Satu Lipiäinen

THE ROLE OF THE FOREST INDUSTRY IN MITIGATING GLOBAL CHANGE: TOWARDS ENERGY EFFICIENT AND LOW-CARBON OPERATION

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Abstract

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The forest industry has increased its energy efficiency substantially in the 21st century, but higher improvement rates could be expected regarding targets set by the European Union and the Intergovernmental Panel on Climate Change. A variety of factors, i.e. technology development, structural changes and climate policies can drive energy efficiency improvement and decarbonization. This thesis looks how the Finnish and Swedish forest industries are developing towards energy efficient and low-carbon operation and evaluates the role of the sector in mitigating global change. These countries have long been forerunners in efficient operation and the decarbonization of the sector.

The dependency on fossil fuels has decreased in the forest industry as energy efficiency has improved and fossil fuel use has been switching to biofuels. Potential opportunities to reduce CO_2 emissions substantially exist: the Finnish and Swedish pulp mills have managed to operate lime kilns using a wide range of biofuels and their recovery boilers have been developed to produce significantly more renewable electricity and heat. New operating modes such as polysulphide cooking seem to provide a cost-effective way to produce pulp with higher material efficiency, but new solutions often cause changes in energy consumption and production. Structural changes, for example start-ups and closures of mills, have had a limited effect on energy efficiency improvement, which highlights the importance of maintaining efficient operation in existing mills.

The forest industry can play a significant role in mitigating global change. The production of bioenergy and biofuels can be increased, notable energy savings can be expected and at least in comparison to other industrial sectors, the forest industry has good premises to achieve net zero industrial emissions before 2050. However, even though the forest industry has developed towards more sustainable operation and feasible technologies for improvement exist, the pace of evolution is slow in light of the urgent targets to mitigate global warming. The forest industry is the fourth largest industrial energy user and the fifth largest fossil CO_2 emitter in the world. Investment cycles are long in the forest industry, and 2050 is only one cycle away. Thus, more research and political guidance are needed immediately to accelerate the evolution worldwide.

Keywords: forest industry, pulp and paper industry, energy efficiency, energy transition, bioenergy, decarbonization, CO_2 emissions

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My warmest thanks go to my husband. Completing a PhD is a challenge but combining it with competitive ultrarunning is impossible without an extremely supportive atmosphere at home. Furthermore, I am probably supposed to thank my husband for letting me forget my research every once in a while, but I am not going to do that. Instead, I want to thank him for walking this path with me. Even though writing two doctoral theses in the same household provided synergy benefits, the path might not be the easiest, especially during the COVID-19 pandemic.

Satu Lipiäinen (née Kähkönen)
September 2022
Lappeenranta, Finland

Contents

List of publications

This dissertation is based on the following papers. The rights have been granted by publishers to include papers in the dissertation.

I. Lipiäinen, S., Kuparinen, K., Sermyagina, E., and Vakkilainen, E. (2022). Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden. *Sustainable Production and Consumption*, 29, pp. 421–431.
II. Kähkönen, S., Vakkilainen, E., and Laukkanen, T. (2019). Impact of structural changes on energy efficiency of Finnish pulp and paper industry. *Energies*, 12(19), pp. 3689–3700.
III. Lipiäinen, S., Kuparinen, K., and Vakkilainen, E. (2021). Effect of polysulphide pulping process on the energy balance of softwood and hardwood kraft pulp mills. *Nordic Pulp and Paper Research Journal*, 36(4), pp. 570–581.
IV. Lipiäinen, S., and Vakkilainen, E. (2021). Role of the Finnish forest industry in mitigating global change: Energy use and greenhouse gas emissions towards 2035. *Mitigation and Adaptation Strategies for Global Change*, 26(2).
V. Lipiäinen, S., Sermyagina, E., Kuparinen, K., and Vakkilainen, E. (2022). Future of forest industry in carbon-neutral reality: Finnish and Swedish visions. *Energy Reports*, 8, pp. 2588–2600.

Author's contribution

I. The author was the principal author and investigator in Publication I. The author was responsible for collecting and analysing the data and writing the original manuscript. Dr Kuparinen and Dr Sermyagina provided valuable comments and suggestions on the manuscript. Professor Vakkilainen supervised the work and gave comments and suggestions during the research.

II. The author was the principal author and investigator in Publication II. The author was responsible for collecting and analysing the data and writing the original manuscript. Professor Vakkilainen supervised the work and gave valuable ideas. Professor Laukkanen commented the manuscript.

III. The author was the corresponding author and responsible for most of the calculations and the writing of the section on results in Publication III. Dr Kuparinen wrote most of the introduction and methods sections, participated in the calculations and commented the manuscript. Professor Vakkilainen supervised the work, provided expertise in the mill balance calculations, and gave valuable comments and remarks.

IV. The author was the principal author and investigator in Publication IV. The author was responsible for the calculations and writing the original manuscript. Professor

Vakkilainen supervised the work, gave valuable ideas and suggestions, and commented the manuscript.

V. The author participated in writing the manuscript in collaboration with Dr Sermyagina and Dr Kuparinen. The author was responsible for the calculations and most of the data gathering. Professor Vakkilainen supervised the work and gave valuable comments and suggestions.

Related publications (not included in the thesis)

Kuparinen, K., Kähkönen, S., and Vakkilainen, E. (2020). New revenue opportunities for pulp and paper sector from carbon capture. *Tappi 2020 Pulping, Engineering, Environmental, Recycling and Sustainability (PEERS) Conference*.

Kuparinen, K., Lipiäinen, S., and Vakkilainen, E. (2021). Can carbon capture be a new revenue opportunity for the pulp and paper sector? *Tappi Journal*, 20(8), pp. 527–540.

Lipiäinen, S., Kuparinen, K., Sermyagina, E., and Vakkilainen, E. (2021). Pulp and paper industry responses to the need for energy transition: Towards green and energy efficient low carbon operation. *Appita Magazine.*

Vakkilainen, E., Kuparinen, K., and Lipiäinen, S. (2021). Use of HTC for utilization of the forest industry sludges. *European Biomass Conference and Exhibition (EBCE) Proceedings.*

Kuparinen, K., Lipiäinen, S., and Vakkilainen, E. (2022). Effect of biomass-based carbon capture on the sustainability and economics of pulp and paper production in the Nordic mills. *Environment, Development and Sustainability.*

Sermyagina, E., Lipiäinen, S., and Kuparinen, K. (2022). Finnish forest industry and its role in mitigating global environmental changes. In *Transitioning to Affordable and Clean Energy*. Edited by Constable, E.

Lipiäinen, S., Apajalahti, E., and Vakkilainen, E. (2022). Role of climate policies in deep decarbonization of pulp and paper industry. *2nd International Conference on Negative CO_2 Emissions*. Göteborg, Sweden.

Saari, J., Sermyagina, E., Kuparinen, K., Lipiäinen, S., Kaikko, J., Hamaguchi, M., and Mendoza-Martinez, C. (2022). Improving kraft pulp mill energy efficiency through low-temperature hydrothermal carbonization of biological sludge. *Energies*, 15(17), pp. 6188.

Nomenclature

Latin alphabet

E	energy consumption	J, Wh
EE	energy efficiency index	-
P	production	tons
S	production share	tons/tons
SEC	specific energy consumption	J/kg, Wh/kg
v	year	a
w	weighting factor	J/kg, Wh/kg

Greek alphabet

ε	energy efficiency improvement rate	%/a
Δ	change	

Superscripts

T,t	year

Subscripts

n	new
o	closed
ref	reference
tot	total
i, x	index
eq	equivalent

Abbreviations

a	year
ADt	air-dry ton
BDt	bone-dry ton
BAT	best available techniques
BCTMP	bleached chemi-thermomechanical pulp
BECCS/U	bioenergy with carbon capture and storage or utilization
BL	black liquor
BLG	black liquor gasification
CaL	calcium looping
CCS	carbon capture and storage
CEPI	Confederation of European Paper Industries
chem	chemical
CLC	chemical looping combustion
COVID-19	coronavirus disease 2019

CTMP	chemi-thermomechanical pulp
DS	dry solids
DIP	deinked pulp
EDA	energy decomposition analysis
EEI	energy efficiency improvement
ETS	emissions trading system
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FIN	Finland
G	generator
GHG	greenhouse gas
GW	groundwood pulp
HFC	hydrofluorocarbons
HHRR	hearth heat release rate
HHV	higher heating value
HW	hardwood
IEA	International Energy Agency
INT	energy efficiency
int	integrated
IPCC	Intergovernmental Panel on Climate Change
LFO	light fuel oil
LMDI	Logarithmic Mean Divisia Index (method)
LULUCF	land use, land use change and forestry
MEA	monoethanolamine
mech	mechanical
Moxy	Mead Oxidation (process)
NG	natural gas
NSSC	neutral sulphite semi-chemical
PFC	perfluorocarbon
PFE	programme for improving energy efficiency
P&P	pulp and paper
PPI	pulp and paper industry
PS	polysulphide
RB	recovery boiler
RCF	recycled fibers
sob	solid volume over bark
SEC	specific energy consumption
STR	structure
SW	softwood
SWE	Sweden
TMP	thermomechanical pulp
TRECS	tradable renewable energy certificate system
USA	United States of America
VOL	volume

1 Introduction

The forest industry is one of the most energy intensive industrial sectors. Globally it accounts for 5% of industrial energy use (Trudeau *et al*., 2011). The sector covers a large share of its energy demand by on-site generated bioenergy, but many mills still rely on the combustion of fossil fuels. The fossil carbon dioxide (CO_2) emissions are the fifth largest in the industrial sector after the iron and steel, concrete, chemicals, and aluminum industries (IEA, 2022a). As an energy-intensive sector with high availability of renewable energy, the forest industry provides interesting opportunities for responding to the global demand for a sustainable energy transition and mitigation of CO_2 emissions. Firstly, the sector has potential to cut industrial emissions by reducing combustion of fossil fuels by switching fuels, electrifying processes, and improving efficiency. Secondly, the sector utilizes mainly sustainable raw materials and can provide a basis for bioeconomy producing renewable materials and fuels to be used by other sectors. Thirdly, the forest industry can participate in generation of negative emissions i.e., removal of CO_2 from the atmosphere. Sustainable supply of raw materials and careful forest management have a great impact on global carbon balance because growing forests sequestrate large amounts of CO_2 and thus act as carbon sinks and storage. Additionally, the negative emissions can be generated by capturing biogenic CO_2 from the flue gases of the mills. The opportunities of the sector are summarized in Figure 1.1.

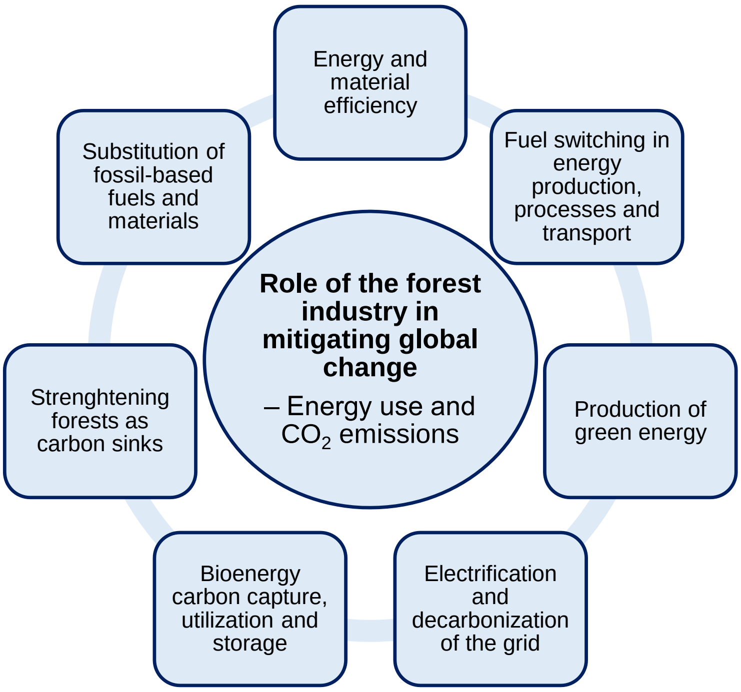


Figure 1.1: The possibilities of the forest industry to contribute to the mitigation of global change in terms of energy use and CO_2 emissions.

Climate change is undeniably one of the most severe and timely issues of the century. The climate is warming because of human-induced greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC) calls for significant reductions of CO_2 emissions and the Paris agreement, that was adopted by 196 parties in 2015, aims to limit the warming to well below 2 °C in comparison to pre-industrial time (United Nations, 2021). The European Union (EU) has set a target to be the first carbon neutral continent by 2050. The EU tightened its 2030 CO_2 emissions reduction target substantially in 2021: a 55% cut in net emissions must be reached by 2030 compared to the 1990 level (European Commission, 2021a). A tightening of other targets has been proposed as well to achieve the CO_2 target: in 2030, 40% of energy should be produced from renewable sources and energy efficiency improvement (EEI) should lead to a 36–39% lower energy consumption in comparison to the expected energy use in 2030. A proposed revision of the Energy Efficiency Directive calls for increasing the annual energy saving requirement for 2024–2030 from 0.8% to 1.5% (European Commission, 2021b).

CO_2 emissions are declining more rapidly in energy and residential sectors in comparison to the more challenging CO_2 emission sources in industrial and transport sectors. Industry accounts for approximately 26% of final energy consumption and 20% of GHG emissions in the EU (Eurostat, 2020; EEA, 2021), and thus fundamental transformation is needed in order to achieve the global and EU's targets. Worrell *et al*. (2009) argue that EEI is the most important and cost-effective measure for CO_2 emissions reduction in the industrial sector. According to the International Energy Agency (IEA) (2021a), industrial EEI can avoid 47 EJ of global energy demand by 2050. Thus, EEI is expected to play a key role in a sustainable transition, but also other important measures, mainly fuel switching, material efficiency improvement and reduction of non-CO_2 GHG emissions, for example methane (CH_4), exist. In addition to the above-mentioned measures, several future scenarios are aiming towards carbon neutrality relying partly on carbon capture technologies (IEA, 2020a).

The forest industry offers an interesting platform to study the development of industrial energy efficiency and fossil CO_2 emissions. The sector has significant potential to save energy by improving its energy efficiency (Fracaro *et al*., 2012). In addition to energy savings and CO_2 emissions reduction, EEI plays an important role in the energy supply security and the competitiveness of energy-intensive industries. The forest industry can replace fossil fuels with (self-generated) biomass. The replacement of oil and natural gas with biofuels in lime kilns is an illustrative example of successful fuel switching in many mills (Kuparinen and Vakkilainen, 2017). The electrification of processes and energy production has also been considered to be a key measure for reducing fossil fuels use and consequently energy-related emissions (Rahnama Mobarakeh, Santos Silva, and Kienberger, 2021). Material efficiency improvement and the reduction of waste is a timely topic within the sector (e.g. Andritz, 2021), for example higher recycling rates of paper reduce the demand for virgin fibres and consequently lower the energy and raw materials use. The efficient utilization of side-streams can provide additional income for a mill in addition to the mitigation of waste. The forest industry has the possibility to reduce non-CO_2 GHG emissions, for example the improved treatment of sludge can lead to substantial reduction in CH_4 emissions (Kong *et al*., 2013).

In addition to traditional measures for CO_2 emissions reduction, the forest industry provides a platform for new opportunities. The forest industry can produce a large palette of bio-based materials and fuels that can substitute fossil-based alternatives and act as carbon storages. Textile fibres, wooden construction materials, lignin-based solutions, pellets, biogas, and liquid biofuels, to name a few, are examples of bio-based products that can be produced by the sector. Modern pulp mills can produce an excess of renewable heat and power (IRENA, 2018), and thus the forest industry can provide bioenergy to be used by other sectors. Furthermore, as the forest industry mills combust large amounts of biomass, they are large point sources of biogenic CO_2 (Rodriguez *et al*., 2021). This feature together with possible heat and electricity surplus makes the sector an interesting platform for bioenergy carbon capture, storage and utilization (BECCS/U), and could transform mills even to become carbon sinks (Kuparinen, Vakkilainen, and Tynjälä, 2019).

Finland and Sweden are important forest industry producers covering approximately 95% of pulp and paper production in the Nordic countries, i.e. Finland, Denmark, Iceland, Norway, and Sweden, and these two produce almost 50% and 20% of European pulp and paper, respectively (FAO, 2022). Finland and Sweden are important forest industry countries also globally: the world's largest softwood pulp mill is in Finland and both countries have continuously invested in new mills and technologies. Several new products such as biodiesel from tall oil and lignin-based products are produced at a commercial volume, and many innovations are being tested on a laboratory or pilot-scale.

Finland and Sweden have ambitious climate targets: both aim to become the first fossil-free welfare societies (Ministry of Economic Affairs and Employment, 2019a; Ministry of Infrastructure of Sweden, 2020). Finland has claimed a non-binding proposal to achieve carbon neutrality by 2035, meaning that GHG emissions would be in balance with carbon sinks. Sweden has a legally binding target to achieve net zero emissions by 2045 (an 85% reduction in CO_2 emissions compared to 1990) (Ministry of the Environment and Energy, 2017). The forest industry accounts for roughly 20% of the final energy consumption in both countries, and thus, the sector must contribute to reducing the energy use, fossil fuel dependency and CO_2 emissions. The Finnish and Swedish forest industries have already put a lot of effort into developing towards more sustainable operation: many mills have succeeded in cutting their GHG emissions and improving energy efficiency. The role of the Finnish and Swedish forest industries as important producers, and energy efficient and low carbon operators combined with ambitious national climate targets makes Finland and Sweden interesting target countries of this thesis that aims to evaluate the sustainable transition of the forest industry and its role in the mitigation of climate change.

1.1 Objectives, methods, and limitations

The objective of this thesis is to look how the forest industry is responding to the need for a sustainable energy transition and evaluate the role of the sector in mitigating global change. The focus is on the Nordic forest industry. The main targets are to increase knowledge and enhance understanding of the ongoing energy transition and future opportunities to mitigate climate change by reducing CO_2 emissions in the forest industry. The main research questions are:

1) *How have energy use and CO_2 emissions developed in the forest industry?*

2) *How have the observed structural changes, as well as energy and climate policies affected the development of the energy use in the forest industry?*

3) *What is the role of technology development in the forest industry and how does the integration of new technologies affect energy use and production?*

4) *What are the future prospects for energy use and CO_2 emissions in the forest industry, and how can the sector contribute to meeting climate targets?*

This thesis consists of five publications. The development of energy consumption, energy production, and CO_2 emissions was studied in Publication I. Finland and Sweden were used as target countries. Their energy performance and effects of national energy and climate policies on the pulp and paper industry (PPI) were compared. Publication II investigated the impact of structural changes, i.e. unit closures and start-ups on the energy efficiency of the PPI. In the 21st century, several units were closed or started up in the Finnish PPI, and thus Finland was an appropriate target country. Polysulphide cooking is a method for improving yield in kraft (sulphate) pulping. Publication III studied what is the effect of polysulphide cooking on the energy balance of kraft pulp mills. The future development of energy use and CO_2 emissions as well as the role of the forest industry in meeting energy and climate policy targets were investigated in Publications IV and V. Finland was chosen as the target country in Publication IV because several notable changes, for example large biorefinery projects are expected in the near future. In Publication V, opportunities and barriers to carbon neutral operation in the forest sector were analysed using Finland and Sweden as target countries. The contributions of the publications to the research areas are presented in Table 1.1.

Table 1.1: Contribution of the publications to the research questions, used methods, and data.

Research question	Publication	Research method	Data sources
How have energy use and CO_2 emissions developed in the forest industry?	I	Data analysis	Literature data
How have the observed structural changes, as well as energy and climate policies affected the development of the energy use in the forest industry?	I, II	Scenario building	Literature data
What is the role of technology development in the forest industry and how does the integration of new technologies affect energy use and production?	I, III, V	Data analysis, modeling	Literature, experimental mill data
What are the future prospects for energy use and CO_2 emissions in the forest industry, and how can the sector contribute to meeting climate targets?	IV, V	Literature review, scenario building	Literature

The methodology of this thesis consists of several research methods, namely data analysis, scenario building, modelling, and literature review, that enable answering the targeted research questions. Statistical data on the Finnish and Swedish forest industries and individual mills were gathered. The trends were analyzed to find out how energy consumption, production, and CO_2 emissions have developed during the research period. To deepen understanding, decomposition analysis (Logarithmic Mean Divisia Index method) was used to answer the question of which factors have contributed to the change of the energy consumption, and the energy efficiency index method was used to investigate the development of energy efficiency. The energy efficiency index method shows how the energy efficiency has developed but does not provide reasons behind the change. Major structural changes, i.e. unit closures and start-ups were recognized as potential reason for significant energy efficiency improvement. Hence, three scenarios were built to evaluate the role of structural changes on the development of energy efficiency.

Data and literature on the development of technologies, mainly lime kilns, dryers, recovery boilers, polysulfide cooking, and carbon capture technologies were analyzed to map the potential and effects of these options on decarbonization and energy balance of mills. All opportunities cannot be studied in detail. In this thesis, effects of polysulphide cooking on the energy balance of kraft pulp mills were modelled and analysed using a spreadsheed-based calculation tool *Millflow*.

After analysing historical development of the forest industry, future prospects were studied. Literature review was utilized to map future opportunities and barriers and find out how the industry sector as well as countries see the upcoming development. A scenario building was chosen as a research tool for obtaining quantitative estimates on the possible future CO_2 emissions, energy consumption, and production. The scenario building enables studying several alternative futures, which makes it a useful tool.

The needed data was gathered from several sources during this research. The Finnish Forest Industries (2020c) and Swedish Forest Industries (2020a) databases provide a significant amount of data on the state of the forest sector, energy use, production, and emissions. Mill-level energy use data is not included in the Finnish statistics, and therefore the needed data was gathered from other sources, mainly from mills' environmental reports and permits, and university theses. The production and energy consumption data is published as supplementary material to Publication II. Later the data was updated adding fuel consumption, CO_2 emissions, and energy production figures. Sector's production, CO_2 emissions, and energy use data were gathered from Swedish Energy Agency (2020), Food and Agriculture Organization of the United Nations (FAO) (2022), and Statistics Finland (2022).

The environmental reports and permits were a key data source for analysing the Finnish forest industry. In Finland, any activities that have a risk of polluting the environment need an environmental permit and significant changes in operations require an application for changing the permit (Regional State Administrative Agency, 2021). Thus, every mill has an up-to-date environmental report that provides data on energy consumption, energy production, and used devices in addition to the emission levels, which enabled creating an accurate picture of the current state of the Finnish forest industry in this thesis work.

Both the quality and availability of data are severe issues when studying energy consumption in different countries. Energy reporting practices and system boundaries vary between different countries and databases, and many statistics do not publish used assumptions. The mills know accurately how much purchased fuels, for example fuel oil or natural gas, they have used, but the amounts of on-site generated biomass are typically rough estimates. Especially Publication II required gathering high-quality mill-level data, but most companies prefer to keep the consumption and production values as a trade secret for commercial purposes, which hampered the data gathering. Even the reported mill-level values can include severe uncertainties as specific energy consumption varies notably depending on the capacity utilization rate and climate conditions (winter/summer). Furthermore, the measuring instruments or procedures can be defective. More discussion on the data quality problems can be found in previous studies (e.g. Farla and Blok, 2001).

Technology development will play a significant role in energy and material efficiency improvement as well as in the use and generation of new renewable fuels. The role of the development is difficult to assess as mills are complicated systems, and the effect of a certain modification can be impossible to isolate. A continuously increasing number of new solutions and possibilities exist and thus this thesis cannot cover all the options. The considered options provide insights into different areas of technology development. Polysulphide cooking represents a possibility to improve material efficiency, while recovery boilers are the largest producers of renewable steam and electricity in the mills. Additionally, fuel switching in lime kilns has substantial potential to reduce fossil CO_2 emissions. Possibilities of BECCS/U as a novel opportunity for pulp and paper mills have also been discussed. Excluded opportunities include but are not limited to power-to-x technologies, the production of bio-based fuels and materials, the optimized utilization of waste heat streams, and the role of pulp and paper mills in stabilizing intermittent energy systems.

This thesis concentrates on analyzing a rather conventional industrial sector namely the forest industry. However, it can be expected that production of advanced bioproducts such as textile fibres increases, but effects of new products on the energy and CO_2 balance of mills fall outside the scope of this thesis. The focus is on the reduction of industrial CO_2 emissions but achieving carbon free operation requires addressing indirect emissions, i.e. CO_2 from the transport and the production of purchased energy as well. Additionally, neither the role of bio-based fuels and materials as substitutes for fossil alternatives nor the possibilities to strengthen forests as carbon sinks are included thoroughly. Moreover, it should be noted that a comprehensive analysis of sustainable operation would require tackling other aspects such as impacts on the environment and human health in addition to the CO_2 emissions reduction.

The future development of the forest sector is challenging to predict as several megatrends such as population growth, development of information technology, changes in global economy, climate change, and growing scarcity of resources affect it. Scenario studies improve understanding of the future but there are always certain limitations. The effect of all factors cannot be included in the future scenarios, and unexpected developments can lead to rapid changes. As an illustrative example, the coronavirus disease 2019 (COVID-19) accelerated the decline of printing and writing papers because demand from offices, publishers, and commercial printing dropped (CEPI, 2021). Hence, the disease was probably one of the reasons that led to paper mill closures in Finland and Sweden.

This thesis focuses on Finland and Sweden. Many of the outcomes can be applied to other industries but there are limitations. The structure of the forest industry and national resources vary significantly between countries. Finland and Sweden have vast domestic wood resources, which has led to high production volumes of virgin fibres. The fibre production provides the possibility to rely on biomass in energy production. Many countries concentrate on the production of paper, which affects the energy use. For example, the Netherlands produces 80% of its paper from recycled fibres, and natural gas covers 97% of fuels used for energy production (Laurijssen, Faaij, and Worrell, 2012). Moreover, countries and areas are in different phases of development. An illustrative example is that the demand for graphic papers is decreasing in developed countries whereas it is increasing notably in developing countries where the population and well-being are growing strongly.

1.2 Main contributions

This thesis improves knowledge on energy use and CO_2 emissions of the forest industry. It shows how the forest industry has responded to the need for sustainable energy transition. The thesis clarifies what factors have affected the changes in energy consumption, production, and CO_2 emissions. The development of energy efficiency and factors affecting it are investigated. EEI potential is notable, and thus awareness of the factors affecting energy efficiency may facilitate the development of mills and processes towards more efficient operation. The thesis uses Finland and Sweden as target countries because they have been forerunners in the energy efficient operation as well as decarbonization of the sector. Better understanding of development of the Finnish and Swedish forest industries can offer important insights to be learned by other countries, energy-intensive sectors, and policymakers.

The world is changing rapidly and achieving ambitious goals such as the EU’s target to be a carbon neutral continent by 2050 requires efforts of all sectors. After contributing to creating a clear picture of the forest industry’s current status and clarifying the development so far, the thesis examines the future prospects of the sector, i.e. what kinds of changes can be expected and what kinds of changes are needed for achieving a carbon neutrality. Developments realized so far are presented, and other opportunities and barriers to reducing dependency on fossil fuels are discussed. Enhanced awareness of the possible development path of the forest industry may support decision-making of industrial operators and policymakers. The potential role of the forest industry in meeting climate goals has been unclear, and this thesis aims shed light on the issue.

1.3 Outline of the thesis

This thesis consists of eight sections. After this introduction, the second section shortly defines the forest industry and presents the most important processes. The section introduces energy consumption, energy production, and CO_2 emissions in the forest industry in general and provides an overview of the current situation and development of the global forest industry. The opportunities for CO_2 emissions mitigation in the forest industry are presented in section three. Section four provides an overview of the current situation and development of the Finnish and Swedish forest industries. Section five shows what can be said about the contribution of new or developed technologies to achieving more sustainable operation. Section six discusses how the Nordic forest sector is likely to be developed and what the opportunities and barriers are when aiming towards carbon neutral operation. In section seven, the role of energy and climate policies on the development of the forest industry as well as a role of the forest industry in meeting the targets are discussed. Finally, section eight concludes the main findings and provides ideas for future research.

2 Energy use and CO_2 emissions in the forest industry

The forest industry is an energy intensive sector that consists of the production of various products in different kinds of mills. This section defines the forest industry and presents its main processes, the principles of energy consumption and production as well as sources of CO_2. The development trends of the global forest industry are briefly introduced to widen the view.

2.1 The forest industry

The forest industry is a broad sector that consists of several activities, and it is not always clear which activities are included. This thesis follows the definition of the forest industry introduced in Sections 6.1.(a), 6.1.(b) and 6.1.(c) of Annex I to Directive 2010/75/EU (The European Parliament and the Council of the European Union, 2010), i.e. the integrated and non-integrated production in industrial installations of:

a) pulp from timber or other fibrous materials
b) paper or cardboard with a production capacity exceeding 20 tons per day
c) mechanical wood products

Pulp and paper are typically considered to be chemical forest industry products, and sawn wood and wood-based panels are seen as mechanical forest industry products. In addition to the main products, several kinds of side streams and wood residues are used for the production of biofuels and chemicals on the mill sites. This thesis focuses mainly on the chemical forest industry, especially kraft pulping due to its high energy intensity and high potential to produce bioenergy. Publications IV and V briefly discuss on the mechanical forest industry and the production of wood-based biofuels and bioproducts besides the PPI. Figure 2.1 shows the classification used in this study.

