the field of this thesis. Further, relevant work from adjacent fields is briefly mentioned. Focus is placed on studies describing the technologies and system solutions which are included in the pathways analysed in the latter part of the thesis.

As stated in the introduction to this thesis, the PPI and especially the kraft pulp industry, due to its high use of biomass and potential for energy-efficient integration of new processes, has the potential of being a major contributor to reducing global CO_2 emissions through delivery of better products (replacing others produced with fossil energy or lower efficiency). However, to fully achieve this potential, the PPI needs to increase its energy efficiency and/or introduce new, efficient technology solutions such as lignin separation, black liquor gasification and carbon sequestration. Research dealing with energy efficiency in the pulp and paper industry has been conducted on both the process and mill levels, showing the techno-economic potential for increased energy efficiency through specific process modifications and the introduction of new, efficient technologies (see Sections 4.1 and 4.2 below), and on a more aggregated level, showing the potential for energy savings within the European or global pulp and paper industry assuming, for example, different policy instruments and/or varying market development (see Section 4.3). Furthermore, in earlier studies, models have been constructed to depict the pulp and paper industry either at a detailed mill level – model mills – or on a more aggregated, national or global, industry level (see Section 4.3).

4.1 Process integration and potential for energy efficiency within the pulp and paper industry

For energy-efficient implementation of technology pathways in the PPI, it is an advantage if the mill has a surplus of steam and/or heat which can be utilized for thermal integration of the new biorefinery processes, or a heating demand at such a temperature level so that it can be supplied with heat from the biorefinery processes. A steam surplus can only be achieved for kraft market pulp mills, whereas all types of mills can have excess heat available at different temperature levels. One way to reduce the process steam demand, and thereby free steam which can be utilized in (new) biorefinery processes, is to thermally integrate the mill processes – process integration; see Chapter 5, Section 5.4. Process integration studies within the PPI have shown large potentials for process steam savings, 15-30% (Group 1999; Fouche and Banerjee 2004; Savulescu, Poulin et al. 2005; Axelsson, Olsson et al. 2008; Persson and Berntsson 2009; Mateos-Espejel, Savulescu et al. 2010). The identified potential seems valid for most types of mills; however, the majority of mills analysed are kraft mills. For kraft mills, process integration studies have also been performed on model mills, depicting both typical Scandinavian mills and green-field mills built with best available technology (BAT). For the model mills depicting typical mills, the potential for steam savings through better process integration and new equipment is similar to the potential identified for real mills, up to 30% (Olsson, Axelsson et al. 2006; Axelsson and Berntsson 2008), and for the BAT mills the potential is somewhat lower (Wising 2003).

For the mechanical PPI, potentials for steam savings and temperature levels of excess heat have been identified for thermo-mechanical (TMP) model mills (Axelsson and Berntsson 2005; Ruohonen and Ahtila 2009) and for a few real TMP and ground wood (GW) mills (Noël 1995; Noël and Boisvert 1998; Schaareman, Verstraeten et al. 2000; Lafourcade, Labidi et al. 2003; Ruohonen and Ahtila 2010; Ruohonen, Hakala et al. 2010; Ruohonen, Hippinen et al. 2010). Recent studies on thermal process integration at paper mills (without virgin pulp production) are scare in the literature. For this type of mill, the focus has instead been on system closure and minimization of water use, something which often also reduces the energy demand even though that is not the primary goal (Paris 2000; Brown, Maréchal et al. 2004; Ordóñez, Hermosilla et al. 2010; Žarković, Rajaković-Ognjanović et al. 2011).

4.2 Selected technology pathways

There are many technology pathways which could be of interest for the mills within the European PPI when striving towards becoming biorefineries. In this thesis, the selection is limited to six:

1. Increased electricity production
2. Export of bark
3. Extraction of lignin
4. Carbon capture and storage[13] (CCS)
5. Black liquor gasification (BLG)
6. Export of heat for district heating

Out of these six, three give traditional products (see Section 4.2.1) and three are new, emerging technologies (see Section 4.2.2).

Other possible pathways, not included in the scope of the thesis, are: hemicellulose extraction (Persson, Nordin et al. 2007; Mao, Genco et al. 2008; Marinova, Mateos-Espejel et al. 2009; Huang, Ramaswamy et al. 2010; Mora, Mahmoudkhani et al. 2011), gasification of biomass (Varma, Chaouki et al. 2010; Isaksson, Mahmoudkhani et al.

[13] CCS is sometimes not considered as a biorefinery technology. However, since CO_2 can be a valuable product it is a competing option for utilization of pulp mill excess heat which has the potential to contribute to substantial reduction of CO_2 emissions.

2011; Wetterlund, Pettersson et al. 2011), upgrading of biomass through e.g. drying (Andersson, Harvey et al. 2006), pelleting (Andersson, Harvey et al. 2006; Wolf, Vidlund et al. 2006), pyrolysis (Ghezzaz and Stuart 2011; Lou, Wu et al. 2012) torrefaction (van der Stelt, Gerhauser et al. 2011), or conversion of the whole pulp mill into an ethanol production plant (Phillips, Jameel et al. 2008; Fornell 2010). As for the studied technologies, some of these technologies can benefit from combined implementation (Consonni, Katofsky et al. 2009; Huang and Ramaswamy 2010; Pettersson and Harvey in press).

The majority of research papers regarding different biorefinery options for the PPI refer to kraft mills (Olsson, Axelsson et al. 2006; Van Heiningen 2006; Towers, Browne et al. 2007; Consonni, Katofsky et al. 2009; Marinova, Mateos-Espejel et al. 2010a, 2010b; Perrin-Levasseur, Maréchal et al. 2010; Pettersson and Harvey 2010). Moreover, some biorefinery technologies such as extraction of lignin and black liquor gasification can only be implemented at chemical pulp mills. For the mechanical PPI, research regarding the potential for introduction of biorefinery concepts has not been performed as extensively. This is mainly because, for pulp produced by mechanical pulping processes, all wood components (cellulose, hemicelluloses and lignin) are present in the pulp (see Chapter 2 for further description). However, this fact does not mean that a mechanical mill cannot be transformed into a biorefinery. It only means that the biorefinery options available for mechanical mills are more limited (and less studied) than chemical/kraft mills.

The references given for the selected technologies in the following sections are mainly related to energy efficiency and the potential for thermal integration of the new technology processes.

4.2.1 Technology pathways based on traditional products

The technology pathways listed below are technically feasible to implement for all kraft and mechanical mills regardless of the production process. Paper mills without virgin pulp production have no bark to access and thus cannot export bark. Increasing the electricity production and increasing the bark exports are possible regardless of geographical position, since the infrastructure for these products is already in place. Export of heat for district heating, on the other hand, depends on the availability of a district heating grid nearby, or a large heat sink for which a grid can be built.

Increased electricity production

For kraft mills, electricity is generated in back-pressure turbines, utilizing the steam produced in the recovery boiler and any other boilers before it is used in the production processes. The electricity production can, for example, be increased by raising the steam quality (when investing in new boilers), increasing the dry solid content of the black liquor, decreasing any throttling and/or reducing the process steam demand, and investing in a condensing turbine, as discussed by e.g. Vakkilainen (2008), Kankkonen

(2010) and Olsson (2006). In this thesis, increased electricity production due to increased dry solid content of the black liquor, reduction of any throttling and/or investment in a condensing turbine to utilize a potential steam surplus are considered.

For a mechanical mill, any on-site electricity production is produced in back-pressure turbines connected to the boilers used to produce process steam. If energy efficiency is increased through process steam savings, increased recovery of steam from the refiners, or a lower electricity use in the refiners, this will lead to a lower demand for steam produced in boilers. Consequently, the fuel demand will be lower but the potential for producing electricity in back-pressure turbines will also be reduced.

During 2009, the mills within CEPI produced 49 TWh of electricity, equal to 48% of their total electricity use.

Export of bark

Kraft and mechanical mills, which use timber as their wood raw material, get falling bark from the de-barking process. This bark can be either used to produce steam or exported, depending on the steam demand of the mill. However, since the falling bark is fairly wet its market value can be low. To increase the dry content, and thus the value of the bark, it can be dried prior to export. In the case of bark export, less bark is burned and consequently less electricity can be produced in back-pressure turbines. Due to this fact, the trade-off between selling the bark and using it internally at the mill depends on the mill steam demand as well as the price of electricity and bark (Eriksson, Harvey et al. 2002; Axelsson and Berntsson 2005; Axelsson and Berntsson 2008). This is also true if biorefinery processes such as BLG or gasification of biomass are introduced (Eriksson, Harvey et al. 2002; Farahani, Worrell et al. 2004).

Export of heat for district heating

The PPI has a large on-site use of energy. Nevertheless, substantial amounts of the primary process energy used exit the processes at different (lower) temperatures (compared to the temperatures they had when entering the process), called excess heat. The excess heat can e.g. be utilized for production of district heating. Since the PPI is energy-intensive, substantial amounts of excess heat are associated with only a limited number of geographical sites, i.e. mills. Further, hot water, such as excess heat used for district heating, can only be transported over limited distances. This is mainly due to the capital cost of the necessary culvert; technically the heat can be transferred for quite long distances without too much heat loss. Consequently, the potential for district heating production within the PPI depends on whether there is a heat sink in the form of, for example, a city or a company with a large heat demand situated nearby, and whether the mill excess heat meets the temperature requirements. In the case of Sweden, an approach for identifying the length of culvert which can be built for utilization of excess heat has been developed (Gustafsson and Larsson 2003). The approach is based on the assumption that the cost for supplying the excess heat as district heating should be equal to the cost of supplying the same amount of heat by investment in a new biofuel boiler.

Within the CEPI countries, the distribution of district heating varies greatly. In Sweden and Finland, district heating currently holds approximately 50% of the heat market, whereas it is almost nonexistent in Spain and Portugal (Werner 2006; Energy Markets Inspectorate 2010; Energiateollisuus 2011). Werner (2006) and Persson and Werner (2011) discuss, amongst other issues, the future competitiveness and expansion of district heating in Europe. They conclude that district heating is competitive, especially if based on excess heat, and describe how the use can be doubled during the upcoming 15-20 years. Werner (2006) also critically analyses other projections of future district heating expansion, made by the European Commission (2004), IEA (2004) and IPCC (2001), and concludes that the environmental benefit of district heating is not recognised on the international policy level concerning climate change and consequently, the international community has very low expectations concerning the future growth of district heating systems in Europe. Compared to other alternatives for utilization of excess heat, district heating is an alternative that can usually be combined with other technology pathways such as electricity production or production of biofuels, and can thereby further reduce the global CO_2 emissions and at the same time improve the economic performance when implementing such pathways (Egeskog, Hansson et al. 2009; Difs, Wetterlund et al. 2010). However, if the excess heat is of high quality (temperature of >95°C or steam) there could be a competition for the excess heat between district heating and other utilization alternatives such as internal, advanced process integration, electricity production, etc. (Bengtsson, Nordman et al. 2002).

In the CEPI countries, the use of industrial excess heat for district heating is not common; Sweden is basically the only country where industrial excess heat has more than a very marginal share of the heat market (Werner 2006). In Sweden, excess heat from the PPI is used for district heating purposes in a number of cities, for example Varberg (the Södra Värö mill), Karlstad (the Stora Enso Skoghall mill), Mönsterås (the Södra Mönsterås mill), Gävle (the Korsnäs mill) and Sundsvall (the SCA Ortviken mill).

4.2.2 Technology pathways producing new, high-value products

Extraction of lignin and black liquor gasification can only be implemented for chemical mills. Carbon capture and storage, on the other hand, is technically possible to implement for any type of pulp and paper mill.

Lignin extraction

In the kraft pulp process, the fibres are used for production of pulp (or paper), and the rest of the wood components – lignin and parts of the hemicelluloses – are dissolved in the black liquor. Lignin can be extracted from the black liquor by using either e.g. acid precipitation (Öhman 2006) or ultrafiltration (Wallberg 2005). Currently, acid precipitation is closer to commercialisation and thus is the process assumed when lignin extraction is discussed. In the acid precipitation process, CO_2 is used to precipitate the lignin, which thereafter can be filtered and washed. From a mill energy systems perspective, lignin extraction will lead to reduced heat content in the black liquor in the recovery boiler, and thus to reduced steam and electricity production, together with an increased steam demand in the evaporation plant due to the increased evaporation load from wash filtrates.

Many alternatives have been discussed with respect to the products which could be based on extracted lignin (Berntsson 2008; Lindgren 2009; Ziegler, Nägele et al. 2009; LigniMatch 2010; Perrin-Levasseur, Benali et al. 2010). Today, the only commercial alternative with large-volume market potential is to use it as a fuel e.g. to replace oil in the lime kiln or for co-combustion in coal power plants. However, in regard to the near future, it can be assumed that the extracted lignin may be used to replace oil both as a fuel and as a feedstock in production of materials and chemicals. Consequently, the future profitability of lignin extraction is dependent on the world prices of both biomass and oil.

Structural changes in the European PPI imply that some mills will be closed down, while the remaining mills will increase their production capacity (CEPI 2011). For increased production capacity, the recovery boiler is often a bottleneck. Axelsson et al. (2006) conclude that for a kraft pulp mill, lignin extraction is an economically attractive alternative for debottlenecking the recovery boiler, if the alternative is to upgrade the recovery boiler and the connected steam turbines. Further, when increasing the production capacity at a kraft pulp mill, lignin extraction shows a better economic performance than increased electricity production for utilization of excess steam (Axelsson, Olsson et al. 2006; Olsson, Axelsson et al. 2006; Laaksometsä, Axelsson et al. 2009). An alternative approach for debottlenecking of the recovery boiler could be to introduce a black liquor gasifier as a booster; see the section on black liquor gasification below.

Today, lignin is extracted at a (small) demonstration plant at the Nordic Paper Bäckhammar mill in Sweden. Further, financial support has been granted by the Swedish Energy Agency (SEA) for building of a full-scale demonstration plant at the Södra Mörrum mill in Sweden.

Carbon capture and storage (CCS)

Being large energy users, pulp and paper mills have large on-site emissions of CO_2. Since these emissions are associated with only a limited number of geographical sites, the PPI, like other energy-intensive industry branches (Rootzén, Kjärstad et al. 2011), is suitable for implementation of carbon capture (CC). Further, since a large share of the CO_2 emissions associated with the European PPI are biogenic, if CCS is implemented the levels of CO_2 in the atmosphere can be further reduced in comparison to implementing CCS only on fossil emission sources (Ekström, Blümer et al. 1997;

Möllersten, Yan et al. 2003; Möllersten, Gao et al. 2004; Hektor and Berntsson 2007; Hektor and Berntsson 2008; Hektor and Berntsson 2009). Since the main source of CO_2 from the pulp and paper industry is boiler flue gases, there are in principle three technology options for capture: post-combustion, pre-combustion and oxy-combustion. In this thesis, post-combustion using chemical absorption is considered since it is the only technique not requiring any reconstruction of the boilers (Hektor and Berntsson 2007). For post-combustion with chemical absorption the energy cost for capture is 50-70% of the total cost and thus cannot be neglected (Abu-Zahra, Niederer et al. 2007; Hektor and Berntsson 2007). Hence, for CC to be economically and technically realistic, the source of CO_2 must be large enough and the energy demand of the capture process should preferably be possible to integrate (fully or partly) with other processes at the capture site. The potential for heat integration of post-combustion CO_2 capture to kraft pulp and paper mills has been studied by Hektor and Berntsson (2007; 2009) who show that thermal integration is possible to a substantial extent.

Generally, the costs of CO_2 transport and storage are assumed to be low compared to the cost for capture. However, that assumption is only valid if a large-scale infrastructure, serving several emission sources, is in place. This is especially true when studying CCS in the industry sector since the industrial point sources usually are smaller than the point sources in the power and heat sector. One way of limiting the cost of CCS is to create capture clusters in regions with several emission sources located near each other. In this way, the transport network can be integrated and thus benefit from economy of scale. Capture clusters in Europe based on emissions from other energy-intensive industry sectors have been identified by Rootzén et al. (2011).

Another option for CC within the European PPI, apart from capture of CO_2 from boiler flue gases, would be to capture CO_2 from the lime kiln at kraft mills using oxy-combustion (Grönkvist, Bryngelsson et al. 2006; Grönkvist, Grundfelt et al. 2008). However, since the technology cannot be applied directly to existing kilns (or boilers), and since the flow of CO_2 from the lime kiln is minor compared to the boiler flue gas flows, this option will not be discussed further.

Today, CO_2 is captured from the flue gases at two Swedish pulp and paper mills, the M-real Husum mill and the StoraEnso Nymölla mill. However, this CO_2 is not transported and stored as pure CO_2 but chemically bound in the production of precipitated calcium carbonate (Grönkvist, Grundfelt et al. 2008).

Black liquor gasification (BLG)

The black liquor generated in the kraft pulp process is burned in the recovery boiler in order to recover the cooking chemicals and produce steam for the mill process steam demand. Another alternative for the recovery of chemicals and energy in the black liquor is to use BLG. In this thesis, the BLG technology considered is the one based on the Chemrec process, since this is the technology which currently is being most developed and is closest to commercialisation.

Introducing BLG will alter a mill's energy balance. As in the case of a conventional recovery boiler, the BLG unit will have a net surplus of steam. The amount of steam, however, will be lower than if the same amount of black liquor is burned in a recovery boiler. Due to the lower steam production, additional fuel needs to be burned in the (bark) boiler if the steam production is to be unchanged. On the other hand, the BLG unit also generates a product gas which can be used to produce either biofuels or electricity. For the case of biofuel production, the mill's electricity production will decrease and for the case of electricity production it will obviously increase. Compared to a conventional recovery boiler, a BLG unit makes the recovery process more complicated and is significantly more expensive (Modig 2005). Thus, for BLG to be a competitive alternative, the monetary and environmental value gained from the produced biofuel or electricity must offset these drawbacks.

System aspects of integration of BLG to kraft mills have been systematically studied by Pettersson (2011) who shows how the potential for reduction of global CO_2 emissions and economic profitability of BLG depend on a number of factors such as the mill steam demand, the degree of heat integration possible, choice of product produced from the product gas, etc. Based on her work, Pettersson concludes, among other things, that BLG generally shows a better performance for market pulp mills than for integrated pulp and paper mills, that production of biofuels from the product gas generally shows a better performance than electricity, and that CCS can be integrated to the mill in a more profitable way if BLG is used than if using a conventional recovery boiler. The economic performance and/or potential for reduction of global CO_2 emissions for BLG have also been investigated by, for example, Andersson and Harvey (2006), Berglin et al. (2003), Ekbom et al. (2005), Eriksson and Harvey (2004), Joelsson and Gustavsson (2008), Consonni et al. (2009), and Larson et al. (2009).

As extraction of lignin, BLG can also be an alternative for debottlenecking of the recovery boiler or for utilization of a steam surplus if installed as a booster, not replacing but complementing the recovery boiler.

In Europe today, the BLG technology is implemented at only one mill, the Smurfit Kappa Piteå mill. However, the BLG plant handles only a small fraction of the black liquor flow. Between the years 2005-2010 the BLG plant was a development plant, focused only on the gasification. By the year 2011, however, a small demonstration plant, incorporating the whole production chain from gasification to production of motor fuels, was built and this plant is currently in the start-up phase.

4.3 Modelling of the pulp and paper industry on different system levels

The PPI industry has been modelled in both detailed studies, on mill level, and in more aggregated studies, on industry or world level. Most of the studies are based on a bottom-up framework.

4.3.1 Mill level

Detailed studies on mill level comprise mill-specific conditions but usually do not consider interactions between a wide range of different techniques and technology solutions – other than the particular technique or technology solution in focus in the given study, perhaps compared to one or two alternatives – and neither do they say anything about the general, industry-wide potential. At mill level, the models used are based on either data from existing mills, case studies, or using reference values due to solid knowledge about the industry, model mill studies. For the kraft PPI, model mills depicting typical Scandinavian mills and model mills based on BAT technology have been developed within the FRAM research programme, along with a model of a BAT mechanical TMP mill producing SC-paper (FRAM 2005). Model mills based on TMP and recycled fiber/de-inked paper (RCF/DIP) have been developed within the ECOTARGET project (ECOTARGET 2005). The model mills developed within the ECOTARGET project have also been used in the development of the Heat Load Model for Pulp and Paper (HLMPP); see Section 5.4.2.

The model mills have been used in a number of research projects focused on analysing the effect of implementation of new technologies. For the kraft model mills, the research has been focused on process integration and implementation of new biorefinery processes, whereas the research on the mechanical model mills generally has been very technology-focused and performed on a more detailed system level. Examples of relevant mill-level studies are given in Section 4.2.1. Obviously these studies are based on knowledge and results gained from studies made on even more detailed system levels.

4.3.2 Industry level

Most aggregated studies at an industry level identify general potential but usually do not consider mill-specific conditions in any detail. Kinstrey and White (2007) for example, study the potential for energy efficiency within the North American pulp and paper industry by comparing the current average energy use with the level of energy use that could be achieved either through implementation of the most efficient commercially available technology (BAT) or implementation of new, advanced technology currently not practised (Practical Minimum). In this way they estimated the potential for energy efficiency on an industry level. A similar approach has been applied by Klugman et al. (2007a, 2007b) who estimate the potential for energy efficiency at a Swedish pulp mill by comparing the mill's energy use with other similar Scandinavian mills and two model mills. Energy and electricity use for BAT for the PPI can be found in e.g. Worrell et al. (2008) and Ecofys (2009).

Davidsdottir and Ruth (2005) and Ruth et al. (2004) use capital vintage modelling to assess changes in energy use and CO_2 emissions due to capital stock turnover and fuel switching for the US pulp and paper industry when implementing different policy measures. They conclude that if increasing the cost for emitting CO_2 alone, the reductions of CO_2 from the PPI can mainly be derived from fuel switching. To overcome the capital stock inertia and thereby achieve larger emission reductions, they suggest a combination of policy instruments to be applied simultaneously, such as a combination of a cost for emitting CO_2 and policies providing incentives that advance the adoption of higher-efficiency technologies.

Murphy et al. (2007) use the CIMS model, a further development based on the ISTUM model presented by e.g. Jaccard and Roop (1990), to analyse how the industrial sector, including the PPI, in Canada would be affected if an economy-wide, compulsory greenhouse gas reduction policy were to be implemented. Regarding the studies based on capital vintage modelling mentioned above, Murphy et al. (2007) find that when introducing a charge for emitting CO_2 the main consequential emission reductions are related to fuel switching. The CIMS model started as a bottom-up model with a high technological explicitness, and has during the years evolved towards an economy-wide hybrid model by inclusion of macro-economic feedbacks and parameters for simulating technological evolution. Although technologically explicit, the pulp and paper industry part in the CIMS model does not reach the same level of detail as the model mills described in Section 4.3.1 do.