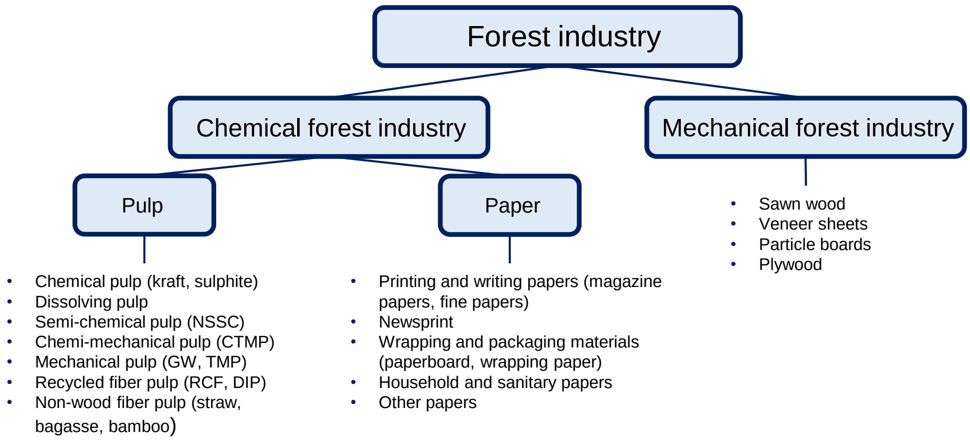


Figure 2.1: Forest industry products classification.

Pulp is produced using a range of chemical, mechanical, and hybrid processes. Extensive literature exists on the various manufacturing methods (Sixta, 2006; Ek, Gellerstedt and Henriksson, 2009; Lönnberg, 2009; Fardim, 2011). Wood is the dominating raw material but non-wood fibres such as bagasse or bamboo are used as well. The recycling rate of paper has been increasing, which has reduced demand for virgin raw materials per produced ton of paper. Mechanical forest industry processes are notably less energy and CO_2 intensive than pulping and papermaking.

2.1.1 Kraft pulping

Kraft pulping is the most common chemical pulping process and it covers almost 80% of all produced wood pulp (FAO, 2022). The kraft pulping process can be divided into the fibre line and recovery cycle (Figure 2.2).

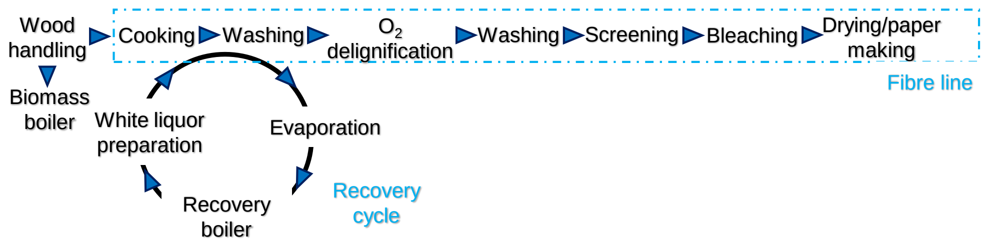


Figure 2.2: The principles of kraft pulping.

Logs delivered to the mill are fed into a debarking drum and later chipped. Wood chips continue to a digester which processes the chips into pulp. The chips are impregnated with alkaline cooking liquor (white liquor) consisting of sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The purpose of the cooking process is to dissolve the lignin which binds the wood fibres together. A part of the hemicelluloses in wood dissolves as well, and approximately 50% of the wood organic matter is lost during cooking. The dissolved matter is separated from the pulp by washing and is transmitted to evaporators. The washed pulp typically continues to an oxygen delignification stage, which is used for removing residual lignin that causes a brown colour in the pulp. The usage of the oxygen delignification stage reduces the need for expensive bleaching chemicals in the following bleaching stage. In the bleaching stage, colourful components in the pulp are bleached with chemicals such as chlorine dioxide (ClO_2), oxygen (O_2), and ozone (O_3). In a stand-alone pulp mill, the bleached pulp is dried and delivered to customers. Integrated mills pump the pulp to a paper machine.

The spent cooking liquor, black liquor, consists of used cooking chemicals and dissolved organic matter. The dry solids (DS) content of the black liquor is below 20% when it leaves the washing stage and is introduced to evaporation. During the evaporation, the DS content is increased to up to 85%. Afterwards the liquor is fed into a recovery boiler where sulphur compounds are reduced back to Na_2S. So called green liquor consisting mainly of Na_2S and sodium carbonate (Na_2CO_3) leaves the boiler and continues to causticization. The causticization process converts Na_2CO_3 to NaOH. The produced white liquor is rich in active cooking chemicals (NaOH and Na_2S) and can be fed to the digester.

2.1.2 Other processes

Mechanical pulping is used mainly for producing raw materials for various graphic papers. The advantage of the process is a high yield (~95%) in comparison to chemical pulping. The drawback is the quality of the paper produced from mechanical pulp. Lignin is not separated from mechanical pulp and that makes the paper to turn yellow as time passes. Mechanical pulping processes can be divided into refining and grinding. Both processes use mechanical energy to separate wood fibres. The processes consume a great amount of electrical energy, part of which can be recovered as steam. Some processes, such as neutral sulphite semi-chemical pulping (NSSC), combine chemical and mechanical methods for producing pulp.

A paper machine consists of a forming section, press section, and drying section. Depending on the paper grade, different aftertreatments can be used. A calendaring section represents an example of typical aftertreatment method. At the forming section, pulp and other raw materials are mixed with water and a web is formed. During the press section, a large amount of water is removed by pressing after which the web continues to the final drying stage. The drying stage is the largest energy consumer of the paper machine. The finished paper is wound into a reel and delivered to customers.

2.2 CO_2 emissions

Greenhouse gases absorb terrestrial radiation, which leads to the greenhouse effect. Thus, an increase in the concentration of GHGs in the atmosphere causes global warming and climate change. The Kyoto Protocol considers seven GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) (Eurostat, 2016). CO_2 is the principal GHG, and it originates from the combustion processes of fossil fuels and biomass, changes in land use, and industrial processes (IPCC, 2018). The combustion of fossil fuels increases the amount of circulating CO_2 in the atmosphere while biomass combustion only releases the carbon absorbed during growth. Carbon release in biomass utilization is included in the land use, land use change, and forestry (LULUCF) sector. Thus, sustainably managed biomass is often considered as a carbon neutral fuel (European Commission, 2022).

2.2.1 CO_2 sources in the forest industry

CO_2 flows in a typical integrated forest industry mill are presented in Figure 2.3. A mechanical forest industry unit and an energy production unit are often located at the same site with a pulp and paper mill. Many processes emit other GHGs in addition to CO_2, mainly CH_4 and N_2O (Zhao *et al*., 2019), but CO_2 is the dominating GHG emission

(Wang *et al.*, 2016). This thesis mainly focuses on the industrial CO_2 emissions that consist of operations inside the mill's gates (system A in Figure 2.3).

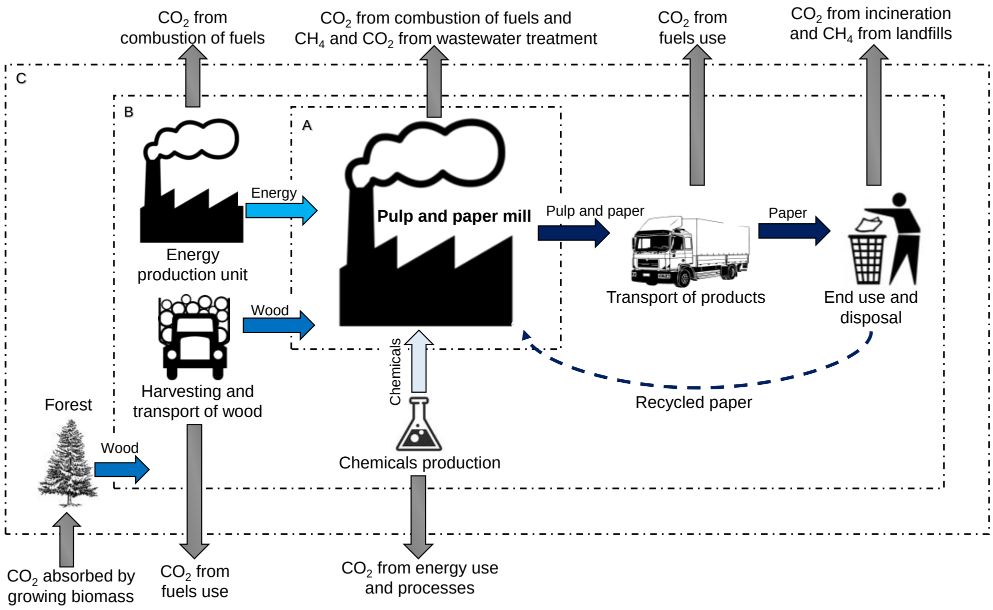


Figure 2.3: The main greenhouse gas flows in a pulp and paper mill.

The lion's share of the industrial emissions originates from the energy production units (Wang *et al.*, 2016), and a part of the emissions are associated with pulp and papermaking processes. Modern kraft pulp mills can meet their energy demands by combusting wood residues (IRENA, 2018) and then most of the produced CO_2 is biogenic. Other mill types that have either higher energy demand and/or lower availability of self-generated biomass, are more dependent on the combustion of fossil fuels. Additionally, many boilers use fossil fuels during start-ups, shutdowns, and other exceptional situations. A lime kiln that is a part of chemical cycle in kraft pulp mills typically combusts oil or natural gas and is thus a significant CO_2 emitter (Kuparinen, Vakkilainen, and Tynjälä, 2019). Lime kilns additionally produce process-based CO_2 that is considered biogenic (Miner and Upton, 2002). Minor amounts of fossil fuels are used in paper dryers.

Additional industrial emissions originate from wastewater treatment plants and possibly landfills (Kong, Hasanbeigi, and Price, 2016). Wang *et al.* (2016) estimated that wastewater treatment is responsible for approximately 10% of the GHG emissions in the pulp and paper production. Landfilling is becoming a scarce option for waste disposal as mills typically re-use or combust generated waste streams. Indirect emissions consist mainly of production of purchased energy as well as the transport of raw materials and products, but also the production of chemicals emits CO_2 (system B in Figure 2.3). Some emissions are produced during the end use and disposal stages. One characteristic feature of the forest industry is the ability of the raw materials to absorb CO_2 from the atmosphere (system C in Figure 2.3).

The forest industry combusts several fuels, which have varying characteristics. For this thesis, one of the most important fuel properties is the CO_2 emission intensity, i.e. how much CO_2 is emitted when one unit of energy is produced using a certain fuel. The chemical composition as well as the moisture content of fuel affect the emission intensity, and thus there are notable differences within the same fuel (Alakangas *et al.*, 2016). However, in this thesis, constant factors are used for estimating CO_2 emissions from the combustion of fuels due to a lack of detailed data on the properties of the fuels. The CO_2 emission intensities for typical forest industry fuels are presented in Table 2.1. In this thesis, other fuels include diesel oil, asphaltene, propane, and other miscellaneous fuels.

Table 2.1: CO_2 emission intensities. Data from Statistics Finland (2021).

Fuel	**CO_2 intensity [$kgCO_2$/GJ]**	**Fuel**	**CO_2 intensity [$kgCO_2$/GJ]**
Biofuels	112	Peat	106
Natural gas	56	Coal	94–96
Fuel oil	78	Other	46–84

2.3 Energy consumption and production

Processes of the forest industry need both heat and electricity. Steam is used mainly for the evaporation of water, the heating of different products such as water, chemicals and air, and for the drying of products (Moya and Pavel, 2018). Driving motors, pumps, and compressors cover the major share of the electricity demand (Boharb *et al.*, 2017). The heat and electricity demands vary substantially within the different products and mill types. Some devices such as lime kilns and dryers consume fuels in addition to heat and electricity. The forest industry is a large energy producer, and a significant share of mills' energy demand can be met by on-site production. The side streams from the processes are efficiently utilized in the energy production, and thus a significant share of fuels can be bio-based.

2.3.1 Key definitions of energy use

Energy use can be expressed using different bases for measurement. Defining the different concepts and terms exactly reduce the number of misunderstandings. The definitions can differ slightly between sources. The terms and their definitions used in this thesis are presented as follows:

- *Energy use*, *energy consumption*, and *energy demand* are often used as synonyms even though according to the first law of thermodynamics, energy cannot be created or destroyed, and therefore the term energy consumption is somewhat misleading. However, the term *energy consumption* is widely used for example in energy statistics because from an economic point of view the energy is consumed (Blok and Nieuwlaar, 2017). In this thesis, these terms refer to a sum of purchased energy and self-generated energy that is used on a mill site to run the processes.

- *Primary energy* is typically considered as energy in its original form, i.e. coal, natural gas, or harvested biomass. Primary energy can be converted into useful energy using different kinds of energy conversion processes, such as power plants. A comparison of different forms of energy (e.g. electricity and biomass) is not reasonable, and thus there is a need to be able to convert all energy sources to primary energy. The conversion is typically done using energy conversion factors. In this thesis, the conversion factors for heat and electricity are 0.80 and 0.40, respectively. The conversion factor should be defined separately for each individual process because energy conversion efficiencies vary significantly, for example primary energy in fuel is used more efficiently in combined heat and power plant than in condensing power plant that produces only electricity. However, in many cases, there is not enough data for defining the conversion factors separately, and thus the same value is used for every case.

- *Final energy use* or *final energy consumption* refers to used energy after the conversion losses. The final energy use excludes energy transmission and distribution losses. In this thesis, this term is used mainly when national energy balances are considered. *Energy use* is occasionally used as a synonym for *final energy use.*

- *Specific energy consumption (SEC)* tells how much input energy is needed to produce one physical unit of output. *SEC* is often used for comparing the energy efficiency of similar processes. For example, if two pulp mills producing the same pulp grade have the *SEC* values of 18 GJ/t_{pulp} and 17 GJ/t_{pulp}, the latter one can be easily considered more efficient than the former one.

2.3.2 Energy consumption in the forest industry

The SEC values vary largely within the mills. The mill type and age, product mix, raw materials, quality requirements, operational and strategic choices, technologies, climate conditions, activity level, and the integration rate affect the mills' energy balance (Hamaguchi, 2013; Vakkilainen and Kivistö, 2014). Large and modern mills typically have a lower energy consumption per produced unit than their smaller and older counterparts. Integrated mills have synergy benefits as there is no need for pulp drying but the pulp can be pumped directly to a paper machine. The utilization rate affects the energy consumption because there is always a basic consumption and when increasing the production to the optimal level, the energy consumption per unit decreases substantially. Products and raw materials have a significant effect on the consumption. The production of chemical pulp requires a large amount of heat, whereas mechanical pulping is an electricity intensive process. The use of recycled fibres saves a lot of energy. Notable differences in energy requirements between wood species, for example hardwood and softwood can also be found. The location of the mill matters because in a cold climate, the heat demand increases, and incoming logs must be thawed in the wintertime. Energy efficiency improvements have reduced the specific energy use but the need for new environmental protection technologies and the higher quality of products can lead to increased consumption.

Table 2.2 introduces typical specific energy consumption values for three pulp and five paper grades. The values are used as reference specific energy consumption values for energy analysis in this thesis. The presented values can be considered somewhat outdated as the values develop over time, but the SEC values for every pulp or paper grade were not presented in fresher publications. The analysis done in this thesis uses reference values as ratios between different pulp or paper grades, and thus the timeline of SEC values does not have a significant effect on the validity.

Table 2.2: Typical specific energy consumption values from Farla, Blok, and Schipper (1997).

Pulp or paper grade	Electricity consumption [kWh/t]	Heat consumption [GJ/t]
Chemical pulp	690	10.0
Mechanical pulp	1,470	-2.1
Recycled fiber input	390	0.4
Household and sanitary papers	670	5.0
Newsprint	390	2.5
Printing and writing paper	560	7.0
Packaging materials	420	5.0
Other papers	500	6.0

2.3.3 Energy supply in the forest industry

Energy system in forest industry mills can be complex and connected, which creates challenges for studying the energy use of the sector. Forest industry mills are both energy users and producers, and they may even sell excess energy. Electricity is typically sold to the grid, and heat can be used for public district heating. The surplus in energy supply additionally leads to interesting opportunities. For example, Jönsson *et al*. (2013) investigated the use of surplus steam for electricity generation, lignin extraction, CO_2 capture, and black liquor gasification with the production of electricity or biofuels. Moreover, a mill may not use all the wood residues for its own energy generation but sell them, which increases the complexity. Many mills have a separate forest industry company or an energy company operating on the same site. Their operations can be highly integrated, which creates challenges for the allocation of energy use and emissions.

Energy supply varies significantly within different kinds of mills. This study gathered data on the Finnish and Swedish pulp and paper mills to illustrate differences in energy production and consumption within the mill types. The data is presented in Figure 2.4.

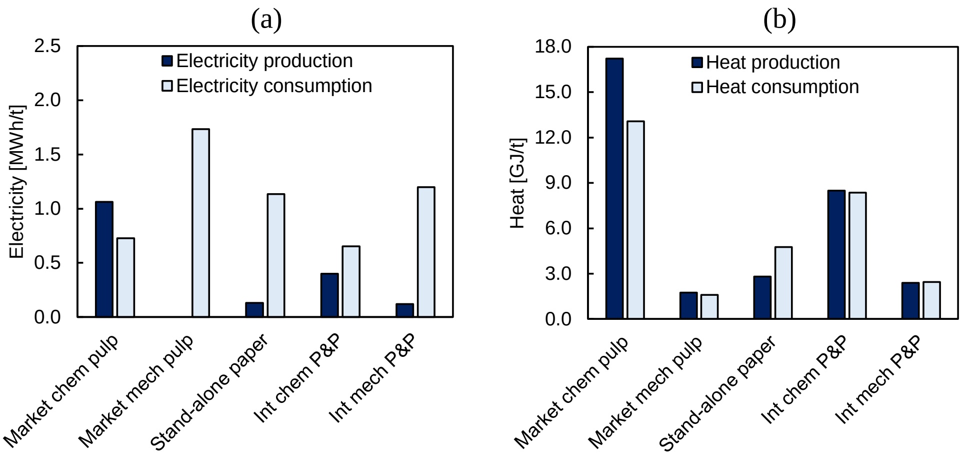


Figure 2.4: Production and consumption of electricity (a) and heat (b) in different kinds of mills in the northern hemisphere. Estimated based on environmental reports and permits (Regional State Administrative Agency, 2021) and data from Swedish Forest Industries Federation (2020). Chem refers to chemical, int to integrated, P&P to pulp and paper, and mech to mechanical.

Kraft pulp mills convert approximately half of the input wood to pulp, while the other half can be used for energy production (Hamaguchi, Cardoso, and Vakkilainen, 2012). A recovery boiler that combusts black liquor is the main energy generation unit in a kraft pulp mill. The recovery boiler combusts organic matter in the black liquor producing steam. Besides the energy production, the recovery boiler regenerates the spent cooking chemicals and minimizes the waste streams that are produced in processes. Delivering bio-based waste to landfills is banned at least in the EU, and the disposal of other waste can be expensive. Thus, several side products of the forest industry are disposed of by incineration. Biosludge is an illustrative example of a side product that does not produce energy during the combustion process due to its high moisture content but is however fed to the recovery or bark boiler to minimize the waste streams. Some stand-alone pulp mills and most integrated chemical pulp and paper mills operate separate biomass boilers that are typically multi-fuel boilers combusting a large variation of biofuels such as bark and chips. Fossil fuels such as peat are occasionally used especially in Finland.

The steam generated by boilers is consumed by pulping and papermaking processes, and back-pressure turbines are used for converting part of the steam to electricity. Especially in stand-alone pulp mills, an additional condensing tail may be used to increase the electricity generation. Several pulp mills purchase electricity, but modern stand-alone pulp mills typically generate both heat and electricity in excess of their own requirements. The surplus is often sold or used in an integrated paper mill. The efficiency of steam use in the mill processes affects the amount of electricity for sale because excess steam can be used for increasing condensing power generation.

Mechanical pulp mills and stand-alone paper mills do not typically have sufficient internal biomass sources to cover their energy demands, and consequently the mills purchase energy and operate fossil fuel boilers. Mechanical forest industry mills, for example sawmills, are not as energy intensive as the chemical forest industry mills, and therefore energy production is not a major issue. Those mills typically purchase electricity from the grid and combust a small amount of wood residues to supply steam. In many cases, a mechanical forest industry mill may be located at the same site with a pulp mill, which provides synergy benefits for energy supply. Other additional energy sources such as electric boilers (for example in Sweden), waste heat boilers, gas turbines, wind turbines, hydropower, and odorous gas boilers are also used in the forest industry.

2.4 The global forest industry: production, energy use, and emissions

Approximately 2% of global industrial fossil CO_2 emissions originate from the PPI (Trudeau *et al*., 2011). Manufacturing sawn wood and wood-based panels requires less energy than pulping and papermaking and is consequently also a less CO_2-intensive process. An estimated magnitude and geographical distribution of the CO_2 emissions of the PPI is presented in Figure 2.5.

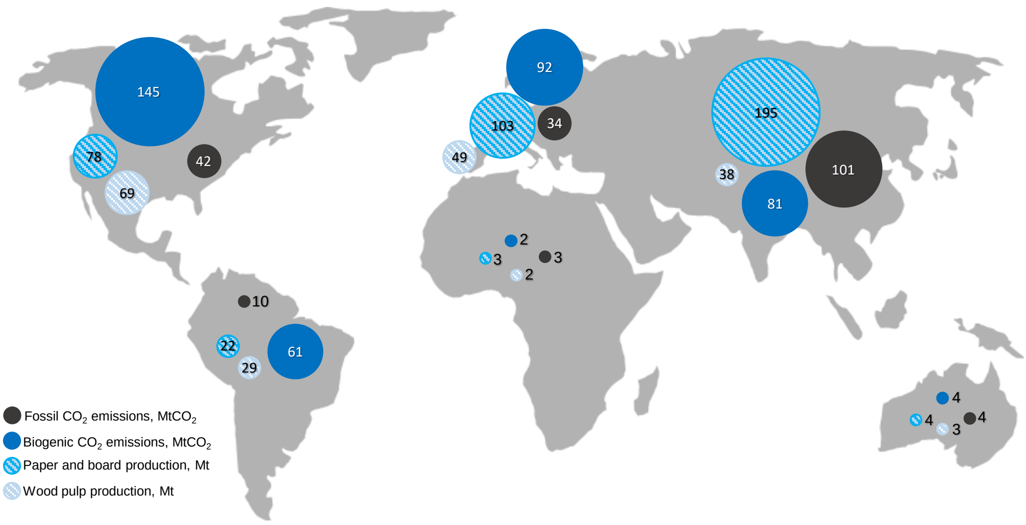


Figure 2.5: CO_2 emissions and production volumes for the pulp and paper industry. Modified from Lipiäinen, Apajalahti, and Vakkilainen (2022).

In 2019, the forest industry produced 190 Mt of wood pulp and 404 Mt of and paper and paperboard (FAO, 2022). The total production volume has been increasing rapidly. Forecasting the development of the forest sector is challenging because several factors such as demographic changes, environmental challenges, competition for natural resources, digitalization and urbanization affect the business environment (Salo, 2017). Despite the uncertainties, the annual demand for paper is expected to increase significantly, reaching 700–900 Mt in 2050 (Moya and Pavel, 2018). The growth highlights the need for more energy and material efficient solutions. Szabo *et al*. (2009) agree that if the emissions are not actively mitigated, energy consumption and consequently fossil CO_2 emissions from the PPI will increase drastically already by 2030 due to the increase in demand for paper. Figure 2.6 illustrates the development of production volumes and energy use in the global PPI.

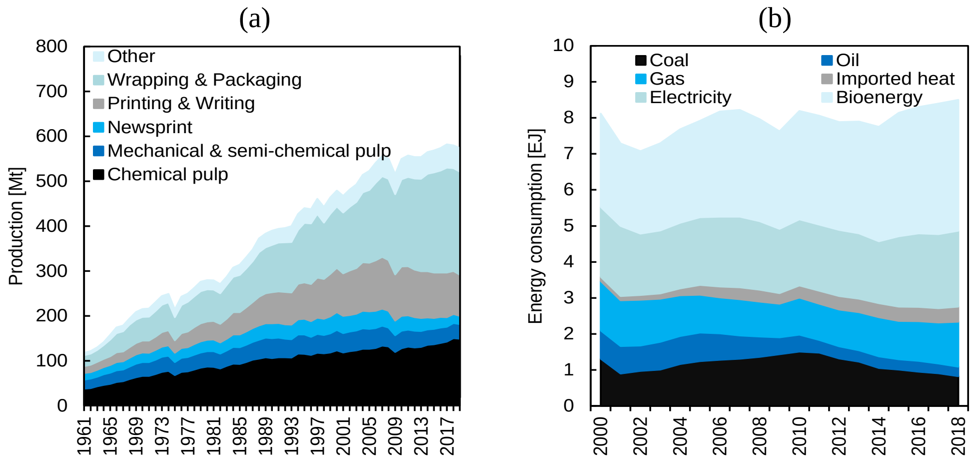


Figure 2.6: The development of the global pulp and paper industry: Production (a) and energy consumption (b). Data from IEA (2020b, 2022b) and FAO (2022).

The first mechanised forest industries developed in countries with abundant forest and energy resources, available markets, and a good economic situation in the 19th century (Lamberg *et al*., 2012). In the early years of the mechanised forest industry, Europe and North America dominated the markets, and newsprint and graphical papers were the major products. Later the production mix of the PPI has faced substantial changes. Currently, demand for printing and writing paper is decreasing in developed countries due to digitalization, whereas the need for packaging materials is increasing as a result of the growing popularity of global markets. Between 2010 and 2020, 122 paper machines were closed in Europe (Finnish Forest Industries, 2021), which illustrates the rapid change. In addition to the changes in the production mix, the location of production has partly moved outside Europe and North America. Especially Asia and South America have become important players. The new producers have benefited from cheap raw materials and large modern mills that convert wood to pulp efficiently (Fornell, Pettersson, and Berntsson, 2010). Many conventional forest industry countries have been investing in new high-value products, such as wood fibre -based textiles, nanocellulose, hemicellulose, lignin, composite materials, and biofuels, as an important strategy to maintain their competitiveness among the new producers. As a result of the development, many new production units are now “biorefineries” rather than simply “pulp mills”.

The PPI is an energy intensive sector, but the sector has developed towards lower energy consumption. After the 1970s, the protection of the environment and reduction of energy use became important issues. The oil crisis motivated mills to improve their energy efficiency. The need for energy savings has led, among other things, to improved technology, larger mill sizes, and higher integration rates. Recently, combatting climate change has become an important driving force for the transition as taxes on energy and CO_2 emissions are increasing in many countries and affecting the production costs. Moreover, possibility to improve their image motivates companies to invest in cleaner energy.

Clear trends in energy consumption can be found in Figure 2.6. Both the fuel mix as well as energy consumption per ton of product have changed notably. It should be noted that use of bioenergy is often under-reported, which may affect the accuracy of the following figures. The total energy use remained mostly unchanged while wood pulp production increased by 9% and paper production by 21% between 2000 and 2018. In 2000, the production of one ton of paper required approximately 25 GJ of energy whereas in 2018 the demand was below 21 GJ/t. The change can be explained by energy efficiency improvements and structural changes. For example, an increase in the share of recycled fibres in the pulp mix has reduced the energy intensity. In 2018, 229 Mt of recycled pulp was produced, which is 72% more than in 2000.

The fossil CO_2 emissions (inc. industrial emissions from combustion of fuels) have decreased by approximately 36% from 260 $MtCO_2$ to 170 $MtCO_2$ in the global PPI (IEA, 2022b). The production of one ton of paper emitted approximately 810 $kgCO_2$ in 2000 and 410 $kgCO_2$ in 2018. The decrease in the total fossil CO_2 emissions can be explained by changes in the fuel mix and the decrease in the energy demand. In 2000, roughly 40% of combusted fuels were bio-based, and the share increased to over 60% in 2018. Fossil fuel consumption decreased by 33% from 3.5 EJ to 2.3 EJ. The most significant drop occurred in the use of oil and coal, whereas the consumption of natural gas remained fairly stable.

3 Decarbonization opportunities

A notable transition towards a low-carbon forest industry is undoubtedly ongoing and forest industry companies have announced ambitious CO_2 reduction targets. Existing examples verify that mills can achieve carbon neutral operation: the Metsä Fibre Äänekoski mill does not use any fossil fuels during normal operation, and the Metsä Fibre Kemi that is expected to start operation in 2023 will also cover its fuel demand by biofuels (Regional State Administrative Agency, 2015, 2020). Decarbonization opportunities of the forest industry include energy and material efficiency improvement, fuel switching, electrification, carbon capture, production of green electricity, fuels, and materials, and strengthening of forest as carbon sinks.

In this thesis, energy efficiency improvement is considered on a general level and well-known energy efficiency improvement opportunities such as improved drying technologies, variable-speed-driven motors or the optimization of heat exchangers are not analysed. Several methods for increasing material efficiency exists. In this thesis, polysulfide cooking, that has shown the potential to increase the yield in kraft pulping, has been chosen to represent material efficiency improvement opportunities. The technology is not widely spread to mills even though it was found almost a century ago, but growing demand for efficient operation, as well as improved energy self-sufficiency in mills, have recently made it attractive. Pulp and papermaking processes that use fuels, i.e. lime kilns and dryers are notable sources of CO_2 emissions and thus the processes are included in this thesis. Lime kilns represent a substantial opportunity for switching from fossil fuels to renewable alternatives. Recovery boilers are the most important heat and electricity producers in the forest industry, and the potential of these devices to increase energy production is analysed. Pulp mills are large point sources of CO_2 and thus the current state and prospects for carbon capture in the forest industry are discussed. This thesis does not focus on the production of green fuels and materials or strengthening of forests as carbon sinks.