Szabó et al. (2009) have developed a bottom-up, global model of the world PPI, PULPSIM, which focuses on energy use and emissions of CO_2. The model is used to analyse the effect on the PPI if introducing new policy instruments compared to the case of "business as usual". Although PULPSIM uses a bottom-up framework, the energy system for the mill configurations studied (including three types of pulping processes and three paper types based on compositions of these pulps) is only schematically represented, based on an overall energy balance, and the authors themselves point out the need for more technological detail. In line with the results from the aggregated studies reviewed above, Szabó et al. (2009) conclude that fuel switching is the major reason for decreased levels of CO_2 emissions in the PPI when subjected to a cost for emitting CO_2. They also state that for the European PPI, which already has a relatively "clean" fuel mix, further emission cuts can only be made if additional, technology-based measures are applied.

4.4 Evaluation of the potential for implementation of new technologies – geographical and infrastructural conditions

When assessing the potential for implementation of technology pathways within the energy-intensive industry in Europe, the physical energy infrastructure and geographical location of the industry, as well as knowledge regarding these facts, are of importance. In some cases it can even be reasonable to adapt the development in other sectors after the structure of the energy-intensive industry. For example, when planning for new biofuel production plants or heat and power plants it could be rational to consider where the existing energy-intensive industry is located, since this type of industry is a large user of both thermal and electric energy but usually at the same time can supply vast amounts of excess heat.

The importance of considering geographical and infrastructural conditions when evaluating the potential for implementation of new technology on a national or European level has been stressed by e.g. Leduc et al. (2009) who developed the geographically explicit optimisation model BEWHERE. The model is used to identify the optimal location of bioenergy conversion plants and biofuel production plants, considering geographical characteristics for the raw material supply and the markets for both end products and residual products. The model has been used on both a national level (Leduc, Lundgren et al. 2010; Leduc, Starfelt et al. 2010; Natarajan, Leduc et al. 2011) and European level (Wetterlund, Leduc et al. 2011; Leduc, Wetterlund et al. submitted for publication).

Apart from closeness to raw material supply and markets for the products produced, the potential for energy efficiency and implementation of new technologies at a specific industrial site is influenced by whether the site consists of one isolated industry or several co-located industries, so-called industrial clusters. Situated in an industrial cluster, the industrial plants can make efficient use of common energy and transport infrastructure and/or reduce their total demand for external heating and cooling by exchanging excess heat via a common utility system. Using total site analysis, TSA (described by e.g. Raissi 1994; Klemeš, Dhole et al. 1997; Perry, Klemeš et al. 2008), the potential for utility savings through implementation of a common utility system has been investigated for e.g. petrochemical clusters (Matsuda, Hirochi et al. 2009; Hackl, Andersson et al. 2011; Stijepovic and Linke 2011). The occurrence of energy-intensive industrial clusters emitting large volumes of CO_2 has been investigated by e.g. Rootzén et al. (2011), who discuss how the geographical positions of these clusters can influence the development of transport and infrastructure for captured CO_2, and by Johansson et al. (submitted for publication), who discuss how the potential for CO_2 abatement within the European petroleum refining industry is influenced by location of the refineries and their proximity to other industries and/or transport and energy infrastructure.

5 Methods, tools and methodology

Due to the span of system levels studied in this thesis, several methods and tools have been used. Further, part of the work was to develop a methodological approach to be used for the thesis work. This chapter first defines the three system levels used and describes how they are connected. Thereafter, the main methods and tools used are presented. Last, the developed approach, based on the mentioned methods and tools, is presented.

5.1 Fundamental assumptions

The assumption that biomass, within the near future, should be viewed as a limited resource is based on the fact that there are numerous studies showing how different biomass-based technologies can substitute fossil-based technologies in order to contribute to decreasing global emissions of CO_2, for example biomass gasification for electricity, heat and/or motor fuel production and/or co-firing of biomass with coal for electricity production (for system studies on European potentials for gasification of biomass and/or co-firing see e.g. Marbe 2005; Egeskog, Hansson et al. 2009; Hansson, Berndes et al. 2009). Realising only a number of these technologies in large scale in order to eliminate the use of fossil fuels in e.g. the transport and/or electricity sector will, however, demand more biomass than may be available (André P.C. 2006). Due to this fact, it is important to use the biomass as efficiently as possible in order to achieve as large global emission reductions per biomass unit as possible. In other words, biomass can be regarded as a limited resource. Consequently, the biomass used in the PPI limits the amount of biomass used elsewhere (for example for co-combustion in coal power plants producing electricity) and thus the CO_2 emissions from such other alternative uses will increase. Conversely, biomass exported from the PPI will decrease the emissions from such alternative applications since more biomass is then available.

This study assumes a future, 20-40 years from now, when the amount of biomass used has reached its limits but fossil fuels still are used to a fairly large extent. Further, at this time in the future, the new emerging technologies are assumed to be commercially available. In Fig. 4, this time in the future is symbolised by the letter B. Point A refers to today where the limit for the amount of biomass available has not yet been reached.

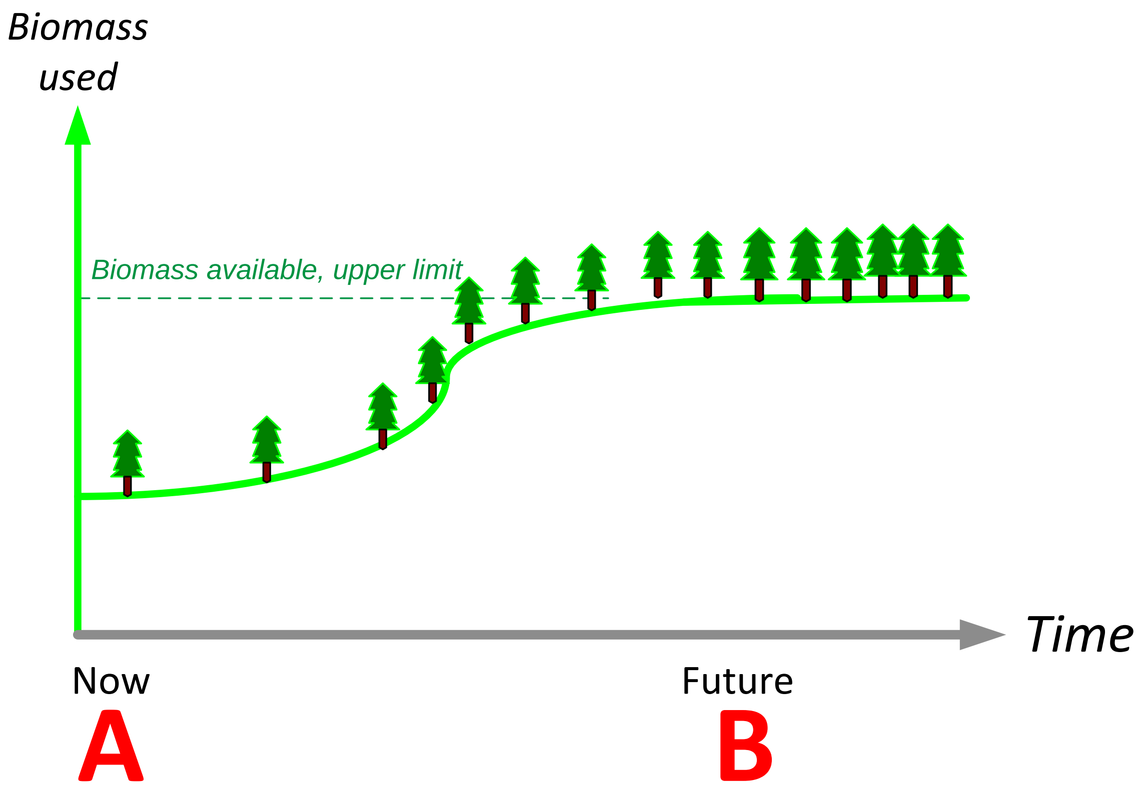


Figure 4. *Explaining the fundamental assumption of biomass as a limited resource based on where in time the study is focused.*

Furthermore, when analysing the potential for implementation of CCS in the PPI, as in Papers V, VII-IX, the captured biogenic CO_2 is assumed to be valued in the same way as captured fossil CO_2. This assumption is based on the fact that all CO_2 has the same effect on the climate and thus, when captured and stored, all CO_2 can be considered equal regardless of origin. It is assumed that in future policy schemes (at time B in Fig. X), captured and stored biogenic CO_2 is granted the same economic compensation as fossil CO_2. However, it can be noted that today, at time A, no such economic compensation is given.

The time perspective is also important when assuming that reductions of CO_2 emissions due to implementation of energy efficiency and new technology actually will be net reductions (as assumed in this thesis). Due to the EU ETS (emission trading scheme), if a static approach considering time A were to be applied, it could be argued that reductions of CO_2 in an industry within the trading scheme would, through lower prices and trade, not give a net reduction but just shift the emissions from one actor to another (SSC 2008). However, considering that the cap for amount of emissions allowed within the trading scheme will be continuously lowered, the reductions can be assumed to be net reductions if implemented in the future, e.g. time B as studied. Further, studies such as this thesis could contribute to showing policy-makers that (extensive) reductions can be technically achieved and consequently that policy instruments can be implemented towards such reductions.

5.2 Approach for analysing the PPI on different system levels

For the European PPI, this thesis uses a systems approach to analyse potential strategic changeovers and their benefits in terms of potential improved economic performance and potential reduction of global CO_2 emissions. A systems approach is essential to avoid sub-optimization when evaluating changes in complex energy systems. In this thesis, two system levels, mill level and industry level, and a surrounding system are used; see Fig. 5. The energy system studied in the appended papers is either on mill level, Papers I-VII and IX, or on industry level, Paper VIII. In order to be able to evaluate the economic performance and CO_2 emission balances when making changes in the studied energy system, the methodological approach of system expansion is used. Using system expansion, all flows entering or leaving the studied system is assumed to cause a change in the surrounding system, as illustrated in Fig 5. The flows for the implementation of technology pathways, as studied in this thesis, are net flows compared to a reference case depicting "business as usual". Consequently, the flows of pulp wood and pulp/paper are cancelled out, leaving only the flows which change due to the implementation of the technology pathways to be analyzed.

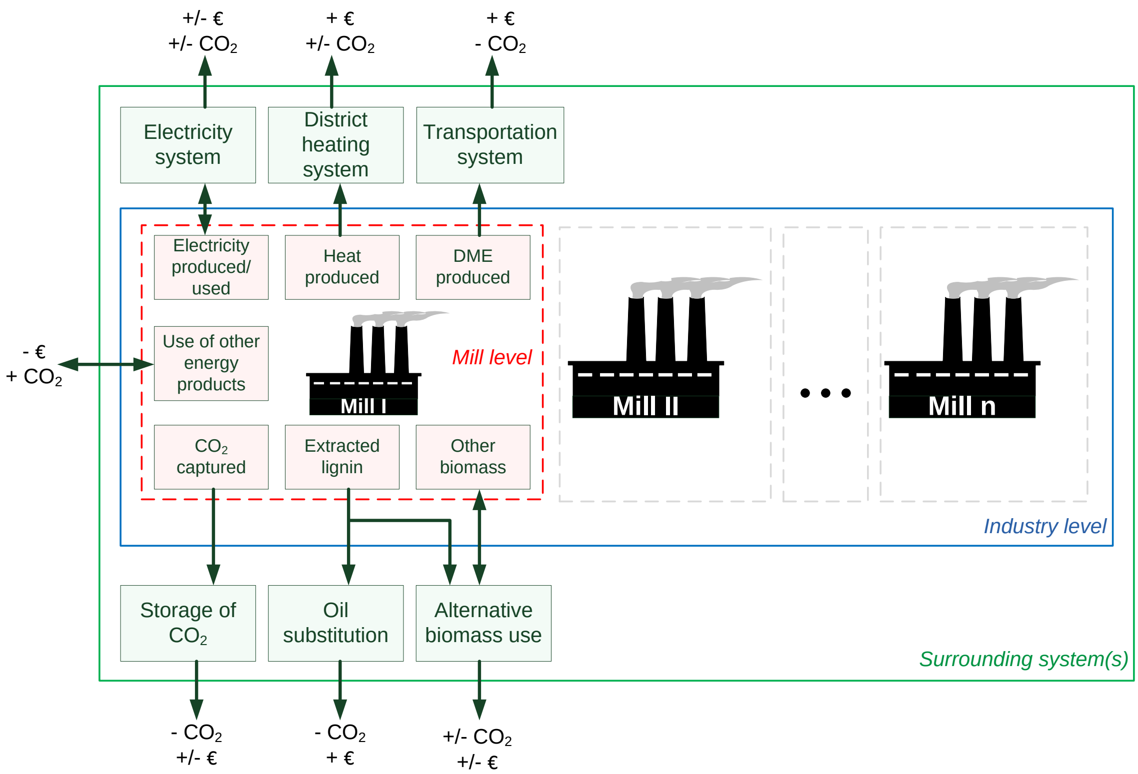


Figure 5. *A schematic representation of the three system levels used and how they are connected with each other. The streams entering and leaving the studied system (mill level or industry level), being evaluated for economic performance and CO_2 emissions in the surrounding system, are also shown.*

The system expansion approach is used in Papers I-III, V, VII and IX. In Papers I and II the studied energy system consists of a kraft pulp mill and an utility whereas the studied energy system in Papers III, V, VII and IX consists of only a kraft pulp mill. In these papers, changes in the studied energy system, in the form of investments in energy efficiency and new technology are evaluated for a variety of conditions in the surrounding system, in the form of energy market scenarios. In the subsequent text the main assumptions for the system expansion are given. For more description and detailed price and emission data used see Sections 5.2.1 and 6.2.3, and for a more thorough description of the assumptions behind these data see Axelsson and Harvey (2010).

The electricity surplus or deficit due to implementation of energy efficiency and technology pathways is assumed to affect the marginal electricity production technology. Due to the long economic lifetime of the pathways studied, the marginal production technology considered refers to the base load build margin (not the operating margin production technology). The assumed base load build margin technology varies depending on fuel prices and policy instruments. Electricity produced based on renewable sources is assumed to be subject to a policy instrument incentive scheme due to which additional revenue is obtained for such electricity. Based on this, it is assumed that all electricity produced is sold to obtain the additional revenue, and that the electricity demand is covered by purchased electricity (non-renewable base load build margin, thus having a lower price).

In a similar way, it is assumed that the excess heat exported from the studied system will be used as part of the base load in a district heating system and thus affect the building of base load capacity. The district heating market is by nature local. Due to this fact, no single marginal production technology for district heating in Europe can be determined. In Papers I-III, three options for the alternative district heating production is used based on data from real district heating grids in Sweden, representing the conditions for a small, a medium sized and a large district heating system respectively. In Paper V the alternative heat supply technology is assumed to be biomass combined heat and power (CHP). Finally, in Papers VII and IX, the alternative heat supply technology is assumed to be a combination of coal CHP and gas boiler.

In the transport system, DME produced by the PPI is assumed to replace diesel. As for electricity produced based on biomass, apart from the DME price, additional revenue is assumed to be obtained due to a policy instrument incentive scheme promoting production of biofuels.

The alternative use of biomass is assumed to be either co-combustion with coal in coal power plants or production of DME. Extracted lignin, a more high-value product compared to other types of biomass such as bark, is either assumed to replace oil, as feedstock for production of materials and chemicals, or other biomass for co-combustion with coal in coal power plants.

5.2.1 Energy market scenarios

The future economic performance, as well as the global emissions of CO_2, associated with the technology pathways studied is dependent on the development of the energy market. Consequently, to identify robust investment options, the performance of the technology pathways should be evaluated for varying future energy market conditions. In Papers I-III, V, VII and IX energy market scenarios are used to reflect a variety of possible future energy market conditions.

To achieve reliable results from an evaluation using energy market scenarios, the energy market parameters within a given scenario must be consistent, i.e. the energy prices must be related to each other (i.e. accounting for energy conversion technology characteristics and applying suitable substitution principles). Consequently, a systematic approach for constructing such consistent scenarios is facilitated by the use of a suitable calculation tool. In this thesis the Energy Price and Carbon Balance Scenarios tool (the ENPAC tool) developed by Axelsson and Harvey (2010) (based on work by Ådahl and Harvey 2007 and Axelsson et al. 2009) was used. The ENPAC tool proposes energy market prices for large-volume customers, based on world market fossil fuel price data and assumed values for energy and climate mitigation policy instruments. Hence, the required user inputs to the tool are fossil fuel prices and charges for emitting CO_2. Based on these inputs, the probable marginal energy conversions technologies in key energy markets are determined, which in turn yield consistent values for energy prices and CO_2 emissions associated with marginal use of fossil fuels, electricity, wood fuel and heat for district heating. Further, using the energy market scenarios a packaged sensitivity analysis of the energy market prices is conducted. The prices and CO_2 emissions associated with marginal use of different energy products, as generated by the ENPAC tool, used as part of the input data in Papers I-III, V, VII and IX, are presented along with other input data in Chapter 6.

Another option for evaluating the future economic performance and global emissions of CO_2 associated with the technology pathways would be to use traditional sensitivity analysis where the energy market parameters are varied separately, often called “one-factor-at-a-time” analysis. Such an approach can be a suitable, simple, option for an analysis where the varied factors are independent of each other. However, energy market parameters are not independent but rather strongly connected to each other and thus a “one-factor-at-a-time” analysis could give unrealistic relations between the energy market prices.

5.2.2 General economic assumptions

In Papers I-III, V, VII and IX, the net annual profit for an “average year” was used for the evaluation of the economic performance (see Eq. 1, Section 5.3). For the cases where the mill is the studied system, Papers V, VII and IX, a capital recovery factor of

0.2[14] was used as a base case; and for the case when the mill was modelled within the same system boundary as a utility, Papers I-III, a capital recovery factor of 0.1 was used as a base case[15]. The same capital recovery factor was used for all investments considered, since a more detailed modelling of individual capital recovery factors would require knowledge, not only about the expected lifetime of each investment, but also about the risk associated with the investment in the view of the decision-maker at the company making the investments. Another, similar, alternative for evaluation of the economic performance would be to use the net present value (NPV). However, such an analysis demands data for each year during the economic lifetime of the investment and it is hard enough to estimate the different energy market prices for an "average" year in the future (as done using the energy market scenario tool; see Section 5.2.1)[16]. The uncertainty regarding the cash flows for individual years in the future, together with the fact that the net annual profit method still considers the time value of money through the capital recovery factor, makes the net annual profit for an average year a good enough method for comparing the selected technology pathways with each other. When significant changes in price and policy conditions are expected over the investment lifetime, it becomes more important to consider later investment options as reactions to the changing conditions (see for example Svensson, Berntsson et al. 2009). This would require the use of NPV instead of an average annual net profit.

The investment cost for the not yet commercial technologies, i.e. black liquor gasification, lignin extraction and CO_2 capture and storage, are assumed to be for the "Nth plant" [17].

5.3 The energy system modelling tool reMIND

In Papers I-III, V, VII and IX the energy system modelling tool reMIND tool is used. When using the tool the work followed a systematic methodology developed and described in Papers I, V and VII. The methodology enables changes in a studied energy system to be analysed in a systematic way. Typical changes that can be studied are: changes due to investments, varying energy market prices, emission targets and policy

[14] A capital recovery factor of 0.2 is equivalent to e.g. an economic lifetime of 10 years and an interest rate of 15% or an economic lifetime of 6 years and an interest rate of 5%.

[15] However, in the papers sensitivity analysis was performed where the capital recovery factor was set to 0.2 for Papers I-III and to 0.1 for Papers V and VII.

[16] Actually, dividing the net annual profit with the capital recovery factor gives the NPV for the investment if assuming that the cash flow is the same for all years during the economic lifetime as for the "average year".

[17] This assumes the time in the future when the emerging technologies are mature, reliable and sold in significant volumes to have reached the Nth plant investment cost. A problem sometimes discussed regarding the Nth plant is the fact that if no one is willing to invest in the first couple of plants the Nth plant will never be built.

instruments. The main steps for a study based on this methodology are briefly described below:

1. Define the studied system (in Papers I-III a pulp mill and a utility producing district heating and in Papers V, VII and IX a pulp mill).
2. Define possible system changes to be evaluated (in this work, the investments in energy-efficiency measures and the implementation of energy-related technologies for utilization of excess steam and heat).
3. Define the surrounding system used for evaluation of the studied system (the energy market scenarios describing energy market prices and policy instruments).
4. Construct a model based on 1-3 (here the energy systems modelling tool reMIND was used).
5. Define the performance indicator(s) to be considered for comparing the system changes to be evaluated (for the work presented in this thesis the net annual profit and global CO_2 emissions).
6. Optimize the system based on the selected performance indicator for different settings in the surrounding system (defined by the aim of the study in question), to see how/whether the optimal solution is affected by changes in the surrounding system (here to find the optimal solution for each energy market scenario studied).
7. Fix certain parameters in order to investigate how close other solutions of interest are to the optimal solution (showing the effect of changes in different system parameters)
8. Analyse the results in relation to the aim of the study (as defined by steps 1-3).

The reMIND tool is based on mixed-integer linear programming and has been used and described by e.g. Karlsson (2011) Nilsson and Söderström (1992), Sandberg (2004) and Karlsson and Söderström (2002). With the tool, an optimization problem can be drawn up graphically using pre-defined equations. The constructed model is then optimized with the objective of minimizing the total annual system cost of the studied energy system, assuming a surrounding system. For this work, the objective has been to study the annual net profit generated by investments in energy efficiency and new technologies at a pulp mill and the effect on global CO_2 emissions from these investments. In this work, changes in the mill’s energy system due to different investment options are in focus, and thus flows that are constant for all different options analysed, such as the pulp production, have been excluded. Hence, the objective function can schematically be described as follows:

min $Z = rI_{tot} - B_{tot} + C_{tot}$ (1)

where r = *Capital recovery factor*

I_{tot} = *Total investment cost (energy efficiency-measures and technology pathways)*

B_{tot} = *Revenue of sold products including policy instruments (electricity, district heating, bark, captured CO_2, biofuels etc.)*

C_{tot} = *Running costs (electricity, chemicals etc.)*

As can be seen in the equation above, the reMIND tool is constructed for minimization of the annual system cost. The modelled energy system is profitable when the annual system cost, *Z*, is negative. Throughout the thesis and the appended papers, the annual system cost is therefore referred to as the studied system's net annual profit. Data for the different parameters, i.e. the investment costs, running costs and revenues for the studied technologies, are described briefly in Chapter 6 and described in more detail in the appended papers (Papers I-III, V, VII and IX).

5.4 Process integration

Of the appended papers, Paper VI is the one which focuses most explicitly on process integration, through the performance of a number of simplified pinch analyses using the Heat Load Model for Pulp and Paper (HLMPP, see Section 5.4.2). However, Papers I-III, V and VII-IX all use results from detailed process integration and pinch analysis studies as part of the input data.

5.4.1 Overview of the main concept of thermal process integration and pinch analysis

Process integration is a holistic method used for process design, where one considers the interaction between the process units and aims at optimizing the whole studied system rather than optimizing each process unit separately. Here, process integration refers to the concept of thermally integrating the heat sources and heat sinks of a process or a system in order to improve the internal heat exchange and thereby reduce the need for external hot and cold utilities. Pinch analysis (Linnhoff 1993; Kemp 2007; Klemeš, Friedler et al. 2010) is a well-known and widely used process integration method[18]. The aim of thermal pinch analysis is to identify process integration opportunities through increased internal heat exchange and thereby show how the hot and cold utility demands can be reduced. Pinch analysis can be used both for green-field designs and for retrofitting existing processes or plants. A pinch analysis for retrofitting existing processes or plants consists of four steps:

[18] Apart from pinch analysis, mathematical programming or exergy calculations can be used when performing a process integration study. There is also an increasing number of process integration studies which, to different extents, combine these three methods and tools.

1. Data gathering of stream data for the process and data for the utility system.
2. Targeting, where the hot and cold Composite Curves and the Grand Composite Curve are established. From these curves the theoretical minimum hot and cold utility demand can be determined.
3. Mapping of the layout of the existing Heat Exchanger Network (HEN).
4. Retrofit, where the layout of the existing HEN is improved by removing pinch violations in order to get closer to the targets identified in step 2.

The data gathering (Step 1) has to be performed manually while steps 2-4 can be performed by using some Pinch Analysis tool. Further, step 1 is usually the most time-consuming part, sometimes constituting up to 75% of the total analysis time.

5.4.2 The Heat Load Model for Pulp and Paper

The HLMPP is a tool developed for estimating the potential for energy-efficiency improvements through process integration (Hakala, Manninen et al. 2008; Ruohonen, Hakala et al. 2009). The HLMPP tool and methodology are based on pinch analysis and an overview of the four steps comprising an HLMPP analysis is shown in Fig. 6. For further description of the tool see Section 2.2 in Paper VI.

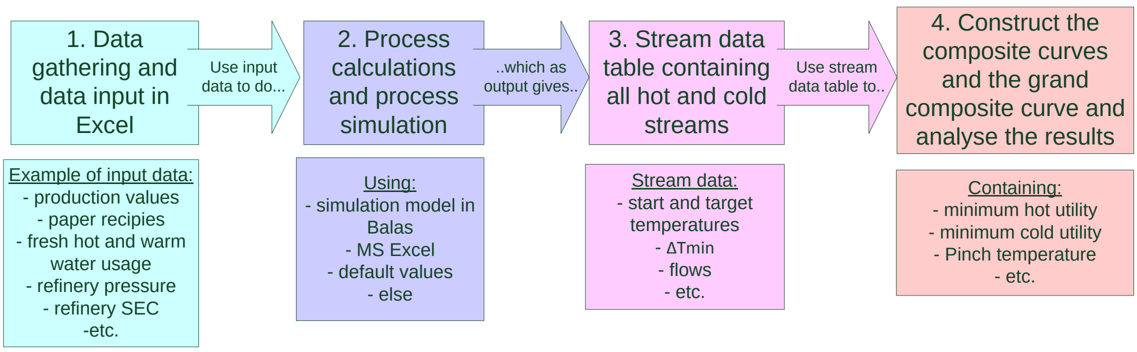


Figure 6. *Overview of the four steps constituting an HLMPP analysis as performed in Paper VI.*

Since the stream data used for construction of the Composite Curves and the Grand Composite Curve are given by process simulation, they do not correspond to the actual set of existing streams at the studied mill. Due to the same fact, the full process layout remains unknown, as do the actual locations of streams and heat exchangers – and thus steps 3 and 4 in a full pinch analysis (Original network design and Retrofit, see Section 5.4.1) cannot be performed. since these steps require good knowledge and data for the actual physical streams and the existing heat exchanger network. However, considerably less input data are required to get the complete stream data for an HLMPP analysis than for a complete pinch analysis. This time-saving characteristic, which is the main advantage, makes the HLMPP suitable for screening of saving potentials, as when doing a pre-study or a more aggregated study or when estimating a rough potential for integration of other, new processes at a mill.

5.5 The methodological approach developed throughout this thesis work

As stated in Chapter 1, the overall aim of this thesis is to evaluate selected technology pathways for the PPI and the potential for their implementation on a European level. Since there is no commonly accepted approach for such a study, part of the work for this thesis was devoted to the development of a methodological approach. The result is presented below.

The suggested approach is based on earlier research regarding process steam savings and the effect of implementing selected technology pathways on the energy balance for different types of mills (Axelsson, Olsson et al. 2006; Axelsson, Olsson et al. 2006; Olsson, Axelsson et al. 2006; Hektor and Berntsson 2007). In order to estimate the potential for implementation of the studied technologies in the whole European PPI stock, this knowledge has been coupled to technical and geographical data for the European PPI and important European energy and transport infrastructure. For evaluation of the future performance of different technology options, the approach assumes earlier research regarding the future development of the energy market. Consequently, the approach assumes detailed research and is based on bottom-up thinking whilst estimating the potential on a European level. The approach is carried out stepwise and an overview of it is presented in Fig. 7. Its different steps are presented below:

I: External, infrastructural preconditions

These are the characteristics of the geographical area surrounding the mills, e.g. data for where potential storage sites for CO_2 and district heating grids are located.

II: Mill-specific data

Mill-specific data are the characteristics of the individual mills constituting the European PPI stock. Data included are e.g. technical age of mill and specific mill equipment, production, fuel usage, process steam demand, CO_2 emissions and estimates of available amounts of excess heat.

III: Potential for energy efficiency and implementation of new technology

The potential for energy efficiency and implementation of new technology pathways at mill level is based on earlier and on-going research by others as well as by the author of this thesis. The results from this part typically show the economic performance and impact on global CO_2 emissions for implementation of specific technology pathways in specific mills. The future economic performance, as well as the global emissions of CO_2, associated with implementation of the different technology pathways are evaluated by using energy market scenarios: see Section 7.

A. Technical/infrastructural potential for implementation of technology pathways

Here mill-specific data for the individual mills are connected to the gathered data for the surrounding infrastructure. The results from this part show how the technical potential for implementation of a certain technology is limited (or enhanced) by the location of the mill – such as the potential for implementation of CCS or export of district heating.

B. Energy use and potential for energy efficiency and implementation of new technology

How the existing energy balance of the individual mills constituting the European PPI stock can be altered is determined by fitting the potential for energy savings known for some mills (III) to mill-specific characteristics. The results from this part typically show how the potential for energy savings and implementation and integration of different technologies depends on mill-specific characteristics such as technical age of process equipment and type of production process.

C. Potential for implementation of technology pathways on a European level

When the effect on the potential for implementation and integration of technology pathways due to the surrounding infrastructure (A) and the mill characteristics (B) has been determined, these two factors are brought together and the final, complete potential for implementation and integration of different technology pathways is estimated for the whole European PPI stock.

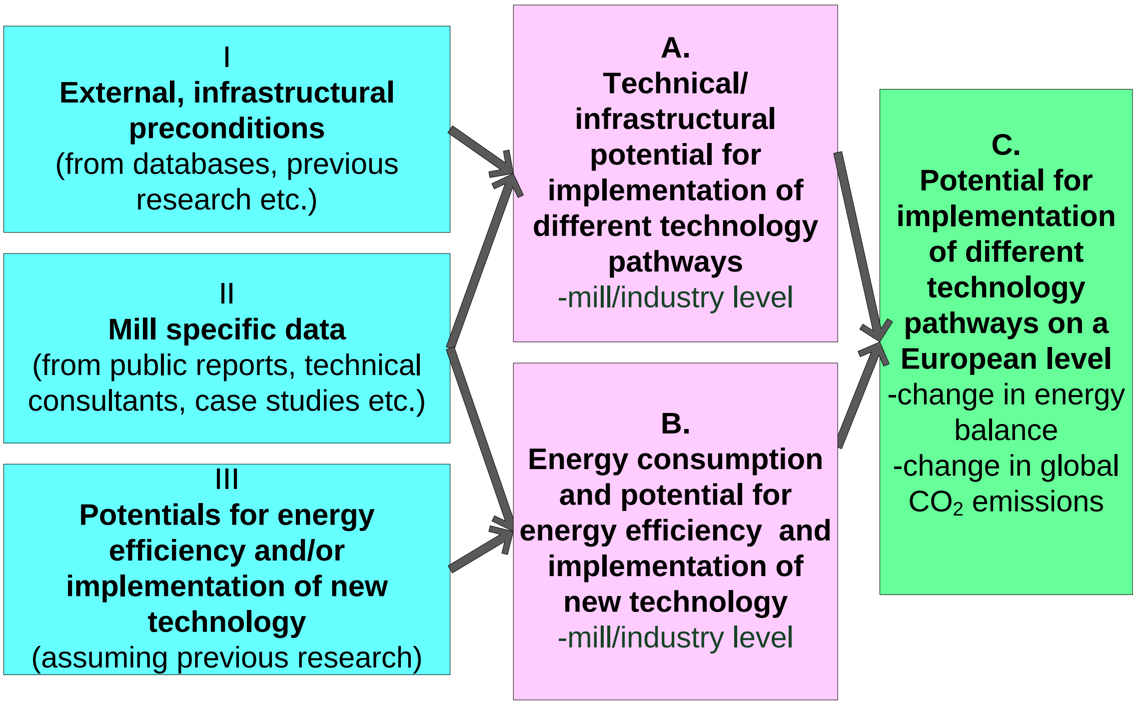


Figure 7. *Overview of the developed methodology.*

6 Input data

This chapter presents a relevant selection of the input data used in this thesis. First, mill-level data are presented. These data mainly concern characteristics for the mills analysed in Papers I-VII and IX, but data for the utility modelled in Papers I-III are also presented. Thereafter, data for the industry-level analysis in Paper VIII are presented. And lastly, the data used for the surrounding system are presented, both with respect to the geographical proximity to other industries and important infrastructure (as used in Paper VIII) and with respect to the surrounding energy market (as used in Papers I-III, V, VII and IX).

6.1 Input data for mill-level analysis

In the subsequent text, central data for the mills analysed in Papers I-VII and IX, and the utility studied in Papers I-III, are presented. The mill data for Papers I-III, V, VII and IX are largely based on previous, detailed research on a lower system level.

6.1.1 Key data for the model mill depicting a typical Scandinavian kraft pulp mill

An overview of key data for the kraft pulp model mill studied in Papers I-III, V, VII and IX is presented in Table 4. A more detailed description can be found in FRAM (2005). The steam produced by the recovery boiler is enough to satisfy the mill steam demand (the mill even has a small steam surplus that is vented), which enables export of all falling bark. The back-pressure turbine is small, compared to the amount of steam produced in the recovery boiler, and thus cannot accommodate all steam produced; hence some steam is throttled. The mill's grand composite curve can be seen in Section 2.

Table 4. *Key mill data for the model mill depicting a typical Scandinavian kraft pulp mill.*

Kraft pulp production, design	[ADt/d]	1000
Process thermal energy use[a]	[GJ/ADt]	14.3
Steam use MP/LP	[t/h]	69/190
Electricity use/production	[MW]	33/24
Oil use in lime kiln	[MW]	22
Biomass surplus (bark sold)	[MW]	31
Steam surplus vented	[MW]	8.2

[a] *Excluding steam conversion to electricity in the back-pressure turbine.*

Axelsson et al. (2006) have shown that the kraft pulp model mill can increase its steam surplus significantly through investments in process integration and new efficient equipment, hereafter denoted energy-efficiency measures. The energy-efficiency measures in which the studied mill can invest in order to achieve the steam surplus are presented in Table 2 in Paper V. At a total cost of approximately 8-14 M€, steam savings of about 0-15 t/h medium pressure (MP) steam, and about 70-95 t/h low pressure (LP) steam, can be achieved. The amount of steam saved depends on which energy-efficiency measures are chosen, since not all can be combined; see further description in Appendix 1, Paper V.

6.1.2 Data for the utility producing district heating studied in Papers I-III

The utility is modelled as a district heating system together with existing, and possible new, district heating production plants. Since the sizes of district heating systems vary, and since the size and the thereon dependent heat production composition of the district heating system influence the potential for introduction of excess heat in the production mix, three typical systems were modelled: Small (S), Medium (M) and Large (L). The heat demand curves for the three systems are based on data from three Swedish municipalities. The total heat demand and the corresponding heat production for the three systems are displayed in Table 5. The data for the mix of heat production plants are based on a survey of existing heat production capacity in Swedish municipalities near kraft pulp mills. As can be seen in Table 5, the larger district heating systems have a greater share of heat produced in combined heat and power (CHP) plants.

Table 5. *Existing capacity and production mix of the three studied district heating systems.*

Type of district heating system		Small	Medium	Large
Top load	[MW]	42[a]	331[a]	483[a]
Heat demand	[GWh/yr]	117[a]	797[a]	1651[a]
Percent of total heat production produced by:				
Waste boiler	[%]	7	22	
Waste CHP	[%]			37
Biomass boiler	[%]	90	23	
Biomass CHP	[%]		26	36
Coal boiler	[%]			7
Top load, oil boiler	[%]	3	29	20

[a] *Information about the heat loads was received from the local energy companies Gävle Energi, Tekniska Verken in Linköping and Tekniska Verken in Finspång*

Apart from utilization of pulp mill excess heat, the utility studied was assumed to be able to invest in new heat production capacity through either waste CHP, biomass CHP or a natural gas combined cycle (NGCC) plant; see e.g. Table 4 in Paper II. Since waste is a limited resource in a local perspective, the amount of waste available for incineration was assumed to be limited to what already exists in the system. It is assumed that CHP plants cannot be in operation at a load less than 50% of their full capacity, since they have a poor degree of efficiency when running at partial capacity (Bärring, Nyström et al. 2003).

6.1.3 Data for the existing and model kraft pulp mills studied in Paper IV

The proposed model in Paper IV was developed on the basis of data and characteristics for two model mills and three existing mills. The model mills depict an average Scandinavian softwood kraft pulp mill (the same mill as referred to in Section 6.1.1, called Type SW in the table below) and a green-field hardwood mill built with BAT (called Ref HW in the table below). The data for the three existing kraft pulp mills were provided by the mills and supplemented by public data. An overview of the mills included in the model development is given in Table 6.

Table 6. *Overview of characteristics for the mills included in the construction of the model.*

	Model mill Type SW	Model mill Ref HW	Södra Cell Värö	Södra Cell Mörrum	Södra Cell Mönsterås
Production [1000 ADt/yr]	327	817	396	427	703
Type of pulp SW/HW	SW	HW	SW[a]	SW/HW[a]	SW/HW[a]
Unbleached/ECF/TCF	ECF	ECF	TCF	ECF/TCF	TCF
Total fuel use [GWh/yr]	2 158	4 285	2 731[b]	3 054[b]	5 637[b]
share biomass[c] [%]	92	100	96[b]	90[b]	96[b]
Total electricity use [GWh/yr]	259	503	298	318	559
Produced at the mill [GWh/yr]	194	814	336	324	662

For the real mills, all data are from the Swedish Forest Industries Federation (SFIF 2008) and refer to 2007 unless stated otherwise. For the model mills, all data are from FRAM (2005).
[a] *Data from Södra Cell (2009)*
[b] *Data from SFIF (2008), recalculated following personal communication with process engineers at the mills.*
[c] *Fossil fuels are mainly used in the lime kiln and for starting up boilers. One way of reducing the use of fossil fuel is to gasify bark and use the produced gas to power the lime kiln.*

For verification, data from three additional existing mills and two additional model mills were used. The mills used for verification were not used in the model development.

6.1.4 Data for the existing TMP mills studied

For the discussion in Paper IV, data and results for six mills – one model mill and five real mills – were used. An overview of key characteristics for these mills is given in Table 7. The data and the HLMPP analysis for mills nos. 1-4 were gathered and performed for the study presented in Paper IV, whereas the data and results for mills 5-6, used for comparison, are based on earlier studies (Axelsson and Berntsson 2005; Ruohonen, Hakala et al. 2010). All of the mills studied are integrated mechanical mills where the pulp production mainly TMP is. Since the steam recovered from the refiners is proportional to the electricity input, the specific electricity consumption (SEC) in the refiners impacts the amount of supplementary steam needed to be produced in boilers. Apart from one mill, Mill 6 which is a state-of-the-art model mill producing SC paper, all of the mills studied produce steam in boilers to supplement the steam generated by the TMP heat recovery.

Table 7. *Data for the four mills studied and two previously studied mills for comparison.*

	Mills analysed with the HLMPP for this paper				Previously studied mills	
	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6
Production capacity paper [kt/yr]	280	780	600	550	697	456
Paper quality	News/ MFC	News	News	SC	TD/news/ LWC	SC
Type of (virgin) pulp production	TMP	TMP	TMP	TMP/GW	TMP	TMP
TMP fibre content [%]	94	64	61	48	53	58
GW fibre content [%]	0	0	0	8	0	0
RCF/DIP content [%]	0	33	31	0	29	0
Bought kraft pulp content [%]	2	0	0	12	14	12
Filler content [%]	4	3	8	32	4	30
Total steam demand [MW]	48	137	105	105	99	65
Steam produced in boilers [%]	29	47	53	42	32	0
Steam surplus/vented [MW]	2[a]	-	-	-	-	21
Refining SEC[b] [kWh/Adt]	2100/2250	1900/2000	1750/2200	2900	1900/2200	3050
Heated fresh water, divided for each PM [$t/t_{paper92}$]	7.0-12.0	3.7-6.0	8.5-11.2	6.5-22.5	7.5-10	4.7

[a] *On a yearly average 2MW is vented; however, the venting is very intermittent.*
[b] *For the mills having TMP lines with refiners with different SEC both SECs are presented.*

6.1.5 Investment costs and data for the technology pathways studied

Table 8 presents the investment and operating costs for the technology pathways studied. The technical and economic data for the technology pathways are largely based on previous research focused on each technology. Energy-related operating costs have been omitted in the table since they vary depending on the energy market prices (see Section 8). To be able to implement (any of) the pathways in an energy-efficient way, the mill’s energy efficiency needs to be improved in order to give a steam or heat surplus which can then be utilized to cover the energy demand of the new processes. The different technologies studied represent different alternative ways to utilize a potential steam surplus. Thus, it is important to note that it is not a full-scale BLG unit that is considered but a booster to complement the recovery boiler.

Technically, the studied technology pathways can be combined, that is, simultaneous investments can be made in more than one technology pathway as long as there is surplus steam or excess heat available. Yet some combinations of pathways are likely (e.g. the combination of production of district heating and all other pathways) and some are less likely since they benefit from economy of scale and compete for the same steam surplus (e.g. the combination of investment in a condensing turbine and investments in CCS). However, which investments are made is determined by optimization and depends on the energy market prices.

In Papers I-III and V the investment costs are given in the monetary value of 2005, whereas in Papers VII and IX (and Table 8 above) the investment costs have been updated to the monetary value of 2008 using CEPCI.

Table 8. *Summary of investment and operating costs for the units needed for implementation of the technology pathways studied.*

	Investment and operating costs[a]	**Based on**
BLGMF/BLGMF with CO_2 separation[b]	$7055BL^{0,6}$ M€, 9.7 k€/yr/BL	Ekbom et al. 2005
BLGCC[b,c]	$5952BL^{0,6}$ M€, 1.0 k€/yr/BL	KAM 2003
BLGCC[b,c] with CO_2 separation	$6365BL^{0,6}$ M€, 1.0 k€/yr/BL	KAM 2003,Ekbom et al. 2005
Lignin extraction plant[d]	$7.2LR^{0,6}$ M€, 5.8 €/MWh	Olsson et al. 2006
Back-pressure steam turbine[e]	$1.3P^{0,6}$ M€	Olsson et al. 2006
Condensing steam turbine[e]	$2.4P^{0,6}$ M€	
CO_2 separation plant for RB flue gases[f, g]	$2.3CO_2{}^{0.7}$, 4% of investment cost	Hektor and Berntsson 2007
CO_2 compressor[f, h]	$1.1P^{0.7}$, 4% of investment cost	
Transportation and storage of CO_2	8 €/t	
Heat pump for DH[i]	0.11Q M€	Bengtsson 2004
Heat exchanger steam-DH[i]	0.68+0.033Q M€	
Heat exchanger heat-DH[i]	0.059+0.042Q M€	

[a] *All values in 2008 money value. All investment costs have been recalculated to 2008 money value using Chemical Engineering's Plant Cost Index (CEPCI).*
[b] *BL refers to the flow of black liquor in MW.*
[c] *Excluding the steam turbine/s.*
[d] *LR refers to the lignin extraction rate in kg/s.*
[e] *P refers to the power output in MW.*
[f] *Operating cost CO_2 absorber and CO_2 compressor; 4% of investment cost.*
[g] *CO_2 refers to the CO_2 capture rate in kg/s.*
[h] P is the compressor electricity demand.
[i] Q refers to the heat supplied by the heat pump or heat exchanged in the heat exchanger in MW.

6.2 Input data for industry level analysis

As previously stated, the European pulp and paper industry is defined as mills located in the countries that are included in CEPI (CEPI 2008), i.e. the countries in Europe with the highest density of pulp and paper industry. However, the European PPI is currently in a situation where many (small) less profitable mills are decommissioned (CEPI 2011). Thus, not all of the mills in production today will still be in production at the time when pathways such as CCS or BLG will be commercially available. To take account of this fact, a selection of mills to be included was made together with PPI consultants from Pöyry. Thereby 171 mills were selected and included, based on their competitive strength and size. Five more mills were then added due to their large size and good availability of data. Hence, here the European PPI is represented by 55 kraft pulp and/or paper mills, 45 mechanical pulp and paper mills, and 76 paper mills without any virgin pulp production (having only bought pulp and/or RCF/DIP). Data for the included mills are presented in Table 9. Due to the large amount of mills included in the study, the data are presented in aggregated form. As can be seen in the table, a large share of the CEPI pulp production and a fair share of CEPI paper production are covered by the included mills.