3.1 Studies on CO_2 emissions cuts in the forest industry

CO_2 flows, the reduction potential, and low-carbon technologies in the forest industry, especially in the PPI, have been widely studied. Möllersten, Yan, and Westermark (2003) found that the implementation of CO_2 reduction measures, i.e. fuel switching, energy saving and CCS could cut emissions by 8–14 $MtCO_2$/a in the Swedish PPI. Kong *et al*. (2017) analyzed the adoption of 23 energy saving technologies in the Chinese PPI and found that an emissions reduction of 19 $MtCO_2$ could be implemented cost-effectively. Fleiter *et al*. (2012) studied the German PPI. They claim that a 19% reduction in emissions can be achieved by 2035 mainly by utilizing waste heat and improved paper drying technologies. According to Griffin, Hammond, and Norman (2018), the PPI in the United Kingdom could cut its emissions by 80% from 1990 to 2050. They highlight the role of bioenergy, grid decarbonization, energy efficiency, waste heat recovery, and the electrification of heat supply. Rahnama Mobarakeh, Santos Silva, and Kienberger (2021) evaluated the decarbonization of Austrian PPI. Their results suggest that full decarbonization requires a combination of several measures, even though the electrification of the steam supply has great CO_2 emissions reduction potential. The Confederation of European Paper Industries (CEPI) (2011) believes that an 80% CO_2 emissions reduction can be achieved in the European forest industry by 2050 compared to 1990 levels. In addition to country or region specific studies, new CO_2 reduction technologies especially BECCS have recently become a popular research topic (Onarheim *et al*., 2017; Kuparinen, Vakkilainen, and Tynjälä, 2019). The complexity of the forest sector, country specific features, the immaturity of new technologies, and the urgent need for emissions reduction call for further studies.

Based on the previous studies, it is possible to conclude that a portfolio for CO_2 reduction measures is wide, and researchers agree there is significant potential for CO_2 emissions reduction. CO_2 intensity has already decreased in the forest sector, but the change can be considered slow in relation to set targets. For example, the European PPI cut its annual CO_2 emissions by 24% from 52.9 $MtCO_2$ to 40.2 $MtCO_2$ between 1991 and 2019 (CEPI, 2020), and thus significant improvements are needed within the next 28 years to meet 2050 targets. Despite the moderate change in the absolute emissions, it should be noted that emissions per produced ton dropped by 47%, which indicates the development towards low carbon operation has been nevertheless promising.

3.2 Energy efficiency

Energy efficiency describes how much energy is needed to produce one unit of product. It plays a key role in energy supply security, competitiveness, and emissions reduction in an industrial sector. Energy efficiency improvement has gained a lot of attention since the oil crisis in the 1970s when increased energy costs drove the reduction of energy use. After the 1990s, the role of energy efficiency improvement in the mitigation of global change has also been recognized (Fracaro *et al*., 2012). The mitigation of global change requires significant reductions in CO_2 emissions. Energy efficiency improvement has been considered the most cost-effective measure to cut energy demand and CO_2 emissions related to it (Worrell *et al*., 2009).

3.2.1 Measurement of energy efficiency

Industry is a large energy user, which also has substantial energy reduction potential. Monitoring industrial energy efficiency is important to be able to indicate progress (Lawrence *et al.*, 2019). Tools for measuring efficiency are needed when different activities are compared. Energy efficiency is an abstract concept, and it is typically measured using different kinds of indexes, such as thermodynamic, physical-thermodynamic, economic-thermodynamic, and economic ones (Farla, Blok, and Schipper, 1997). The most typical indicator for energy efficiency is the specific energy consumption (SEC), which is a physical-thermodynamic indicator (Equation 3.1). The

SEC describes how much energy is needed to produce one physical unit of a product (Blok and Nieuwlaar, 2017).

$$SEC = \frac{E}{P} \tag{3.1}$$

where *SEC* is specific energy consumption, *E* stands for energy consumption and *P* for production. The SEC can be calculated separately for electricity, heat, total energy, and primary energy. The amount of production can be defined in several ways, for example, when calculating the SEC of an industrial plant producing several products, either the sum of all products or just the main product can be used. In the case of the PPI, some studies calculate only the produced tons of paper ignoring pulp production. This gives poor energy efficiency values for mills that produce virgin pulp instead of using recycled fibres or market pulp.

Even though the SEC is a widely utilized indicator, it has several limitations (Lawrence *et al*., 2019). In many cases, there is lack of presented assumptions, and thus the SEC is the most reliable within the same study. The use of SEC can be challenging in the case of the forest industry because there are several integrated processes. Allocating a mill's energy consumption to several outputs is difficult. Usually, it is not clear whether all products or just the sold ones are considered. Moreover, a general problem is that in many cases there is lack of data or information, which further complicates the use of the SEC. Inadequate data leads to the need to make assumptions, for example electricity consumption must be converted to primary energy consumption using a fixed coefficient, even though the conversion efficiency depends strongly on used energy conversion methods. Furthermore, system boundaries are poorly described in many studies, i.e. it is not explicated whether auxiliary operations are included in energy use or not.

Benchmarking is a widely used method for comparing energy efficiency and evaluating the energy saving potential of industrial operators (Rogers, Cooper, and Norman, 2018). Actual consumption is compared with reference specific energy consumption values that need to be chosen carefully. The European Commission (2015) defines the Best Available Techniques (BAT) for the PPI. The BAT values for energy consumption are typical examples of reference values used in benchmarking studies, but there are certain problems with the usage of BAT. Firstly, the selection of the reference mills is very limited, and thus compromises must always be made as every mill is unique. Secondly, the BAT techniques are developing continuously, and therefore especially the investigation of energy efficiency development is challenging.

3.2.2 Studies on energy efficiency in the forest industry

Most of the previous studies on energy efficiency of forest industry have focused on the PPI. Fracaro *et al*. (2012) presented the development of energy efficiency in major pulp and paper producer countries: Brazil, Finland, Sweden, the United States of America (USA), and Canada from 1979 to 2009. The study indicated that the energy efficiency has improved roughly by 0.8%, 0.7%, 0.7%, and 0.4% per year in Brazil, Sweden, the USA, and Finland, respectively. However, the energy efficiency of the Canadian PPI decreased by 0.2% per year. Many studies argue that the PPI has a substantial energy saving potential (Klugman, Karlsson, and Moshfegh, 2007; Fracaro *et al*., 2012; Kong *et al*., 2013; Peng *et al*., 2015; Kong, Hasanbeigi, and Price, 2016). In the future, several possibilities to improve energy efficiency will exist, for example the improved utilization of secondary heat and more efficient drying technologies.

The energy efficiency improvement potential is not currently fully utilized, and there are several barriers that limit improvement. Thollander and Ottosson (2008) claim that the most crucial barriers are the technical risks, cost of production disruption, hassle or inconvenience, technology inappropriate at the mill, lack of time or other priorities, and lack of access to capital. The study found that barriers are not only market-related but also firm-specific. According to Moya and Pavel (2018), existing technology would allow the substantial energy efficiency improvement but adoption of technologies might depend on several factors such as a payback period, the location of the plant and age of equipment, to name a few.

3.3 Technology development

In this thesis, technology development refers to the adoption of novel or currently uncommon technologies as well as to significant improvements to mature solutions. The technology development allows more energy and material efficient operation, increased utilization of biomass, and higher energy production in the forest industry. This is important given that the role of energy and material efficiency has increased because of the scarcity of raw materials and the need to reduce emissions and improve energy security. Employing a new technology is always a risk, and therefore mills may not be willing to invest. Studies and mill-scale trials may help to overcome the concerns and are thus important. Novel technologies are continuously being developed and existing ones improved, and thus the portfolio of interesting technologies is large, and not all opportunities can be included in this thesis. This thesis considers polysulfide cooking, the development of recovery boilers, decarbonization of lime kilns and dryers and opportunities of BECCS.

3.3.1 Decarbonization of lime kilns and dryers

A lime kiln is typically the only source of fossil CO_2 in a modern kraft pulp mill during normal operation. In many mills, natural gas or fuel oil is combusted to achieve the temperature required for the calcining process. Fuel switching in lime kilns has been a popular research topic (Gorog *et al*., 2015; Kurian and Divya, 2015; Kuparinen and Vakkilainen, 2017). Side streams and processed biomass from pulp mills including lignin, crude tall oil, concentrated non-condensable gases, turpentine, tall oil pitch, stripper off gases, wood powder, gasified biomass, pyrolysis oil, and torrefied biomass, as well as hydrogen, electricity, and electric-gas plasma have been suggested as alternative lime kiln fuel (Francey, Tran, and Jones, 2009; Kuparinen and Vakkilainen, 2017; Andersson and Skogström, 2020; Hart, 2020a, 2020b; Svensson, Wiertzema, and Harvey, 2021). However, a range of technical challenges, such as the instability of operation or concentration of non-process elements are hindering the use of renewable fuels (Manning and Tran, 2015; Hart, 2020b).

Drying is responsible for the greatest energy consumption during the papermaking process. The major share of water is removed by mechanical dewatering, but reaching the final dryness requires the use of thermal drying which is an energy consuming process (Karlsson and Paltakari, 2009). The heat needed for thermal drying is mostly delivered as steam from boilers, but also direct fuel (natural gas, liquified petroleum gas) combustion is utilized especially in coating stages. Fossil CO_2 emissions are minor in comparison to lime kilns and boilers: based on environmental reports and permits Finnish mills using gas-fired dryers emit approximately 36 $kgCO_2$/t of paper during the drying process. The emissions can be reduced by electrifying the drying processes, switching to renewable fuels, and improving the efficiency of both mechanical and thermal drying (Larsson and Nodin, 2013; Nilsson *et al*., 2016; Valmet, 2019). However, as drying significantly affects the quality of paper and costs, forest industry companies have not focused on decarbonization (Kong, Hasanbeigi, and Price, 2012).

3.3.2 Development of recovery boilers

The capacity as well as the steam parameters of the recovery boilers have significantly increased during the last decades (Vakkilainen, 2019). Modern recovery boilers typically operate at or above a temperature of 505 °C and steam pressures of 100–105 bar (Vakkilainen and Kivistö, 2014). The high steam parameters allow increased electricity generation, but the temperature growth is limited by ash properties (Vakkilainen, 2014). Especially potassium and chlorine, which are corrosive compounds, lead to problems at high temperatures. Other measures such as increasing black liquor dry solids content, flue gas heat recovery, preheating of combustion air and water, and use of condensing turbines can also be used for intensifying the electricity production (Vakkilainen and Kivistö, 2014). Energy demand has decreased in mills, for example due to closed water cycles, and this has also increased the availability of excess heat and electricity in mills, but the focus of this thesis is on the opportunity to increase steam and electricity production.

Black liquor gasification (BLG) has been suggested as an efficient alternative for a conventional recovery boiler (Pettersson and Harvey, 2012). The gasification converts organic matter in the black liquor into volatile compounds, mainly hydrogen (H_2), carbon monoxide (CO), and CO_2. The produced syngas can be combusted in a gas turbine or used as raw material for chemicals. The technology has been known since the 1960s (Kohl, 1986), but it has not reached a large-scale commercial stage, and thus the conventional recovery technologies will play an important role also in the future. The main drawbacks of BLG are high investment costs and problems with chemical recovery and gas cleaning.

3.3.3 Polysulphide cooking

One of the major drawbacks of kraft pulping is the significant loss of carbohydrates during the cooking. Polysulphide (PS) cooking aims to improve the yield and consequently material efficiency by preserving hemicelluloses during the early stage of the cooking (Gustafsson *et al*., 2011). PS addition can lead to a pulp yield increase of 1–3% in comparison to conventional kraft cooking (MacLeod, 2007). As less hemicelluloses end up in the recovery boiler, there may be a possibility to increase production without expensive modifications if the recovery boiler is a bottleneck of the process. In addition to the yield increase, PS pulping enables cooking to reduced kappa numbers without reducing the yield, which lead to a lower demand for bleaching chemicals (Tench *et al*., 1999; Colodette *et al*., 2001; Dobson and Bennington, 2002). PS cooking has been known since the 1940s but it is not a widespread process (Kleppe and Minja, 1998). The effects of PS cooking on corrosion, pulp strength, recovery cycles and costs have been concerns that have most probably hindered the spread of the technology (Kleppe and Minja, 1998; Colodette *et al*., 2001).

The Mead Oxidation (Moxy) process is the most used PS generation method in the industry. In a Moxy reactor, a part of the sulphide sulphur in the cooking liquor is converted into PS sulphur using white liquor oxidation. White liquor must be clarified carefully before the oxidation reaction. In addition to investing in PS reactors and white liquor clarification units, modifications to the piping are needed. In a Moxy reactor, 60–70% of Na_2S oxidizes. Approximately two thirds of the oxidized sulphur forms PS (Na_2S_2) and the rest forms sodium thiosulphate ($Na_2S_2O_3$), following reactions 3.2 and 3.3 (Arpalahti *et al*., 2008). Figure 3.1 shows a simplified block diagram of PS pulping.

$$4\,Na_2S + O_2 + 2\,H_2O \rightarrow 2\,Na_2S_2 + 4\,NaOH \tag{3.2}$$
$$2\,Na_2S + 2\,O_2 + H_2O \rightarrow Na_2S_2O_3 + 2\,NaOH \tag{3.3}$$

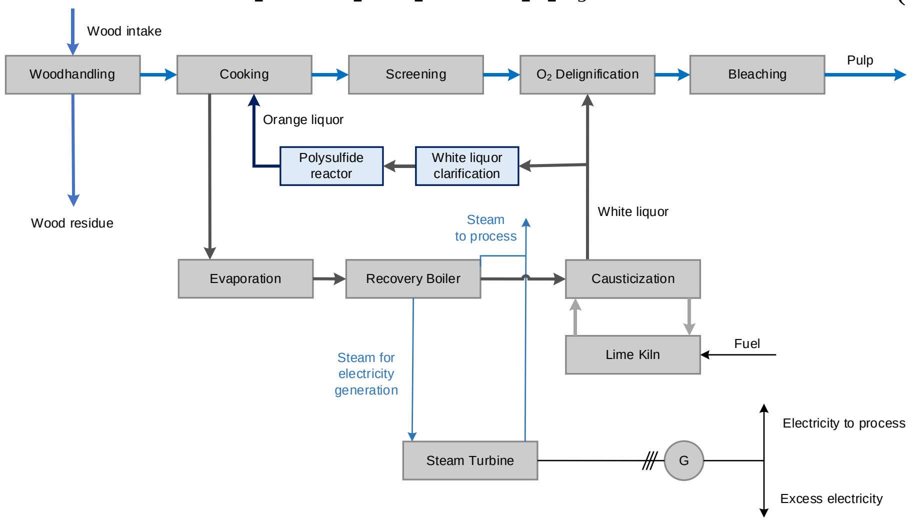


Figure 3.1: A process chart of the polysulphide pulping process.

3.3.4 Carbon capture technologies

Pulp mills provide large point sources of CO_2 with a relatively high CO_2 concentrations, and according to Garðarsdóttir *et al*. (2018), the large pulp mills can offer a possibility to reduce emissions with lower costs than some smaller fossil CO_2 sources. Capturing biogenic CO_2 could transform a pulp mill into a negative emitter, and the required capture rate can be modest. Kuparinen *et al.* (2021) studied BECCS in Nordic pulp and paper mills and found that capture rates below 6% would transform all the studied market kraft pulp mills into negative emitters. The concept is attractive because emission reductions are possible without additional biomass harvesting (Kuparinen, Lipiäinen, and Vakkilainen, 2021). Moreover, especially stand-alone pulp mills typically have excess heat and electricity, which can cover the energy demand for the carbon capture process (IEAGHG, 2016). Pulp and paper mills have the possibility to utilize CO_2 on-site. For example, tall oil acidulation, brown stock washing, and lignin extraction typically use CO_2 (Ruostemaa, 2018). However, the on-site utilization possibilities are minor compared to the capture potential (Kuparinen, Vakkilainen, and Tynjälä, 2019). Regardless of the advantages, a lack of long-term policies, concerns about technology, companies' limited responsibility for climate change and the absence of customer demand for negative emissions are hindering the implementation of BECCS (Rodriguez *et al*., 2021).

Different carbon capture technologies including pre-combustion, post-combustion, and oxy-combustion methods could be possible to implement in pulp mills. Currently, the monoethanolamine (MEA) process is the most studied option (Jönsson and Berntsson, 2012; Leeson *et al*., 2017; Onarheim *et al*., 2017; Kuparinen, Vakkilainen, and Tynjälä, 2019). This is a proven and commercially available technology that can be used for capturing CO_2 from boilers and lime kilns. An oxy-combustion process would require oxygen source and possibly modifications to flue gas passages (Kuparinen, Vakkilainen, and Tynjälä, 2019). Black liquor gasification is a widely studied technology, and it could be combined with pre-combustion carbon capture (Pettersson and Harvey, 2012). However, no commercial demonstrations have been implemented successfully with these technologies (Onarheim *et al*., 2015). Calcium looping (CaL) has also been considered as an interesting possibility to capture carbon in kraft pulp mills (Sun *et al*., 2013). It is proposed that lime mud from the lime kiln could be used as a sorbent. Hektor and Berntsson (2007) mention chemical looping combustion (CLC) as a possibility to capture CO_2 from recovery boiler but they highlight that the option requires further investigations.

4 Development of the Nordic forest industry

The Nordic forest industry is concentrated in Finland and Sweden. These countries cover approximately 95% of pulp and paper production in the region (FAO, 2022). Other Nordic countries can be considered as minor producers: annual pulp and paper productions were 0.05 Mt and 0.2 Mt in Denmark, and 1.0 Mt and 1.2 Mt in Norway in 2019. Iceland produces neither paper nor pulp. Finland and Sweden are also the largest pulp producers in Europe producing approximately half of all virgin fibres and surpassed only by Germany in paper production. Forests cover 74% of the land area in Finland and 69% in Sweden (FAO, 2020b, 2020a), which is an important reason for the development of an advanced forest industry. The forest industry is a significant employer and source of income in both countries: for example it accounts approximately for 20% of both the export and gross domestic product of manufacturing in Finland (Finnish Forest Industries, 2020c). Forest industries in both countries are export oriented: approximately 75% and 80% of forest industry products are exported in Finland and Sweden, respectively (Finnish Forest Industries, 2020b; Swedish Forest Industries Federation, 2020).

4.1 Production volumes

Production volumes in the Finnish and Swedish forest industries in 1990 and 2019 are presented in Table 4.1. In 2019, 9.7 and 9.6 Mt of paper were produced in Finland and Sweden, respectively. In Finland, printing and writing papers covered the largest share of total paper production (47%) followed by packaging materials (46%). In Sweden, packaging materials covered 62% of paper production, and printing and writing papers accounted only for 25%. Pulp production was approximately 12 Mt in both countries, and the share of chemical pulp was high (73%). Production relies heavily on virgin fibres in both countries: only 5–10% of the raw material mix consists of recycled fibres (Finnish Forest Industries, 2020c; Swedish Forest Industries Federation, 2020).

Table 4.1: Production of the Finnish and Swedish forest industries. Data from FAO (2022).

	Finland			Sweden		
Pulp or paper grade	**1990**	**2019**	**Change**	**1990**	**2019**	**Change**
Chemical pulp [Mt]	5.16	8.72	69%	6.97	8.88	27%
Mechanical pulp [Mt]	3.73	3.28	-12%	3.24	3.19	-2%
Newsprint [Mt]	1.43	0.27	-81%	2.27	0.89	-61%
Printing & writing paper [Mt]	4.68	4.60	-2%	1.66	2.37	43%
Packaging materials [Mt]	2.32	4.44	91%	3.97	5.95	50%
Household & sanitary papers [Mt]	0.16	0.20	22%	0.28	0.36	26%
Other paper & paperboard [Mt]	0.37	0.20	-46%	0.23	0.06	-74%
Sawn wood [Mm^3]	7.50	11.39	52%	12.02	18.73	+56%
Wood-based panels [Mm^3]	1.34	1.29	-4%	1.12	0.65	-48%

The business environment of the forest industry is changing, and production volumes have responded to the change (Table 4.1). Production mixes and volumes have developed in several forest industry countries, but this thesis investigated a recent structural change especially in the Finnish PPI. The development of production has undergone similar trends in Finland and Sweden. The production of chemical pulp and packaging materials has increased significantly, whereas a decline in the production of printing and writing papers, especially newsprint, has been notable. The comparison of the years 1990 and 2019 does not catch the recent trend in the production of printing and writing papers. In Finland, the annual production peaked in 2004 being 9.5 Mt. In 2019, the production was 4.9 Mt lower than in 2004. In Sweden, the largest annual production of printing and writing papers was reached in 2012 (3.4 Mt), and the production dropped by 1.1 Mt by 2019.

In addition to changes in pulp and paper production, the Finnish forest industry has invested in new bioproducts. To give a few examples, the UPM Kaukas in Lappeenranta started to produce BioVerno^{TM} diesel and naphtha from crude tall oil in 2014 (UPM Kymmene Oyj, 2020). The refinery uses hydrotreatment technology, but the drawback of the process is the usage of fossil-based natural gas. In 2015, the Stora Enso Sunila in Kotka started to separate lignin using the LignoBoost^{TM} process, which has a capacity of 50,000 t/a (Stora Enso, 2020). Lignin can be used as a biofuel or as a valuable raw material in several applications such as the production of resins. The Stora Enso Imatra operates a facility that produces microfibrillated cellulose that enables substituting fossil-based materials in packaging (Stora Enso, 2021). Numerous additional innovative wood-based products are in the design or demonstration phase in Finland (Sermyagina, Lipiäinen, and Kuparinen, 2022). Even though examples of implemented retrofits and new units exist, the number of installations remains rather small due to the lack of knowledge, unestablished markets for new products and uncertainty concerning their economic feasibility (Mäki *et al*., 2021).

The changing demands for different pulp or paper grades have manifested as unit closures, start-ups, and conversions. Table 4.2 presents the most significant changes in the Finnish PPI in the 2010s and at the beginning of the 2020s. During the economic crisis around 2009, several pulp and paper mills were closed permanently in Finland. Numerous closures have occurred also after that. Most of the closed capacity consists of printing and writing paper mills, and the typical announced reason for a closure was reduced demand for paper and poor competitiveness. The global pandemic due to COVID-19 accelerated the decrease in the demand for printing and writing papers due to changes in consumer behaviour, for example reduced consumption of paper in offices, and thus the Finnish PPI cut its capacity by almost 1.6 Mt around 2021. Four mills converted their paper machines to produce paperboard due to increasing demand for packaging materials. The capacity for chemical pulp increased significantly by 1.6 Mt (24%) from 2010 to 2019. The Metsä Fibre Äänekoski biorefinery, the largest pulp mill in the northern hemisphere, started in 2017. The mill annually produces 1.3 Mt of kraft pulp, and it is also an important producer of bioenergy and bioproducts such as tall oil, turpentine, and sulfuric acid. Another biorefinery project is under construction. The Metsä Fibre Kemi mill is expected to start operation in 2023. The mill will produce 1.5 Mt of kraft pulp per year. Several additional biorefineries have been planned (Finnpulp, 2022; Kaicell Fibers, 2022; Vataset, 2022). The share of pulp in the production mix has increased significantly, which has been criticized as paper has a higher added value. However, pulp has huge potential to act as a platform for new innovations such as pharmaceuticals and textile fibres.

Table 4.2: Structural changes including unit closures (†), start-ups, and conversions in the Finnish pulp and paper industry.

Unit	Capacity change [t/a]	Product	Year
Simpele (Metsä Board)	-55,000	Special paper	2010
Simpele (Metsä Board)	+80,000	Paperboard	2011
Myllykoski (UPM)†	-600,000	Magazine paper	2011
Myllykoski (UPM)†	-213,000	Groundwood	2011
Ääneskoski (M-Real)†	-200,000	Fine paper	2012
Rauma (UPM)†	-245,000	Magazine paper	2013
Veitsiluoto (Stora Enso)†	-190,000	Magazine paper	2014
Lohja (Loparex)†	-68,000	Other paper	2014
Kaukas (UPM)†	-270,000	Magazine paper	2014
Jämsänkoski (UPM)†	-270,000	Magazine paper	2014
Kauttua (Jujo Thermal)†	-10,000	Other paper	2015
Varkaus (Stora Enso)	-285,000	Fine paper	2015
Varkaus (Stora Enso)	+380,000	Paperboard	2015
Imatra (Stora Enso)	+20,000	Paperboard	2015
Kymi (UPM)	+170,000	Chemical pulp	2015
Tervasaari (UPM)†	-100,000	Other paper	2016
Kyrö (Metsä Board)†	-105,000	Other paper	2016
Kyrö (Metsä Board)†	-74,000	Groundwood	2016
Kotka (Kotkamills)	-185,000	Magazine paper	2016
Kotka (Kotkamills)	+400,000	Paperboard	2016
Äänekoski (Metsä Fibre)	-500,000	Chemical pulp	2017
Äänekoski (Metsä Fibre)	+1,300,000	Chemical pulp	2017
Kaukas (UPM)	+30,000	Chemical pulp	2018
Kymi (UPM)	+100,000	Chemical pulp	2017
Oulu (Stora Enso)	-1,080,000	Fine paper	2020
Oulu (Stora Enso)	+450,000	Paperboard	2020
Kaipola (UPM)†	-720,000	Magazine paper	2021
Nokia (Essity AB)†	-25,000	Hygiene paper	2021
Veitsiluoto (Stora Enso)†	-850,000	Magazine paper	2021
Veitsiluoto (Stora Enso)†	-380,000	Chemical pulp	2021
Kemi (Metsä Fibre)	-620,000	Chemical pulp	2023
Kemi (Metsä Fibre)	+1,500,000	Chemical pulp	2023

4.2 Energy use and CO_2 emissions

The forest industry is responsible for a significant share of the energy consumption in Finland and Sweden. This thesis presents the current role of the Finnish and Swedish forest industries in national energy and CO_2 balances. Present forest industry related CO_2 emission sources are identified, and their magnitudes are estimated.

Energy intensive industries need to transform towards more sustainable operation in order to participate in tackling climate change, and to improve industrial competitiveness and energy security. This section introduces how the Finnish and Swedish forest industries have responded to the need for change in the 21st century. An analysis of general trends shows how energy consumption, production, and CO_2 emissions have changed but does not explain reasons behind the development. Therefore, this thesis uses decomposition analysis and the energy efficiency index method to shed light on the reasons behind the changes in energy consumption. In addition, energy and climate policies (section 7), as well as changes in technology (section 5) are utilized as explanations.

4.2.1 Current status of energy use and CO_2 emissions

In Finland, the forest industry accounted for approximately 23% (317 PJ) and 22% (19 TWh) of the total final energy and electricity consumption in 2019 (Statistics Finland, 2022). In Sweden, 20% (269 PJ) of total final energy consumption and 17% (21 TWh) of electricity consumption was covered by the forest industry in the same year (Swedish Energy Agency, 2020). The Finnish forest industry produced 10 TWh of electricity in 2016 (Finnish Forest Industries, 2020c). This means that over half of the electricity consumed by the sector is generated on-site. The Swedish forest industry produces less electricity than the Finnish one: the production was 6 TWh in 2019, i.e. 30% of consumed electricity (Swedish Forest Industries Federation, 2020). Industrial fuel consumption in the Finnish forest industry in 2019 was 231 PJ. Energy production relies heavily on biofuels: only 13% of the used fuels are fossil fuels. Biomass is the dominant fuel also in the Swedish forest industry. It accounted for 96% of total fuel consumption in 2019. The share of biofuels is high in comparison to the European PPI, which has 40% fossil fuels in its fuel mix (Eurostat, 2018). Despite the high share of biofuels, the forest industry uses 8 PJ and 34 PJ of fossil fuels in Sweden and Finland, respectively. In addition to the industries' own energy production, both heat and electricity are purchased. Energy sources in the Finnish and Swedish forest industries are presented in Figure 4.1.

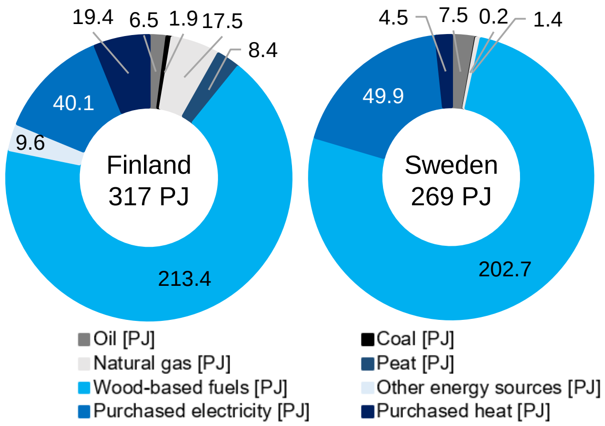


Figure 4.1: Energy sources in the Finnish and Swedish forest industries in 2019. Data from Swedish Energy Agency (2020), Swedish Forest Industries Federation (2020) and Statistics Finland (2022).

Fossil CO_2 emissions of the forest industry consists of direct and indirect emissions. Figure 4.2 introduces the most important sources and magnitudes of fossil CO_2 emissions in the Finnish and Swedish forest industries. Used assumptions for constructing Figure 4.2 are presented in detail in Publication V.