Table 9. *Production capacity data for the mills included in this thesis compared to CEPI totals.*

Type of mill[a]	Kraft		Mechanical	Paper
	Market pulp	Pulp & Paper	Pulp & Paper	
Mills [No.]	23	32	45	76
Pulp cap. [kADt/yr]	10 400[b]	13 500[b]	12 095[c]	14 775[d]
Paper cap. [t/yr]	-	16 781	22 132	27 169
CEPI total pulp production[e]	*11 573*	*14 305*	*14 686*	-
CEPI total paper production[e]				*102 570*

[a] Kraft refers to mills that have the kraft process; they may also have other pulp production, e.g. CTMP. Mechanical refers to mills that have some mechanical pulping process (TMP, CTMP, GW/PGW or RMP). They may also use other pulps in the process such as RCF/DIP or bought kraft pulp. The paper mills have no pulp production from virgin pulp; they only use RCF/DIP and/or bought pulp.
[b] Including only kraft pulp produced on site. If all pulp produced on site is included, the numbers are 10,485 and 15,115 kADt/yr respectively.
[c] Including only mechanical pulp. If both mechanical pulp and RCF/DIP are included, the figure is 17 420 kADt/yr.
[d] The number refers to RCF and DIP.
[e] Figures from CEPI 2008 referring to the year 2007.

6.3 Input data for analysis of the connections to surrounding system(s)

Below, the data for the analysis of the connections to surrounding systems are presented for two dimensions of surrounding systems: (1) data for the geographical proximity between the PPI and other energy-intensive industries and important energy infrastructure, and (2) data for the surrounding (European) energy market.

6.3.1 Data for other heavy industries and power plants

The mapping of the PPI in relation to other heavy industries and the power and heat sector in Europe was done in collaboration with fellow researchers within the Pathways project, Johan Rootzén and Jan Kjärstad. The other heavy industry sectors are presented in Rootzén et al. (2011) and the power sector is presented in e.g. Kjärstad and Johnsson (2007). The information was collected and stored in Chalmers' industry database (Chalmers IN db) and Chalmers' power plant database (Chalmers PP db), sub-databases to the Chalmers energy infrastructure database which is designed to cover both the supply side and the demand side of the European energy systems (Kjärstad and Johnsson 2007).

6.3.2 Data for the scenarios describing possible future energy markets

In this thesis, the scenarios for energy prices and associated CO_2 emissions used were generated using the ENPAC tool (see Section 5.2.1). Since the ENPAC tool was further developed and updated in parallel to the thesis work, different versions of the tool, giving somewhat different price and emission levels, have been used. However, the general concept of the tool and the underlying structure for determining prices and emissions remained the same throughout the work. In Tables 10-12 the scenario data used for the analysis in Papers I-III, V, VII and IX are presented. It should be noted that the prices refer to the monetary value of 2005 for Tables 10 and 11 and the monetary value of 2008 for Table 12.

Table 10. *Key data for the four energy market scenarios used in Papers I-III.*

Scenario input data		**1**	**2**	**3**	**4**
Fossil fuel price level		Low	Medium-Low	Medium-high	High
CO_2 charge level		Low	High	Low	High
CO_2 charge	[€/t CO2]	27	44	27	44
Green electricity policy instrument	[€/MWh]	16	5	16	5
Resulting prices and values of policy instruments[a] [€/MWh]					
Electricity		55	60	59	63
Wood chips		17	24	18	34
Heavy fuel oil (incl. CO_2)		29	34	41	46
Resulting marginal/alternative technologies and their CO_2 emissions [kg/MWh]					
Electricity		374	136	723	136
(marginal production of electricity)		(NGCC)	(CP CCS)	(CP)	(CP CCS)
Biomass		329	329	329	159
(alternative use of biomass)		(CP)	(CP)	(CP)	(CP)

[a] *Not all price data used are displayed here. For prices of natural gas, coal and waste see Paper II.*

Table 11. *Key data for the four energy market scenarios used in Paper V.*

Scenario input data		**1**	**2**	**3**	**4**
Fossil fuel price level		Low	Low	High	High
CO_2 charge level		Low	High	Low	High
CO_2 charge	[€/t CO2]	26	42	26	42
Green electricity policy instrument	[€/MWh]	16	5	16	5
Resulting prices and values of policy instruments [€/MWh]					
Electricity		54	59	57	62
Bark/by-products		14	20	15	21
Lignin		17	23	18	25
Heavy fuel oil (incl. CO_2)		29	29	49	49
District heating[a]		14	21	31	30
Resulting marginal/alternative technologies and their CO_2 emissions [kg/MWh]					
Electricity		374	136	723	136
(marginal production of electricity)		(NGCC)	(CP CCS)	(CP)	(CP CCS)
Biomass		329	329	122	159
(alternative use of biomass)		(CP)	(CP)	(DME)	(DME)
District heating		278	373	-143	140
(alternative heat supply technology)		(bio CHP)	(bio CHP)	(bio CHP)	(bio CHP)

[a] *Based on new biomass CHP as the competing heat supplier and an investment in 18 km of piping (for a maximum of 40 MW and 4000 h).*

As can be seen in Tables 10-12, one difference between the sets of scenarios used is how district heating is valued. It is only in the last version of the tool (used in Papers VIII and IX) that district heating has been an integrated part. Using this version of the tool, two levels for pricing district heating are given: a lower level based on the assumption that the heat price is set by the heat production price in a coal CHP unit, and a higher level assuming that the price is set by stand-alone gas boilers. This gives a large price span and, since excess heat is assumed to be base load or middle load in the heat supply of a district heating grid, a fairly low price can be expected. Thus, in Papers VII and IX, a weighted average between the two suggested price levels of 75% of the lower price and 25% of the higher price was used. The CO_2 emission related to the alternative heat supply technology was weighted accordingly. In Papers I-III, the district heating system was integrated into the studied system by studying the mill and a utility within the same system boundary. Due to this fact, the need for determining marginal production and emissions district heating in a surrounding system was eliminated since this part of the surrounding system was integrated in the model. Based on results from Papers I-III, in Paper V, the alternative district heat supply technology was assumed to be biomass CHP.

Table 12. *Key data for four of the six energy market scenarios used for 2030 in Papers VII and IX.*

Scenario input data		**1**	**3**	**4**	**6**
Fossil fuel price level		Low	Low	High	High
CO_2 charge level		Low	High	Low	High
CO_2 charge	[€/t CO_2]	35	109	35	109
Green electricity policy instrument	[€/MWh]	26	26	26	26
Resulting prices and values of policy instruments [€/MWh]					
Electricity		68	90	74	98
DME		57	77	88	109
Bark/by-products/wood chips[a]		27	52	30	56
Heavy fuel oil (incl. CO_2)		45	67	67	89
District heating		19	49	27	56
Biofuel policy instrument		46	67	20	41
Resulting marginal/alternative technologies and their CO_2 emissions [kg/MWh]					
Electricity		679	129	679	129
(marginal production of electricity)		(CP)	(CP CCS)	(CP)	(CP CCS)
Biomass		227	244	227	244
(marginal user of biomass)		(CP/DME)	(CP/DME)	(CP/DME)	(CP/DME)
District heating production		242	468	242	468
(alternative heat supply technology)		(CCHP/GB)	(CCHP/GB)	(CCHP/GB)	(CCHP/GB)
Transportation		273	273	273	273
(alternative transportation technology)		(Diesel)	(Diesel)	(Diesel)	(Diesel)

[a] *In the past years the prices of wood by-products and chips have been very similar.*

Further, at the time of this thesis work, the ENPAC tool did not include any policy instrument promoting production of biofuels. In Papers VII and IX (the only papers with production of biofuels at the mill), such a policy instrument was assumed and set at a level such that a stand-alone DME production plant (producing DME via gasification of solid biomass) will have the same willingness to pay for wood fuel as a coal power plant. This implies that in the scenarios used, both coal power plants and DME production plants are marginal users of biomass.

7 Results research theme 1: General integration opportunities in existing mills

As the first part of the results of this thesis, this chapter focuses on how general integration opportunities can be identified for kraft pulp mills and TMP mills. The first part of the chapter presents a methodology developed for estimating existing steam balances of kraft mills by using a limited amount of data. Thereafter, for TMP mills, the potentials for thermal energy efficiency and excess heat temperature levels are presented.

For a pulp and paper mill, biorefinery concepts can be thermally integrated in three ways: (1) use of excess heat, or steam, from the mill processes to cover heat demands in the biorefinery processes, (2) use of excess heat, or steam, from the biorefinery processes to cover heat demands in the mill processes, and (3) a combination of the two alternatives mentioned above. Further, generally, to be able to make fair assumptions regarding the potential for energy efficiency and the development towards a more sustainable energy system, the existing energy system needs to be known since the characteristics of the present system heavily affect the potential and consequences of future changes.

In this work, results from Papers IV and VI aim to act as building blocks in the task of acquiring knowledge and data concerning integration opportunities in existing European kraft pulp mills and TMP mills. The aim is to analyse how/whether general integration opportunities can be identified and to identify factors that influence the integration opportunities, in order to determine whether previously identified integration potentials for specific mills can be extrapolated to the European mill stock. The work adds to the previous knowledge gained from detailed process integration (case) studies made on existing, and model, kraft mills.

7.1 Kraft pulp mills – a methodological approach for estimating steam balances

In Paper IV a model for systematic estimation of the existing steam balances for individual kraft pulp mills was developed on the basis of data from five kraft pulp mills. The model is a systematic, Excel-based tool that links production- and energy-related data to the steam balance of a mill. Input data for each mill are put into a pre-defined form and, based on these input data, the existing steam balance is calculated stepwise.

The term ‘steam balance’ refers to the amount of high-pressure (HP) steam produced, process steam consumed at different pressure levels (HP, MP2, MP and LP), throttled steam, steam through back-pressure and condensing turbines, vented steam and steam used for the production of sold heat.

Throughout the model development process, emphasis was put on the trade-off between simplicity of the model, e.g. by limiting the amount of input data needed to just data that are either publicly available or can be easily obtained, and accuracy, checked by comparing model results with real mill data. The model was developed by using a systematic step-by-step approach based on (1) detailed energy balances of model kraft pulp mills and real kraft pulp mills, (2) public mill data for production, energy and electricity, and (3) previous research and case studies regarding energy efficiency and new technology solutions.

Fig. 8 shows how the data needed to estimate the steam balance of a mill were identified through identification of factors influencing the steam balance and identification of the relationships between these factors and specific mill data. These factors and relationships are further described in Paper IV.

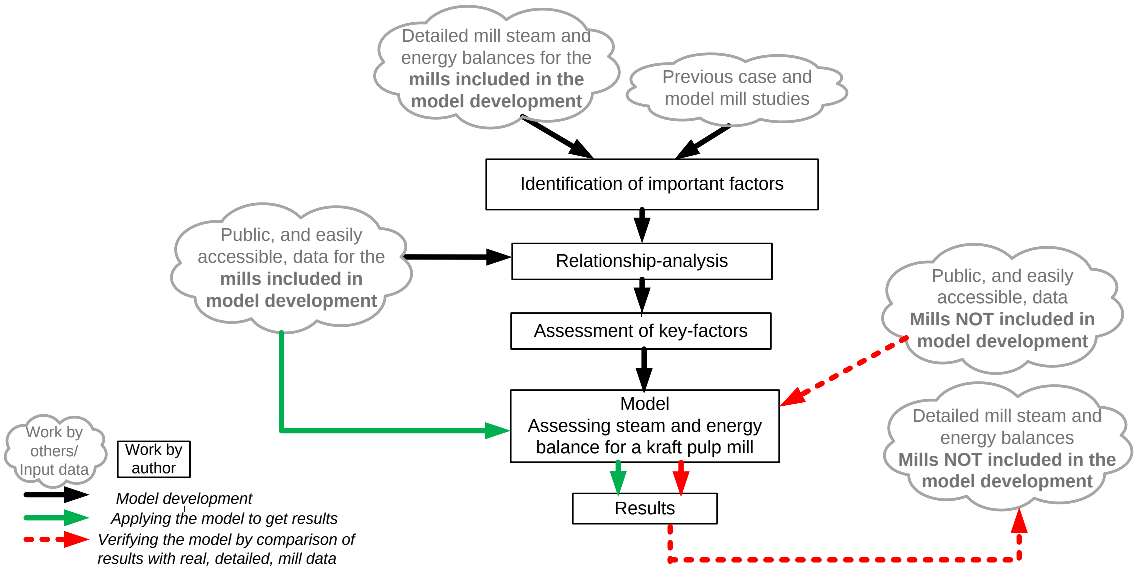
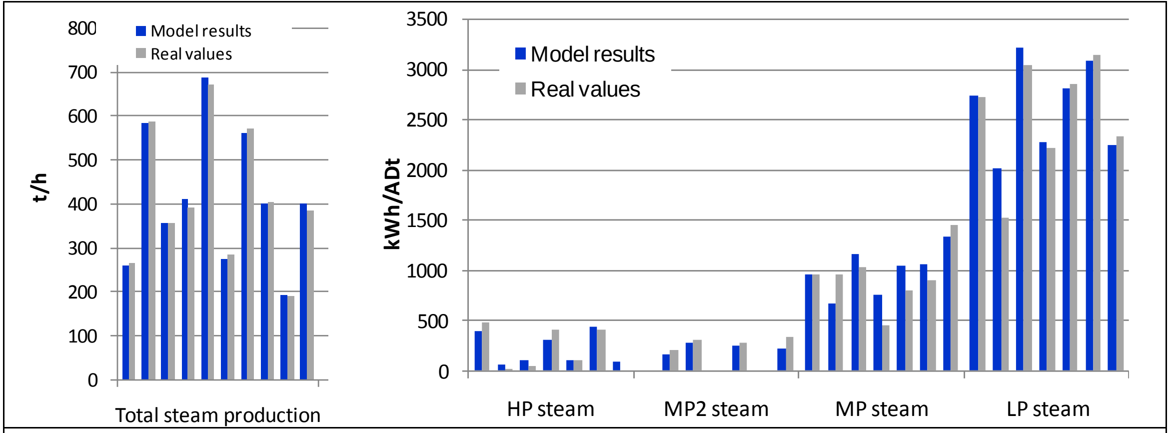


Figure 8. *Description of the methodological approach developed for estimation of kraft pulp mill steam balances. The black arrows show the process of model developments and the green arrows and the red dotted arrows show the process of applying the model to generate results and perform validation.*

To evaluate the proposed model, the results obtained with it were compared to actual data for the five mills included in the model development as well as six additional mills not included. Fig. 9 presents the comparison for the total steam production and the steam use at different pressure levels. As can be seen, the model gives a fair estimate of the steam use at different pressure levels. The largest difference between model values and real values was obtained for the estimated MP steam use for mills with low total process steam consumption. This is probably because a new and efficient design of e.g. the evaporator uses less steam in total but more MP steam.



Note: Full sets of real data for process steam use at different pressure levels were not available for all mills, hence a limited number is presented.

Figure 9. *Model validity for estimating process steam use. The figure shows the distribution obtained by using the model compared with real values.*

One problem that emerged during the validation of the model was that not all mills know their actual steam use in different processes and/or at different pressure levels. In some cases, the mills had data only for parts of their process steam use and, consequently, in these cases not all steam data could be compared with the results gained from the model. Further, since the amount of detailed data available for the development of the model was limited, and referred almost exclusively to Swedish mills, the model may not be equally applicable for all European kraft pulp mills. It would thus be interesting to further apply and validate it with data from non-Swedish mills. Nevertheless, in light of the results from the validation the model would appear to be quite accurate.

When using data from public sources, the risk of errors in the reported data must be borne in mind. For this model, one main source of public data used was the Environmental database managed by the Swedish Forest Industries Federation. In the course of the model work, some data in the database were compared to detailed mill data obtained from the mills' internal energy reports. This revealed certain errors in the database such as errors in the amount of pulp and/or paper produced and errors in the total amount of energy used (in one case the energy used in the lime kiln was excluded, giving an error of 22% in the amount of total fuel usage). As stated above, the model yields good results when using accurate input data. However, since there is no guarantee that the publicly reported data are correct, the main uncertainties are probably not in the model itself but in the data retrieved from public sources.

7.1.1 Summary of conclusions from this sub-chapter

From this work regarding the development of a methodology developed for estimating existing steam balances of kraft mills using limited amounts of data, the following conclusions can be drawn:

- The minimum amount of data needed to estimate the steam balance of a kraft pulp mill is data for production, fuel usage, power balance, heat sales, recovery boiler steam pressure, and pressure of steam used for soot blowing.
- Using this limited amount of data the developed model gives a fair estimate of the steam balance of a kraft pulp mill, e.g. the model accuracy for total steam production is +/- 8%.
- If data were available, the model could be developed further to include an assessment of the steam use in different processes in order, for example, to calculate the potential for introducing new, efficient technology solutions, such as lignin extraction and black liquor gasification.
- The key factor for a good, accurate analysis on a more aggregated level is the availability and accuracy of input data.

7.2 The mechanical pulp and paper industry – potential for increased thermal energy efficiency in TMP mills

In Paper VI, the potential for steam savings is identified together with excess heat temperature levels for four Scandinavian TMP mills by using the HLMPP (see Section 5.4.2 for description of the HLMPP tool). The results are compared with similar results from previous studies for two other TMP mills. The main results are presented in Table 13, Fig. 10 and Fig 11.

As can be seen in Table 13, the theoretical potential for steam savings for the four mills studied ranges between 2 and 20%. These levels of steam savings are comparable to the levels previously identified for TMP mills; see Mills 5-6. However, as can also be seen, both the current steam use and the amount of theoretical steam savings identified vary a lot between the mills.

In Fig. 10 it can be seen that, in general, there is excess heat available but it has a rather low temperature. Only one mill has a pinch temperature >80°C and that is a state-of-the-art model mill. Furthermore, it can be seen that two of the mills, Mill 4 and Mill 5, only have a heating demand and thus their Grand Composite Curves are un-pinched. For these two mills the heat demand curve starts close to 0°C; this indicates a high water usage and, hence, some of the fresh water, heated to a rather moderate temperature level, will be heated using external hot utility (steam). Finally, from the Grand Composite Curves, it can also be seen that for Mills 1-3 there is a small temperature span between the heating demand and the cooling demand just around the pinch point. This indicates that implementation of a heat pump could be of interest since heat from below the pinch could be raised to a temperature above the pinch with a small temperature lift, saving additional 2-12 MW of steam for Mills 1-3, corresponding to ~7-8% of the mills' original steam consumption.

Table 13. *Overview of main results in form of steam-saving potentials and excess heat temperature levels for the four mills analysed and two previously studied mills for comparison.*

	Mills analysed with the HLMPP for this thesis				Previously studied mills	
	Mill 1	Mill 2	Mill 3	Mill 4	Mill 5	Mill 6
Original steam demand [MW]	48	137	105	105	99	65
[kW/$t_{paper92}$]	*66.3*	*53.4*	*62.6*	*77.2*	*51.1*	*49.4*
Theoretical savings potential [MW]	9.7	2.9	5.1	20.7	9.0	3.4
[kW/$t_{paper92}$]	*13.4*	*1.1*	*3.1*	*15.2*	*4.6*	*2.6*
[%]	*20*	*2*	*5*	*20*	*9*	*5*
Hot water (>80°C) available [MW]	0	0	0	0	0	4.0
[kW/$t_{paper92}$]	*0*	*0*	*0*	*0*	*0*	*3.1*
Pinch temperature [°C]	65	72	65	0[a]	0[a]	117

[a]If maximum heat recovery is achieved; these mills have only a heating demand and no cooling demand. This is shown by un-pinched Grand Composite Curves in Fig. 10 and thus the temperature is not a pinch temperature but the starting temperature for the heat demand curve.

It should be noted that the discussion presented above is based on the Grand Composite Curves showing the situation for the case of minimum theoretical steam consumption. If no retrofit measures are made, the mills will have higher steam consumption and the Grand Composite Curves will not look the same. However, an analysis showed that, if a global ΔT is set and adjusted so that the steam demand in the GCC corresponds to the current steam demand, the pinch temperature remains low, between 18°C and 62°C, and thus the discussion above can be assumed to be valid also if no retrofit measures to achieve a lower steam consumption are made.

To be able to draw some general conclusions regarding the steam use and the potential for steam savings, an analysis was made to try to identify any relationship between steam use and the potential for steam savings and other important process parameters. The parameters studied were: (1) Technical age of equipment, (2) TMP share of pulp used, (3) Daily paper production and (4) Fresh warm water usage. For parameters 1-3, no significant correlation was found, neither with the current steam consumption nor with the theoretical minimum steam consumption. A correlation was found only for the fourth parameter, the fresh warm water usage, as presented in Fig. 11. It was also found that the fresh water usage affects the pinch temperature or, for the two mills with un-pinched Grand Composite Curves, the start temperature for the heat demand curve. A low fresh warm water usage gives a high pinch temperature and thus a more usable temperature of the excess heat available. These results are in line with similar results from earlier studies made on kraft pulp mills showing that a lower use of heated fresh water gives excess heat at higher temperatures, and thus a larger potential for further process integration (Wising, Berntsson et al. 2005; Axelsson, Olsson et al. 2006). Hence, it can be concluded that water management is important, also for energy efficiency purposes in mechanical pulp and paper mills, and that the energy and water demand at a mill should be analysed together when striving for increased energy efficiency.

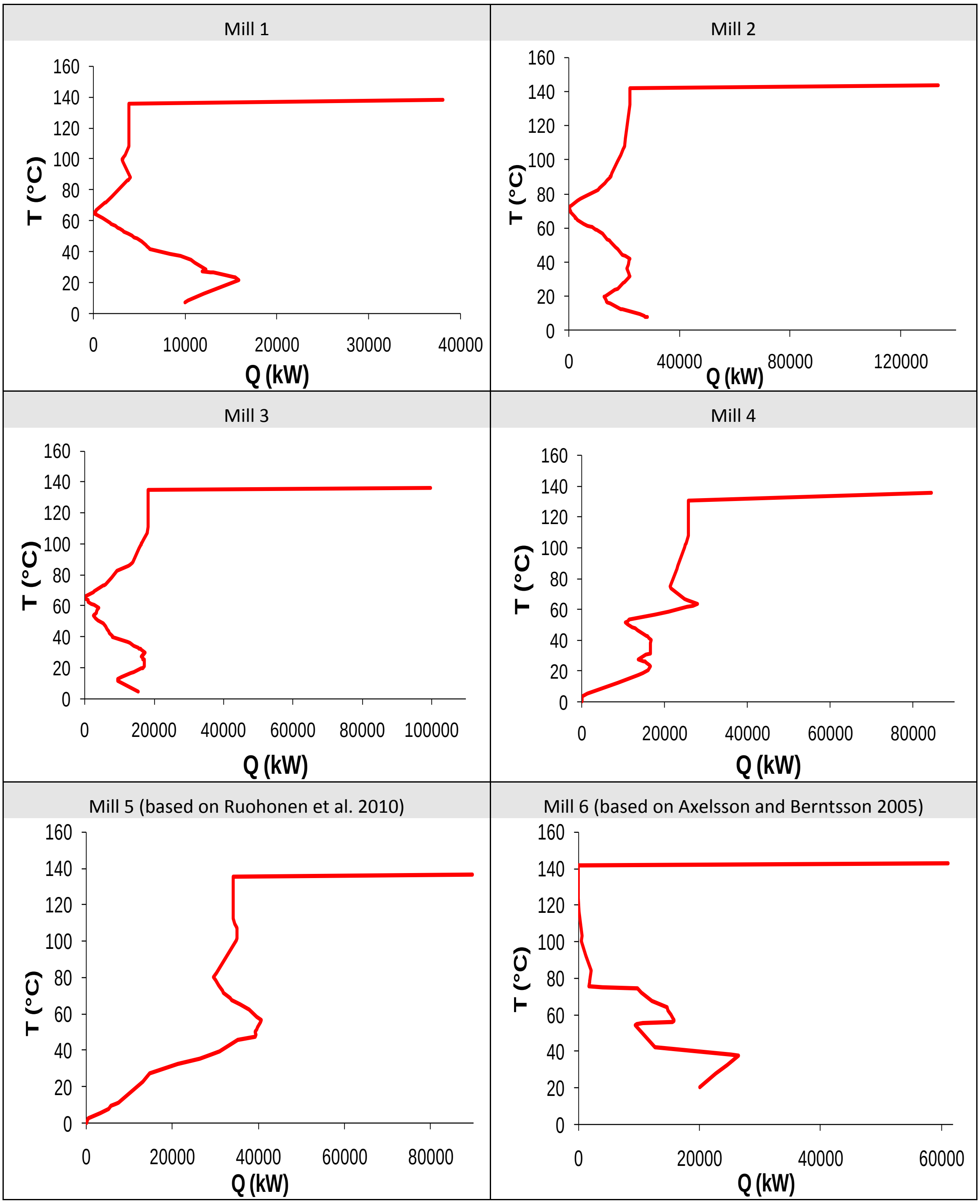


Figure 10. *Grand composite curves for the mills analysed using the HLMPP tool, No. 1-4, presented with grand composite curves for previously analysed mills, No. 5-6. The red lines represent the Grand Composite Curves after potential retrofits.*

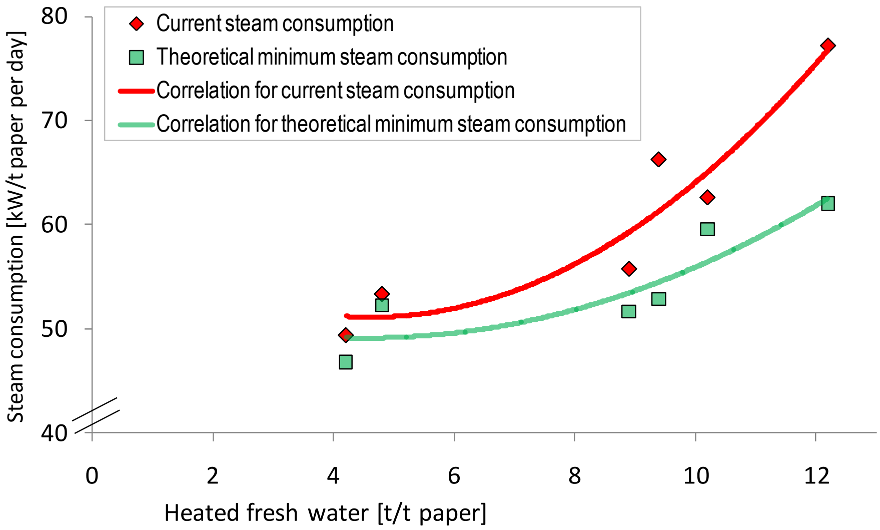


Figure 11. *Linkage between fresh warm water consumption, steam use and theoretical minimum steam consumption.*

7.2.1 Summary of conclusions from this sub-chapter

For this work regarding excess heat temperature levels, potential for steam savings and integration opportunities in TMP mills, the main conclusions are:

- For the TMP mills studied, the theoretical steam-saving potential varies between 2% and 20%. Looking at the shape of the Grand Composite Curves, three of the studied mills show promising potentials for further steam savings of up to 12 MW (equal to ~7-8% of the mills' original steam consumption) by installation of heat pumps.
- For TMP mills, the level of fresh warm water usage affects both the steam consumption and the pinch temperature and thus also the potential for efficient integration of different biorefinery processes.
- The pinch temperature, and thus the temperature of excess heat, is quite low, ranging from 18 to 72°C for all of the studied mills (both for the existing configuration of the HENs and if maximum energy recovery is achieved), except for the model mill based on best available technology (which shows a pinch temperature of 117°C if maximum energy recovery is achieved). Further, two of the mills are un-pinched and have no cooling demand and thus no excess heat available.
- Due to a low pinch temperature, possible biorefinery applications for TMP mill excess heat are rare, at least if the mill has a high fresh water usage. However, due to the same fact, thermal integration with new biorefinery processes could supply part of the mill's heating demand and thereby further reduce its current steam demand.

7.3 Addressing the research question in theme 1

Based on the results and conclusions above, the research questions in theme 1 regarding general integration opportunities in different types of existing mills, as stated in the aim, can be addressed:

What are the characteristics of the mills' existing energy systems and how do they influence the potential for thermal integration of new processes? TMP mills, generally, have a heating demand partly at lower temperatures than kraft mills. This means that they could benefit from receiving heat if integrated with another process. Kraft mills on the other hand, having higher pinch temperatures, have a larger potential to supply heat and steam to new processes. Most of the existing kraft mills studied currently throttle steam. This shows a potential for increased electricity production if investments in new turbines are made. For the TMP mills studied, the fresh warm water usage was proven to greatly influence both the potential for steam savings and the pinch temperature.

How large is the potential for process steam savings for different types of mills? The theoretical potential for steam savings (2-20% of current steam use) in the TMP mills studied is somewhat lower than the theoretical potential identified for kraft mills in previous research. Generally, TMP mills cannot reach self-sufficiency in thermal energy by increased process integration alone, and thus the steam savings, if achieved, will not lead to a steam surplus (as for kraft pulp mills) but to a reduction of the fuel usage.

At what temperature(s) can excess heat be made available? The amount and temperature of the excess heat depend on the type and size of the mill. Generally, TMP (and probably also ground wood mills and pure paper mills) mills have lower pinch temperatures, <80°C, compared to kraft mills, usually having pinch temperatures >90°C.

Are there ways to draw general conclusions for different types of mills? The model for estimating steam balances for kraft mills seems to give accurate estimations. From earlier validation studies, the HLMPP also has been proven to give fairly accurate results, at least for the system above the pinch temperature. Although both models would benefit from further validation and use, it can be concluded that fairly accurate estimates can be made regarding the general integration opportunities for different types of mills based on a limited amount of data (provided that the data are accessible).

8 Results research theme 2: Economic performance and global CO_2 emissions assuming different future developments of the European energy market

This chapter presents the main findings from the papers which compare the performance of the selected technology pathways for utilization of kraft pulp mill excess heat. First, it is shown how changes in energy market prices and the assumed district heating system influence both the pricing of excess heat and the trade-off between using the excess heat for production of electricity and export of district heating. Thereafter, the economic performance and the potential for reduction of global CO_2 emissions are evaluated and compared for a number of both proven and new technology pathways.

As stated in the introduction, for a kraft pulp mill there are many technology pathways available for improvement of energy efficiency and additional sales of (new) products. From a future perspective, however, it is not as clear which technology pathway is the most profitable one or which pathway gives the lowest emissions of CO_2 due to uncertainties in the future value of different products. This can lead to uncertainty for the kraft pulp mill regarding the choice of technology pathway. In this chapter, the economic performance and the potential for reduction of global CO_2 emissions are evaluated and compared for a number of selected technology pathways assuming different developments of the future energy market.

The work done for the results presented in this chapter is largely based on earlier, detailed research work. This earlier research has identified the potential for increased process integration and steam savings in the kraft pulp model mill, as well as the technical and economic data for the different pathways compared. The contribution of the present work is to bring together this earlier work, to compare the different pathways and to analyse them using a higher systems perspective.

8.1 Trade-off between using kraft pulp mill excess heat internally in mill processes and using it externally for production of district heating

In Papers I and II, an average Scandinavian kraft pulp mill is modelled within the same system boundary as a utility; see Sections 6.1.1 and 6.1.2 for input data. The purpose of the study was to analyse the trade-off, in terms of economics and CO_2 emission consequences, between using low- and medium-quality pulp mill excess heat (warm and hot water) internally at the mill or externally for production of district heating. In Paper III, high-quality excess heat (steam) was also included in the analysis. This, however, did not significantly change the results in any way but rather strengthened the general conclusions that were drawn. The analysis in Papers I-III was made for four scenarios for the future energy market (see Table 10) and three types of district heating systems with differently sized heat loads and heat production mixes: Small (S), Medium (M) and Large (L). The main results from Papers I and II are presented in Figs. 12 and 13. Based on the results, four main questions can be addressed, as presented below.

How do external factors affect the economic profitability for external use of industrial excess heat as district heating? As can be seen in Fig. 12, small district heating systems show a larger potential for profitable excess heat co-operation and a larger robustness for the obtained solutions with respect to energy market prices compared to medium and large systems, which have greater potential for large-scale biomass CHP. If the heat load is small, however, the culvert cost will have a large influence on the economic performance and thus a low capital recovery factor is necessary in order to obtain profitability. For the scenarios with low CO_2 charge, and consequently a lower biomass price (Scenarios 1 and 3), the potential for profitable co-operation regarding the mill's excess heat is lower than for the scenarios with high CO_2 charge (Scenarios 2 and 4). These general conclusions are further strengthened if also high-quality excess heat is included (as in Paper III) or if a capital recovery factor of 0.2 is used (as in Papers V, VII and IX).

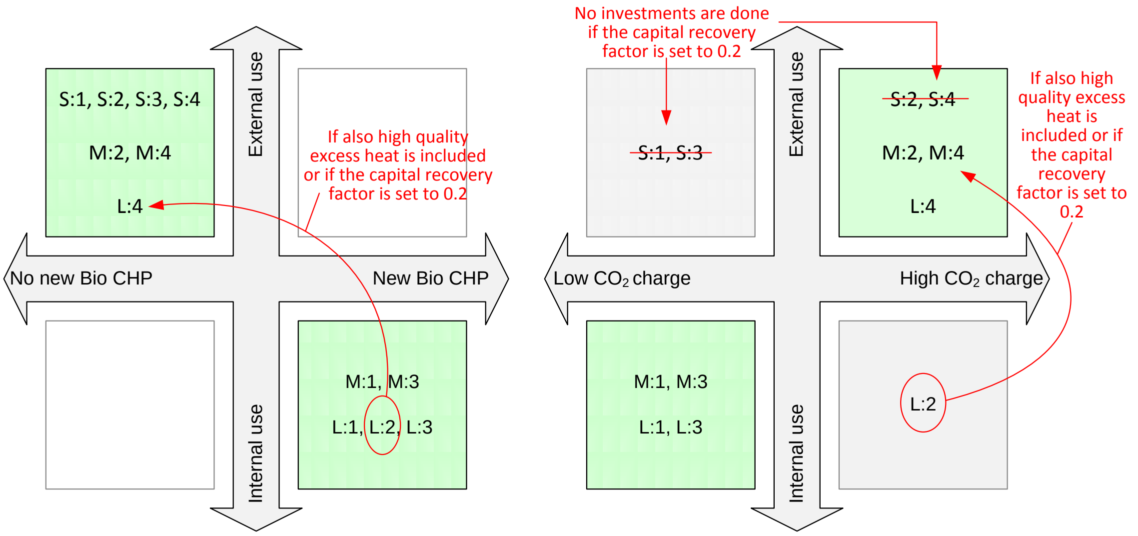


Figure 12. *Two positioning maps showing the characteristics of the optimal solutions for the studied systems with small (S), medium (M) and large (L) district heating loads (S:1-4, M:1-4 and L:1-4). In the positioning map to the left, it can be seen that external use of excess heat seems to be competing with investment in new Bio CHP. In the map to the right, the tendency shown is that a high CO_2 charge benefits external use of excess heat rather than internal use of the excess heat (and thus investment in biomass CHP for district heating production). The red marks and comments refer to how the results change if more excess heat is available or if the capital recovery factor is set to 0.2 instead of 0.1.*

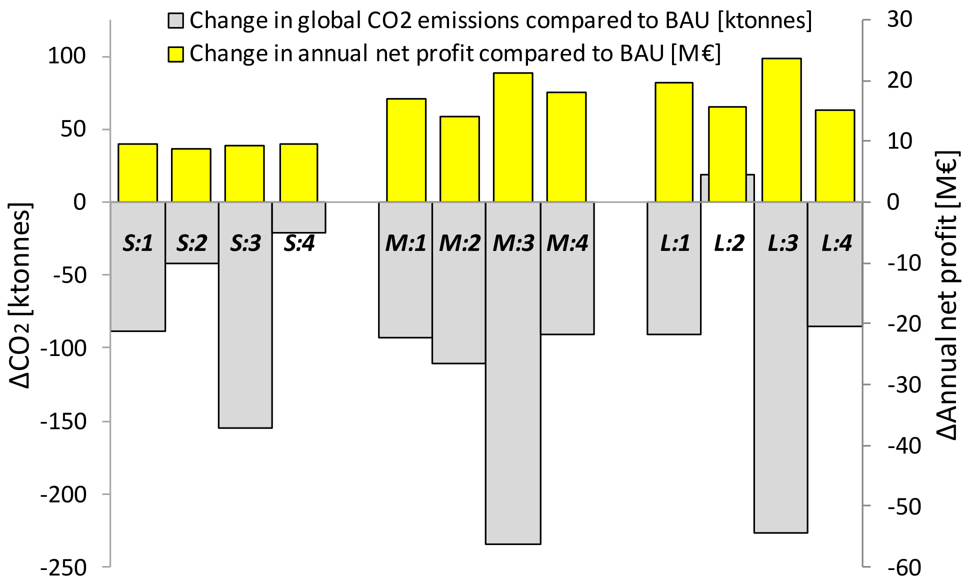


Figure 13. *The change in economic performance (yellow bars) and emissions of global CO_2 (grey bars) for the studied systems when investing in energy efficiency and new district heating capacity compared to BAU (not making any investments at all). Are any of the utilization options for the industrial excess heat more robust to the uncertainty of future energy prices than the others? Apart from the L:2 case, the cases with internal use of the excess heat as the optimal solution are somewhat more robust to changes in energy prices than the cases with external use. It is interesting to note that for Scenario 2 the optimal solutions are very close to the alternative solution for all studied systems.*

How does the choice of use of the excess heat affect the electricity production and the use of biomass in the system? For most systems studied, the alternative to external utilization of the excess heat is an investment in a biomass CHP; see Fig. 12. Consequently, when the excess heat is used internally, both the electricity production and the biomass use increase for the system as a whole. Compared to “business as usual” (BAU), however, there is an increase in the net electricity production for all of the studied systems and scenarios, independently of the use of excess heat, due to the increased electricity production at the mill (enabled by investments in new, larger turbines).

How does the choice of use of the excess heat influence the system’s global CO_2 emissions? As regards total system emissions, external use of the excess heat gives lower CO_2 emissions than internal use for most of the studied scenarios. It should be noted, however, that from a CO_2 emissions point of view, the changes in the electricity balance and the biomass use are valued rather differently in the scenarios depending on the marginal techniques assumed. This can be seen for S:1-S:4 in Fig. 13 where the optimal solution is the same (in terms of investments made and amount of electricity and biomass produced and used) – the only difference is in how this solution and its energy flows are valued. Further, it can be seen that regardless of how the excess heat is utilized, the largest emission reductions are achieved for Scenario 3. This is mainly due to the assumption that, in Scenario 3, the additional electricity produced in the studied system replaces electricity produced in coal power plants.

8.1.1 Summary of conclusions from this sub-chapter

From the work presented above, the following main conclusions can be drawn:

- For the scenarios with low CO_2 charge and a low biomass price (1 and 3), the potential for profitable co-operation regarding the mill's excess heat is lower than for the scenarios with high CO_2 charge and a high biomass price (Scenarios 2 and 4).
- For the cases where internal use of the excess heat (no co-operation) is preferred, the utility invests in a biomass CHP, and thus for those cases both the electricity production and the biomass use increase compared to when the excess heat is used for district heating purposes (external use).
- External use of the excess heat gives somewhat lower CO_2 emissions than internal use for most of the studied scenarios.
- Since both internal use (in combination with new biomass CHP) and external use of the excess heat are profitable investment strategies (on the given assumptions), leading to reductions of the system's global CO_2 emissions, the choice of strategy is not as important as the actual choice to do something.

8.2 Pricing of excess heat

In Paper III, the aim was to provide a broader understanding of the factors affecting the pricing of kraft pulp mill excess heat, and to analyse how the potential profit from excess heat co-operation and the associated price risk are distributed between the mill and the utility. For the analysis, supply and demand curves showing the mill's willingness to sell excess heat and the utility's willingness to buy excess heat were constructed. These curves are displayed in Fig. 14.

Analysing the curves, it can be concluded that for the scenarios with high CO_2 charge and high biomass price (Scenarios 2 and 4) there is a large span between the highest price that the utility is willing to pay for the excess heat and the lowest price that the mill demands for selling excess heat, which implies that there is a good potential for profitable co-operation. On the other hand, for the two Scenarios with a low CO_2 charge and biomass price (Scenarios 1 and 3) there is almost no, or a negative, span between the curves and thus no potential for profitable excess heat co-operation.

It should be noted that, in order to make the excess heat available, quite large changes need to be made in the studied pulp mill, such as rebuilding the evaporation train and rearranging the heat exchangers in the secondary heating system. In practice, excess heat can sometimes be available through smaller changes and thus at a lower cost. Further, the studied mill does not use external fuel, meaning that the excess heat utilized internally does not replace fuel but instead increases the amount of electricity produced in the new condensing turbine. The results could therefore change if the studied industry were not a kraft pulp mill but an integrated pulp and paper mill or a biorefinery, having a steam (and fuel) deficit.

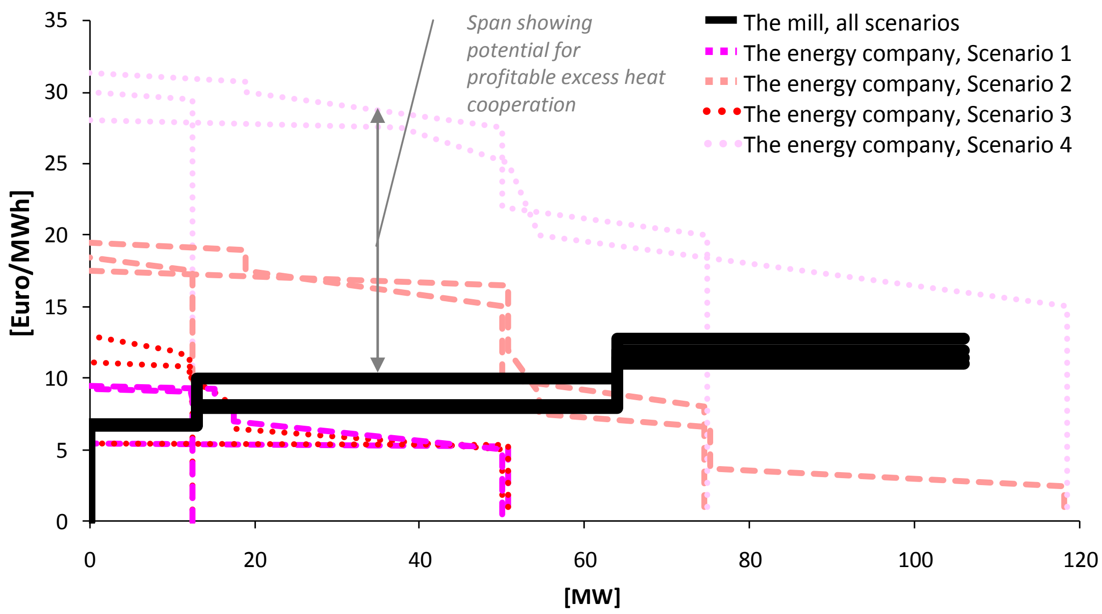


Figure 14. *Supply and demand curves showing the price for which the mill is willing to sell excess heat and the utility is willing to buy excess heat given the four energy market scenarios. Any span between these curves indicates a potential for profitable excess heat co-operation (exemplified by the grey arrow).*

8.2.1 Summary of conclusions from this sub-chapter

From the results some main conclusions can be drawn:

- The development of the future energy market strongly affects the price for which the utility is willing to buy excess heat, but has hardly any effect on the price for which the mill is willing to sell excess heat.
- The large span of the utility's willingness to pay between the different scenarios implies that the development of the future energy market has a larger effect on the profitability of potential excess heat co-operation than the level of excess heat available at the mill or the size of the utility's heat load.
- If there is a co-operation regarding the mill's excess heat, the utility has potential for the largest profit. However, due to the same variation, *the utility also bears the largest price risk.*

8.3 Comparison of technology pathways for utilization of kraft pulp mill excess heat

As described in Section 6.1.1, a typical Scandinavian kraft pulp mill can invest in a variety of energy-efficiency investments for decreasing its steam demand and increasing the amount of surplus steam and excess heat. Since the mill is already self-sufficient in thermal energy supply from the wood material input alone, the surplus steam and excess heat do not generate any positive cash flow if not utilized for production of sellable products. However, the utilization itself requires additional investments (as presented in Section 6.1.5). In Paper V, the following five energy-related technology pathways, utilizing the steam surplus and/or excess heat, were studied for four future energy market scenarios (presented in Table 11):

- Increased electricity production
- Selling of bark
- Export of excess heat for district heating purposes
- Extraction of lignin
- CCS

The technical and economic data for the studied pathways are based on previous research and presented in Section 6.1.5. In Table 14, the studied technology pathways and their characteristics are briefly presented. The pathways can be combined, that is, simultaneous investments can be made in more than one pathway as long as there is enough surplus steam or excess heat available. Yet some combinations of pathways are more likely (e.g. the combination of export of heat for district heating purposes and all other pathways) and some are less likely since they benefit from economy of scale and compete for the same steam surplus (e.g. the combination of investment in a condensing turbine and investments in CCS). In this work, investments which are made, both in energy efficiency and in technology pathways to utilize a potential steam surplus, are determined by optimization and thus depend on the energy market prices.