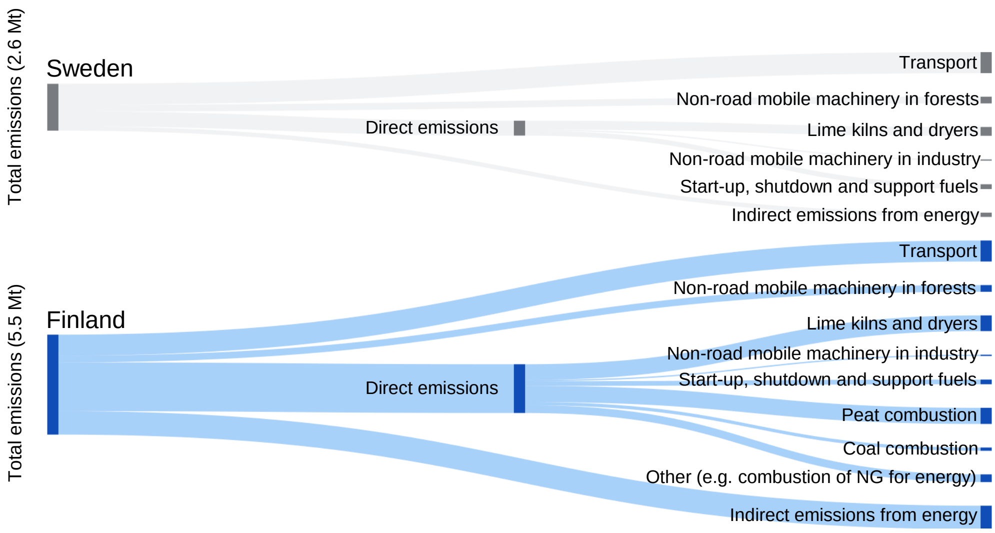


Figure 4.2: Fossil CO_2 emission sources in the Finnish and Swedish forest industries. Calculated using the author's evaluations and data from Swedish Forest Industries Federation (2018), Finnish Forest Industries (2020c, 2020a), Swedish Energy Agency (2020), FAO (2022), and Regional State Administrative Agency (2021).

Industrial fossil CO_2 emissions from the forest industry account for approximately 5% of national emissions in Finland and 2% in Sweden (Statistics Finland, 2022; Statistics Sweden, 2022). When forest industry related emissions such as the production of purchased electricity and transport of products and raw materials are taken into account, the role of the forest industry in the national emissions increases to 10% and 5% in Finland and Sweden. In addition to fossil CO_2 emissions, the forest industry produces annually approximately 20 Mt of biogenic CO_2 in both countries.

In the Finnish forest industry, natural gas and oil are used mainly in lime kilns and as start-up and shutdown fuels whereas peat and coal are co-combusted with biomass in multi-fuel boilers. Minor amount of fossil fuels, mainly natural gas, are used in drying devices. Industrial fossil CO_2 emissions from the Finnish forest industry were approximately 2.7 Mt in 2019. The Swedish forest industry has the lowest carbon-intensity globally: 0.8 Mt of industrial fossil CO_2 was emitted in 2019, which corresponds to approximately 85 kgCO_2/ton of paper. For comparison, the European average is 300 kgCO_2/ton of paper (CEPI, 2020). Most of the emissions originate from lime kilns and dryers, and during the start-ups and shutdowns of biomass boilers. In addition to the industrial CO_2 emissions, the transport of products and raw materials as well as the production of purchased electricity emits significant amounts of CO_2. Indirect emissions from the production of raw materials, for example chemicals, were excluded.

4.2.2 General development trends in energy use and CO_2 emissions

Figure 4.3 presents energy and CO_2 emissions trends in the Finnish and Swedish PPIs between 2002 and 2017. Energy use and especially fossil fuel consumption has been decreasing in both countries. Significant drops around 2009 are the result of a decrease in production volumes due to the economic crisis. A blip around 2005 in the Finnish figures was caused by a long industrial strike.

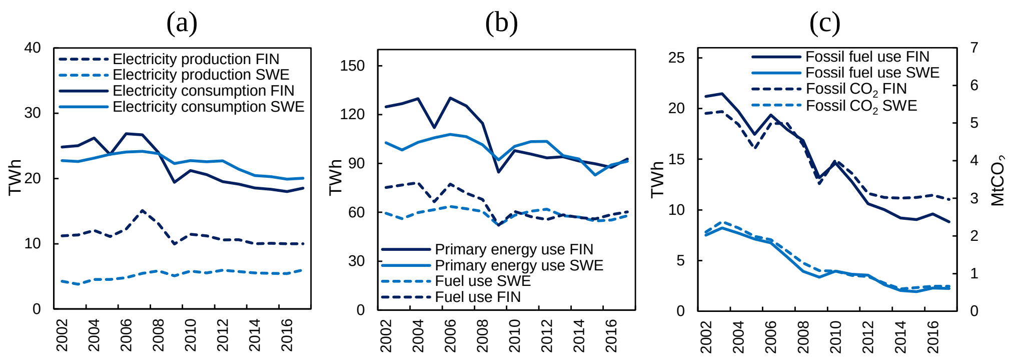


Figure 4.3: Trends in electricity consumption and production (a), primary energy and fuel use (b), and CO_2 emissions and fossil fuels use (c) in the Finnish (FIN) and Swedish (SWE) PPIs. Data from Finnish Forest Industries (2020c), Swedish Energy Agency (2020), Swedish Forest Industries Federation (2020), and Statistics Finland (2022).

Electricity consumption decreased by 25% in the Finnish PPI between 2002 and 2017. At the same time, electricity production decreased only by 11%. Therefore, electricity self-sufficiency has increased from 45% to 54%. A similar trend applies to the Swedish PPI: electricity consumption decreased by 12%, whereas electricity production increased by 41%, which has increased self-sufficiency from 19% to 30%. Fuel consumption decreased by 20% in Finland and by 3% in Sweden. The decrease was the most notable in fossil fuels, and thus the share of biofuels in the fuel mix increased from 87% to 96% in Sweden and from 72% to 85% in Finland. The reduced use of fossil fuels led to a substantial drop in fossil CO_2 emissions. However, after a strong decline at the beginning of the 21st century, the fossil CO_2 emissions have remained fairly stable since 2013 in both countries.

Changes can be seen in both the specific energy consumption and specific emissions. In 2002, the Finnish PPI consumed 1.94 MWh of electricity per ton of paper whereas the same figure was 1.80 MWh/t in 2017. During the same period, the specific electricity consumption decreased from 2.12 MWh/t to 1.95 MWh/t in Sweden. The primary energy consumption was calculated as a sum of the purchased heat and electricity, used fuels, and other energy sources. Energy sold by mills was excluded due to data availability issues. Primary energy consumption dropped from 9.57 MWh/t to 8.91 MWh/t in Sweden and from 9.76 MWh/t to 9.02 MWh/t in Finland. The progress is partially a result from EEI but changes in structure have played a role as well. Specific fossil CO_2 emissions in the Finnish PPI were 410 $kgCO_2$/t of paper in 2002 and 290 $kgCO_2$/t of paper in 2017. In Sweden, specific CO_2 emissions were low already in 2002 (200 $kgCO_2$/t of paper) but decreased to 60 $kgCO_2$/t of paper in 2017.

4.2.3 Impact of volume, structure, and energy efficiency

The impact of different factors, for example volume, structure, and efficiency, on the development of energy consumption can be studied using an energy decomposition analysis (EDA). Several methods for decomposition exist, but there is no widely accepted standard method (Ang, 1995; Greening, Boyd, and Roop, 2007). This thesis used the Logarithmic Mean Divisia Index method (LMDI) presented by Ang (2005). LMDI is a flexible method that is easy to use, and no residual term is generated. The method was earlier used successfully for investigating changes in the PPI’s energy use by Stenqvist (2014). As well as the study by Stenqvist, this thesis used physical indicators instead of monetary ones because they easily enable comparisons between countries and are suitable for energy intensive industries. The used method is a time series type of EDA, which means all years within the studied period are considered instead of only the first and the last one. The equations 4.1–4.3 (Ang, 2005; Stenqvist, 2014) were utilized to decompose changes in the energy consumption of Finnish and Swedish PPIs. In this thesis, volume (VOL) refers to changes in the production volume, structure (STR) describes what kinds of products are produced, and efficiency describes the changes in the energy intensity (INT) of the used processes.

$$\Delta E_{t,T(\mathrm{VOL})} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{P^T}{P^t}\right) \tag{4.1}$$

$$\Delta E_{t,T(STR)} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{S_i^T}{S_i^t}\right) \tag{4.2}$$

$$\Delta E_{t,T(INT)} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{SEC_i^T}{SEC_i^t}\right) \tag{4.3}$$

E_i^T is the energy consumption in a sub-sector *i* in year *T*, P^T is the total production volume of a sector in year *T*, S_i^T is the production share of a sub-sector in year *T*, SEC_i^T is the specific energy consumption of a sub-sector in year *T*, and *t* is *T-1*. Following product categories were used: mechanical pulp that includes semi-chemical and chemi-mechanical pulp, chemical pulp, recycled fiber, newsprint, printing and writing papers, hygiene papers, wrapping and packaging papers, and other papers. Used data sources are presented with details in Publication I. The results of the decomposition analysis are presented in Figure 4.4.

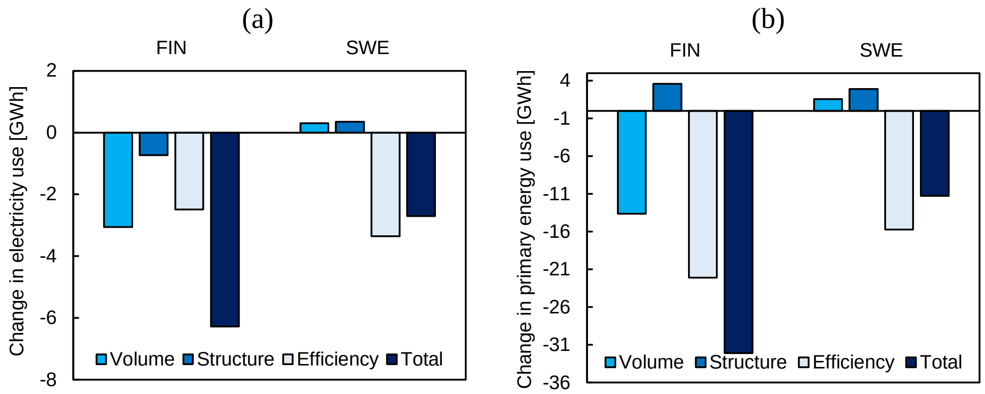


Figure 4.4: Contribution of volume, structure, and efficiency changes to the development of electricity consumption (a) and primary energy consumption (b) in the Finnish and Swedish pulp and paper industries between 2002 and 2017.

Changes in volume, structure and efficiency affected the energy consumption of the Finnish and Swedish PPIs between 2002 and 2017. The electricity and primary energy consumption drops were 6.3 TWh and 35.8 TWh in Finland and 2.7 TWh and 11.3 TWh in Sweden. Production volumes decreased by 13% in Finland, which explains a large share of the overall decrease. In Sweden, the volume change (1%) does not play an important role. The changes in production structure led to increased energy consumption except in the case of electricity consumption in Finland. The share of heat-intensive chemical pulp increased from 61% to 72%, whereas the production of electricity-intensive mechanical pulp decreased. The shift from the production of graphic papers to paperboards may also have reduced the energy intensity. In Sweden, changes in structure have increased energy consumption. An important explanation is the decreased production of newsprint which has a low energy intensity. The share of newsprint in the production mix dropped from 23% to 10%. The results suggest that both countries have improved their energy efficiency. In Finland, the EEI reduced electricity and primary energy consumption by 10% and 20%, respectively. In Sweden, the EEI led to a drop of 15% in both electricity and primary energy consumption.

4.2.4 Development of energy efficiency

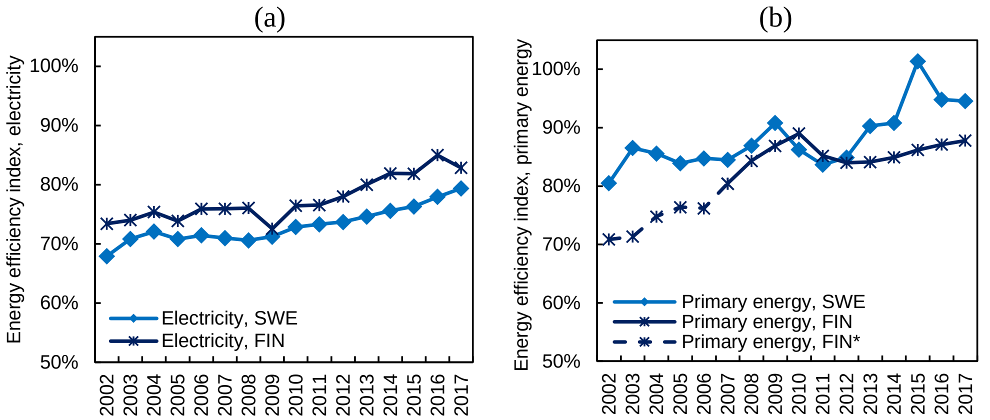
This thesis utilized the energy efficiency index method to assess the development of energy efficiency in the Finnish and Swedish PPIs between 2002 and 2017. The method was earlier employed by Fracaro *et al*. (2012) and Farla, Blok and Schipper (1997). The energy efficiency index can be used for cross-time and between-country comparisons (Farla, Blok, and Schipper, 1997), but the method has some drawbacks as it does not take into account independent factors affecting efficiency. For example, the effect of climate conditions is not included. In this thesis, the statistically recorded energy consumption was compared to reference consumption (Equation 4.4). The energy consumption varies substantially between different processes, and the total consumption is calculated as a sum of energy consumed by the production of different pulp and paper grades (Equation 4.5). A physical-thermodynamic index was chosen over monetary ones because changes in the feedstock, structure of the sector, and prices may have a severe effect on the validity of results when using monetary indexes.

$$EE = \frac{E_{ref}}{E} \tag{4.4}$$

$$E_{ref} = \sum_{i=1}^{n} P_i \cdot SEC_i \tag{4.5}$$

where EE is the energy efficiency index, E_{ref} is the reference energy consumption, E is the statistically recorded energy consumption, P_i is the production volume of a given product, and SEC_i is the specific energy consumption of a given product. The used specific energy consumption reference values are presented in Table 2.2.

Even though Finland and Sweden have historically had energy efficient PPIs, the efficiency continued to improve from 2002 to 2017 (Figure 4.5). The results suggest that the annual electricity efficiency improvement was on average 0.8% and 1.0% in the Finnish and Swedish PPIs, respectively. The strike in 2005 and the economic crisis around 2009 led to a drop in the energy efficiency in Finland, because several mills were shut down or only partially operating. In Sweden, the development has been more linear. A proposed revision of the Energy Efficiency Directive calls for increasing the annual energy saving requirement for 2024–2030 from 0.8% to 1.5% (European Commission, 2021b). In comparison to that target, the annual energy efficiency improvement rate should be higher in the Finnish and Swedish PPIs.



*Due to data issues, data from Statistics Finland (2022) was used in addition to data from Finnish Forest Industries (2020) for estimating primary energy use in 2007–2017 in Finland.

Figure 4.5: Development of energy efficiency: electricity (a) and primary energy (b) in the Finnish and Swedish pulp and paper industries.

The energy efficiency index method is less applicable to analysing primary energy use than electricity use because the mills use primary energy for several purposes, and mill-specific energy conversion factors are unknown. The used method considers only the input energy, and therefore the excess in on-site generated energy leads to a lower primary energy efficiency index. In Sweden, the primary energy efficiency index has fluctuated notably because not every Swedish mill has reported their energy consumption for every year. In Finland, the primary energy efficiency acted contrariwise in comparison to the electricity efficiency and leaped upward in 2009. As the method does not consider changes in the sold electricity, the drop in sold electricity during the economic crisis can at least partly explain the increase in the efficiency. Despite the data issues, it is safe to argue that the efficiency increased in the studied period. The Finnish and Swedish forest industries have been efficient operators in comparison to other important forest industry countries (Fracaro *et al*., 2012). These countries succeeded to make further EEIs in the 21st century, which indicates that also other PPI countries have substantial EEI potential.

4.2.5 **Impact of structural changes on energy efficiency**

The electricity consumption of the Finnish PPI decreased by approximately 17% from 2010 to 2017 as a result of decreased production volumes, changes in the production mix and EEI. The EEI is a sum of several factors such as improved technology and more optimal operational modes. The Finnish PPI has been going through a structural change, which has led to the closure of several mills as well as the start-up of new production units (Table 4.2). Neither the closed nor new units operate with average energy efficiency and therefore it can be safely assumed that these changes have affected the energy efficiency. The role of the industrial transformation in EEI is still mostly unknown.

This thesis investigated the impact of structural changes, i.e. mill closures and start-ups on the energy efficiency of the Finnish PPI. The studied period was limited to 2011–2017 due to data availability issues. Specific heat and electricity consumption values for Finnish pulp and paper mills were collected for the analysis. The values can be found in the supplementary material of Publication II. The impact of structural changes was studied creating three scenarios (Figure 4.6). The first is a reference scenario that is based on statistically recorded electricity consumption and production volumes of the Finnish PPI. The second is used for studying energy use without any unit closures, and the third without any unit start-ups. In the scenario II, the changes in production volume due to the closures are divided to mills that operate with an average energy consumption and the total production volume is kept unchanged. In the scenario III, the same procedure was used for new capacity. An average mill was defined using the specific energy consumption of at least five Finnish pulp and paper mills producing similar products as the changed mill. A capacity utilization rate of 85% was used for closed and started mills instead of full capacity, because mills rarely meet their maximum capacity because of maintenance stoppages, disruptions, etc. The energy consumption values obtained from scenarios II and III were compared to the reference scenario to evaluate the effects of structural changes. The focus was on changes in electricity consumption because data on heat consumption of the total PPI was not available. However, heat saving due to structural changes are calculated in this thesis even though the EEI regarding the heat consumption cannot be defined.

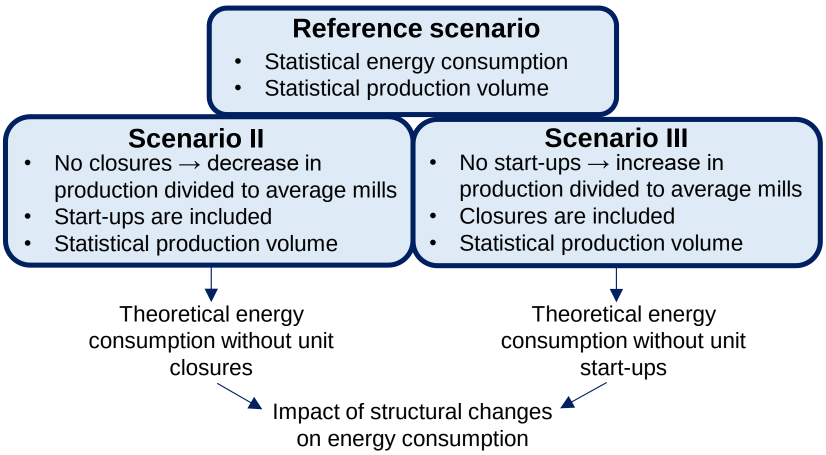


Figure 4.6: Method for studying the impact of structural changes on the energy efficiency of the Finnish pulp and paper industry.

Many Finnish mills are integrated, i.e. the same mill produces several products, and therefore the energy consumption must be decomposed to enable the comparison of similar products. To facilitate the division, all mills were categorized into the following groups: chemical pulp, groundwood, refiner mechanical pulp, semi-chemical pulp, chemi-mechanical pulp, recycled pulp, paperboard, magazine paper, fine paper, and other paper. The decomposition of energy consumption was made using Equation 4.6.

$$SEC_i = \frac{E_{tot}}{\sum_{i=1}^{n} P_i w_i} \cdot w_i \tag{4.6}$$

where w_i is the weighting factor of a pulp or paper grade, E_{tot} is the total energy consumption, and P_i is the production of a pulp or paper grade. The typical specific energy consumption values for the Finnish mills were adopted from Pöyry (2016), and they can be found in Publication II.

The electricity consumption decreased by approximately 2,300 GWh in the Finnish PPI between 2011 and 2017. In this thesis, it was estimated that a decrease of approximately 1,000 GWh was due to changes in production volume and the production mix, and the remaining 1,300 GWh was a result of EEI. Figure 4.7 illustrates the impact of structural changes on the energy efficiency of the Finnish PPI. The structural changes covered roughly 300 GWh of the estimated total EEI (1,300 GWh), which means the structural changes accounted for approximately 22% of the total EEI, and 78% of the improvement was a result of other factors. The results confirm that the structural changes have contributed to the EEI, but the role is less significant than might have been expected. The major share of the improvement is caused by other factors such as technology development and more optimal operational modes. The impact of structural changes is not limited to the EEI. The closures and start-ups have significantly affected energy production, the fuel mix, and CO_2 intensity. Several closed units met their energy demand by combusting fossil fuels, whereas the energy production of new units is mostly based on biomass. The changes in energy production and CO_2 intensity are largely a result of the changes in the production mix, for example the increase in chemical pulp capacity.

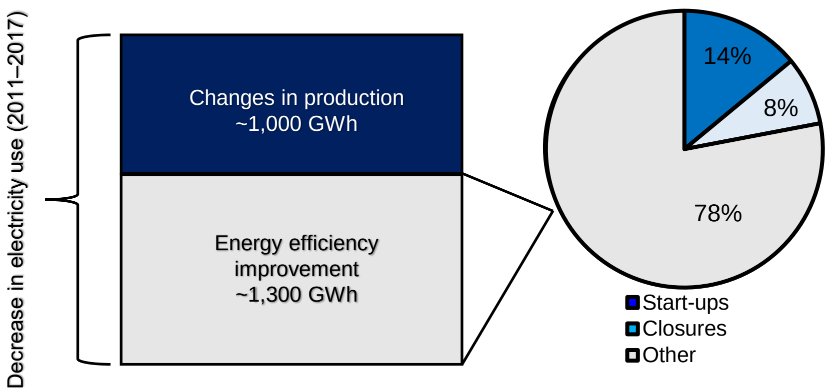


Figure 4.7: Impact of closures and start-ups on the energy efficiency of the Finnish pulp and paper industry between 2011 and 2017.

The results suggest that unit closures led to heat and electricity savings of 190 GWh and 110 GWh, respectively. Savings due to start-ups were 380 GWh of heat and 190 GWh of electricity. Therefore, it can be safely concluded that structural changes reduced heat consumption significantly more than electricity consumption. This finding is in line with the prevailing trends. Many new technologies, for example improvements in pressing and drying devices, decrease heat consumption in the mills significantly, whereas employing those technologies requires increased amounts of electricity. Moreover, modern mills typically have advanced environmental protection technologies that increase electricity consumption in comparison to older mills. Therefore, old mills use heat less efficiently than the average mills whereas modern mills are significantly more efficient heat consumers than the average ones. The difference in electricity consumption is smaller between old, modern, and average mills due to changes in the utilized technologies.

Additional interesting findings suggest that the unit start-ups have reduced energy consumption significantly more than the unit closures, i.e. the new mills have notably higher efficiency than average ones, but the closed mills do not significantly differ from the average units. The new mills typically employ the best available techniques, and thus have high energy saving potential in comparison to the average mills. Thus, building the new mills has the highest energy saving potential, but it might not be the most cost-effective solution. Another explanation for the results is the high-level maintenance and regular upgrades of old mills in the Finnish PPI. The efficiency of old mills can be kept at a good level if they are continuously improved. Thus, the results highlight the importance of paying attention to continuous EEI in the existing mills. If the study had been conducted using data from other countries, the result could have been different. In countries with older mills or old units with lower energy efficiency, the role of closures on the EEI could be higher. Many factors such as data accuracy affect the results, and thus they should be considered as a best estimate with the used assumptions and the gathered data.

5 The role of technology development in energy transition

Technology development provides opportunities to improve operation in the forest industry. Finland and Sweden have undergone technological progress, but some promising technologies such as BECCS/U are still in a developmental phase. Technological development provides future opportunities but also explains reasons behind the changes in energy consumption, production, and CO_2 emissions. This thesis analysed the development of lime kilns and dryers, recovery boilers, as well as the effects of polysulphide cooking on the energy balance of kraft pulp mills, and prospects for BECCS/U.

5.1 Decarbonization of lime kilns and dryers

Lime kilns are responsible for approximately 7% and 8% of total fuel consumption in the Finnish and Swedish forest industries. As the lime kilns traditionally combust fossil fuels, their decarbonization has become an important topic. Finland and Sweden have been forerunners in switching from fossil fuels to bio-based alternatives: for example most of the wood-powder operated lime kilns exist in these countries (Valmet, 2018). Sweden started the fuel switching earlier than Finland, and currently 90% of the Swedish lime kilns operate by combusting biofuels, mainly tall oil pitch or wood powder (Berglin and Von Schenck, 2022). The current fuel use in the lime kilns of the Finnish forest industries was estimated using mainly environmental permits and reports. It should be noted that fuel consumption varies within different years due to fuel availability and possible operational problems. Newly-built lime kilns can operate using only biomass, but if existing lime kilns are modified to combust biomass, there might be a significant demand to use fossil-based support fuels. The estimated fuel use is presented in Figure 5.1.

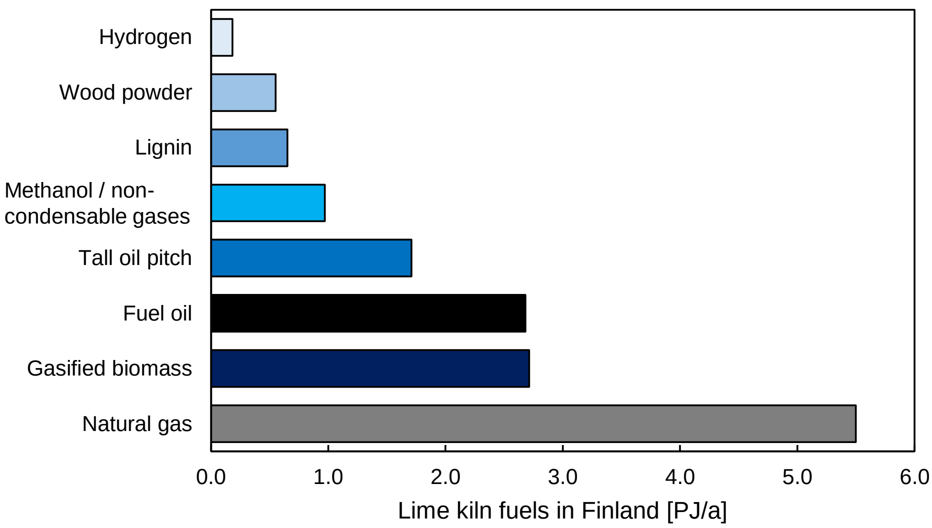


Figure 5.1: Lime kiln fuels in the Finnish PPI.

In Finland, several mills still combust natural gas and fuel oil in lime kilns, but there was significant progress in the 2010s. The Stora Enso Varkaus mill as well as the Metsä Fibre Joutseno, and Äänekoski mills started to use gasified bark in lime kiln in 2012, 2013, and 2017, respectively. The Stora Enso Enocell mill replaced fuel oil with wood powder from 2015 achieving an oil saving of 70–90 t/d (Stora Enso, 2017). The Stora Enso Sunila mill has used the Lignoboost™ process to separate lignin from black liquor since 2015. A part of the lignin is combusted in a lime kiln to replace natural gas. In the Stora Enso Oulu mill, pitch oil and hydrogen accounts for a fuel supply of ~119 GWh/a and ~51 GWh/a (Regional State Administrative Agency, 2021). The hydrogen is produced in a nearby chlorate production plant. The UPM Pietarsaari mill used to operate with gasified biomass but currently the main fuel is pitch oil. Technology development is typically slow in conservative industries, but the decarbonization of lime kilns in Finland and Sweden shows that rather significant changes can be achieved within a decade.

Lime kilns typically emit 100–250 kgCO_2/ADt (Kuparinen, Vakkilainen, and Tynjälä, 2019). The global production of kraft pulp was 146 Mt in 2019 (FAO, 2022), and thus the CO_2 reduction potential for lime kilns can be roughly estimated at 15–36 MtCO_2/a. The Finnish and Swedish mills have shown encouraging examples of successful low-carbon lime kiln operation, and it can be expected that fuel switching will continue in other countries.

As dryers are not major users of fossil fuels, their decarbonization has not been as topical as the decarbonization of lime kilns. However, some investments have been implemented. For example, natural gas combustion in dryers decreased by 20% by investing in a Twinroll™ dewatering press in the Metsä Board Joutseno bleached chemi-thermomechanical pulp (BCTMP) mill in Lappeenranta, Finland (Valmet, 2019).

5.2 Development of recovery boiler technology

The recovery boilers produce a major share of the electricity in the Finnish and Swedish forest industries. There have been notable changes in both the boilers and their operation. Between 2002 and 2017, eleven recovery boilers were closed in Sweden and five new ones were built. In Finland, eight boilers were closed and three built. A recovery boiler in Äänekoski, which is the newest boiler in Finland, has a very high capacity of 7,200 tDS/d, and it can sell over 1 TWh/a of electricity (IRENA, 2018). The Swedish recovery boilers have recently developed towards significantly higher pressures and temperatures. Obbola, Östrand, Iggesund, and Skoghall were built between 2005 and 2015, and they all operate at pressures higher than 100 bar and temperatures over 500 °C.

Figure 5.2 illustrates the development of recovery boilers in Finland and Sweden. Between 2002 and 2017, the average capacity grew from 1706 tDS/d to 2621 tDS/d in Finland, and from 1214 tDS/d to 1627 tDS/d in Sweden. Additionally, the steam parameters have increased, which enables higher electricity production. The average steam temperature increased from 440 °C to 463 °C and from 481 °C to 491 °C in Sweden and Finland. The average pressure grew from 51 bar to 69 bar in Sweden and from 83 bar to 91 bar in Finland. The black liquor dry solids contents increased in both countries, from 69% to 74% in Sweden and from 77% to 79% in Finland, which allows higher steam generation. The development of recovery boilers in the Finnish and Swedish pulp mills underlines that there is a possibility to increase renewable energy production in the forest industry by renovating the boilers. In addition to the progress of recovery boilers, the Swedish forest industry especially has increased its electricity production by investing in new back-pressure turbines.