Table 14. *Overview and short description of the five technology pathways studied.*

Pathway	Increased electricity production	Bark (sold)	District heating	Lignin extraction	CCS
Type	Proven	Proven	Proven	New	New
Description:	Investment in new, larger, back-pressure and condensing turbines for increased electricity production.	Selling all or parts of the falling bark instead of burning it in the bark boiler.	Using excess heat for production of district heating. The excess heat is used either directly or by a heat pump, depending on quality of heat.	Extracting lignin from the black liquor. Due to the lignin extraction, less steam is produced in the recovery boiler, decreasing the electricity production.	Using the excess steam for the heat demand needed to regenerate the absorption medium, mono-ethanolamine (MEA), when capturing CO_2 from the recovery boiler flue gases.

All of the pathways have different effects on the mill's energy balance. How these effects are valued from an economic point of view in the energy market scenarios used largely determines the optimal solution. The optimal solution for the four scenarios analysed is presented in Table 15 together with the BAU (the existing energy balance when no investments are made) case as a reference. As can be seen in the table, the optimal solution is a combination of the proven technology pathways, reducing the global emissions of CO_2, for all of the energy market scenarios studied. For the scenarios where the CO_2 charge, and thus also the biomass price, is high, the bark is exported; and for the scenarios with a low CO_2 charge, the bark is used internally to further increase the electricity production.

Table 15. *Optimal solution compared to BAU for the four energy market scenarios.*

	Scenario: CO_2 charge level Oil price level		1 Low Low	2 High Low	3 Low High	4 High High
		BAU	Optimal	Optimal	Optimal	Optimal
Annual net profit	compared to BAU [ΔM€/yr]		+5.4	+5.2	+9.0	+7.3
Global CO_2 emissions	compared to BAU [Δkt/yr]		-23	-87	-64	-41
Pulp produced	[Adt/d]	1000	1000	1000	1000	1000
Electricity produced	[GWh/yr]	190	375	287	359	287
Bark sold	[GWh/yr]	242	0	242	0	242
District heating	[GWh/yr]	0	121	198	198	198
Lignin extracted	[GWh/yr]	0	0	0	0	0
CO_2 captured by CCS	[kt/yr]	0	0	0	0	0

Apart from identifying the optimal solution, it is also of interest to identify how close other, non-optimal, solutions are, in order to see whether the marginal cost for further CO_2 emission reductions is high or low. By fixing selected parameters, five such solutions were identified. The purpose of these solutions is to illustrate the effect of implementing the five studied technology pathways: (1) Max Electricity, (2) Max Bark, (3) Max DH, (4) Max Bark + lignin and (5) CCS on RB (recovery boiler). The solutions are based on one technology pathway each, but can to different extents, depending on the dominant pathway, also be combined with other pathways; see Table 16.

In Fig. 15 four diagrams are presented, one for each studied future energy market scenario. The diagrams show the annual net profit and the global CO_2 emissions for the optimal solution as well as for the five other solutions. A more detailed description of the five solutions' resulting energy balances can be found in Appendix 4 in Paper V. The BAU case is used as baseline for the comparison for each scenario, and is represented by the intersection of the x-axis and the y-axis in the four figures. In this way each diagram is divided into four quadrants. Solutions that are positioned in the lower right quadrant have both higher annual net profit and lower global CO_2 emissions than the BAU case for that scenario. They are therefore very interesting since they give an increase in profit for the mill and, at the same time, reduce the global emissions of CO_2. As can be seen in Fig. 15 this includes most of the studied solutions. Solutions positioned in the upper right quadrant are more profitable than the BAU case, but give higher emissions of CO_2. These solutions can be interesting for the mill from an economic point of view. Solutions positioned in the lower left quadrant are not profitable for the mill since they give a lower annual net profit than the BAU case. However, they reduce the global emissions of CO_2 and can thus be interesting from an environmental point of view.

Table 16. *Overview of the solutions based on the five technology pathways studied.*

Solution	Based mainly on pathway	Description
1.Max Electricity	Increased electricity production	Maximizes the electricity production, but can be combined with production of district heating if the district heat is produced with excess heat only (not surplus steam).
2.Max Bark	Bark (sold)	Maximizes the bark sales (no bark to bark boiler). Any leftover steam surplus can be utilized in any other pathways (in the most profitable way defined by the model and the energy market scenarios).
3.Max DH	District heating	Maximizes the district heating production. The preferred heat source, steam or excess heat, used for production of district heat is chosen by the model. Any leftover steam surplus can be utilized in any other pathways (in the most profitable way defined by the model and the energy market scenarios).
4.Max Bark + lignin	Lignin extraction	Maximizes the bark sales (no bark to bark boiler) and extracts 59 MW of lignin. Can be combined with production of district heating if the district heat is produced only with excess heat (not surplus steam).
5.CCS on RB	CCS	Captures the CO_2 in the recovery boiler flue gases with a capture efficiency of 90%. Any (small) leftover steam surplus can be utilized in any other pathways (in the most profitable way defined by the model and the energy market scenarios). Can be combined with production of district heating.

As can be seen in Fig. 15, the pattern in trade-off between the technology pathways is similar for the scenarios having the same level of CO_2 charge. For the two scenarios with low CO_2 charge, Scenarios 1 and 3, the solutions based on the proven pathways (Max Electricity, Max Bark and Max DH) are substantially more profitable than the solutions based on new emerging pathways (Max Bark + lignin and CCS on RB), the CCS pathway being directly unprofitable for both scenarios and the lignin extraction pathway directly unprofitable in Scenario 1. For the two scenarios with high CO_2 charge, Scenarios 2 and 4, all of the studied solutions are profitable compared to doing nothing – BAU. However, the variation in reduction of global CO_2 emissions between the solutions based on different pathways is large in all scenarios, CCS giving by far the largest reduction for all studied scenarios. Consequently, for Scenarios 2 and 4 the marginal cost is low for further, and large, reduction of CO_2 emissions (compared to the optimal solution). This means that if the future energy market resembles the one described in Scenario 2 or 4, there is a potential of reaching large reductions in CO_2 with only small additional economic incentives (such as technology-specific subsidies) since in these two scenarios the differences in net annual profit between the technology pathways are small but the difference in global emissions of CO_2 is high.

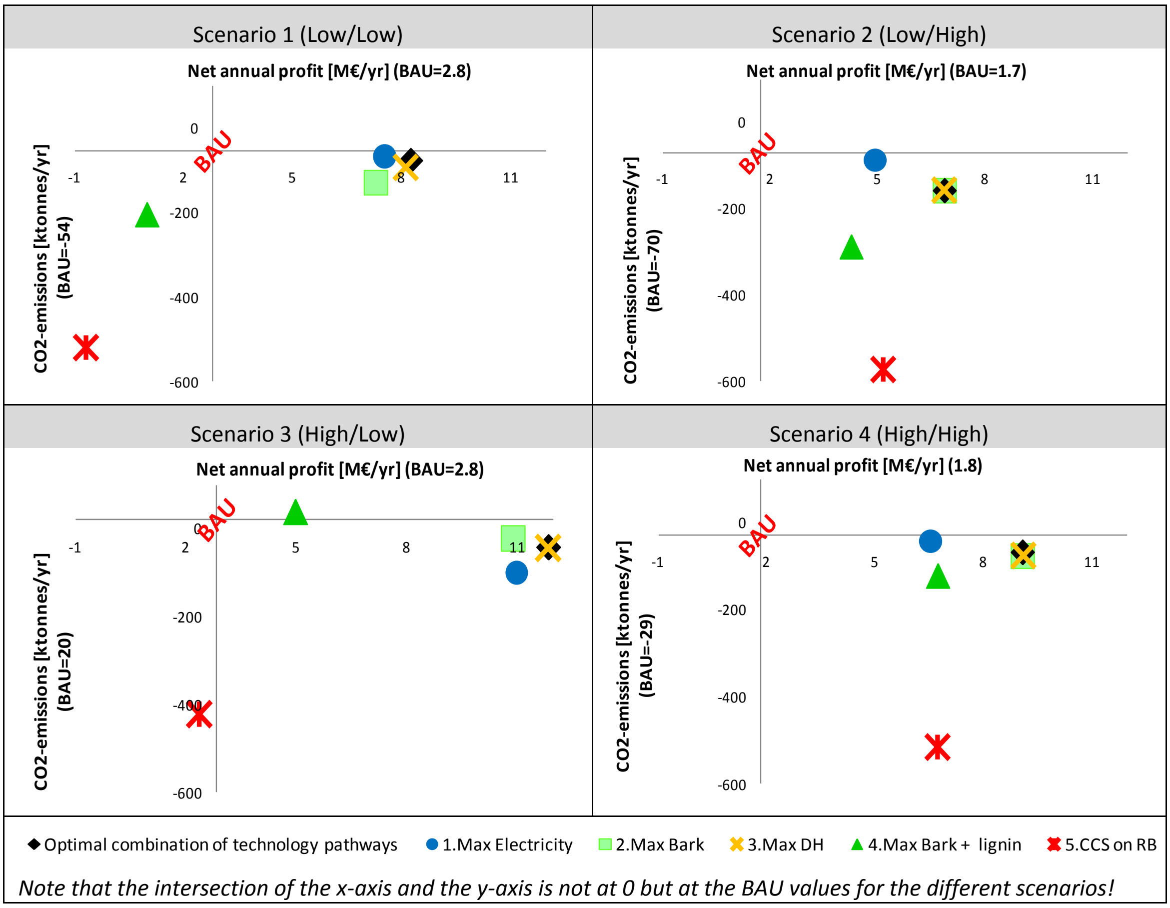


Figure 15. *Change in annual net profit and global CO_2 emissions for the optimal solution and the cases dominated by the technology pathways compared to the BAU case. The right column represents the scenarios with high CO_2 charge and the left column the scenarios with low CO_2 charge.*

In Paper VII, the comparison of different pathways for utilization of the pulp mill excess heat and steam was further investigated. Compared to Paper V, Paper VII has the following differences:

- The option of investment in a BLG booster with production of either DME (BLGMF) or electricity (BLGCC) is included as an alternative for utilization of any surplus steam. The BLG booster can be combined with CCS (denoted BLGMF:CCS or BLGCC:CCS). Data for the BLG pathway are presented with other input data in Section 6.1.5.
- Extracted lignin can be used in the lime kiln to replace fuel oil, or be sold as a wood fuel or a replacement for oil (both as a fuel and as a feedstock for production of materials and chemicals). Therefore in Paper VII, two lignin cases are considered: one where lignin is valued as wood chips (as in Paper V) and one where it is valued as fuel oil.
- The four energy market scenarios used are applied for two time frames, 2020 and 2030. Apart from the level of energy market prices, the main difference between 2020 and 2030 is that CCS is only assumed to be commercially

available for the 2030 scenarios. This affects both the on-site emissions at the pulp mill and the emissions related to the surrounding system.

- A more extensive sensitivity analysis is performed outside the energy market scenarios in order to include more parameters affecting the results, for example the level of policy instruments and the effect of the estimate of the investment cost. Table 17 presents the parameters included in the sensitivity analysis.
- All energy market prices and investment costs are updated to the monetary value of 2008.

All in all, in Paper VII, six cases for utilization of the excess heat and steam are considered; see Table 18.

Table 17. *Parameters included in the sensitivity analysis.*

Parameter	Cases
District heating production	1. The amount of district heating possible to deliver is increased by 100%, to between 20 and 100 MW depending on season. 2. No possibility to deliver district heat.
Capital recovery factor	The capital recovery factor is changed from 0.2 to 0.1.
Investment costs for non-commercial technologies	The investment costs for the non-commercial technologies, i.e. black liquor gasification, lignin extraction, and CO_2 capture and storage, are increased by 25%.
Green electricity policy instrument support level	1. The support is increased by 50%. 2. The support is decreased by 50%. 3. No support is considered.
Biofuel policy instrument support level	1. The support is decreased by 50%. 2. No support is considered.

Table 18. *Presentation of the possible outcomes studied (cases) including case code and case description.*

Case code	Case description
BLGMF	45% of the BL to the BLGMF/DME plant.
BLGMF:CCS	45% of the BL to the BLGMF/DME plant. The removed CO_2 (part of the BLGMF process) is compressed and sent for storage. If profitable, a part of the CO_2 from the recovery boiler (and bark boiler) flue gases can also be captured by absorption[a].
BLGCC	45% of the BL to the BLGCC plant. Possible investment in a new back-pressure steam turbine and/or a condensing steam turbine.
BLGCC:CCS	45% of the BL to the BLGCC plant. Possible investment in a new back-pressure steam turbine and/or a condensing steam turbine. The BLGCC plant is modified to include CO_2 capture (different gas cleaning including a water gas shift). If profitable, a part of the CO_2 from the recovery boiler (and bark boiler) flue gases can also be captured by absorption[1].
Lignin:wood fuel	Lignin is extracted from the black liquor, which leads to a decrease of the energy content in the BL to the RB (max 44%). The lignin is sold as fuel and priced as wood chips.
Lignin:oil	Lignin is extracted from the black liquor, which leads to a decrease of the energy content in the BL to the RB (max 44%). The lignin is sold as fuel and priced as fuel oil.
RB:Electricity	100% of BL to the RB. Investment in a new back-pressure steam turbine and a condensing steam turbine.
RB:CCS	100% of BL to the RB. Investment in a CO_2 capture plant connected to the recovery boiler flue gases and a new back-pressure steam turbine.

[a] If there is a further steam surplus, that surplus can be utilized for example to capture a part of the CO_2 from the recovery boiler flue gases.

Fig. 16 presents the results for two of the energy market scenarios, low/low and high/high, for 2020 and 2030 (referred to as 1 and 4 in Table 12; the results for the other scenarios can be found in Figs. 4 and 5 in Paper VII).

A baseline case is used for comparison of the different energy-related technologies within each energy market scenario. The baseline case is business as usual (BAU) and is represented by the intersection of the x-axis and the y-axis. For the business as usual case, no investments are made and the kraft pulp mill's energy balance is unchanged.

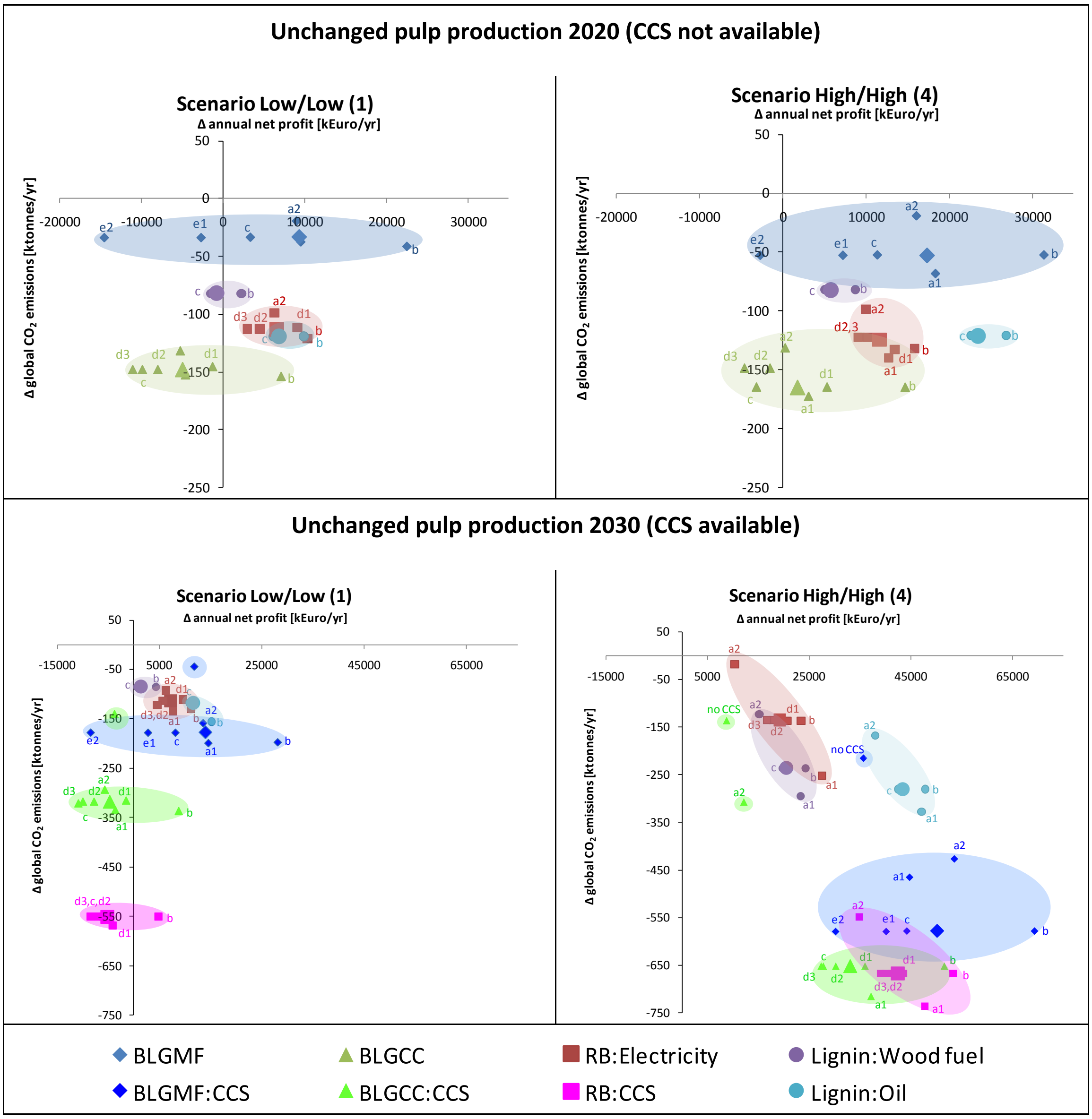


Figure 16. *Results for the studied cases and the sensitivity analysis for the case of unchanged production presented for scenarios Low/Low (1) and High/High (4). For each studied case, the larger centre point represents the optimal solution for that case given the energy market scenario prices. The smaller points show how the optimal solution shifts when changing certain parameters in the sensitivity analysis. The shaded areas show the span between the solutions given in the sensitivity analysis.*

The bullet list below summarises the main findings from Paper VII:

- Generally, in scenarios assuming a low oil price level, BLGMF has the best economic performance; and in scenarios assuming a high oil price level, extraction of lignin that can be valued as oil has the best economic performance out of the studied technologies. However, contrary to lignin, the BLGMF case is valued as oil, very sensitive to changes of several parameters, especially the level of support for biofuels.
- All the studied technology cases decrease global CO_2 emissions significantly compared to not making investments. For the year 2020, where there is assumed to be no possibility for CCS, BLGCC gives the highest CO_2 reduction potential, followed by investments in new turbines in connection with the recovery boiler and extraction of lignin that can be priced as oil. For the year 2030, where there is assumed to be an established infrastructure for CCS, investments in CCS coupled to the recovery boiler flue gases render the highest CO_2 reduction potential, followed by BLGCC and BLGMF, where CCS also can be included.
- The level of financial support for green electricity does not significantly influence the results, partly due to the assumed design of the support system, where only new production capacity is entitled to support. However, the level of support for biofuels affects the results to a large extent since it significantly influences the economic performance of the BLGMF case. If conditions influencing the BLGMF case positively are not considered, such as inclusion of CCS, a substantial level of the support for biofuels is needed in order for BLGMF to be competitive compared to extraction of lignin that can be valued as oil.
- The results show that for technologies with substantial investment costs, BLGMF, BLGCC and CCS coupled to the boiler flue gases, a 25% increase of the investment cost has a quite large influence on the economic performance. For lignin extraction, which is not yet a commercialised technology but has a lower investment compared to the other non-commercial, a 25% increase of the investment cost has a very low influence on the economic performance.
- The possibility to capture CO_2 from the recovery boiler flue gases gives a large CO_2 reduction potential. However, the profitability of capturing the CO_2 is strongly dependent on the CO_2 charge – e.g. it is only for the scenarios with a high CO_2 charge that CCS coupled to the boiler flue gases is more profitable than investments in new turbines. CCS decreases the global CO_2 emissions and the economic performance for BLGMF and BLGCC both in absolute terms and in relation to the other technologies.
- Extraction of lignin that can be valued as oil has a very good economic performance, even in the scenarios with a low oil price. The CO_2 emissions reduction from lignin extraction is also fairly stable between the scenarios.

For the scenarios with a low oil price the support for biofuel is high, which of course is questionable. This is due to the approach used for determining the level (see Section

6.3.2). The sensitivity analysis shows for example the consequences of a 50% reduction of the support, which in the scenarios with low oil prices results in a more reasonable level of the support. At this level, BLGMF is never the most profitable option (in the scenarios with a low oil price). Further, an aspect that is often discussed in connection with BLG is the availability factor of the equipment. If the production capacity is assumed to be unchanged, the availability of the BLG plant is not very critical, since the recovery boiler can handle the entire black liquor flow if necessary.

Using the model constructed for Paper VII, in Paper IX three different options for debottlenecking of the recovery boiler assuming a 25% production capacity increase are compared:

1. Upgrading the recovery boiler
2. Lignin extraction
3. Black liquor gasification (as a booster)

The same energy-efficiency measures as in the case with unchanged production are considered, most of which can be scaled corresponding to the increased production.

The results from Paper IX show that, generally, BLGMF and lignin extraction with lignin valued as oil achieve the best economic performance. Capturing and storing CO_2 from the upgraded recovery boiler flue gases gives the highest CO_2 emissions reduction, but is an economically attractive option only in scenarios with a high CO_2 emissions charge. Comparing the results from Paper IX with the results from Paper VII where the production capacity was unchanged, it can be seen that the BLG cases (both with and without CCS) benefit from economy of scale. Lignin extraction, however, does not show the same scale dependence. Thus, the BLGMF case becomes more profitable than lignin extraction with lignin valued as oil for some of the scenarios where lignin extraction was shown to be more profitable for the case of unchanged production capacity.