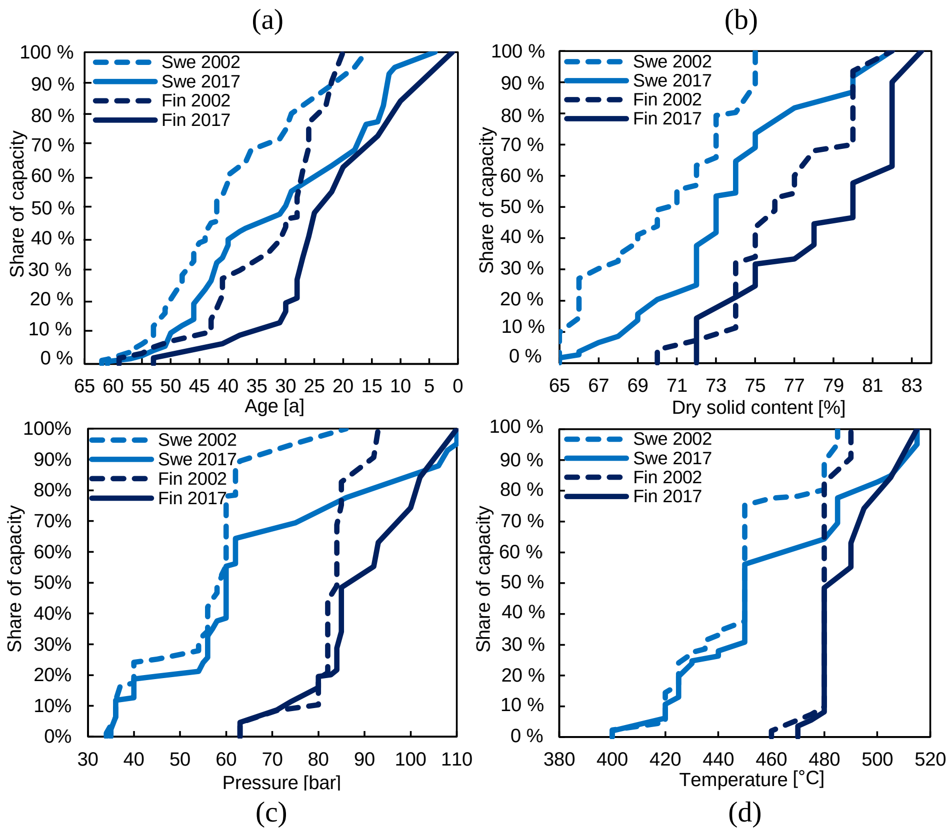


Figure 5.2: Development of recovery boilers in the Nordic countries: age (a), dry solids content (b), steam pressure (c), and steam temperature (d).

5.3 Effect of polysulphide cooking on energy and material balance

Polysulphide cooking and its opportunities have been known for a long time, but only a few mills produce pulp through the polysulphide process. The demand for higher material efficiency and improved energy self-sufficiency in mills has made the technology interesting again. In Finland, one mill has converted its cooking process from traditional sulphate cooking to polysulphide cooking. A lack of knowledge and concerns on the impact of process change on the mill hinder the implementation of investments. This thesis aims at clarifying the effect of PS cooking on the energy and material balance of a softwood (SW) and hardwood (HW) kraft mills.

5.3.1 Millflow and input values

The effect of polysulphide cooking on the kraft process was studied using *Millflow* which is a spreadsheet-based calculation tool for energy and mass balances of kraft pulp mills. *Millflow* was developed at LUT University. It is introduced in more details in previous works (Vakkilainen and Kivistö, 2008; Hamaguchi, Vakkilainen, and Ryder, 2011; Kuparinen, 2019). For this research, the calculation tool was updated with mill data concerning PS cooking. Two kraft pulp mill models were utilized. Both are stand-alone mills, and their energy supply is covered by a recovery boiler. Other biomass boilers are not used during the normal operation. The main input process values for conventional kraft and PS cooking at SW and HW mills are shown in Table 5.1. The input values give a general picture of the operation of the mills, but the operational values are not constant in the reality but change depending on several factors such as capacity utilization rate.

Table 5.1: Main input values for conventional kraft and PS cooking at SW and HW mills.

	Unit	SW mill, base case	SW mill, PS case	HW mill, base case	HW mill, PS case
Production					
Operating hours	h/a	8,400	8,400	8,400	8,400
Bleached pulp production	ADt/a	600,000	613,334	1,500,000	1,528,300
Wood handling					
Wood required	m^3sob/d	7,960	7,960	16,710	16,710
Residue generated	BDt/d	607	607	1274	1274
Cooking					
Yield	%	45	46	53	54
Polysulphide concentration	gS/l	-	5	-	5
White liquor flow to digester	m^3/d	6,485	6,485	12,242	12,245
White liquor dry solids	%	13.9	14.4	15.6	16.0
White liquor sulfidity	%	38.7	26.3	32.0	20.1
Active alkali charge as Na_2O	%	17.5	16.2	17.1	15.9
Active alkali as NaOH	gNaOH/l	129	120	140	131
Effective alkali as NaOH	gNaOH/l	104	104	118	118
Causticity	%	84	84	83	83
Kappa after cooking	-	30	30	18	18

Mill SW is a northern mill producing 600,000 t/a of bleached SW pulp. The mill represents a typical existing kraft pulp mill. In an earlier study, the model was checked against mill operation data and found to be reasonably accurate to be used for studying operation of mills (Vakkilainen and Kivistö, 2008). Mill measurements were used to model the effects of PS cooking on the SW kraft pulp mill. Literature data (Hara, 1991; Jiang, Crofut, and Jones, 1994; Nishijima, Inaba, and Smith, 1995) as well as vendor data were used to compile the model. The PS concentration of cooking liquor varies, and it was set at 5.0 gS/l in this thesis. The yield of the cooking increased by one percentage unit according to mill trial. The increase is lower than in many previous studies (e.g. Demuner *et al*., 2020), which may be a result of the already high yield in the reference mill and a need to retain pulp strength. Equations 3.3 and 3.4 were used to calculate the composition of the PS liquor.

Mill HW is a southern eucalyptus mill producing 1,500,000 t/a of bleached HW pulp. The mill represents a typical modern mill in the southern hemisphere. It is presented in more detail in Hamaguchi, Vakkilainen, and Ryder (2011), Kuparinen and Vakkilainen (2017) and Kuparinen (2019). There is a lack of published practical experience on PS pulping from large eucalyptus kraft pulp mills. Therefore, changes in the reference SW mill are utilized in the HW mill model to enhance understanding of the effects of PS cooking on a eucalyptus mill. The PS concentration is set at 5.0 gS/l as in the case of the SW mill. Based on laboratory experiments (Zanão *et al*., 2019; Demuner *et al*., 2020), the yield increase was set to one percentage unit also for the HW mill.

5.3.2 **Effect of polysulphide cooking on kraft pulp mills**

The calculated results are largely consistent with the earlier studies and mill trials. Simultaneous modifications to mills can be done in addition to the implementation of PS cooking, which can affect the reported results. This should be considered when evaluating the effects of PS cooking. Changes in cooking affect the recovery cycle. In the SW mill, the evaporator load decreased from 566 t_{H2O}/h to 546 t_{H2O}/h, which reduced steam consumption per ton of pulp by 5.6%. In the reference mill, the washing stage was modified at the same time as the implementation of the PS process, which led to a higher DS content in the black liquor, and thus affected the evaporator. The increased pulp yield reduced the organic matter in the recovery boiler. The heating value decreased by 0.8%. The black liquor DS flow per produced pulp ton and the boiler load decreased, which may enable a further increase in pulp production. Changes in black liquor reduced the steam production per ton of pulp by 3.2%.

According to the results, the implementation of PS cooking slightly increases the demand for steam, but it can be expected that careful consideration of the process parameters can lead to improvements in the energy balance. In the SW mill, the increase in steam demand together with reduced steam production led to a reduction of 5.8% in power generation. The amount of sellable electricity decreased by 28.4%, but the mill was still able to meet its energy demand by combusting black liquor in a recovery boiler. Older mills that have poorer steam economy might not be able to implement PS cooking without additional energy production, which may have hindered the spread of the technology. The results of the SW and HW mill calculations using *Millflow* are presented in Table 5.2.

Table 5.2: Effects of polysulphide cooking on a SW and HW kraft pulp mill.

	Unit	SW mill, base case	SW mill, PS case	HW mill, base case	HW mill, PS case
Recovery boiler and evaporator					
Evaporator load	t_{H2O}/h	566	546	1,286	1,301
Black liquor dry solids flow	tDS/ADt	1.93	1.89	1.46	1.43
HHRR (boiler load)	MW/m^2	2.85	2.83	3.43	3.41
Black liquor HHV	MJ/kgDS	13.97	13.87	13.65	13.55
Net steam flow	t/h	454	449	859	850
RB steam/BL solids virgin	kg/kg	3.44	3.40	3.54	3.42
Steam generation	MJ/ADt	21,350	20,670	16,280	15,810
RB flue gas	Nm^3/ADt	6,743	6,601	5,590	5,478
Organics in BL	%	69.8	68.9	65.2	64.3
Reduction	%	95	95	94	94
Heat consumption					
Cooking	MJ/ADt	2,780	2,980	1,829	1,960
Bleaching	MJ/ADt	870	1,150	580	767
Evaporation	MJ/ADt	5,199	4,909	2,988	2,966
Drying	MJ/ADt	2,410	2,580	2,100	2,248
Recovery boiler	MJ/ADt	1,780	1,790	977	963
Miscellaneous	MJ/ADt	1,168	1,157	707	706
Steam consumption, total	MJ/ADt	14,210	14,570	9,180	9,611
Electricity					
Steam for power generation	MJ/ADt	3,697	3,406	3,380	3,113
Power generation	MW	69	65	157	147
Power consumption	kWh/ADt	739	731	602	598
Excess power for sale	MW	16	12	49	39

HHRR = heart heat release rate, HHV = higher heating value, RB = recovery boiler, BL= black liquor

The effects of PS cooking on the HW mill were studied by updating South American mill model using data based on the literature, mill trials and the reference SW pulp mill. Changes in the cooking were similar to the case of the SW mill. It was assumed that the washing stage was not modified in the HW mill. Thus, the evaporator load increased by 1.1%. However, less steam was needed for evaporation per a ton of pulp. The heating value of black liquor decreased by 0.7%. The black liquor DS flow was 2% lower in PS cooking than in conventional kraft cooking. The changes in black liquor led to a 2.9% decrease in heat generation per a ton of pulp. As the pulp production increased, the absolute steam generation decreased by 1.1%. PS cooking affects the steam consumption, and according to the results, total steam consumption was 4.7% higher with PS cooking than for its kraft counterpart. Changes in steam production and consumption led to a 6.2% decrease in power generation, and 22.4% less sellable electricity was available. In the case of the South American mill, it should be noted that sellable electricity may not be such a valuable product as in the northern mill due to restricted access to the national distribution network.

5.3.3 Economic analysis of polysulphide cooking

A simple economic analysis was done to evaluate the feasibility of PS implementation in the northern SW and the southern HW mills (Figure 5.3). The prices of electricity, pulp and wood were used as key variables. Investment in the PS process was assumed to be 15 M€ for the SW mill (Partanen, 2012), and it was scaled up to 27 M€ for the HW mill. The used values for the lifetime of the investment and interest were 25 years and 7%. Annual operation and maintenance costs were 5% of the investment. Bleaching chemical costs were set at 35 €/ADt based on Onarheim *et al*. (2017). As previous studies have reported yield increases up to 3% for SW, two additional cases were calculated.

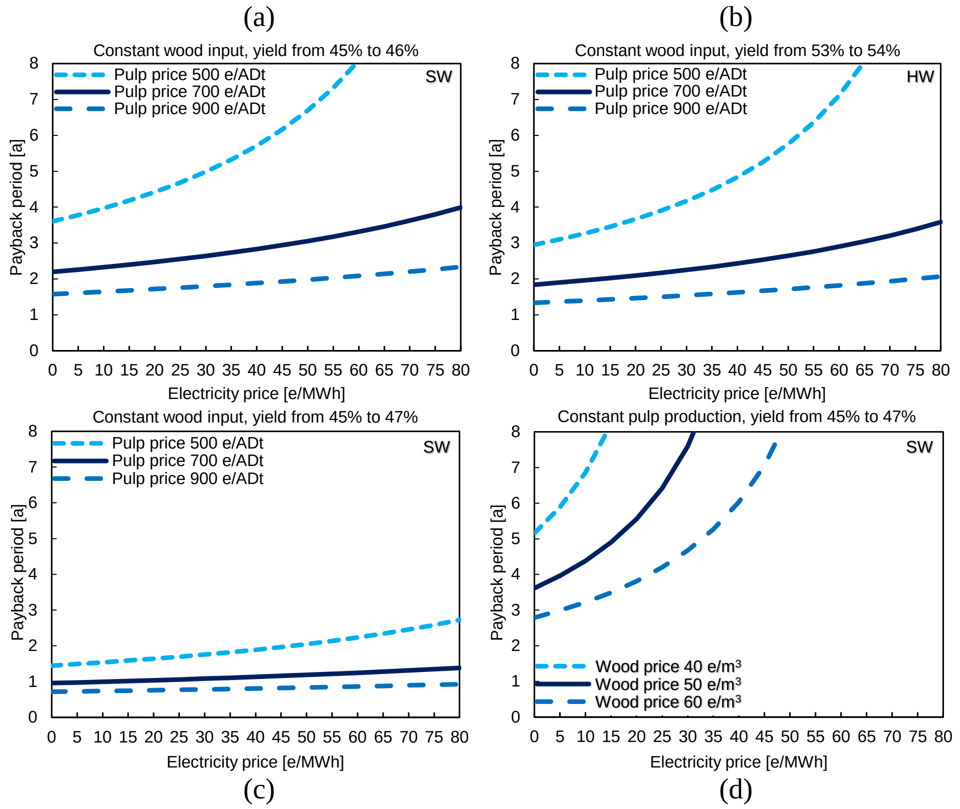


Figure 5.3: Economic analysis of the implementation of polysulphide cooking: softwood mill with a moderate yield increase and constant wood input (a), hardwood mill with a moderate yield increase and constant wood input (b), softwood mill with a high yield increase and constant wood input (c), and softwood mill with a high yield increase with a constant pulp production (d).

The results indicate that implementing PS cooking can be economically feasible. The analysis highlights that a yield increase should be used for increasing pulp production instead of saving in wood costs. The additional case shows that if a higher yield increase can be reached, the payback period is reduced substantially. Electricity prices have a significant effect on the feasibility if the mill can sell the electricity, which might not be the case in remote areas. The type of the mill affects the feasibility of PS implementation. In this thesis, energy-independent market pulp mills were analyzed. If the PS pulping is implemented in an integrated pulp and paper mill that has a high energy demand, the decrease in the steam and electricity supply may lead to the need to purchase additional energy, which may reduce the attractiveness of the investment.

5.4 Carbon capture

Reaching net-zero or negative emissions in a global scale is most probably impossible without carbon capture technologies (IEA, 2021b). Carbon capture cannot replace CO_2 reduction measures, but it can be used for offsetting residual hard-to-abate emissions. The PPI has an opportunity to capture biogenic CO_2, which could lead even to negative emissions in mills that use little or no fossil fuels. BECCS was identified as an important contributor to CO_2 emissions reduction in the Swedish PPI already in the early 2000s (Möllersten, Yan, and Westermark, 2003). The progress of BECCS/U in the Finnish and Swedish forest industries was reviewed in this thesis, but a large-scale BECCS has been seen only as future possibility. Currently, minor amounts of CO_2 are utilized in the production of precipitated calcium carbonate that is needed for paper production, and the Stora Enso Skutskär has announced to start a BECCS pilot plant in the early 2023 (Stora Enso, 2022). Thus, even though the companies have started to show interest in carbon neutrality, the development has been slower than it may have been expected.

Carbon capture is still seen as an interesting future opportunity. In Sweden, BECCS is expected to provide 1.8 Mt and 3–10 Mt of negative CO_2 emissions in 2030 and 2045, and thus contribute significantly to the decarbonization of the Swedish energy system (Karlsson *et al.*, 2021). A substantial share of the BECCS projects could be implemented within the PPI. Sweden has at least two large-scale forest industry CCS projects in the design-phase. The capacities of the planned units are 0.26 $MtCO_2$ and 0.8 $MtCO_2$ (Torvanger, 2019). The larger unit would capture carbon from the flue gases of the mill and the smaller one would be integrated in a black liquor gasifier. Implementation of the project would overcome the industrial CO_2 emissions of the Swedish forest industry. The national strategy of Finland does not include BECCS (Ministry of Economic Affairs and Employment, 2019b). No significant CCS projects exist in the Finnish forest industry, and it is expected that a large-scale CCS will not be feasible in Finland until 2030 because of lack of incentives and possible technical challenges (Teir *et al.*, 2011).

In the future, BECCS/U may have a role in the forest industry in offsetting CO_2 emissions from sources that might need time to achieve carbon neutral operation, for example fossil-based support fuels. Moreover, in some cases it might be easier to capture biogenic carbon from mills that has excess in bioenergy than eliminate fossil fuels in mills that have no access on renewable energy or the use of renewable energy is otherwise challenging. In a long term, the combustion of fossil fuels must be stopped, but carbon capture could be one measure in a temporary solution.

6 Towards a carbon neutral forest industry

The forest industry has cut its fossil CO_2 emissions in the 21st century, but urgent climate goals are calling for the sector to do more. The Paris Agreement aims at limiting global warming to well below 2 °C (United Nations, 2021), the EU is aiming to be a carbon neutral continent by 2050 (European Commission, 2020), and several countries have set their own carbon neutrality goals, for example Finland and Sweden are aiming to be carbon neutral by 2035 and 2045, respectively (Ministry of the Environment and Energy, 2017; Ministry of Economic Affairs and Employment, 2019a). Additionally, industrial sectors have set ambitious CO_2 reduction targets (Swedish Forest Industries Federation, 2018; Finnish Forest Industries, 2020a). This section evaluates the future prospects of the forest industry. Possible changes related to energy use and CO_2 emissions are identified, and barriers and opportunities to achieving carbon neutral operation are discussed.

6.1 Prospects for the Finnish forest industry in 2035

This thesis examined the future of energy use and CO_2 emissions in the Finnish forest industry in 2035 under five scenarios. The scenario-building approach enables studying several alternative futures, and thus provides a broad view of possible outcomes.

6.1.1 Basis for the future scenarios

The volume, structure, and efficiency of production define the energy consumption of the sector, and thus these factors were chosen as the main parameters for studying development of energy use. The future energy consumption was calculated using Equation 6.1. The EEI term applies to old, i.e. existing capacity, whereas the EEI of new capacity is included in specific energy consumption values (Table 6.2).

$$E = E_{ref} + \overbrace{\left(1 - \frac{\Delta P_x}{P_{tot,x}}\right)}^{\text{Share of old capacity}} \overbrace{\left[E_{ref}(1-\varepsilon)^{(v_x - v_{ref})} - E_{ref}\right]}^{\text{Energy efficiency improvement}} + \overbrace{\sum_{i=1}^{n}\left(SEC_{n,i}P_{n,i} - SEC_{o,i}P_{o,i}\right)}^{\text{Impact of structure and volume changes}} \qquad (6.1)$$

where E is the future energy consumption, E_{ref} is the energy consumption in a reference year (2017), ΔP_x stands for the new production capacity in a certain year, $P_{tot,x}$ is the total production in a certain year, ε is EEI rate, v_x is the reviewed year, v_{ref} is a reference year (2017), $SEC_{n,i}$ is the SEC of new capacity of a certain pulp or paper grade, $SEC_{o,i}$ is the SEC of the closed capacity of a certain pulp or paper grade, $P_{n,i}$ is the new capacity of a certain pulp or paper grade, and $P_{o,i}$ is the closed capacity of a certain pulp or paper grade.

Three different development paths for production volume and mix were created. The first path follows current trends. The second one assumes that new biorefinery projects will be realized in Finland, and thus the production of chemical pulp and new bioproducts will increase more strongly than in recent years. The last development path for the production predicts a decline in the forest industry. The chosen annual development rates for the production volumes are presented in Table 6.1. The volumes for scenarios I–IV were created based on previous studies and estimates of the forest industry trends (Hänninen and Katila, 2013; Pöyry, 2016; Koljonen *et al*., 2019; FAO, 2022). The production of chemical pulp was restricted to 10 Mt to secure wood availability, and thus the building of new biorefineries in scenarios III and IV leads to the closure of old pulp mills.

Table 6.1: Changes in production volumes of the Finnish forest industry within the scenarios.

Pulp and paper grades	**Unit**	**Scenarios I&II**	**Scenarios III&IV**	**Scenario V**
Mechanical pulp	%/a	-1.7	-2.0	-2.5
Chemical pulp	%/a	0.5	1.2	-0.5
Printing & writing paper	%/a	-2.0	-1.5	-3.0
Packaging materials	%/a	0.3	0.5	-0.5
Other papers	%/a	0.5	0.7	-0.5
Sawn wood	%/a	0.3	-0.1	-2.0
Wood-based panels	%/a	-0.2	-0.5	-2.0
Solid biofuels	%/a	1.0	3.0	0.5
Liquid biofuels	%/a	5.0	11.0	2.0
New bioproducts	1000	100	400	50

New mills are typically more efficient than older ones, and thus separate specific energy consumption values were defined (Table 6.2). Two EEI paths were chosen: a general EEI rate was set at 0.39% per year for low EEI scenarios based on Fracaro *et al.* (2012) and the higher EEI rate was set at twice as high (0.78%). Higher EEI rates have been reported (Odyssee-Mure, 2017), and thus results of the scenarios should not be overly optimistic.

Table 6.2: Specific energy consumption values for new and old units. Estimated based on Farla, Blok, and Schipper (1997) and Pöyry (2016).

		SEC, electricity		**SEC, heat**	
Product	**Unit**	**Old**	**New**	**Old**	**New**
Mechanical pulp	MWh/t	1.92	1.60	0.17	-0.19
Chemical pulp	MWh/t	0.67	0.53	3.19	2.83
Printing & writing paper	MWh/t	0.82	0.61	1.37	1.21
Packaging materials	MWh/t	0.57	0.52	1.48	1.26
Other paper	MWh/t	1.25	0.85	2.41	1.81
Sawn wood	MWh/m^3	0.08	0.08	0.31	0.31
Wood-based panels	MWh/m^3	0.16	0.16	0.61	0.60
Solid biofuels	MWh/t	-	0.25	-	0.72
Liquid biofuels	MWh/t	-	1.33	-	1.47
New bioproducts	MWh/t	-	1.00	-	1.00

Electricity production was evaluated following the logic presented in Equation 6.1. The electricity production depends strongly on the mill type and energy supply strategy. Specific electricity production values were estimated based on the operation of existing Finnish mills, and the set estimates were 1.38 MWh/t and 0.84 MWh/t for new and old market chemical pulp mills, 0.58 MWh/t and 0.28 MWh/t for new and old integrated mechanical pulp and paper mills, and 1.27 MWh/t and 0.92 MWh/t for new and old integrated chemical pulp and paper mills. The annual EEI rate of 0.10% for low EEI scenarios and 0.20% for high EEI scenarios was included for electricity production.

Different products, process alternatives, and mill configurations affect the fossil CO_2 intensity (Kuparinen, Lipiäinen, and Vakkilainen, 2021), and thus a decrease in energy consumption may not always lead to a decrease in the fossil CO_2 emissions. In this thesis, separate scenarios for the development of CO_2 emissions were created (Table 6.3). Only CO_2 emissions generated by forest industry companies by combusting fossil fuels were included. This thesis excluded the effect of carbon capture technologies from the scenarios for 2035 as it has been evaluated that CCS will not be feasible before 2030 due to technical challenges and a lack of incentives (Teir *et al*., 2011).

Table 6.3: Used scenarios and their features.

Scenario	Name	Features
Reference (2017)	Frozen situation	Combustion of peat 0.93 $MtCO_2$, combustion of coal 0.27 $MtCO_2$, lime kilns 0.95 $MtCO_2$, residual use of fossil fuels 0.24 $MtCO_2$, start-up and shutdown fuels 0.24 $MtCO_2$
Scenario I	No significant new investments	Current production trends continue. Annual EEI is low, 0.39% per year. Use of peat and coal decrease by 50% and 100%. 50% of lime kilns use biofuels. No major changes to the residual use of fossil fuels.
Scenario II	Active energy efficiency improvement	Current production trends continue. Annual EEI is high, 0.78% per year. Use of peat and coal decrease by 100% and 100%. 100% of lime kilns use biofuels. No major changes to the residual use of fossil fuels.
Scenario III	New investment	Biorefinery projects realize. Annual EEI is low, 0.39% per year. Use of peat and coal decrease by 75% and 100%. 75% of lime kilns use biofuels. No major changes to the residual use of fossil fuels.
Scenario IV	New investment and active energy efficiency improvement	Biorefinery projects realize. Annual EEI is high, 0.78% per year. Use of peat and coal decrease by 100% and 100%. 100% of lime kilns use biofuels. 50% decrease in the residual use of fossil fuels.
Scenario V	Decline in the forest industry	Production volumes decrease. Annual EEI is low, 0.39% per year. Use of peat and coal decrease by 100% and 100%. 50% of lime kilns use biofuels. No major changes to the residual use of fossil fuels.

Current fossil CO_2 emissions were estimated using the fossil fuel mix in the Finnish forest industry in 2017 (Finnish Forest Industries, 2020c) and the emission intensities for fuels (Table 2.1). The emissions were divided into major emission sources, i.e. lime kilns, biomass and recovery boilers using fossil fuels during start-ups, shutdowns, and other exceptional situations, boilers combusting peat and coal, and residual sources. Specific CO_2 emissions for lime kilns and biomass boilers were estimated based on Kuparinen, Vakkilainen, and Tynjälä (2019).

The combustion of coal will be banned in 2029 in Finland (Finnish Government and Ministry of Economic Affairs and Employment, 2019), and the combustion of peat will most probably end later (Soimakallio *et al*., 2020). Scenarios II and IV represent a forest industry that is willing to invest in clean technologies which lead to ending the use of peat and the decarbonization of lime kilns, whereas in scenarios I and III, the forest industry puts less effort into the decarbonization. In scenario V, the forest industry is not willing to invest in alternative fuels in the lime kilns, but the use of peat ends due to decreased energy demand and the closure of mills. No major changes in the use of start-up and shutdown fuels are expected by 2035 as they are a minor source of fossil CO_2 emissions and convenient alternatives are currently relatively challenging to find.

6.1.2 **Results of the future scenarios**

The estimated changes in production volume and structure, and energy efficiency will affect energy production and consumption in the Finnish forest industry by 2035. The total production volume changes by -6.3% in scenarios I–II, by 0.3% in scenarios III–IV and by -20.4% in scenario V. The changes in total volume are moderate, but the structure changes significantly. The production of heat-intensive chemical pulp is expected to increase, whereas electricity-intensive mechanical pulp will be produced in smaller volumes. The share of new bioproducts is extremely difficult to predict. In these scenarios, the share remains low. Every scenario predicts a decrease in electricity consumption, the heat demand may even increase if new biorefineries are built. EEI leads to energy savings from 5.9% to 12.1% within the scenarios

Figure 6.1 presents the key results of the scenarios. The decrease in electricity demand can lead to various changes. The combustion of fuels for electricity production may decrease either on mill-sites or outside the mill, which would lead to a reduction in fossil or biogenic CO_2 emissions, depending on the used fuels. Because electricity production typically depends on the heat demand, drop in electricity demand may not lead to a decrease in electricity production. Mills may sell excess electricity, which could lead to a larger amount of renewable electricity on the market. Another interesting option is that the availability of on-site generated electricity could make running new processes such as power-to-x technologies more attractive. If a mill is a net importer of electricity, savings in the electricity demand may lead to an increase in self-sufficiency. The scenarios did not consider the possible electrification of the forest industry processes or energy supply, which would increase the electricity demand. However, as significant electrification as in other sectors, for example in the steel industry, is not expected in the forest industry due to the nature of the processes and the tendency to produce energy from the mills' own residues. The scenarios predicted a decrease in the production of electricity-intensive mechanical pulp. Mechanical pulp mills do not typically produce electricity, and therefore a cut in the electricity demand of the forest industry due to a drop in mechanical pulp capacity only reduces the amount of purchased electricity and thus has a limited effect on the sector. The expected increase in chemical pulp production is likely to increase electricity production. The increase in electricity production can have similar effects to the decrease in electricity consumption.