8.3.1 Summary of conclusions from this sub-chapter

From Papers V, VII and IX, evaluating and comparing technology pathways for utilization of kraft pulp mill excess heat presented above, the following main conclusions can be drawn:

- The results show that if investments are made in energy-efficiency measures and different technology pathways to utilize the steam surplus, the energy balance of the kraft pulp mill can be significantly altered and the mill can produce a considerable amount of (new) products in addition to the pulp.
- The new and emerging technology pathways, especially BLG and CCS, combined with energy efficiency, hold much larger potential for reduction of global emissions of CO_2 than the proven pathways.

- The economic performances of the proven pathways (electricity production, district heating production and selling bark) are, however, much more robust than the economic performance of the emerging pathways for varying energy market prices.
- The results show that for a high CO_2 charge and a high biomass price, there is a potential for reaching large reductions in CO_2 if only relatively minor additional economic incentives are given. Yet, due to the low marginal cost of further reduction of CO_2 emissions in these scenarios, such economic support does not need to be large. Applying a high cost of CO_2 alone may not be enough to reach the full potential of CO_2 emissions reduction, since a high cost of CO_2 also profits the proven pathways.
- The investment cost for the non-commercial, capital-intensive technologies BLG and CCS is highly uncertain but has a significant effect on the economic performance. This makes the future economic performance of these technologies hard to predict.
- Lignin extraction is a less capital-intensive technology than the other emerging technologies. Further, its economic performance and potential for reduction of CO_2 emissions are not highly influenced by any of the parameters studied outside the energy market scenarios, and can therefore be said to be a fairly robust investment compared to e.g. BLGMF which is highly influenced by several parameters such as biofuel policy instruments and investment costs. Furthermore, if the lignin is valued as oil, lignin extraction shows a good economic performance for all of the scenarios studied.
- BLGMF and BLGCC benefit from economy of scale and thus have a better economic performance when increasing the production capacity than when the production capacity remains unchanged.

8.4 Addressing the research question in theme 2

Based on the work done in Papers I-III, V, VII and IX, as summarised above, the research questions for theme 2 can be addressed:

How do assumptions regarding different energy market parameters influence the economic performance and CO_2 emissions for the pathways? The economic performances of BLG and CCS are largely dependent on the CO_2 charge and biomass price level. For BLGMF the level of assumed biofuel support also strongly affects the economic performance. In terms of the potential for reduction of global CO_2 emissions, the individual technologies show fairly similar performance for the different scenarios if CCS is not considered. If CCS is considered a commercially available technology, and thus is implemented both in the European power system and at the mill, this has a large effect on the potential for reduction of global CO_2 emissions. The energy market scenario parameters have a larger effect on the economic performance and potential for reduction of global CO_2 emissions than individual non-market parameters have.

Are any of the studied pathways "robust" given the uncertainty of the future energy market and parameters such as policy instruments and investment costs? The proven technology pathways are more robust to changing energy market parameters than the new, emerging pathways. They show stable economic performance and, compared to the emerging pathways, moderate reductions of the global CO_2 emissions. For the new, emerging technology pathways, lignin extraction shows the most robust performance, perhaps due to its lower capital intensity compared to BLG and CCS. If the extracted lignin can be valued as oil, lignin extraction will show a very good economic performance, even in the scenarios with a low oil price. The CO_2 emissions reduction from lignin extraction is also fairly stable between the scenarios, although not as low as for the other emerging technologies if CCS is considered. With respect to the potential for reduction of global CO_2 emissions, the emerging technologies show a large, robust reduction potential for all of the studied scenarios.

9 Results research theme 3: Factors influencing the potential for industry-wide implementation

This chapter shows the results for how the potential for implementation of CCS in the European PPI is influenced by the geographical proximity to potential future transport and storage infrastructure.

Apart from the development of the future energy market conditions, for some of the pathways studied, external preconditions, such as geographical location and existing and new infrastructures, will largely influence the potential for (profitable) implementation. This is especially true for CCS, impacted by the future transport and storage infrastructure, and district heating, impacted by e.g. the distance to (large) district heating sinks. In contrast, the potentials for increased electricity production, export of bark and/or lignin and black liquor gasification, are not significantly affected by the surrounding infrastructure and geographical conditions. Instead these technologies are more dependent on the process conditions of the individual mills, e.g. black liquor gasification and lignin extraction can only be implemented by kraft mills.

9.1 Carbon capture and storage

The potential for implementation of CCS within the European PPI is analysed in Paper VIII. Technical and economic data for the technology are based on work by Hektor et al. (Hektor and Berntsson 2007) and partly presented in Section 6.2.5.

As described in Chapter 2, the kraft PPI has large on-site emissions of CO_2 due to the burning of black liquor in the recovery boiler, whereas the mechanical PPI and the paper mills based mainly on recycled fibers (RCF) generally have lower on-site emissions.

In this study, the European PPI is represented by 176 mills, including kraft, mechanical and paper mills; see Section 6.2. The amounts of on-site CO_2 emissions from the pulp and paper mills included are presented in Table 18. For comparison, the total on-site emissions of CO_2 for all CEPI mills are also included (CEPI 2008). The fossil CO_2 emissions were gathered from the Chalmers industry database (for more details see work by Rootzén et al. 2011). The biogenic CO_2 emissions, on the other hand, are not reported centrally, either for the EU or by CEPI. Thus, these emissions were gathered by screening national statistics, sustainability reports, annual reports and web pages for all of the mills included in the study. However, numbers for biogenic CO_2 emissions were mostly not clearly stated and thus the data were compiled partly by calculations based on stated biomass use or production of kraft pulp (or assumed to be zero if no such information was found).

Table 18. *CO_2 emissions for the mills included in the analysis compared to CEPI total emissions.*

Type of mill	Kraft		Mechanical	Paper	Share of CEPI
	Market pulp	Pulp & Paper	Pulp & Paper		emissions[%]
Mills [No.]	23	32	43[1]	70[2]	
Fossil CO_2 [kt/yr]	1 425	3 246	4 759	9 420	48%
Biogenic CO_2 [kt/yr]	23 857	32 052	5 524	2 217	96%
Total CO_2 [kt/yr]	25 282	35 298	10 283	11 637	78%
CEPI total fossil[3]				*39 605*	
CEPI total biogenic[4]				*66 113*	

[1] For 2 mills no data could be found in either E-PRTR registers or web pages.
[2] For 6 mills no data could be found in either E-PRTR registers or web pages.
[3] Figures from (CEPI 2008) referring to the year 2006.
[4] Based on the figures for biomass utilization as part of the primary energy demand from CEPI 2008 and calculated assuming CO_2 emission of 346 kg/MWh.

The reason why the share of fossil emissions included is smaller than the share of biogenic emissions included is that many small South European paper mills, using mainly fossil fuels for their energy needs, were excluded from the study due to their small size. Excluding these small mills is not a problem since they are not likely to be implementing carbon capture due to their relative small on-site emissions. The geographical distribution of these emissions is shown in Fig. 17. As can be seen, the regions with the highest emissions are located around the Baltic Sea (in Sweden and Finland), in the south of Spain and in the middle of Portugal, where the kraft PPI industry is located.

Today, CCS is not a commercial technology and the necessary infrastructure for both transport and storage is neither in place nor definitely planned. It is thus hard to predict which mills will have the most favourable preconditions for implementing CCS. However, a reasonable approach is to assume that infrastructure is most likely to be developed first in proximity to sites with many large point sources, hereafter denoted *capture clusters*. Depending on how the biogenic CO_2 is viewed from a mitigation point of view, it can also be assumed that infrastructure will first be built around large fossil point sources or around large point sources regardless of the emissions origin. Further, it is reasonable to assume that mills with larger emissions will have a larger potential for profitable introduction of CC than sites with small emissions. Based on these assumptions, a matrix was constructed containing six future cases for implementation of CCS in the European PPI; see Table 19.

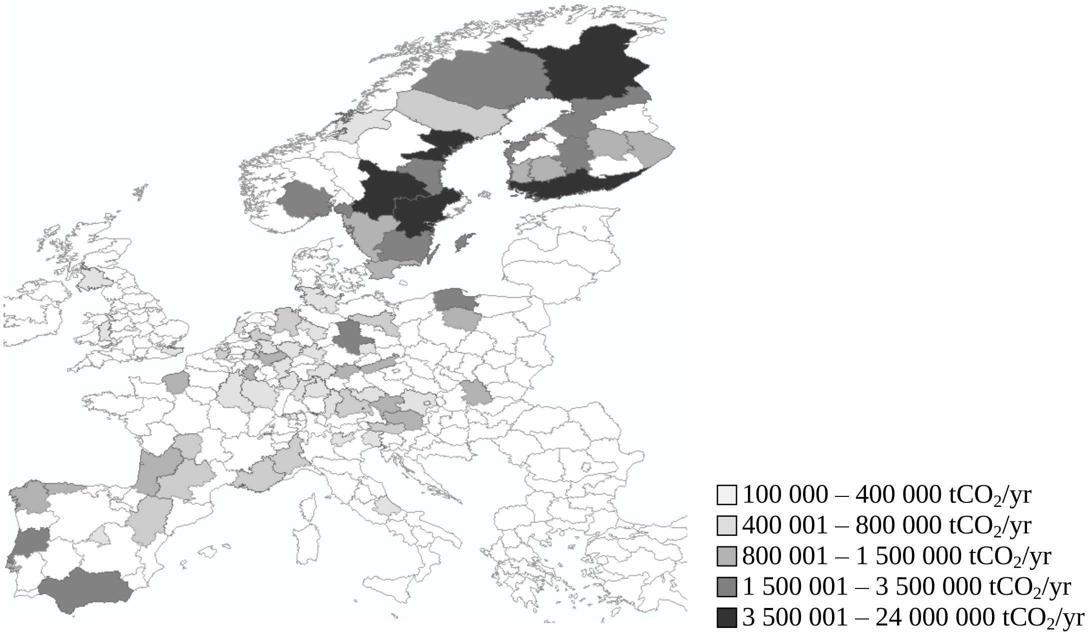


Figure 17. *The geographical distribution of on-site CO_2 emissions from the European PPI. Regions coloured in grey have a high density of emissions; the darker the colour, the higher the emissions.*

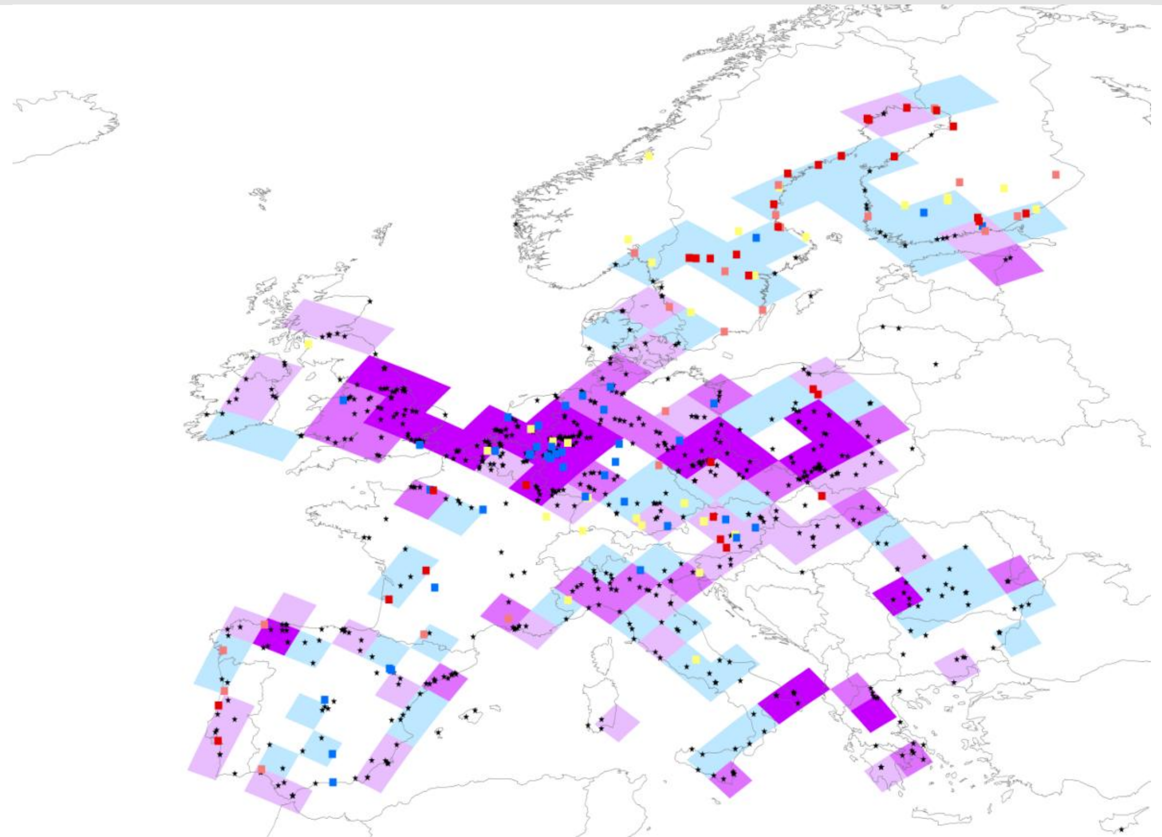
The capture clusters are generated on the basis of the sum of emissions from the PPI, other heavy industries and power plants. The emission data for other heavy industries and power plants are based on data from Chalmers' industry database (Chalmers IN db, see e.g. Rootzén, Kjärstad et al. 2011) and Chalmers' power plant database (Chalmers PP db, see e.g. Kjärstad and Johnsson 2007). The geographical positioning of the PPI in relation to the geographical positioning of other energy-intensive industries, power plants and capture clusters is displayed in Fig. 18.

Table 19. *Case description for the six future cases considered for implementation of CCS in the European PPI.*

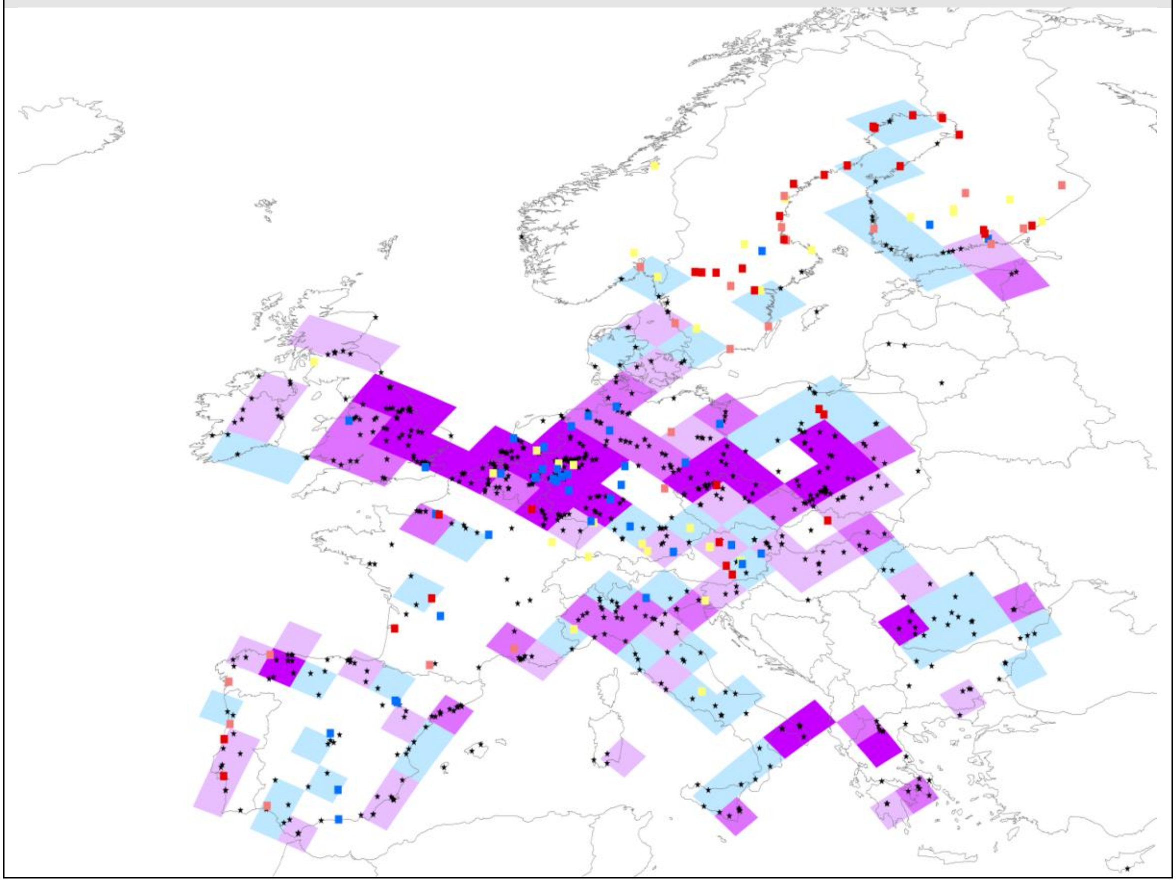
Including mills with emissions:	Capture done only by mills in… 1...capture clusters	2...fossil capture clusters	3...fossil capture clusters > 10 $MtCO_2/yr$[a]
A: >0.1 $MtCO_2/yr$	A1	A2	A3
B: >0.5 $MtCO_2/yr$	B1	B2	B3

[a] *When discussing capture clusters, sizes below 10 $MtCO_2/yr$ are rarely mentioned, at least not for the first developed infrastructure.*

1: Fossil and biogenic clusters >1MtCO$_2$/yr



2: Fossil clusters >1MtCO$_2$/yr



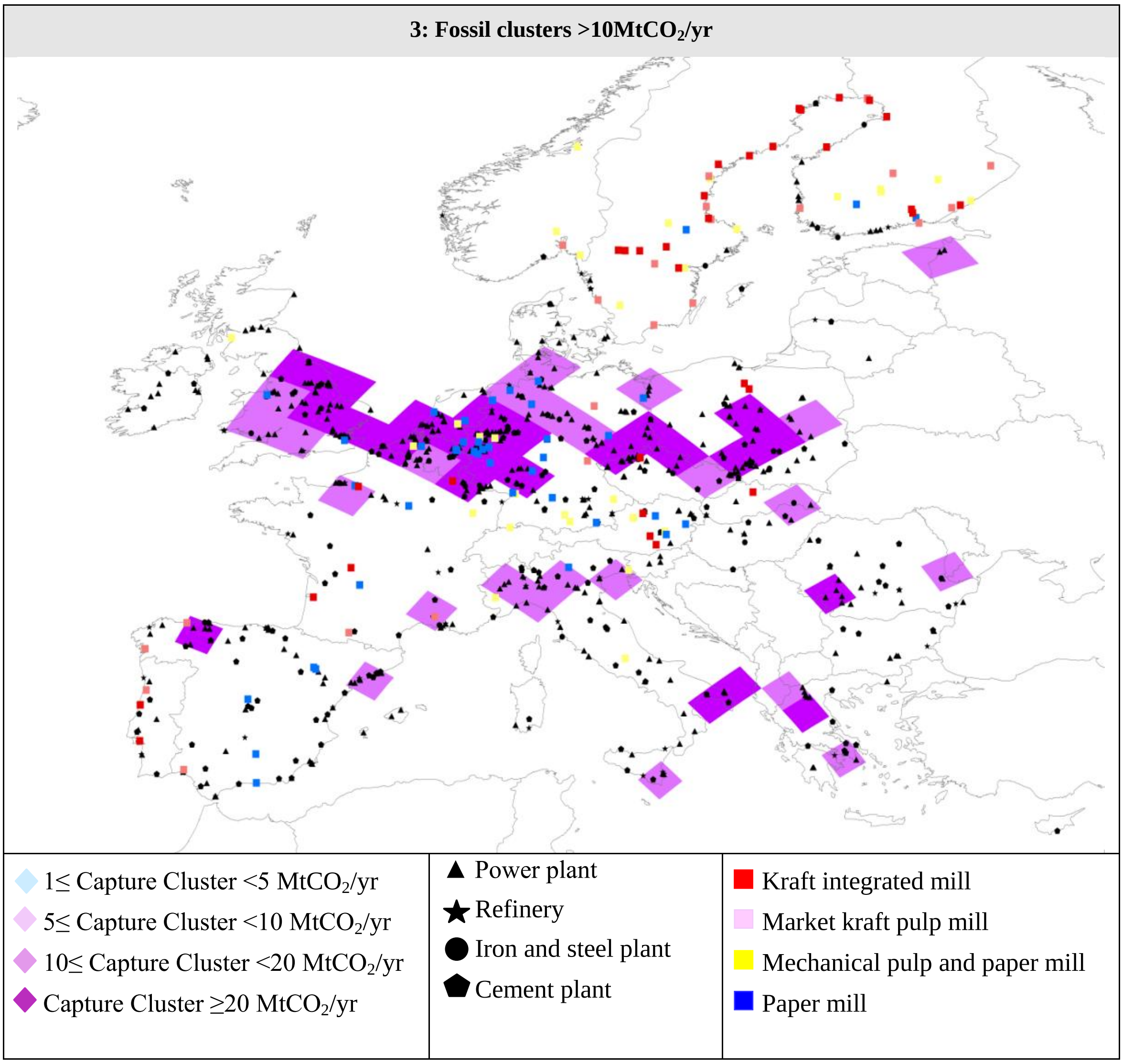


Figure 18. *The geographical distribution of pulp and paper mills emitting >0.1 Mt CO_2/yr in relation to other large industrial point sources and power plants emitting >0.5 Mt CO_2/yr. Possible capture cluster areas are represented by coloured squares (150x150 km).*

As can be seen in Fig. 18, most of the large emitting kraft pulp and paper mills are located far away from most of the large fossil capture clusters created by other energy-intensive industries and power plants. The figure shows that, with respect to transport and storage of CO_2, the most beneficial geographical positions are held by paper mills in central Europe. Those mills have much smaller on-site emissions than the kraft PPI[19] but, as can be seen in the figure, they are located in or near the largest fossil capture clusters created by other energy-intensive industries and power plants and they are also located near the potential storage sites in the North Sea.
Regarding the distribution between large emitters and small emitters amongst the mills included in the study, it can be seen in Fig. 19 that one third of the mills (the ones with

[19] However, they have CO_2 emissions > 0.1MtCO_2/yr and are consequently larger than the paper mills omitted in the study, mentioned earlier when discussing the content in Table 18.

emissions >0.5 Mt/yr, B) are responsible for about 75% of the emissions. This third is constituted by all of the kraft mills included, one mechanical mill and one paper mill. Further, from Fig. 19 it can be seen that if CCS is to be implemented for large point sources only within the European PPI (B), the captured CO_2 will almost solely be biogenic.