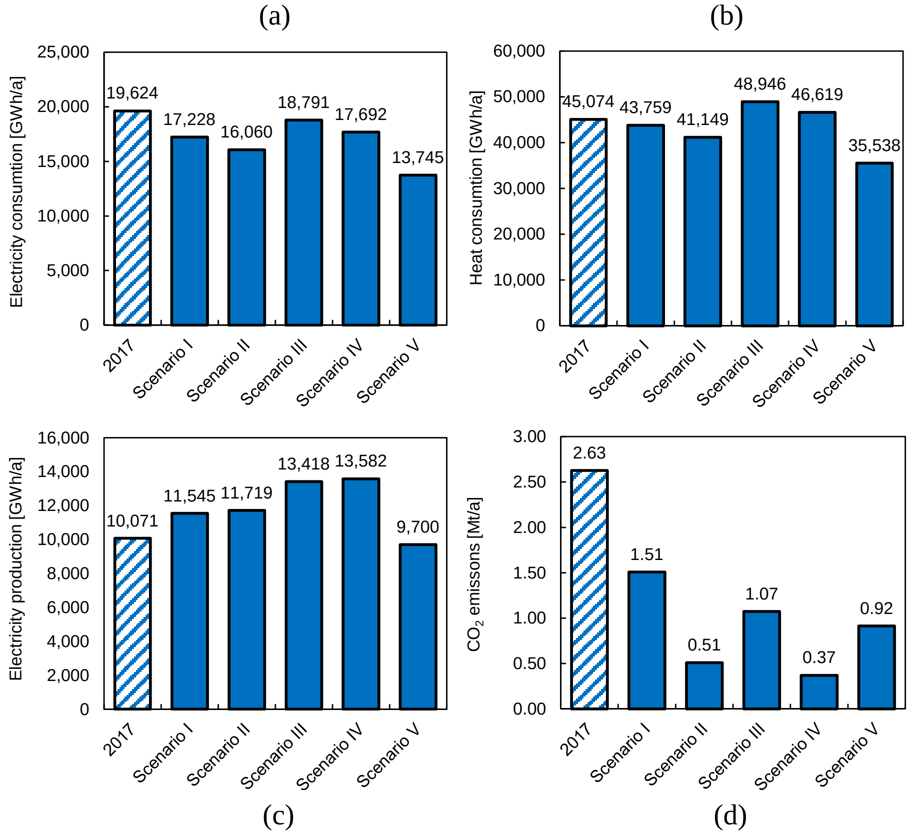


Figure 6.1: Electricity consumption (a), heat consumption (b), electricity production (c), and CO_2 emissions (d) in the Finnish forest industry in 2035.

Future heat demand depends strongly on the implementation of the new biorefineries. In scenario III, the heat demand increased by 8% whereas in scenario V, it dropped by 22%. Changes in the heat demand have a limited effect on a national level as the mills typically meet their own heat demand. However, a decrease in the heat demand can lead to a decline in electricity production in combined heat and power plants.

CO_2 reductions in the scenarios varies between 43% and 86%. A report by Pöyry (Vasara *et al*., 2020) agrees that very low emissions are possible in the Finnish forest industry in

2035. As the Swedish forest industry has a relatively similar structure to the Finnish one and has already achieved almost 80% lower emissions than the Finnish forest industry, it is realistic to expect substantial emission reductions.

6.2 The Finnish and Swedish visions

Finland and Sweden are aiming towards a carbon-neutral society and consequently both countries have created roadmaps for fossil-free operation in collaboration with different sectors including energy-intensive industries (Fossil Free Sweden, 2017; Paloneva and Takamäki, 2021). The roadmaps aim to improve the understanding of the needed CO_2 reductions, opportunities, costs, and obstacles to the implementation of the reductions. The sectors highlight the role of the replacement of fossil fuels by bio-based alternatives and electricity as well as energy efficiency improvement. The main challenge is that current bioenergy resources will not meet the demand of all sectors and electricity production and the distribution capacity is not sufficient especially during the peak loads. However, the forest sector has good premises for decarbonization due to the availability of on-site biomass and its already low dependency on fossil-based energy sources. Figure 6.2 presents the expected additional annual CO_2 reductions by 2050.

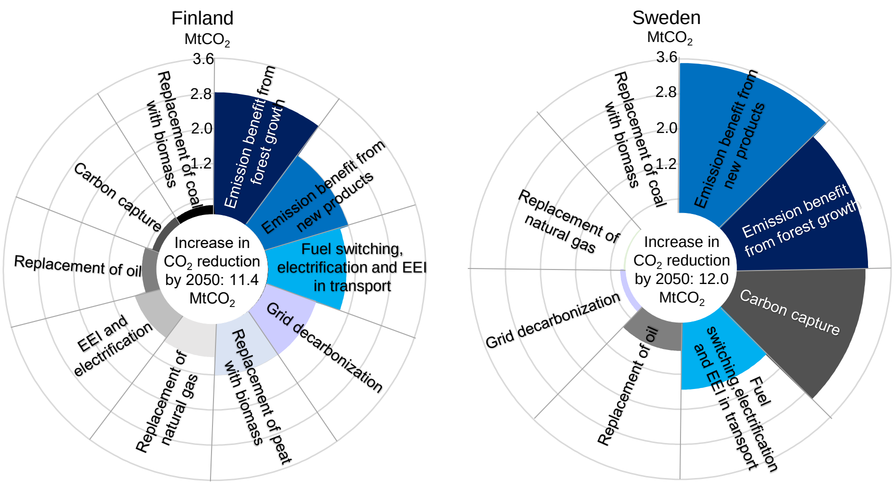


Figure 6.2: The vision of the Finnish and Swedish forest sectors by 2050: possible sources and magnitudes of CO_2 emissions reductions. The values represent increases in CO_2 reductions in comparison to current levels, i.e. the current emission benefit from forest growth or production of bioproducts is not included.

The roadmaps created by the Finnish and Swedish forest industries expect that the sector can significantly contribute to the CO_2 emissions reduction in the future (Swedish Forest Industries Federation, 2018; Finnish Forest Industries, 2020a). The forest industries in both countries already provide climate benefits, for example by producing bioproducts. The roadmaps presented by the Swedish Forest Industries Federation (2018) and the

Finnish Forest Industries (2020a) do not provide numerical estimates for all the expected cuts to CO_2 emissions, and thus Figure 6.2 is supplemented by calculations and evaluations. Hence, the estimates should be considered indicative. Assumptions used for constructing the figure are presented in Publication V.

The Swedish forest industry aims to be fossil carbon-free by 2045. The target includes indirect CO_2 emissions, i.e. the transport of products and raw materials and production of purchased electricity. The Finnish roadmap claims that industrial fossil CO_2 emissions can be reduced by 90% by 2035 compared to 2017, and substantial reductions can be expected from the decarbonization of transport and electrical grid. The electricity production in Finland and Sweden is already based on renewable sources, and Finland is expected to almost achieve a carbon neutral grid by the end of the 2030s, and Sweden has a target to have a 100% renewable-based electricity system by 2040 (Ministry of Economic Affairs and Employment, 2019b; Ministry of the Environment, 2020). Thus, emission reductions from the grid decarbonization can be considered realistic. Decarbonization of the freight transport used by the forest industry is expected to be more challenging.

It is the aim to switch current industrial fossil fuels to bioenergy in both countries. In Finland, the reduction potential for fuel switching is higher because the Swedish forest industry is already a minor user of fossil fuels. The Finnish forest industry does not find carbon capture technologies to be important solutions, but in Sweden it is expected that 3–10 Mt of biogenic CO_2 will be captured by 2050, and a substantial share of the projects could be implemented within the PPI (Karlsson *et al.*, 2021). Both countries believe that enhanced forest growth as well as the production of bioproducts will offer significant additional climate benefits. However, the forest growth is extremely difficult to predict as several factors affect it, and thus it is possible that the climate benefit could be even larger in the future. Moreover, the calculation of emission balance of LULUCF sector is challenging and procedures are changing, which makes the evaluation of the role of the forest growth in mitigating CO_2 emissions even more difficult

6.3 Barriers to decarbonization

The energy consumption of the forest industry is expected to decrease in Finland and Sweden due to energy efficiency improvements, but the improvements will not enable full decarbonization of the industrial sector, but fuel switching and possibly carbon capture technologies are needed. Viable measures for decarbonization exist, but there are still notable technical, economic, and political barriers.

The combustion of peat and coal in power boilers currently emits approximately 1.1 $MtCO_2$/a in the Finnish forest industry. The mills are striving to reduce the share of peat in the boilers (Pöyry Finland Oy, 2018), but eliminating peat completely requires modifications to existing boilers (Afry, 2020). Peat includes substantial amounts of sulphur, which reacts with alkali chlorides in biomass. Alkali chlorides tend to form a sticky mixture that causes corrosion. Moreover, conventional biomass has a lower heating value than peat, which leads to higher flue gas flows, and thus the need for boiler modifications. If the peat combustion ends, elemental sulphur can be added to the boiler, but this leads to hydrogen chloride (HCl) emissions. One challenge for replacing the peat is possibly increasing competition for biomass. Only three boilers use coal in the Finnish forest industry, and it can be expected that ending the coal combustion will not cause significant challenges.

Forested countries like Finland and Sweden have rather good premises for switching fossil fuels in energy production to bio-based alternatives, but many other forest industry countries suffer from a lack of available biomass. In those countries, renewable electricity may play an important role in future energy supply, but there are still problems needed to be solved by the energy sector. Obrist *et al*. (2022) expect that high-temperature heat pumps may have the potential to contribute to meeting the carbon-free heat demand in mills. Also electric boilers provide an interesting opportunity for steam production without emissions.

The forest industry in Finland and Sweden utilizes auxiliary boilers for securing steam supply during exceptional situations. These boilers typically combust fuel oil or natural gas. Electric boilers that can rapidly respond to changes in steam demand (Herre *et al*., 2020) could replace fossil fuel-fired auxiliary boiler, but high electricity prices have limited this kind of development. Moreover, start-up and shutdown fuels of biomass boilers are currently fossil fuels. Fossil fuels are applicable to auxiliary fuels, for example due to their good storability. Start-ups and shutdowns are minor fossil CO_2 emission sources and thus not much effort has been put into finding alternative fuels. However, thr Metsä Fibre Äänekoski combusts biogenic pitch oil or methanol as a supporting fuel eliminating the use of fossil fuels (Regional State Administrative Agency, 2015). Many mills sell the side streams applicable for energy use or already combust them in a lime kiln, and thus mill may not be willing to combust the streams as support fuels.

Even though Finland and Sweden have already been decarbonizing lime kilns, the replacement includes possible problems, namely, ring formation, lime quality issues, corrosion, an increase in flue gas flows, and environmental effects (Kuparinen and Vakkilainen, 2017). Furthermore, need to maintain high temperature in the lime kiln set requirements for the heating value of fuel (Vakkilainen and Kivistö, 2008). Biogenic side streams from processes may be sold or refined into products, and thus suitable low-cost fuels can be challenging to find. Concerns about the costs and effects on paper quality hinder the decarbonization of dryers.

BECCS is an interesting opportunity for the PPI, but the political environment does not support its implementation (Fridahl and Lehtveer, 2018). For example, the EU emissions trading system (ETS) does not take into account biogenic emissions (Moya and Pavel, 2018). Moreover, there is a lack of suitable underground formations in Finland and Sweden, which leads to a need for a pipeline transportation and/or shipping as well as storages and CO_2 hubs. The North Sea or Barents Sea have been considered the most potential locations for storages (Teir *et al*., 2011). Possibly high transport costs may hinder the attractiveness of BECCS. Furthermore, at least a part of the technology is still in the development phase (Minx *et al.*, 2018), and mills may not be eager to invest as they may not find further emissions reductions to be their own responsibility (Rodriguez *et al*., 2021).

6.4 Uncertainties in predicting the future of the forest industry

Several megatrends affect social, economic, and industrial developments worldwide, but the magnitude of the impacts is impossible to predict accurately. Additionally, unexpected phenomena such as the economic crisis in 2009 and the COVID-19 pandemic since 2020 affect the business environment of the forest industry. These kinds of phenomena can lead to dramatic and unpredictable changes such as unit closures in the forest industry. For example, electricity consumption in the Finnish forest industry dropped by 12% between 2019 and 2020 (Statistics Finland, 2022) due to a large industrial strike and effects of the pandemic on the demand for pulp and paper. The drop was the largest after the decline during the economic crisis: between 2007 and 2009, the electricity demand decreased by 30%. Additionally, the electricity consumption in 2020 was the lowest since 1987. It remains to be seen if the effects of COVID-19 have a long-lasting impact on the production volumes and energy use of the forest industry. During the crisis, a few units have already closed or are planned to be closed in Finland.

Forecasting the future production mix includes several uncertainties. The transformation from conventional forest industry products to innovative bioproducts has been expected for several years but pulp, paper, and sawn goods still overwhelmingly dominate the range of products. Increasing demand, technological development and a need for CO_2 emissions reduction will most probably accelerate the transformation, but a far-reaching change will take time. Currently, it is impossible to predict which new products will break through to become high-volume products.

The structure of the forest industry as well as national resources affect the energy consumption, production, and CO_2 emissions. Thus, the development path towards lower carbon intensity varies significantly between different countries. For example, the Finnish forest industry can relatively easily eliminate coal from the fuel mix as there are a lot of wood residues available. The case is different in countries that mainly utilize market pulp to produce paper and use coal as a main fuel. There are no crucial technical barriers to the decarbonization of the forest industry, but on a global scale, the replacement of fossil fuels in the energy production will be a major challenge.

7 The forest industry and energy and climate policies

Finland and Sweden have set ambitious climate targets. On the one hand, the political environment has most probably affected the operation of the forest industry. On the other hand, the forest sector has versatile opportunities to contribute to achieving the set goals.

7.1 The role of policies in the energy transition of the forest industry

The energy transition in the Finnish and Swedish forest industries is at least partly driven by ambitious national energy and climate policies: Finland has stated an aim to become carbon neutral by 2035 and Sweden ten years later (Ministry of the Environment and Energy, 2017; Ministry of Economic Affairs and Employment, 2019a). Several previous studies have investigated the effect of energy and climate policies on the development of the Swedish PPI (Ericsson, Nilsson, and Nilsson, 2011; Blomberg, Henriksson, and Lundmark, 2012; Henriksson, Söderholm, and Wårell, 2012; Gulbrandsen and Stenqvist, 2013; Henriksson and Lundmark, 2013; Ottosson and Magnusson, 2013; Bergquist and Söderholm, 2016; Scordato *et al*., 2018). The studies claim that national measures such as programme for energy efficiency improvement, introduced in 2005, carbon tax which came into force in 1991 and tradable renewable electricity certificate scheme (TRECS), which begun in 2003, have accelerated the sustainable energy transition in Sweden. A part of the studies focused on EU measures, mainly the ETS. Prices for the EU ETS have been low, and there have been more emission allowances than the sector has needed. Thus, it can be assumed that the ETS has had a limited effect on the forest industry. However, the ETS has had an indirect effect on the forest sector because it has caused an increase in prices for purchased energy.

Figure 7.1 presents energy prices in Finland and Sweden from 2002 to 2017. The price development can partially explain changes in energy consumption and production trends as well as differences between Finland and Sweden. Several factors affect the energy use of the forest industry at the same time, and thus the following analysis includes some uncertainties. The validation of the findings would require further studies. However, it can be safely claimed that changes in fuel prices have had effect on the fuel use. The prices increased from the beginning of the 2000s by the economic crisis around 2009. After the crisis, the prices increased globally, and an energy tax reform in 2011 in Finland increased the growth. During the periods of increasing energy prices, fossil fuel consumption has dropped (Figure 7.1). For example, the fossil fuel use dropped by 27% in the Finnish forest industry between 2010 and 2012 when the fuel prices were growing strongly. Later, the fuel prices have been more stable or even decreased significantly. The price for fuel oil dropped by one third in Finland from 2012 to 2016. During the period of decreasing prices, fossil fuel consumption has not decreased notably in the forest industry. Political decisions are likely to have an effect on the fossil fuel use in the Finnish forest industry in the near future as the use of coal for energy purposes will be banned and there is also an ambition to end the combustion of peat. If coal and peat are replaced with renewable fuels, the industrial fossil CO_2 emissions may drop by 40%.

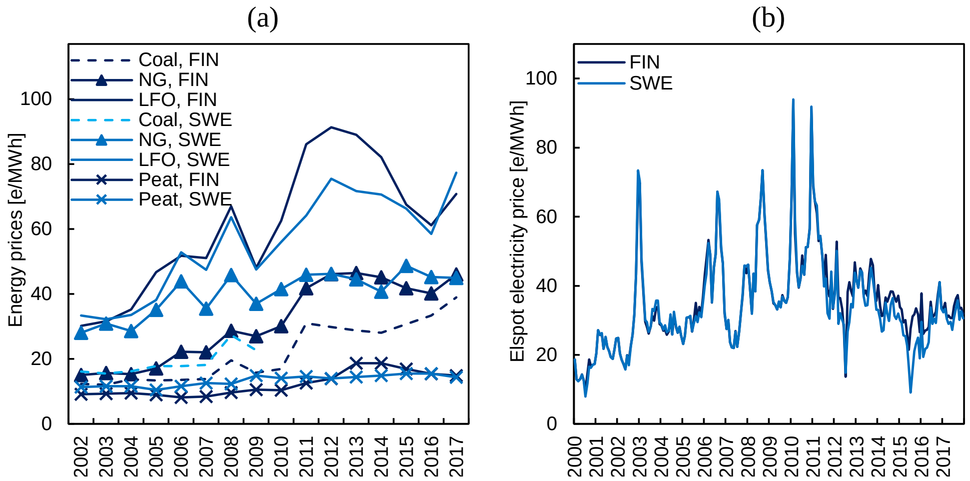


Figure 7.1: Development of fuel prices (a) and electricity prices (b) in Finland and Sweden. Data from Swedish Energy Agency (2020), Nordpool (2021), and Statistics Finland (2022). NG stands for natural gas and LFO for light fuel oil.

Finland has had higher electricity prices and tax on electricity for industrial users than Sweden (Espensen *et al*., 2014; Ministry of Employment and the Economy, 2016), which may be one reason for higher electricity production in the Finnish forest industry. The electricity market reform in 1996 and introduction of EU ETS in 2005 has increased electricity prices in Sweden (Ericsson, Nilsson, and Nilsson, 2011). The prices were high between 2002 and 2010, and during that period electricity production increased by 3.3 % per year in the Swedish forest industry. The TRECS as an interesting possibility for additional income, has most probably accelerated the growth in electricity production. Between 2010 and 2017, electricity prices decreased, and the increase in electricity production was only 0.4% per year. The electricity production in the Finnish forest industry has not correlated clearly with electricity prices. One explanation could be the already high production. However, for example a mill's configuration and production mix affect the electricity production possibilities, and thus the magnitude of the effect of electricity prices on the electricity production is difficult to evaluate with high certainty.

Both Finland and Sweden have employed a voluntary energy efficiency improvement programme (Stenqvist, 2013; Energy efficiency Agreements, 2020). In Sweden, a programme for improving energy efficiency (PFE) was used between 2005 and 2014. Mills that committed to improving their energy efficiency were granted an electricity tax exemption. In Finland, the energy efficiency improvement programme has been used since 2008. Both countries have reported promising results. The Swedish PPI reported an annual energy saving of 670 GWh between 2004 and 2009 (Ericsson, Nilsson, and Nilsson, 2011), which is evidence of the success of the programme. The Finnish PPI including almost all PPI companies has participated in the energy efficiency improvement programme since 2008. During the first period from 2008 to 2016, the Finnish PPI saved 5,233 GWh of heat, electricity, and fuels (Motiva, 2017). The examples of Finland and

Sweden demonstrate the use of voluntary energy efficiency improvement programmes can be effective. However, it should be noted that improvements that may have been made without the programme may have been reported in the results of the programme.

7.2 Role of the forest industry in meeting policy targets

The role of the Finnish forest industry in mitigating global change, i.e. meeting the national energy and climate policy targets was studied in Publication IV. The forest industry has a substantial industrial fossil CO_2 emissions reduction potential. According to the future scenarios, the emissions reductions could lead to a 2–4% decrease in national emissions by 2035, in comparison to 2018. The estimated lower energy demand of the forest industry can improve the national energy supply security and reduce indirect CO_2 emissions that originate from the production of energy purchased by the forest industry. A decrease in electricity demand and a potential increase in electricity production could lead to an increased amount of renewable market electricity. Finland has a target to increase the share of renewables to 51% in the national final energy consumption and to 30% in the final energy consumption for road transportation by 2030 (Ministry of Economic Affairs and Employment, 2019a). In addition to the expected increase in renewable energy production, the forest industry has the potential to produce substantial amounts of renewable fuels that may be needed, for example in the transport sector. Thus, the forest industry can contribute to meeting these targets. Additionally, several wood-based products can substitute fossil-based materials and act as long-term carbon storages.

Based on the roadmaps to a low carbon forest industry in Finland and Sweden, the forest industry could bring additional annual fossil CO_2 emissions cuts of 11.4 $MtCO_2$ and 12.0 $MtCO_2$ by 2050 (Figure 6.2). The greenhouse gas emissions of Finland and Sweden were approximately 53 $MtCO_{2,eq}$ and 51 $MtCO_{2,eq}$ in 2019 (Statistics Finland, 2022; Statistics Sweden, 2022). Thus, the potential contribution of the forest sector is promising, but the forest sector has a diverse role as a notable consumer of energy and a producer of bioproducts, fuels and energy, and thus its effects on the climate are difficult to evaluate.

The role of the forest industry in mitigating global change and meeting energy and climate policy targets is complicated. The sector can produce several bio-based products but at the same time forests are an important carbon sink. Hence, an important question is how to use forests and how much. For example, Siljander and Ekholm (2018) argue that forests are more cost-effective in emission reduction as carbon sinks than as a bioenergy source. However, they agree that wood-based products can contribute to the mitigation of global change. It should be noted that most of the bioenergy is generated from side-streams of the forest industry, and thus do not accelerate harvesting of wood. Untapping the potential of wood-based materials and energy in CO_2 emissions reduction requires ensuring sustainable cultivation and harvesting of wood. More studies are needed to obtain better estimations on the climate effects of the forest growth, and the potential of bioproducts as substitutes for fossil materials and carbon storages (Howard *et al*., 2021).

8 Conclusions

The forest industry is an energy intensive sector, and it is the fifth largest industrial fossil CO_2 emitter after iron and steel, concrete, chemicals, and aluminum industries. The Paris agreement calls for limiting global warming to well below 2 °C and several political targets, such as EU's target to be the first carbon neutral continent by 2050, aim at making significant cuts in CO_2 emissions. As an energy-intensive sector, the forest industry is expected to substantially contribute to the emissions reductions as well as to the sustainable energy transition. The change will be crucial for the sector as well because the prices for fossil fuels and emissions will lead to notable growth in production costs if no action is taken.

A large palette of measures for the reduction of fossil CO_2 emissions is available for the forest industry including fuel switching from fossil fuels to renewables, electrification, energy and material efficiency improvement, bioenergy carbon capture, increased production of renewable energy, biofuels and biomaterials, and strengthening of forests as carbon sinks. This thesis increased understanding of the development and current state of energy consumption, production, and CO_2 emissions in the forest industry. Factors affecting the trends in the 21st century were analyzed, and the focus was on the development of energy efficiency. Energy efficiency improvement has been seen as the most cost-effective measure to tackle the need for CO_2 emissions reduction. Improved awareness of factors affecting energy efficiency may enable more effective development. After looking at historical trends, the thesis investigated how the forest industry is expected to develop in the future and what kinds of opportunities it has for improving its operation. The identification of opportunities and barriers to decarbonization provides tools for both industrial operators and policymakers for creating roadmaps towards low-carbon forest industry. The Finnish and Swedish forest industries as forerunners in energy efficient and low carbon operation were used as example countries to answer the targeted research questions introduced at the beginning of this thesis.

8.1 Main findings

1) How have energy use and CO_2 emissions developed in the forest industry?

The forest industry has responded to the need for a sustainable energy transition. The development can be clearly seen within the Finnish and Swedish forest industries, and the global forest industry has also shown significant progress towards low carbon operation. The share of fossil fuels has decreased in the fuel mix of the forest industry. In Finland and Sweden, 85% and 96% of industrial fuels were bio-based in 2017, whereas the same figures were 72% and 85% in 2002. Globally, the share of biofuels increased from 31% to 48% between 2000 and 2018. The lower dependency on fossil fuels has been possible mainly due to energy and material efficiency improvement and switching the fossil fuels to bio-based alternatives in lime kilns and power boilers. In addition to the increase in the utilization of biomass, pulp mills have increased their own renewable electricity production, which has been possible by rebuilding recovery boilers and investing in both back-pressure and condensing turbines. Improvements in energy use led to substantial cuts in fossil CO_2 emissions: in 2002 production of paper ton emitted 410 kgCO_2 in Finland and 200 kgCO_2 in Sweden whereas the emissions were 290 kgCO_2 and 60 kgCO_2 in 2017.

The forest industry has succeeded in decarbonization rather well in comparison to other energy-intensive industry sectors, and the Finnish and Swedish forest industries have achieved a lower fossil fuel dependency and higher efficiency in comparison to their counterparts in other countries. Even though the forest industry has managed to cut fossil CO_2 emissions, the sector may have not met all expectations or potential. Energy efficiency has been continuously increasing in the Finnish and Swedish forest industries, but higher improvement rates are needed to meet EU and IPCC targets. Carbon capture was identified as an important measure to cut emissions in the forest industry already 20 years ago but there is still little progress. For a long time, pulp mills have expected to enlarge their product portfolio towards biofuels and biomaterials, but the number of retrofits is still limited, and capacities for new products are relatively small.

2) How have the observed structural changes, as well as energy and climate policies affected the development of the energy use in the forest industry?

Structural changes, i.e. closures and additions of capacity have a limited effect on the energy efficiency of the forest industry. The results suggest that the contribution of the structural changes to the electrical energy efficiency improvement was surprisingly only about 20% in the studied period in spite of several old mill closures. 80% of the improvement was due to other reasons such as improved operational modes or renovations. Thus, the results highlight the importance of continuous improvement in existing mills. Moreover, the structural changes decreased heat consumption more than electricity consumption. Many new technologies such as improved drying devices tend to use more electricity instead of heat, and for example environmental protection devices typically increase electricity consumption of the modern mills. In this thesis, the Finnish pulp and paper industry in the 2010s was used to study the structural changes. Even though the situation may vary within countries it can be expected that the impact of structural changes is rather limited in other regions as well.

Energy and climate policies have promoted a sustainable transition in the forest industry, but the used measures have not led to fundamental changes in the Finnish and Swedish forest industries in the 21st century. An analysis of fossil fuels use and prices provides evidence that fossil fuel consumption in the forest industry somewhat follows the energy prices, but several factors affect the energy use of the sector, and thus evaluating the effect of policies and energy prices accurately is a challenge. A notable increase in electricity production in the Swedish forest industry indicates that a national renewable electricity support system can encourage mills to increase electricity production, but contemporaneous changes in electricity prices makes the evaluation of the magnitude of the effect challenging. The Finnish and Swedish forest industries have saved energy while participating in voluntary energy efficiency improvement programmes, and thus these kinds of programmes can be successful. The political environment may play a major role in the future development of the forest industry. Finland aims to ban the combustion of peat and coal, which will affect the fuel mix of the forest industry. The adoption of new concepts and products such as bioenergy carbon capture or the production of power-to-x fuels requires a stable and consistent political framework to be attractive from the forest industry companies' points of view.

3) *What is the role of technology development in the forest industry and how does the integration of new technologies affect energy use and production?*

New or improved technologies provide several future opportunities for the forest industry. Technological development enables improved material and energy efficiency, greater renewable electricity production potential and fuel switching in challenging applications. The future may offer additional interesting opportunities such as carbon capture. If the sector seizes all existing opportunities, significant changes towards improved operation will be achieved. However, the sector can be considered quite conventional, and typically changes are small and slow. Only the most profitable and reliable investments are implemented: CO_2 reduction potential without economic profitability may not motivate the mills to invest in new technologies. Encouraging examples on successful technology development can be found from the Finnish and Swedish forest industries. Pulp mills have shown that lime kilns can be converted to combust bio-based fuels. Several alternatives, such as wood powder, gasified biomass, lignin, hydrogen, methanol, and tall oil pitch, have been utilized. Examples are promising as the decarbonization potential of lime kilns is globally roughly 15–36 $MtCO_2$/a. A development of recovery boilers contributes to the sustainable energy transition. Finnish and Swedish pulp mills demonstrate that new and rebuilt recovery boilers can operate with notably higher steam parameters and dry solids contents than older ones, which enables an increase in steam and electricity production.

Integration of new technologies tends to affect both energy consumption and production in mills. Modern mills that typically have an excess in energy will more likely invest in new technologies than older mills that may have a need for additional energy production. Changes in business environments and energy self-sufficiency have made long-known polysulfide cooking again an attractive opportunity to improve material efficiency in kraft pulp mills through a yield increase in the cooking. As less organic material ends up in the recovery boiler, the method allows an increase in pulp production if the boiler is a bottleneck of the process. Polysulphide cooking increases steam consumption slightly but it is not a problem in modern stand-alone mills. The implementation of polysulphide cooking can be feasible as profit from increased pulp production should overcome the investment costs as well as losses from the reduced energy production. Moreover, previous laboratory studies and mill scale experiments have not reported serious issues in pulp quality or mill operation.

4) What are the future prospects for energy use and CO_2 emissions in the forest industry, and how can the sector contribute to meeting climate targets?

The forest industry is expected to continue to develop towards more sustainable production. As there are no crucial barriers and new pulp mills can already achieve carbon neutrality during normal operation, it can be rather safely argued that the forest industry has an opportunity to eliminate industrial fossil CO_2 emissions by 2050. There is still the potential for energy efficiency improvements and there are also possibilities to increase the use of on-site biomass for energy or raw materials. Modern pulp mills can already produce notable amounts of excess electricity. Especially pulp mills provide interesting platforms for bioenergy carbon capture. However, the development pace so far has been moderate, and the investment cycles are long in the sector. Mills are renovated within 30–50 years, and therefore changes may not be fast in the future. 2050 is already only one investing cycle away, and thus significant efforts must be put into decarbonization immediately. Moreover, reaching the net-zero emissions in a relatively near future may require adding the carbon capture to a portfolio of measures for cutting CO_2.

The forest industry has good premises to achieve carbon neutrality and the sector can contribute to achieving climate goals. The reduction of industrial fossil CO_2 emissions can play a substantial role in mitigating global change, but the forest sector may have a significantly larger role as it has possibilities to produce renewable energy, fuels and products, and strengthen forests as carbon sinks. The palette of possible new products is wide, including textile fibres, lignin-derived products, power-to-x fuels, chemicals, and more. The realization of novel concepts must be profitable for mills, which in many cases requires changes in the political environment. In Finland and Sweden, the forest sector is expected to provide additional annual CO_2 benefits of 11.4 $MtCO_2$ and 12.0 $MtCO_2$ by 2050. Even though this thesis focused on industrial emissions, reaching the full decarbonization potential of the sector requires addressing the indirect emissions from electricity production, transport, production of raw materials as well as from the disposal stage. This kind of decarbonization requires technology development, collaboration between different sectors and even countries as well as political guidance.

8.2 Future research

This thesis considered only a few options for CO_2 emissions reductions in the forest industry focusing on the Finnish and Swedish forest industries. There are several open questions related to options that were not included in this thesis, and each one of the considered opportunities include numerous additional questions, as well. One key question for future research is how to utilize existing opportunities to achieve the largest benefits, for example related to CO_2 emissions reductions. For example, the forest industry can choose several pathways: in addition to producing conventional products, it can focus on producing renewable fuels, running carbon capture processes or sell renewable energy. The effects of retrofitting new technologies to mills for energy use and CO_2 emissions should be evaluated at the industrial level.

This thesis presented implemented improvements as well as the potential for future CO_2 emissions cuts in the Finnish and Swedish forest industries. The possibilities should be evaluated numerically also at a global level. For example, Finland and Sweden show that recovery boilers have notable opportunities for improvement, which could substantially increase renewable electricity production, but the global potential remains unclear. Moreover, analyzing the decarbonization pathways in forest industry countries with different production mixes and business environments requires further studies.

This thesis estimated the impact of structural changes, i.e. capacity closures and start-ups, on the energy efficiency. In addition to the structural changes, several factors such as large investments, for example the modernization of departments, improved waste heat utilization, or closing water cycles, and small investments as well as changes in operational modes all affect efficiency. The magnitude of the impacts remains unclear. In the future, it would be interesting to evaluate the contribution of different factors to the energy efficiency improvement. Studying the topic would require a large amount of data on changes implemented in mills as well as operational modes and the energy consumption of the mills.

Data quality and availability were significant challenges in this thesis. Comparison of different countries and mills is complicated as every mill is unique and the mills have their own reporting practices. Even though a few benchmarking studies on the forest industry’s energy consumption exist, there might be room for further studies. For example, the reference energy consumption values used in this thesis were introduced already in 1997. There was a lack of recent publications that would have presented clearly specific energy consumption values for different product grades. Moreover, as numerous factors affect the energy demand of a mill, there would be a need for a tool or a method that would better allow the comparison of energy consumption and efficiency between different kinds of mills, and even the same mill between different years.

Business environment has changed drastically during this research due to rapid and unexpected incidents. Both the COVID-19 pandemic and Russian invasion of Ukraine have affected energy prices, energy supply security, markets, supply of raw materials, and economics especially in Europe. At the same time, the EU ETS price has increased significantly. The increasing energy prices most probably accelerate the transition to renewable energy in the forest industry. Natural gas has been the most important fuel in the Finnish and European forest industry after biomass and the sharply rising prices and disruptions to supply encourage mills to find alternative energy sources. On the other hand, the situation may set barriers to decarbonization because for example the price of electricity is breaking the records and may thus hinder the electrification of processes and energy production. As these are only examples of the possible impacts of energy crisis on the forest sector, the implications as whole remain to be seen in the future and provide interesting research questions.

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Pulp and paper industry in energy transition: Towards energy-efficient and low carbon operation in Finland and Sweden

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A B S T R A C T

Mitigation of global warming, energy security and industrial competitiveness urge the energy-intensive pulp and paper industry (PPI) to transform energy use practices. This study investigates how the PPI has responded to the need for the energy transition in the 2000s. Finland and Sweden as forerunners of energy-efficient operation and decarbonization of the PPI are used as target countries. Understanding of changes in energy consumption is complemented using decomposition analysis (Logarithmic Mean Divisia Index Method) and the energy efficiency index approach. Analysis of companies' investments in energy technologies is used for explaining changes in energy production. Evidence of significant development towards the more sustainable operation of the PPI was found. Energy consumption per produced unit has decreased, i.e., energy efficiency has improved. Fossil fuels have been partially replaced with bio-based alternatives. Thus, the CO_2 intensity has decreased substantially. The generation of renewable electricity has increased in both countries. Examples of Finland and Sweden indicate that the PPI has great potential to contribute to CO_2 emission reduction worldwide in the future as energy efficiency can be further improved, and the share of fossil fuels can be decreased increasing the use of biofuels and self-generated green electricity at least in kraft pulp mills.

1. Introduction

The pulp and paper industry (PPI) presents an energy-intensive sector, which accounted for approximately 6% of global industrial energy consumption in 2017 (International Energy Agency (IEA) 2020a; International Energy Agency (IEA), 2020b). Regardless of a continuous increase in renewable fuel use, pulp and paper mills still rely on fossil fuels and emit a significant amount of both biogenic and fossil carbon dioxide (CO_2). Fully decarbonizing industry is crucial to stabilize climate and limit global warming well below 2 °C (Rissman et al., 2020). In line with the Paris Agreement's target, the European Union (EU) aims to be climate-neutral by 2050 (European Commission, 2021a). The targets call the PPI to transform toward carbon-negative operation. The transition is important also for maintaining the competitiveness of the sector. Energy prices have been increasing, and optimization of energy consumption is needed in many mills (Johansson et al., 2011). The PPI is a large energy producer as only part of the initial biomass is turned into final products. Most side streams are effectively converted into energy. This means that the PPI has good possibilities to increase renewable energy production, which may play an important role in the sustainable energy transition.

Finland and Sweden are the largest pulp producers in Europe and surpassed only by Germany in paper production (FAO, 2019). Both Finland and Sweden produced approximately 10.3 Mt of paper in 2017, and pulp production was 11.1 Mt in Finland and 12.2 Mt in Sweden. The PPI in these countries has shown significant progress towards reducing the impact of climate change. Between 1973 and 1990, the Swedish PPI decreased its CO_2 emissions by 80% while production increased by 18% by reducing oil use (Lindmark et al., 2011). Switching fuel oil with internally produced biofuels started as a result of the oil crisis in 1973 and has steadily continued motivated by market price changes and taxes on fossil fuel use. In 2019, the remaining shares of fossil fuels in the fuel mix were only 5% and 13% in the Swedish and Finnish PPIs, respectively (Finnish Forest Industries, 2020a; Swedish Forest Industries, 2020). For comparison, the global PPI covered 52% of its fuel demand with oil, natural gas, and coal on average in 2018 (International Energy Agency (IEA), 2020b).

Finland and Sweden can be considered as forerunners of energy-efficient operation and industrial decarbonization. Stenqvist (2014) investigated energy trends and performance in

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Nomenclature

ACT	Activity
BECCS/U	Bioenergy with carbon capture and storage or utilization
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DS	Dry solids
ECS	Electricity certificate scheme
EDA	Energy decomposition analysis
E	Energy consumption
EE	Energy efficiency
EED	Energy efficiency directive
ETS	Emission Trading System
EU	European Union
FAO	Forest and Agricultural Organization of United Nations
I	Specific energy consumption of sub-sector
i	Sub-sector
IEA	International Energy Agency
INT	Intensity
LMDI	Logarithmic mean divisia index
PFE	Programme for Improving Energy Efficiency in Energy-Intensive Industries
PPI	Pulp and paper industry
P	Production volume of grade
ref	Reference
S	Production share of sub-sector
SEC	Specific energy consumption
STR	Structure
T	Year
Y	Total production volume of sector

the Swedish PPI between 1984 and 2011 and found that energy efficiency improvement led to the avoidance of 50 PJ (40%) of primary energy use. Koreneff et al. (2019) recently studied the energy efficiency of the Finnish PPI. The study proved that the Finnish pulp and paper sector is competitive energy-wise, and its energy consumption is lower than the EU average. The Finnish and Swedish PPIs have higher energy efficiency in comparison with other major pulp and paper producers (Fracaro et al., 2012). Several studies, however, argue that there is still untapped energy efficiency improvement potential as well as CO_2 reduction opportunities (Blomberg et al., 2012; Möllersten et al., 2003).

In addition to energy efficiency improvement and fuel switching, the PPI has shown interest in increasing on-site green electricity generation in the Swedish PPI (Ericsson et al., 2011). The growing interest has manifested itself in the investments into the recovery boiler technology with higher steam parameters and both back-pressure and condensing turbines. To increase the share of renewable electricity in the energy mix, some pulp and paper companies have even participated in wind power projects.

Both Finland and Sweden have ambitious climate policies, which makes the PPI's energy transition particularly interesting in those countries. Finland has stated a target to be carbon-neutral by 2035 and carbon-negative soon after that (Ministry of Employment and the Economy, 2019). Sweden aims to be a net-zero emitter by 2045 (IEA, 2019). Both countries have also created roadmaps to the carbon-neutral operation of the PPI (Finnish Forest Industries, 2020b; The Swedish Forest Industries Federation, 2018). Effects of energy policy on the development of energy use of the Swedish PPI have been intensively investigated (Bergquist and Söderholm, 2016; Blomberg et al., 2012; Ericsson et al., 2011; Gulbrandsen and Stenqvist, 2013; Henriksson et al., 2012; Henriksson and Lundmark, 2013; Ottosson and Magnusson, 2013; Scordato et al., 2018). Many of these studies have found that national policy measures such as carbon tax, green electricity certificate scheme (ECS), which came into force in 2003, the program for improving energy efficiency in energy-intensive industries, launched in 2005, as well as the EU's measures, e.g., emission trading system (ETS), have positively affected the energy efficiency and CO_2 emissions of the Swedish PPI.

This study investigates how the PPI has reacted to the need for the energy transition in the 2000s. Even though several previous studies have investigated energy use in the Swedish PPI, the analyzed years were between 1973 and 2011. Both Sweden and Finland started decreasing their greenhouse gas emissions only after 2000 (Le Quéré et al., 2019). It is therefore important to find out how the trends have developed since. Moreover, only a few published works examined the Finnish PPI. This study aims at a deeper understanding of the development of energy consumption, energy production, and CO_2 emissions in the Finnish and Swedish PPIs in the past 20 years analyzing energy trends. Statistical data shows the absolute changes but does not explain the reasons behind them. This study uses energy decomposition analysis and the energy efficiency index method to enhance comprehension of changes in energy consumption. Awareness of changes in energy production is improved by analyzing the development of the used energy generation technologies, mainly recovery boilers. In addition, energy and climate policies as major drivers for change are included in the analysis. Energy transition in the Finnish and Swedish PPIs has been a success so far and thus better understanding of it may provide valuable insights to be learned by global pulp and paper producers as well as other energy-intensive industries and policymakers.

2. Methods and materials

2.2. Analysis of trends in energy consumption

Corresponding to current EU aims, both electricity and primary energy consumption have decreased in the Finnish and Swedish pulp and paper industries between 2002 and 2017 (Finnish Forest Industries, 2020a; Swedish Forest Industries, 2020). Production volume and structure, and energy efficiency affect energy consumption, but the magnitudes of those factors' effects are unknown. Energy decomposition analysis (EDA) is a widely used method for studying the development of energy trends (Greening et al., 2007). The method can be used to analyze the effect of different factors, such as activity (ACT), structure (STR), and energy efficiency (INT), on the energy consumption of a considered sector. The activity means the changes in total production volumes of the sector, the structure describes how the production mix of the sector has changed, and the energy efficiency expresses the changes in the energy intensity.

Numerous decomposition analysis tools are available (Ang, 1995), but currently, there is no standardized methodology (Greening et al., 2007). The present study employs a Logarithmic Mean Divisia Index Method (LMDI) presented by Ang (2005). The method was used successfully by Stenqvist (Stenqvist, 2014) for analyzing the energy trends in the Swedish PPI between 1984 and 2011. The LMDI has several advantages: it yields perfect decomposition results without the residual term and is flexible and easy to utilize. As in the study of Stenqvist, the use of physical indicators was chosen over monetary indicators as they are more suitable for energy-intensive industries and easily enable cross-country comparison. Strictly speaking, the decomposition analysis can show the correlation but cannot show causality e.g. both variables can have a third, common variable that causes the changes, which means the cause and effect needs to be estab-

Table 1
Reference specific energy consumption values for different grades. Adapted from (Farla et al., 1997).

Product category	Electricity consumption [MWh/t]	Heat consumption [MWh/t]	Primary energy consumption [MWh/t]
Mechanical pulp	1.47	−0.58	2.95
Chemical pulp	0.69	2.78	5.21
Recycled fiber input	0.39	0.11	1.11
Household and sanitary paper	0.67	1.39	3.40
Newsprint	0.39	0.69	1.84
Printing and writing paper	0.56	1.94	3.82
Wrapping and packaging paper and board	0.42	1.39	2.78
Other papers	0.50	1.67	3.33

lished outside the decomposition analysis. The following equations (Ang, 2005; Stenqvist, 2014) are used to investigate changes in energy consumption.

$$\Delta E_{t,T(ACT)} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{Y^T}{Y^t}\right) \quad (1)$$

$$\Delta E_{t,T(STR)} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{S_i^T}{S_i^t}\right) \quad (2)$$

$$\Delta E_{t,T(INT)} = \sum_i \frac{E_i^T - E_i^t}{lnE_i^T - lnE_i^t} \ln\left(\frac{I_i^T}{I_i^t}\right) \quad (3)$$

In Eqs 1–3, E_i^T is energy consumption in sub-sector i in year T, Y^T stands for total production volume of the sector in year T, S_i^T is production share of sub-sector in year T, I_i^T equals the specific energy consumption of sub-sector in year T, and t is T-1. Statistical data on specific energy consumptions of sub-sectors is not available, thus estimations are made by using weighting factors (Table 1). The Finnish and Swedish PPIs are divided into eight groups: mechanical pulp that includes semi-chemical and chemimechanical pulp, chemical pulp, recycled fiber, newsprint, printing and writing papers, hygiene papers, wrapping and packaging papers, and other papers. Production volumes for each grade are presented in Appendix A. The changes are calculated year by year and finally summed up over the studied period.

The improvement of energy efficiency has been considered the most cost-effective way to reduce energy consumption and CO_2 emissions (Worrell et al., 2009), and according to the EU Energy Efficiency Directive (EED), energy efficiency needs to be prioritized to meet the new EU 2030 climate target (European Commission, 2021b). Comprehensive assessment of energy efficiency can also highlight the saving potential or provide tools for evaluating the effectiveness of energy policy measures (Fracaro et al., 2012). Hence, the development of energy efficiency is analyzed in this study.

Several indexes, such as economic, thermodynamic, and physical-thermodynamic, have been developed for comparing the energy efficiency of different types of energy users (Patterson, 1996). In this study, the actual energy consumption is compared with the reference consumption (Eq. (4)). The total consumption of the sectors is a sum of different production grades multiplied by their specific energy consumption, and this is how the reference energy consumption is calculated in this study (Eq (5)). The same method was employed by Fracaro et al. (2012) and Farla et al. (1997). Monetary indexes are not used in this study because changes in prices, feedstock, and sector structure can have a fierce effect on the validity of the indexes (Blok and Nieuwlaar, 2017).

$$EE = \frac{E_{ref}}{E} \quad (4)$$

$$E_{ref} = \sum_{i=1}^{n} P_i SEC_i \quad (5)$$

In Eqs (4) and 5, EE is energy efficiency, E_{ref} stands for reference energy consumption, E is total energy use, P_i is production volume of grade and SEC_i is the specific energy consumption of grade. The same product groups as in the decomposition analysis are used.

Both electricity and primary energy efficiencies are studied. The conversion factors of 0.40 and 0.80 (Fracaro et al., 2012) for electricity and heat production are used to investigate the primary energy use. Mills' primary energy consumption is defined as a sum of used fuels, purchased electricity and heat, and other energy sources. Sold energy is not subtracted from primary energy consumption due to a lack of data. The reference-specific energy consumption values are adapted from (Farla et al., 1997) and presented in Table 1. The values evolve over time, but no fresher publications present values for every grade. Moreover, in this study, the values act as ratios between different grades, and thus the timelines of the values do not significantly affect the validity.

2.3. Analysis of trends in energy production

Development of electricity production, fuel switching, and used energy technologies are investigated in this study. Recovery boilers are globally the most important biomass users for energy (Kuparinen et al., 2019) and the major energy conversion devices in both Finnish and Swedish PPIs, and thus their development is considered in detail. The recovery boiler is an essential unit of the kraft (sulfate) pulp mills. In addition to producing steam, it regenerates the used cooking chemicals and minimizes the waste streams. The capacity of the recovery boilers, as well as the steam parameters, have significantly increased during the last decades (Vakkilainen, 2019). The latest recovery boilers typically operate within or above steam pressures of 100–105 bar and temperature of 505 °C (Vakkilainen and Kivistö, 2014). The increase in the steam parameters enables higher electricity generation, but ash properties are limiting the growth of steam temperature (Vakkilainen, 2014). The corrosive compounds, mainly potassium and chlorine, cause challenges in the high temperatures. Other measures such as increasing black liquor dry solids content, flue gas heat recovery, preheating of combustion air and water, and the use of condensing turbines lead also to improved electricity production and energy efficiency (Vakkilainen and Kivistö, 2014).

A lime kiln is an essential device of the kraft pulp mill where the calcining takes place to convert lime mud into burnt lime. The lime kiln is typically the only user of fossil fuels in a modern kraft pulp mill and thus its decarbonization has become an important issue. Its operation requires high temperatures that are reached by combusting fuels like oil and natural gas. Substituting fossil fuels has been investigated widely, and several mills are already combusting renewable alternatives e.g. wood residues, biogas, or

Table 2
Collected data and data sources.

Type of data	Source
Reference specific energy consumption values	Farla et al. (1997)
Heat, electricity and fuel consumption	(Finnish Forest Industries, 2020a; Statistics Finland 2020; Swedish Energy Agency, 2020; Swedish Forest Industries, 2020)
Electricity production	(Finnish Forest Industries, 2020a; Swedish Forest Industries, 2020)
Production volumes	Food and Agriculture Organization of the United Nations (FAO) 2019
Specific energy consumptions and productions	(Kähkönen et al. (2019); Swedish Forest Industries, 2020)
Energy prices	(Nordpool 2021; Statistics Finland 2020; Swedish Energy Agency 2020)
Investments in greener energy production and consumption, and technology development (recovery boilers, lime kilns, etc.)	Collected from several sources: press releases, the environmental permits, and the reports of pulp and paper companies. The most important source for the Finnish mills was the environmental permit database (Regional State Administrative Agency, 2021).

pitch oil (Francey et al., 2009; Kuparinen and Vakkilainen, 2017; Manning and Tran, 2015).

2.4. Data on energy use in the Finnish and Swedish pulp and paper industries

Collected data and data sources are presented in Table 2. The availability of data limited the studied period to 2002–2017. The analysis of energy data was complemented by reviewing investments in green energy production. The energy consumption data includes several uncertainties and problems with quality. The Finnish statistics do not separate the energy consumption of chemical and mechanical forest industries. Thus, the electricity consumption of sawnwood and wood-based panels was evaluated and subtracted from the total consumption. All reported fuels were included since the fuel consumption of the mechanical forest industry is challenging to evaluate accurately, and its share is minor in comparison with the chemical forest industry. Energy reporting practices vary significantly between the mills and countries. Thus, the comprehensive comparison of different energy users is a complicated task. Moreover, available statistical data does not always state precisely what kinds of assumptions were used or what was included in the numbers. The availability and quality problems of data in energy analysis were discussed also in the previous studies (Farla and Blok, 2001). In this study, different data sources report slightly different values, but the overall trends remain the same.

3. Results

3.1. Current state of energy consumption and production

Energy consumption and production were disaggregated to different mill types to improve understanding of the current state of the Finnish and Swedish PPIs (Fig. 1). The mills are categorized according to their major products, even though many mills produce several additional commercial streams. Only electricity and fuels consumption were included because differences in reporting between mills led to a lack of comparable values.

The mills producing chemical pulp account for the major share of electricity production and biofuels use in both countries. Kraft pulp mills convert approximately 50% of input wood to pulp and the rest is typically used as a biofuel for energy generation. Kraft pulp mills account for 86% and 91% of all produced electricity in the Finnish and Swedish PPI, respectively. Production of market mechanical pulp is the most electricity-intensive process. However, these mills consume only a minor share of total consumption due to low production volume.

Sweden has the least carbon-intensive PPI worldwide with a fossil fuel use of only 0.1 MWh/t of product. Stand-alone paper mills have the highest fossil fuel intensity in both countries. The main reason for that is the lack of wood residues, which tends to favor the combustion of fossil fuels. Many Finnish stand-alone paper mills have chosen to produce energy with their own boilers combusting fossil fuels, which leads to high fossil fuel intensity. Despite the low fossil fuel intensity, chemical pulp mills cover approximately 60% of total fossil fuel use in both countries. Sweden still uses minor amounts of oil in lime kilns whereas some Finnish chemical pulp mills combust peat in multifuel boilers in addition to fossil fuel usage in the lime kilns. Fossil fuel use in chemical pulp mills is almost five times higher in Finland than in Sweden.

3.2. Trends in energy consumption and production, and CO_2 emissions

Energy use continued to develop towards more sustainable operation in the Finnish and Swedish PPIs in the 2000s (Fig. 2). Energy prices, presented in Fig. 3, play an important role in the development of energy use. The Finnish values in 2005 are affected by a long industrial strike. Another blip around 2009 for both Sweden and Finland is because of a production slump caused by the economic downturn.

Electricity and primary energy consumption decreased in both countries. The PPI's electricity consumption decreased by 12% in Sweden and by 25% in Finland between 2002 and 2017, and the primary energy consumption dropped by 11% and by 27% during the same years. Electricity consumption per ton of paper decreased from 1.94 MWh/ton to 1.80 MWh/ton in Finland and from 2.12 MWh/ton to 1.95 MWh/ton in Sweden. Primary energy consumption per ton of paper decreased from 9.76 MWh/ton to 9.02 MWh/ton in Finland and from 9.57 MWh/ton to 8.91 MWh/ton in Sweden. Not only improved energy efficiency but also changes in the volume and structure affect the energy use. The role of different factors in the energy consumption changes will be analyzed in Section 3.2.1.

Total fuel consumption decreased by 3% in Sweden and 20% in Finland, and the share of biofuels increased from 87% to 96% and from 72% to 85%. In both countries, fossil fuel consumption reduced rapidly in the early 2000s, but the progress stagnated around 2013. Fossil fuel prices play a key role in the stagnation. The prices increased from the beginning of the 2000s to the economic crisis around 2009. After the crisis, the increase continued. The increase occurred worldwide but energy tax reform in Finland in 2011 led to even higher growth. Between 2010 and 2012, fossil fuel use decreased by 27% in the Finnish PPI. After peaking in 2012, the fuel prices started to decrease strongly. For example, the oil price dropped by one-third in Finland from 2012 to 2016.

The decrease in fossil fuel use has led to 70% and 58% reductions in fossil CO_2 emissions in the Swedish and Finnish PPIs, respectively. In 2002, the Finnish PPI emitted 410 $kgCO_2$/ton of paper whereas the number was 290 $kgCO_2$/ton of paper in 2017. In Sweden, amount of generated CO_2 per produced paper ton was as low as 200 $kgCO_2$/ton already in 2002, but it decreased notably be-

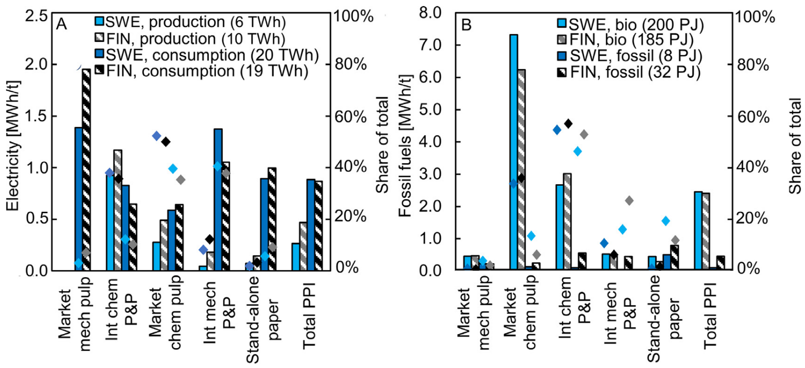

Fig. 1. Energy balances for market mechanical pulp mills, market chemical pulp mills, integrated chemical pulp and paper mills, integrated mechanical pulp, and paper mills, and stand-alone paper mills in the Finnish and Swedish PPIs: specific electricity production and consumption (A) and specific fuels consumption (B). The right axis presents the share of each mill type in the total production and consumption (diamond symbols). In the case of integrates, the specific energy consumptions are calculated per ton of all products. Values are from 2017 when possible. Data from (Kähkönen et al., 2019; Swedish Forest Industries, 2020).

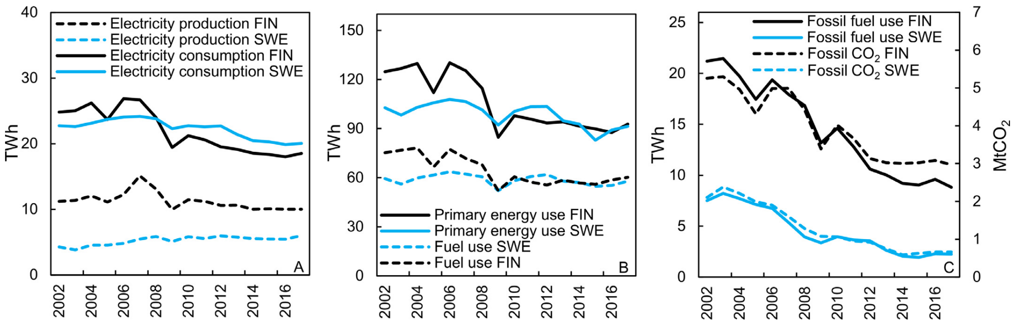

Fig. 2. Development of electricity consumption and production (A), fuels and primary energy use (B), and fossil fuels use and CO_2 emissions (C) in the Finnish and Swedish PPIs. Data from (Finnish Forest Industries, 2020a; Statistics Finland, 2020; Swedish Energy Agency, 2020; Swedish Forest Industries, 2020).

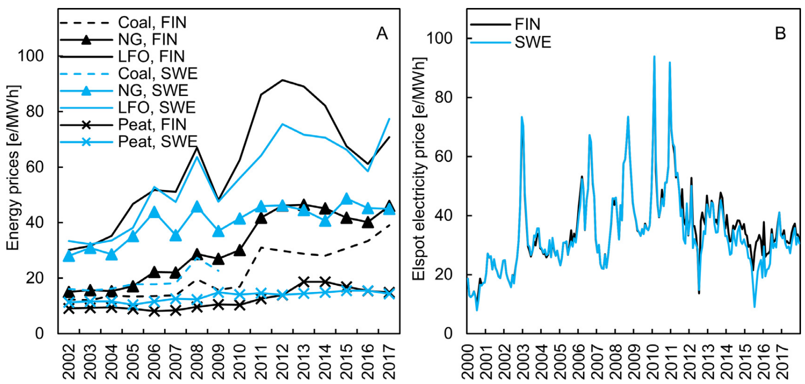

Fig. 3. Development of energy prices in Finland and Sweden: (A) fuel prices and (B) Nordpool electricity prices. Electricity prices do not include taxes. Data from (Nordpool, 2021; Statistics Finland, 2020; Swedish Energy Agency, 2020).

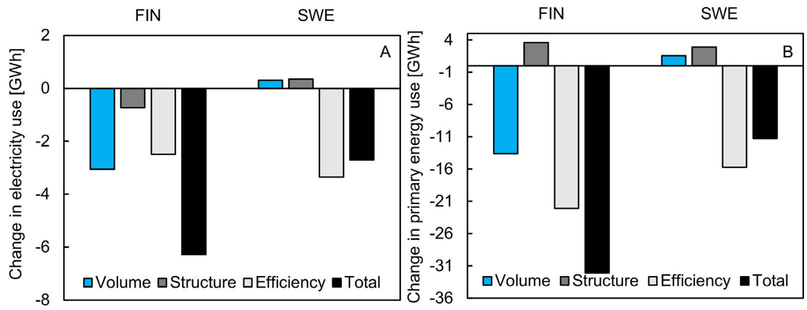

Fig. 4. Results of decomposition analysis for electricity consumption (A) and primary energy consumption (B) between 2002 and 2017.

ing 60 $kgCO_2$/ton in 2017. The values include only emissions from fossil fuel combustion in the mills. The Swedish PPI reported the lowest CO_2 emissions so far in 2014 (0.59 Mt). In Finland, the lowest value was in 2017 (2.97 Mt) but the value was practically unchangeable during the period of decreasing fossil fuel prices (2013–2016). In Finland, CO_2 emissions have not decreased as much as fossil fuel use because the share of natural gas has declined in the fossil fuel mix. The measures implemented to reduce CO_2 emissions in the Finnish and Swedish PPI are presented in more detail in Section 3.2.3.