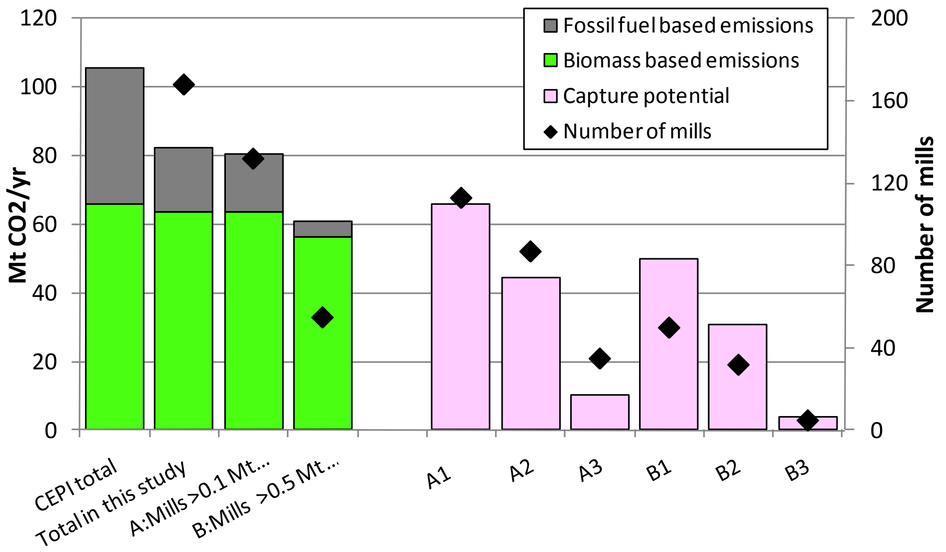


Figure 19. *The distribution of included emissions divided by size and origin along with the potential for captured CO_2 emissions for the six studied capture cases presented in Table 19*[20].

9.1.1 Summary of conclusions from this sub-chapter

From the results presented above the following main conclusions can be drawn:

- Regarding the total on-site CO_2 emissions from the PPI, a large part is biogenic. Further, a third of the mills are responsible for about 75% of the emissions and for these mills the majority of the CO_2 emissions is biogenic. Consequently, implementing CCS in the European PPI will lead to capture of mainly biogenic CO_2. Considering CCS in the PPI, it is thus important that capture of biogenic CO_2 is granted the same financial support as capture of fossil CO_2.
- If CCS is to be introduced on a large scale in order to reach large CO_2 emission reductions within the European PPI, the emission-intensive Scandinavian kraft PPI must be included in such a capture scheme. If this is done, up to around 60 $MtCO_2$/yr could be captured from the European PPI. This is more than the total amount of fossil CO_2 emitted per year in Sweden (~50 $MtCO_2$/yr according to SEA 2010).
- However, the CO_2 emission-intensive kraft PPI holds a very poor geographical position compared to potential large capture clusters and storage places. Thus it

[20] The total number of mills included in the CEPI statistics, giving the emissions in the bar at far left (denoted CEPI total), was 1147 (in the year 2007).

can be questioned whether the biogenic emissions from the Scandinavian PPI are large enough to motivate the development of infrastructure.

9.2 Addressing the research question in theme 3

An important part of the work for this research theme was to develop a methodology which could be used to answer the research questions posed. Here the developed methodology was applied to CCS within the PPI, but could just as well be applied to other industry branches or other technologies influenced by external geographical factors, e.g. district heating.

Below, the research questions in theme 3 are addressed for the case of CCS:

Which process characteristics and external, geographical and infrastructural, factors influence the potential for large-scale implementation of the pathways? In what way do these characteristics and factors influence the potential? The process characteristic which has the largest effect on the potential for implementation of CCS in the European PPI is the on-site emissions of CO_2. For the PPI, it is almost exclusively kraft mills which have on-site emissions of >0.5 $MtCO_2$/yr and thus the kraft PPI holds the largest potential for <u>capture</u> of CO_2. However, geographical and infrastructural factors such as the proximity to so-called capture clusters and storage sites affect the potential for <u>transport and storage</u>. With respect to geographical position in capture clusters, the paper mills in Central Europe hold the largest potential for transport and storage, but they have very small on-site emissions of CO_2. It can thus be concluded that there is a mis-match between where the PPI's CO_2 emissions are located and where the largest emission sources in Europe (and thus probably the future infrastructure for transport of CO_2) are located.

10 Discussion

This chapter gives a discussion on different aspects of the approach used for the thesis work and on the reliability and accuracy of input data.

10.1 Mill characteristics and mill-level input data

This thesis and its results are largely based on mill-level studies of an average Scandinavian market kraft pulp (model) mill. In practice, however, all mills are different with respect to process equipment and layout, proximity to infrastructure etc. This fact of course influences the generality of the results. Still, levels of steam savings similar to the levels used in the study have been identified also for real market kraft pulp mills in case studies, and thus the results are regarded as fairly general for kraft pulp mills. The European PPI, though, consists not only of kraft pulp mills but also of kraft integrated pulp and paper mills, mechanical pulp and paper mills, and paper mills for which the analyses in Papers I-V, VII and IX are not applicable. An integrated kraft pulp and paper mill can implement the same technologies as a kraft pulp mill but cannot, due to a higher process steam demand, achieve a steam surplus in the same way. This characteristic will influence both the economic performance and the related CO_2 emissions of the technologies, since external fuel must be imported to cover the energy demand of the new processes.

For the analysis in Papers I-III, V, VII and IX, the steam surplus that can be generated through energy-efficiency measures and used for energy-efficient implementation of the selected pathways is large. If the steam surplus had been smaller, this would have affected the economic performance of the pathways, especially the capital-intensive BLG cases which benefit from economy of scale.

The investment costs used for the new, emerging technologies (BLG, CCS and lignin extraction) are estimated for commercially available plants, that is, the “Nth plant”. These technologies, however, still need to be demonstrated in large scale in order to reach commercialisation. Consequently, the estimated investment cost for these technologies is rather uncertain. In order to consider this uncertainty, a sensitivity analysis of the investment cost for the not yet commercial technologies was included in Papers VII and IX.

10.2 Assumptions, methods, tools and methodologies

Below, different aspects of the methods, tools and methodologies used are discussed.

10.2.1 Inherent limitations when using a engineering bottom-up approach

Based on a engineering bottom-up approach, the work for this thesis uses disaggregated models, containing a detailed representation of current and emerging technologies that can be used to meet demands for different energy products. Technologies that provide products which can fulfil the same demand/service are here assumed to be perfect substitutes. They have, however, different estimated capital and operating costs, energy use, and emissions profiles. Based on the estimated future capital and operating costs, the technologies studied, generally, appear to be profitable relative to the existing capital stock of equipment. Further, like most studies based on bottom-up models, this thesis also finds that substantial emissions reduction related to energy use could be profitable or available at low cost if new, low-emission technologies were to be implemented in large scale. On the contrary, econometric top-down models seldom identify such potentials for large emission reductions at low or negative costs. One reason for this divergence is that an engineering bottom-up approach assumes that a simple capital and operating cost estimate indicates the full social cost[21] of technological change In addition, some low-cost, low-emission technologies are not perfect substitutes for their competitors (or at least not viewed as such buy the investors).

10.2.2 Using the reMIND tool based on mixed-integer linear programming

For the thesis work aiming at answering the research questions regarding economic performance and global CO_2 emissions for the selected pathways, the reMIND modelling tool was used. The reMIND tool, like most tools based on mixed-integer linear programming, uses “perfect foresight”. This means that the future energy market prices are assumed to be known by the model at the time when the investments are made, and that the uncertainty of the development of the energy market is handled by performing sensitivity analysis or, as in this work, analysing different future energy market conditions. In practice, however, the future energy market prices are usually not known at the time of investment. To more fully depict this fact, optimization under uncertainty can be used. In general, however, optimization under uncertainty is more complicated than “regular” optimization and demands more data (e.g. probability functions for the different uncertain parameters) and thus is more difficult to use. Further, since optimization under uncertainty commonly assumes a decision-making perspective, it is more difficult to analyse the results obtained by an analysis from another perspective – such as a more general policy perspective.

[21] Social cost is the total cost of any action (for example production of goods or services) due to the consequences imposed on society by the action. The social cost is the sum of private costs, which are met by the individuals or companies concerned, and indirect costs, which are passed on to third parties (e.g. future generations or the society as a whole).

10.2.3 Accuracy of the HLMPP

To a large extent, the accuracy of the HLMPP depends on how well the default values set in the model correspond to the real values of the same process parameters in different mills. Such knowledge can only be gained by applying the model to several mills and thereby checking the accuracy of the default values as well as the results given by the model. Being a new model, the HLMPP has not yet been widely applied and validated. The previous studies performed using the tool, however, have given results which correspond quite well to the results obtained by detailed analysis both for pressurized ground wood (PGW) mills and for pulp and paper mills with TMP and DIP lines. Further validation is, nonetheless, essential in order to establish the accuracy of the tool.

10.2.4 Using different versions of the ENPAC tool

As stated, this thesis work uses energy market prices and related emission for different energy carriers generated by the ENPAC tool. Since the ENPAC tool was further developed and updated in parallel to the thesis work, different versions of the tool were used. The versions mainly give different absolute values for the prices of different energy carriers. Independently of which version is used, however, the results generally show the same structure (see Chapter 8).

10.3 Data availability and reliability of data for the industry-level analysis

When performing the industry level analysis, one major recurrent problem was the constant lack of public data and statistics. Mill-level data for total fuel and electricity balances, together with data for fossil and biogenic CO_2 emissions, were only compiled and openly published on a national level for the mills in Sweden. Further, when contacting multinational companies within the PPI, the companies refused to share such (in Sweden public) data for their European mills. Therefore, data for the non-Swedish mills were retrieved from many different sources, mainly environmental reports and company homepages.

Further, when using data from public sources, the risk of errors in the reported data must be borne in mind. For the studies presented in this thesis, one source of public data was the Environmental database managed by the Swedish Forest Industries Federation. In the course of the work on this thesis, some data in the database were compared to detailed mill data from the mills' internal energy reports. This comparison revealed certain errors in the database, such as errors in the amount of pulp and/or paper produced and errors in the total amount of energy used (in one case the energy used in the lime kiln was excluded, giving an error of 22% in the amount of total fuel usage). Unfortunately, it can be assumed that similar errors may occur in other public databases and documents (such as environmental and annual reports).

As for most models, the models used in this thesis work show accurate and good results when using accurate input data. However, since there is no guarantee that the publicly reported data are correct; the main uncertainties are perhaps not in the models themselves but in the data retrieved from public sources. To avoid such errors, the data retrieved from public sources were checked for reasonability and, in cases where data were found to be outside the expected range, the data were either subjected to supplementary calculations or, if possible, checked with the mill in question.

11 Conclusions

Short summaries of the main findings from the appended papers, addressing the three research question themes, are given at the end of Chapters 7, 8 and 9 and their respective sub-chapters. This chapter states the main conclusions of the thesis, based on the findings for each research question theme and the results of the appended papers.

This thesis aims at analysing selected future technology pathways for the European PPI, focusing on kraft pulp mills. The pathways studied are strategic in nature and will, if implemented, have a significant effect on a mill's energy system. For the kraft pulp industry, this thesis gives new insights into the question of economic performance and potential for reduction of global CO_2 emissions for different technology pathways assuming different developments of the future energy market. The thesis also gives new methodological insights and shows how earlier, detailed research can be lifted to a higher system level in order to be put in context and to answer research questions on a more aggregated industry level.

Given the assumptions stated in Chapters 5 and 6 and the results presented in Chapters 7, 8 and 9, the following main conclusions are drawn:

Using high-temperature excess heat internally gives, in general, a better economic performance and a larger potential for reduction of global CO_2 emissions than using the excess heat externally. It can be concluded that for efficient use of excess heat, it is important to identify the temperature levels where excess heat is available. Exporting high-temperature excess heat for district heating purposes does not give any radical improvement in either economic performance or reduction of global CO_2 emissions compared to utilizing it for other purposes internally at the mill. However, if the mill has substantial amounts of excess heat which cannot be utilized internally (typically of a temperature around 90° or lower), export for district heating purposes can be an interesting option since it can be combined with the other studied pathways. For low-temperature excess heat, another alternative is to invest in a heat pump to increase the temperature to higher, internally usable, temperatures. This option has only been marginally studied in this thesis, but can be an interesting option worth further analysis.

The new, emerging technology pathways that can be combined with carbon capture show the largest potential for reduction of global CO_2 emissions; however, the proven technology pathways show a more robust economic performance. The results show that for a kraft pulp mill the new and emerging technology pathways, which can be combined with carbon capture (i.e. BLG and increased electricity production in combination with CCS coupled to the recovery boiler flue gases) and with improved energy efficiency, hold much larger potential for reduction of global emissions of CO_2 than the proven pathways for all of the energy market scenarios studied. However, studying the trade-off between the different pathways for different CO_2 charges and corresponding developments in the energy market, it can be concluded that from an economic point of view the proven pathways (electricity production, district heating production and selling bark) are much more robust and thus likely to be preferred by the industry. Generally, applying a high cost of CO_2 will profit both the emerging and the proven pathways, and consequently applying a high cost of CO_2 alone may not be enough to reach the full potential for CO_2 emissions reduction held by the emerging pathways.

The technology pathways giving the largest reductions of global CO_2 emissions never have the best economic performance; however, for a future with high CO_2 charge, the marginal cost for further reductions is low. For the variety of energy market conditions studied, the results show that the technologies achieving the largest CO_2 emission reductions never have the best economic performance. Consequently, if the full (technical) potential for CO_2 emission reductions in the kraft PPI is to be achieved, some additional economic incentive may be needed (or the CO_2 charge needs to be higher than the highest level assumed in this thesis). For a future with high CO_2 charge and a high biomass price, however, the results show that the marginal cost of further reduction of CO_2 emissions is low, and consequently in these scenarios the additional economic support for reaching large CO_2 reductions does not need to be large. Nonetheless, it should be noted that implementing more than one policy instrument at the same time increases the complexity of the system, reduces the transparency of the system, and might not lead to the desired result. Further, targeted policy instruments can distort the market and, if the CO_2 charge is assumed to be set on sound grounds, it can be questioned whether it is reasonable to allocate additional economic resources to specific technologies through such policy instruments.

If lignin can be valued as oil rather than biomass, extraction of lignin shows both a good economic performance and fairly large potential for reduction of CO_2 emissions. For the variety of energy market scenarios studied, extraction of lignin shows fairly robust results for economic performance and potential for reduction of global CO_2. How well extraction of lignin performs compared to the performance of the other technology pathways studied, however, largely depends on how the lignin is valued. If lignin is valued as biomass (chips or pellets), the economic performance is low compared to the proven pathways, and the potential for reduction of global CO_2 emissions is much lower than the potential for reduction held by the other emerging technology pathways. On the other hand, if lignin is valued as oil, lignin extraction shows a very good, robust, economic performance compared to all of the technology pathways studied – even the best, for some energy market scenarios. The potential for reduction of global CO_2 emissions is also larger if lignin is valued as oil, although, the potential is never as large as the potential for CO_2 emission reductions held by the BLG:CCS and CCS coupled to the recovery boiler flue gases.

If electricity is produced from the product gas (BLGCC) and/or if BLG is combined with CCS, BLG holds a potential for large reductions of global CO_2 emissions, compared to the other pathways studied. If CCS is assumed not to be available, BLGCC holds the largest potential for reduction of global CO_2 emissions. Also, if CCS is assumed to be available, BLGCC has a potential for CO_2 emissions reduction comparable with CCS on the recovery boiler flue gases (which generally hold the largest potential for reduction if CCS is assumed to be available). For the assumptions made, BLGMF generally has a better economic performance than BLGCC but has a lower potential for reduction of global CO_2 emissions. However, the economic performance of BLGMF is highly influenced by several parameters such as biofuel policy instruments and investment costs. Both BLGMF and BLGCC benefit from economy of scale and have a better economic performance if a production capacity increase is assumed (and BLG is used to debottleneck the recovery boiler), compared to when the production capacity remains unchanged.

It is important to consider the uncertainty of the future energy market. Some of the pathways studied are not commercially viable today, and by the time they are commercially viable the (volatile) energy market might not resemble the current energy market. This thesis work shows that the development of the energy market (energy market scenarios) has a greater influence on the economic performance and global CO_2 emissions of the studied technology pathways than has the uncertainty of single parameters, such as the capital recovery factor and the investment cost for emerging technologies.

For the European PPI, CCS has an up-hill road in order to be a viable, large-scale alternative for reduction of CO_2 emissions. The amount of CO_2 that can be captured and stored depends heavily on the expansion of CO_2 transport infrastructure. Assuming a very widespread development of CO_2 transport infrastructure, up to ~60 $MtCO_2$/yr could be captured. This is more than the total annual fossil CO_2 emissions in Sweden. However, when matching the PPI capture potential with the potential for CCS in other energy-intensive industries and the emission from the power and heat sector, the majority of the PPI emissions originate from kraft pulp and paper mills far away from potential fossil capture clusters, especially if only the largest clusters are considered (>10 $MtCO_2$/yr). The paper mills in central Europe are geographically most suitable for CCS, but these mills generally have much lower on-site emissions than the Scandinavian kraft pulp and paper mills. It should thus be further investigated whether the biogenic capture clusters in Scandinavia are large enough to motivate the infrastructure needed for transport to potential storage sites.

Bringing earlier, detailed research together and analysing it on a higher systems level gives new insights and enables answering research questions on a more

aggregated industry level. This thesis gives new insights and shows how earlier detailed research can be lifted to a higher system level in order to be put in context and to answer research questions on a more aggregated, industry level. The thesis also shows how general estimates of steam use and integration potentials are done for different mills. As an example of how the methodology can be used, a case study of the potential for implementation of CCS in the European PPI is presented. For CCS, earlier, detailed research has shown a promising potential for implementation and thermal integration in kraft pulp mills. Using the methodology developed throughout this thesis work, a broader perspective on CCS in the European PPI is given, based on this earlier research. The option of CCS is compared with alternative pathways and the potential for industry-wide implementation is estimated. The developed methodology could just as well be applied to other technologies influenced by external geographical factors, e.g. district heating, or other industry branches such as the oil refinery industry.

Improving the availability (and accuracy) of public data and statistics is a key factor if good industry-level analyses are to be performed. This thesis work shows that, for kraft pulp mills, fairly accurate estimates can be made regarding the process steam use based on only a small amount of data. In Sweden such data are public or easily accessible. On a European level, however, such data are difficult to obtain and the industry is very restrictive when asked to contribute with data. If this were to change, studies regarding the potential for and effect of large-scale implementation of the studied pathways in the European PPI could more easily be performed.

12 Further work

This chapter points out some interesting areas where future work can be performed.

There is an increasing amount of research and development activities regarding extraction of hemicelluloses prior to cooking at a kraft mill. This is partly due to the currently beneficial economic conditions for production of dissolving pulp, where the hemicelluloses must be separated from the wood fibres. Removing the hemicelluloses (and/or converting kraft pulp production lines into dissolving pulp lines) will, however, alter the energy balance of the mill since it reduces the energy content in the black liquor. It remains to be studied how extraction of hemicelluloses can be thermally integrated at different types of mills, how its profitability and global CO_2 emissions effect compares to other technology options, and how it can be combined with other technologies, e.g. black liquor gasification.

This thesis mainly focuses on technology pathways of interest for kraft market pulp mills, having both internal biomass streams available and potential for a steam surplus. For other types of mills, other technologies can be of more interest. Such technologies are gasification of biomass, upgrading of biomass through e.g. drying, pelleting, pyrolysis and torrefaction, etc. For implementation of such technologies, the existing PPI, compared to building green-field stand-alone plants, could benefit from having the biomass-handling infrastructure in place and the potential for heat integration between the mill processes and the new biorefinery processes. It is of interest to study which factors affect the potential for large-scale implementation of such technologies. It would also be interesting to study how such implementation would affect the overall energy balance, and consequently the global CO_2 emissions, of the European PPI.

This thesis focuses on the integration of technology pathways to existing, European kraft pulp mills. Relative to the PPI in e.g. China and South America, the European mills are rather old and small. It would be interesting to study whether/how the size and age of the mills affect the economic performance and the potential for reduction of global CO_2 emissions for the studied pathways.

Finally, based on the results from this work regarding CCS in the European PPI, it could be of interest to go further with the investigation of whether the biogenic capture clusters in Scandinavia are large enough to motivate the infrastructure needed for transport to potential storage sites. If this is to be done, more knowledge regarding potential capture sites bordering the Baltic Sea and more cost estimations for different transport alternatives are needed. It could also be worthwhile to look further into the option of mineralization of CO_2, assuming that the mineralization technology reaches a technological breakthrough.

13 Abbreviations

Adt	Air Dry tonne
BAT	Best Available Technology
BAU	Business As Usual
BL	Black Liquor
BLG	Black Liquor Gasification
BLGCC	Black Liquor Gasification Combined Cycle
BLGMF	Black Liquor Gasification with Motor Fuel production
CC	Carbon Capture
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CEPCI	Chemical Engineering Plant Cost Index
CEPI	Confederation of European Paper Industries
CHP	Combined Heat and Power
CP	Coal Power
CTMP	Chemi-ThermoMechanical Pulp
d	Day
DH	District Heating
DIP	De-Inked Pulp
DME	DiMethyl Ether
EC	European Commission
ECF	Elementary Chlorine Free (bleaching)
ETS	Emission Trading Scheme (EU)
GB	Gas Boiler
GW	Ground Wood (pulp)
HEN	Heat Exchanger Network
HLMPP	Heat Load Model for Pulp and Paper
HP	High Pressure (steam, ~60-100 bar)
HW	HardWood (e.g. birch, eucalyptus)
LP	Low Pressure (steam, ~2-5 bar)
LWC	Light Weight Coated
MFC	Machine Finished Coated
MEA	Mono-EthanolAmine
MP	Medium Pressure (steam, ~9-14 bar)
MP2	Steam with a pressure between HP and MP (~25 bar)
News	Newsprint
NGCC	Natural Gas Combined Cycle
PGW	Pressurised Ground Wood pulp

PPI	Pulp and Paper Industry
RB	Recovery Boiler
RCF	ReCycled Fibre
SEA	Swedish Energy Agency
SEC	Specific Electricity Consumption
SF	Statistics Finland
SW	SoftWood (e.g. spruce, pine)
TCF	Totally Chlorine Free (bleaching)
TD	Telephone Directory
TMP	Thermo-Mechanical Pulp

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