Finland and Sweden belong to the same electricity market area, Nordpool, but due to limited border connection capacity, spot prices have been higher in Finland than in Sweden (Ministry of the Employment and the Economy, 2016). Moreover, the tax on electricity for industrial users is only 0.05 cents/kWh in Sweden whereas it has been 0.703 cents/kWh in Finland (Espensen et al., 2014). The Finnish PPI has been producing notably more electricity than the Swedish one, which can be explained at least partly by higher electricity prices. Between 2002 and 2017, the electricity production increased by 1.8 TWh (41%) in Sweden whereas in Finland, the electricity production decreased by 1.2 TWh (−11%). The electricity self-sufficiency increased from 45% to 54% in Finland and from 19% to 30% in Sweden. The electricity prices increased at the beginning of the 2000s due to electricity market reform in 1996 and the introduction of EU ETS in 2005 (Ericsson et al., 2011). It can be noted that electricity prices have affected the PPI's electricity production in Sweden. Between 2002 and 2010 electricity prices increased by 106% (Nordpool, 2021), and electricity production in mills increased on average by 3.3% per year during the period. The electricity prices decreased by 45% from 2010 to 2017 and during those years the growth rate for electricity production was only 0.4% per year. The increase in prices alone does not explain the growth in electricity production. The tradable renewable electricity certificate system (TRECS) that was introduced in 2003 has been a significant source of income for the Swedish mills that produce renewable electricity. The Finnish PPI has not been affected by the electricity price changes as strongly as the Swedish one. One explanation is most probably the historically high electricity production in Finland. The Swedish PPI had a target to increase its electricity production by 2 TWh from 2007 to 2020 (Swedish Forest Industries, 2012). After the period of stable electricity production, (Swedish Forest Industries, 2020) reported the annual electricity production of 6.6 TWh, which is 1.2 TWh more than in 2007. Thus, there has still been progress, but the target seems to be unreachable. Despite the decrease in electricity production in absolute terms in Finland, more electricity is currently produced per produced ton. One important explanation for that is a structural change. Capacity with a lower tendency to produce electricity, i.e. mechanical pulp and paper mills, have been closed whereas kraft pulp production has increased. In addition to structural changes, technology change has contributed to the increase in electricity production in both countries (Section 3.2.4).

3.2.1. Influence of volume, structure, and intensity on energy consumption

Changes in volume, structure, and intensity have contributed to changes in the energy consumption of the PPIs in Finland and Sweden, as Fig. 4 shows. From 2002 to 2017, electricity consumption decreased in both Finnish and Swedish PPIs by 6.3 TWh and 2.7 TWh, respectively. A similar trend was observed in primary energy consumption, which decreased 35.8 TWh and 11.3 TWh. Production volume declined by 13% in Finland, which explains the large drop in energy use. In Sweden, production increased by 1%.

The changes in the structure have slightly increased energy consumption in all cases excluding the electricity consumption in Finland. Between 2002 and 2017, the share of chemical pulp in the total pulp mix increased from 61% to 72% in Finland. As chemical pulping is a heat-intensive process and mechanical pulping relies mostly on electricity, the electricity intensity has decreased whereas the primary energy intensity has increased. Especially production of graphical papers has decreased notably in both countries whereas production of chemical pulp has increased significantly. In 2017, significantly more pulp was produced per ton of paper than in 2002. This has increased the export of pulp but also affected the energy demand by increasing the primary energy consumption. In addition, the energy intensity in Finland may have decreased as some mills changed from producing printing and writing paper to packaging materials. In Sweden, the most significant decrease was in the production of newsprint, which consumes less heat and electricity than the other paper grades. The share of newsprint in total paper production decreased from 23% to 10%. This change increased the electricity and primary energy intensity.

Energy efficiency improvement has played a major role in both countries. The decomposition analysis suggests that energy efficiency improvement led to a 10% and 15% decrease in electricity consumption between 2002 and 2017 in the Finnish and Swedish PPIs, respectively. The improved efficiency saved 20% and 15% of primary energy in Finland and Sweden.

3.2.2. Energy efficiency

Fig. 5 presents the development of energy efficiency in the Finnish and Swedish PPIs. The results suggest that the electricity efficiency has improved on average by 0.8% per year in the Finnish PPI and 1.0% per year in the Swedish PPI. The strike in

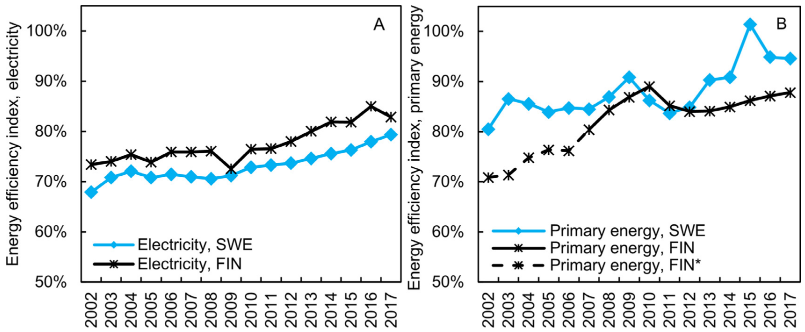

Fig. 5. Energy efficiency development in the Finnish and Swedish PPIs. Statistics Finland (2020) data was needed for calculating primary energy use that covers the years 2007–2017 in Finland. Years before that are constructed using data from (Finnish Forest Industries, 2020a).

2005 and the economic crisis around 2009 decreased the electricity efficiency in Finland. Many mills were shut down or switched to the part load, which reduced the overall efficiency. In 2016, there was a major leap upward in the electricity efficiency of the Finnish PPI, but the growth flattened only a year after that, thus the leap can probably be explained by a statistical error. Electricity efficiency has not followed energy prices as clearly as fuels use. Between 2002 and 2009, the electricity efficiency of the Swedish PPI improved 0.7% per year and between 2009 and 2017 twice that much, 1.4% per year. As electricity prices peaked around 2010, the development can be considered somewhat unexpected. However, especially large energy efficiency investments take time, and thus the effect of energy prices is challenging to assess.

The energy efficiency index method is less applicable for analyzing primary energy use. There are typically problems with data quality and for example, mill-specific energy conversion factors are unknown. Moreover, the used method considers only the input energy, and therefore mills with excess energy have a lower primary energy efficiency index. The produced energy should be considered, but it was not possible due to a lack of data. The primary energy efficiency development in Sweden has fluctuated notably. It was found that some mills have probably not reported correctly all their values every year, which is the main explanation for the fluctuation. Despite the data issues, it can be argued that the primary energy efficiency has increased in both countries.

Voluntary energy efficiency improvement programs have played a role in the energy efficiency improvement in both countries. Sweden introduced the program for improving energy efficiency (PFE) in 2005. The PFE offers electricity tax exemption to energy-intensive industries that commit to improving their energy efficiency (Stenqvist, 2013). In 2007, participating companies covered 85% of the electricity demand of all eligible companies (Stenqvist and Nilsson, 2012). Between 2004–2009, pulp and paper industries reported an annual electricity saving of 670 GWh (Ericsson et al., 2011), which is evidence of the success of the program. The PFE ran for ten years, after which it was ended in 2014 because energy tax exemptions below the EU minimum were no longer accepted by the EU. The Finnish PPI has been participating in the voluntary Energy Efficiency Agreements program since 2008 (Energy efficiency Agreements, 2020). All pulp and paper companies except one minor operator are involved in the program. After the first period of the program (2008–2016), the PPI reported a decrease of 5233 GWh in annual energy consumption (inc. heat, electricity, and fuels) (Motiva, 2017).

3.2.3. CO_2 reduction

Fossil CO_2 emissions decreased by 2.29 $MtCO_2$/a and 1.44 $MtCO_2$/a in the Finnish and Swedish PPIs from 2002 to 2017. Decrease in energy demand, i.e. improved efficiency, mill closures, etc., led to lower demand for fossil fuels, but also fuel switching played an important role. Currently, the Swedish mills cover their energy demand by combusting biomass or purchasing electricity. In Finland, fossil fuels are used in energy production, but significantly less than at the beginning of the 2000s. The combustion of peat in multifuel boilers decreased by 9.4 PJ (−54%) between 2002 and 2017, and many mills have stated an aim to increase further the share of biomass. Natural gas is still used for steam generation, but the use decreased by 29.4 PJ (−69%). Switching fuels in lime kilns has contributed to the CO_2 emissions reduction. The Swedish mills started to replace fossil fuels earlier than the Finnish ones, and currently, most of the lime kilns in Sweden combust biomass. In Finland, a notable number of mills still combust oil or natural gas, but there has been significant progress during the 2010s. Metsä fibre invested in biomass gasifiers. The Joutseno mill started to replace natural gas in the lime kiln in 2013 with producer gas, which was estimated to decrease CO_2 emissions by 60,000 tCO_2/a (Seppälä, 2010). The Äänekoski mill does not emit fossil CO_2 at all for it covers the fuel demand of the lime kiln with its large gasifier (85 MW). Stora Enso has put efforts into fuel switching in several mills. Sunila mill has combusted lignin as the main fuel since 2015 (Regional State Administrative Agency, 2014). Before the renovation, the lime kiln accounted for 85% of fossil CO_2 emissions in the mill. Enocell mill started to replace oil with sawdust in 2015. The estimated oil saving is 70–90 t/d (Stora Enso, 2017). Pitch oil (~119 GWh/a) is the main lime kiln fuel in the Oulu mill (Regional State Administrative Agency, 2020). Hydrogen (~51 GWh/a) from nearby chemical products facilities is combusted as well. Varkaus mill has replaced the most (80 GWh/a) of oil with producer gas since 2012 (Regional State Administrative Agency, 2015). UPM has implemented decarbonizing measures as well. Pietarsaari mill started decarbonization of the lime kiln early introducing a gasifier (35 MW) in 1983, but currently, the main fuel is pitch oil (Regional State Administrative Agency, 2017; UPM, 2009).

3.2.4. Producing additional renewable energy

As important producers of kraft pulp, Finland and Sweden have a large recovery boiler capacity. In 2017, the total capacity was 44,560 tds/d and 48,820 tds/d in Finland and Sweden. The average Finnish boilers are newer and bigger than the Swedish ones. Corresponding to the higher electricity production, the Finnish boilers

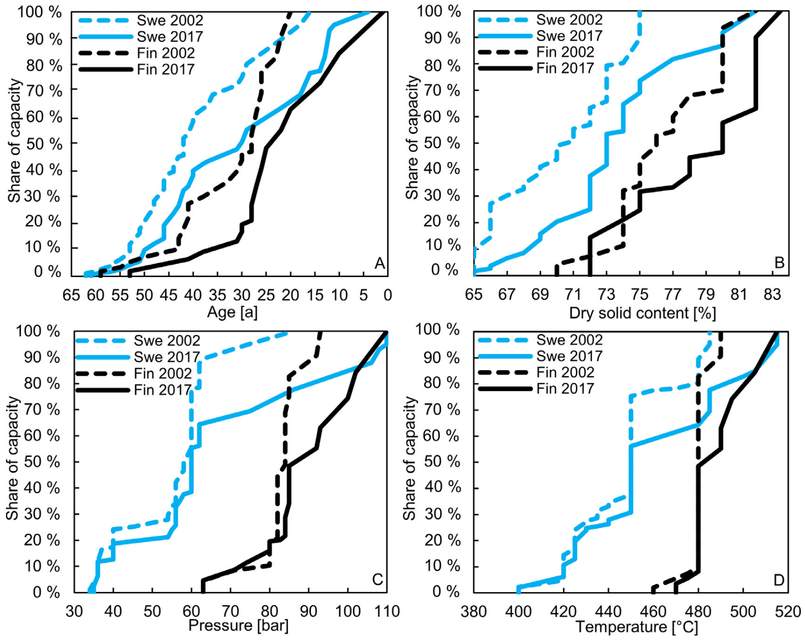

Fig. 6. Properties and development of the Swedish and Finnish recovery boilers: age (A), dry solids content (B), steam pressure (C), and steam temperature (D).

operate with higher steam parameters and dry solids contents. The difference has been attributed to traditionally higher electricity prices and therefore more willingness during the early 1990s to invest in electricity generation in Finland. The development tendencies of recovery boilers in Finland and Sweden (Fig. 6) provide an illustrative example of ongoing technological change, which promotes sustainable operation. The average capacity of the boilers increased from 1214 tds/d to 1627 tds/d in Sweden and from 1706 tds/d to 2621 tds/d in Finland between 2002 and 2017. Steam parameters have increased as well. In Sweden, the average steam temperature increased from 440 °C to 463 °C and steam pressure from 51 bar to 69 bar. In Finland, the increases were from 481 °C to 491 °C and from 83 bar to 91 bar. In addition to steam parameters, a high dry solids content of black liquor (low amount of moisture) enables increased steam production. The dry solids content increased from 69% to 74% in Sweden and from 77% to 79% in Finland.

The increase in the parameters somewhat correlates with the age of recovery boiler. Old boilers with low parameters have been stopped and renovated, and modern boilers have been built. However, as boilers of the same age operate with rather different parameters in Finland and Sweden, age of the boiler does not fully explain the development, but also strategic decisions of companies have played a role. Between 2002 and 2017, 11 recovery boilers stopped operation in Sweden and 8 in Finland. For the stopped boilers, average values for steam temperature, pressure and dry solids content of black liquor were relatively low in comparison to new mills: 448 °C, 55 bar, 68% in Sweden and 479 °C, 82 bar and 75% in Finland. However, the development of parameters was low until 1990s after which there has been significant progress. New boilers operate with high capacity and/or high steam parameters. The recovery boiler in Äänekoski, which is the newest boiler in Finland, is the biggest in the northern hemisphere at 7200 tds/d and can produce over 1 TWh/a of excess, sellable electricity (IRENA, 2018). Several recent Swedish recovery boilers have high pressures and temperatures. Obbola, Östrand, Iggesund, and Skoghall were built between 2005 and 2015, and they all operate with pressures higher than 100 bar and temperatures higher than 500 °C. In addition to new or renovated recovery boiler capacity, the Swedish mills invested in new back-pressure turbines to increase electricity production.

4. Discussion

The results of this study indicate that the Finnish and Swedish PPIs have successfully evolved toward green and energy-efficient operation in the 21st century. Significant progress was achieved in energy efficiency, fuel switching, and renewable electricity production, and hence in CO_2 emissions reduction. In addition to direct emissions presented in this study, industry-related transportation and externally generated electricity causes emissions. Thus, to achieve the actual deep decarbonization of the sector, those emissions must be addressed as well. Moreover, the reduction of fossil CO_2 emissions represents only one aspect of sustainable operation. A comprehensive analysis would require consideration of additional perspectives such as other emissions, impacts on environment and human health, e.g. (Ahmed et al., 2021; Tun et al., 2021), but this was outside the scope of this study.

Energy efficiency improvement in the Finnish and Swedish PPIs indicates that the sector has untapped energy efficiency improvement potential worldwide. Many previous studies have found energy saving possibilities as well e.g. (Fleiter et al., 2012; Klugman et al., 2007; Kong et al., 2013; Peng et al., 2015). Realizing the potential is a cost-effective way to reduce both energy use and CO_2 emissions, and thus governments should encourage the PPI to improve energy efficiency. Examples of Finland and Sweden suggest that voluntary agreements on energy efficiency can be successful. However, market-related public policy instruments cannot overcome firm-specific factors barriers, such as lack of time or awareness (Thollander and Ottosson, 2008). Even though the energy efficiency improvement in the Finnish and Swedish PPI was notable, more efforts should be put on in the future as the EU EED calls for saving of 1.5% in final energy consumption each year from 2024 to 2030 (European Commission, 2021b). The advanced decarbonization of the PPI requires fuel switching in addition to energy efficiency improvement. Many Finnish and Swedish mills do not need fossil fuels during normal operation, and thus the fossil-free operation is technically feasible. The results suggest that fossil fuel use has followed closely energy prices. Taxes on energy can be an important driver for fuel switching, but governments must be aware that too ambitious decarbonization may force companies to move their production to countries with lower production costs, which can lead to carbon leakage and an increase in global CO_2 emissions. Finland and Sweden have maintained their position as important pulp and paper producers despite the heavy taxation. The PPI has the potential to produce significant amounts of green electricity. The results provide evidence that national renewable energy policies can produce an increase in industrial renewable energy production and consumption. The green electricity certificate system together with increased electricity prices had a major role in increased electricity production in the Swedish mills.

The CO_2 reduction potential can be roughly estimated by comparing the performance of Finland and Sweden to Europe. The Confederation of European Paper Industries Confederation of European Paper Industries (CEPI), 2019 representing 92% of the European PPI emitted 32.2 $MtCO_2$ of direct fossil CO_2 emissions in 2017, which corresponds to emission intensity of 303 $kgCO_2$/ton of product (inc. paper and market pulp) Confederation of European Paper Industries (CEPI), 2019. The emission intensity of the Finnish and Swedish PPI was 132 $kgCO_2$/ton of product in the same year. If the CEPI countries could reach the same emission intensity as Finland and Sweden, emissions of the EU27 including the UK would decrease by 18.2 $MtCO_2$/a. The estimate is rough and does not consider important factors such as the effect of sector structure but it, however, highlights the existing improvement potential.

Resource availability and sector structure affect the decarbonization possibilities of different countries. The models of the Finnish and Swedish PPIs do not apply to every country but show that substantial improvements in energy utilization can be achieved. An example of a paper producer that differs drastically from Finland and Sweden is the Netherlands that produces more than 80% of paper from recycled fibers and meets the energy demand by generating heat and electricity from natural gas, which covers 97% of the fuel mix (Laurijssen et al., 2012). The recycling rate of paper is high in Finland and Sweden as well, but as over 90% of the produced paper is exported, the recycled fibers cannot play a major role. The business environment of the Finnish and Swedish PPIs is relatively similar: both countries have abundant biomass resources and comparable sector structures. The lack of domestic fossil fuel resources has accelerated the transition to renewable energy sources. The large production of kraft pulp provides a possibility to generate bioenergy. Despite the similarities, there have been differences in the energy transition in the PPIs of Finland and Sweden, which highlights the fact that every country needs different solutions and policy measures for aiming towards a more sustainable operation. Development and future decarbonization possibilities in other PPI countries should be addressed in future studies.

Global annual demand for paper is expected to increase from current 400 Mt to 700–900 Mt in 2050 (Moya and Pavel, 2018), and thus energy efficiency improvements as well as sustainable energy sources are highly needed. Even though this study focused on the energy utilization, the PPI has the potential to contribute to the mitigation of CO_2 emissions not only by reducing its fossil fuel consumption but also by producing biofuels and biomaterials that can substitute fossil-based alternatives and act as carbon storages. Furthermore, pulp mills are an attractive platform for bioenergy with carbon capture and storage or utilization (BECCS/U) and thus provide a possibility for negative CO_2 emissions. BECCS/U could enable reaching a carbon-neutral PPI in the countries where advanced decarbonization has already taken place. The production of new bioproducts and BECCS/U can reduce CO_2 emissions substantially but as neither is yet widely practiced the actual impact is still unclear. Hence, PPI's portfolio of tools for combatting climate change is large: energy efficiency improvement, fuel switching, production of green energy, biofuels and biomaterials as well as carbon capture. However, the structure of the sector and energy mix vary from the country to country, and thus needed tools for decarbonization dependent on the location of the mill.

5. Conclusions

The PPI has responded to the need for energy transition by improving energy efficiency, switching to bio-based fuels, and increasing on-site renewable electricity production. The transition towards more sustainable operation is important for achieving global as well as regional CO_2 reduction targets and maintaining the competitiveness of the sector. Finland and Sweden as forerunners of decarbonizing the PPI have increased the share of biofuels in their fuel mix to 85% and 96% by 2017 by improving energy efficiency and replacing fossil fuels in the lime kilns and power boilers with bio-based alternatives. Electricity and primary energy consumption in the PPI decreased substantially in both countries between 2002 and 2017. Changes in volume and structure of the production affected the energy consumption, but the energy efficiency improvement was responsible for the largest saving. Production of green electricity increased significantly in Sweden due to increased electricity prices and a renewable electricity certificate system.

The development of the Finnish and Swedish PPIs proves that even though the PPI is energy-intensive, it can achieve low fossil CO_2 emissions, at least in countries with vast forest resources. Finland and Sweden have traditionally been efficient operators, but they were still able to improve the efficiency of PPI substantially in the 2000s, which indicates that also other PPI countries have significant improvement potential. The decrease in CO_2 emissions stagnated in both countries around 2013 due to low energy prices despite the countries' ambitious objectives to reach carbon neutral operation. It is a question of future research to investigate how the Finland and Sweden as well as other PPI producers can keep on proceeding towards deep decarbonization maintaining their competitiveness at the same time.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Production volumes

Table A.1.

Table A.1
Production volumes disaggregated by type of paper in the Finnish and Swedish pulp and paper industries between 2002 and 2017. Data from Food and Agriculture Organization of the United Nations (FAO), 2019.

Finland								
Year	Mechanical and semi-chemical pulp	Chemical pulp	Printing and writing papers	Newsprint	Other papers	Household and sanitary papers	Wrapping and packaging papers	Recovered paper
2002	4.59	7.14	8.08	1.01	0.35	0.15	3.20	0.70
2003	4.60	7.35	8.32	0.95	0.34	0.15	3.30	0.69
2004	4.83	7.78	9.47	0.72	0.32	0.18	3.35	0.74
2005	4.36	6.77	8.30	0.52	0.26	0.16	3.16	0.60
2006	5.17	7.95	9.21	0.58	0.34	0.20	3.86	0.73
2007	5.16	7.70	9.22	0.55	0.35	0.21	4.01	0.74
2008	4.47	7.16	8.33	0.50	0.35	0.17	3.78	0.72
2009	3.30	5.52	6.72	0.14	0.30	0.14	3.31	0.54
2010	3.78	6.73	7.27	0.20	0.36	0.15	3.78	0.58
2011	3.61	6.75	7.05	0.28	0.33	0.16	3.52	0.58
2012	3.41	6.83	6.37	0.25	0.47	0.15	3.61	0.57
2013	3.45	7.07	6.12	0.19	0.24	0.24	3.80	0.63
2014	3.46	7.01	5.81	0.28	0.25	0.25	3.82	0.61
2015	3.32	7.13	5.65	0.27	0.25	0.25	3.91	0.61
2016	3.46	7.46	5.21	0.30	0.24	0.24	4.15	0.55
2017	3.14	7.96	5.12	0.30	0.62	0.62	3.62	0.64

Sweden								
Year	Mechanical and semi-chemical pulp	Chemical pulp	Printing and writing papers	Newsprint	Other papers	Household and sanitary papers	Wrapping and packaging papers	Recovered paper
2002	3.30	8.05	2.81	2.42	0.11	0.30	5.08	1.47
2003	3.50	8.24	2.82	2.55	0.12	0.30	5.28	1.49
2004	3.69	8.42	3.03	2.65	0.13	0.31	5.47	1.50
2005	3.74	8.37	3.12	2.57	0.16	0.32	5.61	1.57
2006	3.77	8.64	3.41	2.54	0.14	0.32	5.66	1.53
2007	3.94	8.65	2.99	2.55	0.12	0.32	5.54	1.57
2008	3.83	8.24	3.26	2.56	0.12	0.33	5.39	2.02
2009	3.60	7.87	3.01	2.20	0.12	0.34	5.27	1.86
2010	3.82	8.05	3.26	2.26	0.10	0.35	5.45	1.84
2011	3.85	8.01	3.35	2.12	0.06	0.35	5.42	1.50
2012	3.85	8.19	3.43	2.01	0.06	0.36	5.55	1.33
2013	3.52	8.20	3.28	1.56	0.06	0.35	5.54	1.24
2014	3.26	8.28	3.07	1.26	0.06	0.35	5.68	1.16
2015	3.30	8.32	2.87	1.20	0.06	0.36	5.78	1.21
2016	3.28	8.54	2.59	1.02	0.06	0.36	6.07	1.16
2017	3.41	8.75	2.58	1.01	0.07	0.36	6.24	1.16

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Impact of Structural Changes on Energy Efficiency of Finnish Pulp and Paper Industry

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Abstract: A key challenge in prevention of global warming is how to increase energy efficiency, to be able to deal with increased fossil CO_2 emissions from rising energy usage. Increasing energy efficiency will decrease energy usage and is in a key role in emission mitigation. The focus is the pulp and paper industry, which is energy-intensive. Development of industrial energy efficiency has been studied before but the role of industrial transformation is still mostly unknown. The knowledge must be improved, to be able to predict future developments in the most effective way. In this research, impact of various production unit closures and start-ups on energy efficiency of the Finnish pulp and paper industry were studied utilizing statistical analysis. Results indicate that about 20% of the Finnish pulp and paper industry energy efficiency improvement between 2011 and 2017 is caused by the major structural changes. The rest, 80% of the progress, was mainly due to improved technology and more optimal operational modes. Additional findings suggest that modern mill start-ups have a significantly greater potential to reduce energy consumption than old mill closures.

Keywords: energy efficiency; pulp; paper; energy consumption; structural change

1. Introduction

World energy usage increases as a result from global population growth and increasing level of wellbeing [1]. Energy supply security, reduction of greenhouse gas emissions, and efforts to reduce global warming are the main issues acting as a driving force for changing our present energy usage [2]. Energy efficiency improvement has an important role in the cost-effective energy saving and in the sustainable development [3]. Energy efficiency means an ability to produce a high number of products with as low an amount of energy as possible. In addition to environmental advantages, enhancing energy efficiency lowers operating costs and consequently improves competitiveness [4]. Of the various sectors, industry was the largest energy consumer in the world in 2016: its share was about 30% of total consumed energy [5]. Therefore, significant results can be reached by improving industrial energy efficiency [6,7].

In Finland, industry and construction consumed 47% of total electricity in 2015 [8]. Inside the field of Finnish industry, forest industry was clearly the major consumer [9]. Production of pulp and, subsequently, paper requires significant amounts of energy. A high number of factors affect the energy consumption of pulp and paper industry mills, such as the type, size, age, and location of the mill, type of products, raw materials, and processes, as well as operational choices [10]. Even if energy consumption is measured to sufficient accuracy, evaluating the role of various changes to energy efficiency is challenging. Many factors have an influence on energy efficiency, but in many cases the size of the impact is unknown. By enhancing awareness about affecting factors, it is possible to develop mills and processes in an efficient way towards energy efficient operation. Several studies have been done relating energy efficiency measurement and improvement on industry [11–17]. Mostly, they concentrate on finding relevant energy intensity values [18,19]. Less attention has been paid to the effect of structural changes, i.e., retirements and additions of capacity.

The aim of this work is to study the impact of structural changes on energy efficiency of Finnish pulp and paper industry. EU (European Union) and IPPC (Integrated Pollution Prevention and Control) have called for intensification of energy usage [9]. At the same time, the business environment of pulp and paper industry is rapidly changing, and consequently pulp and paper industry has gone through a large structural change. Pulp and paper industry has been forced to implement notable changes to operate in a profitable way despite the challenging business environment. The demand for printing and writing paper is decreasing in EU, whereas an increasing amount of packaging materials is needed [20]. Thus, production grades are changing. Many mills have or are planning to enlarge their product portfolio towards new bioproducts, such as biofuels and biomaterials [21]. The major changes seen in Finland have been old unit closures, new unit start-ups and conversions of paper mills to products with increased demand, such as paperboard. It can safely be assumed that neither closed and nor started units have an average energy efficiency. Therefore, this study focuses on the effect of closures and start-ups on the pulp and paper industrial energy efficiency.

This paper consists of five parts. Section 2 introduces Finnish pulp and paper industry, especially developments in its production and energy consumption. Section 3 presents research methods and data gathering process. Results are shown in Section 4. Section 5 is discussion that considers received results. Finland was chosen as the target country of the research. It belongs to the major forest industry countries and the structural change has been significant in the past decade. The study is executed as a scenario analysis. Mill energy consumption data, gathered from various sources, is used for creating three scenarios, which are compared. The study focuses on energy aspects and for example economic measures are excluded.

2. Finnish Pulp and Paper Industry

Two-thirds of Finland is covered by forests [22]. Due to the ample resources Finland is one of the most important countries for the forest industry in the world. Forest industry was the second-largest employer in Finland in 2017 with 42,000 employees and accounting about 20% of both gross value of manufacturing and export [23].

Pulp and paper industry consumes most of the energy the forest industry uses. Mechanical forest industry is much less energy intensive. Its main products are sawn wood and wood-based panels. New forest industry bioproducts such as pellets, biogas, or biofuels are still of small volume. Wood pulp is the main virgin fiber material of paper. Also recycled or non-wood fiber is used. Chemical pulp is produced using sulphate process, sulphite process or other minor pulping processes. These processes are based on separating lignin from wood fibers by using alkaline chemicals in cooking. 80% of pulp produced in the world is produced by sulphate process [24]. In Finland, the sulphite process has not been used since 1992 [22]. Mechanical pulping consists of a grinding and refining processes, which utilizes mechanical energy to separate wood fibers. Many pulping processes accounted for as mechanical pulping are actually combinations of chemical and mechanical stages. Pulps produced by different processes have various properties and manufacturing costs. In addition to chosen process, properties are affected by treatment of fiber after pulping, such as bleaching. Paper is made in a paper machine that consists of forming, pressing, and drying sections. Different finishing processes like calendaring and coating can be utilized to achieve needed paper properties. The major paper grades are packaging papers and paperboards, printing and writing papers, and tissue papers.

2.1. Production

The major products of Finnish forest industry are pulp, paper, and mechanical forest industry products such as sawn wood and wood-based panels. In addition, a wide range of bioproducts is produced. Between 2010 and 2017, production of pulp and mechanical forest industry products has increased 336,000 tons and 2,350,000 m^3, respectively [20,25]. Paper production has been declining and in 2017 paper production was 1,462,000 tons lower than in 2010 [20]. Finland is an important exporter of pulp and paper products [26]. Exported pulp and paper were 3.7 million tons and 10 million tons in 2018, respectively [20].

Finnish forest industry has gone through a large structural change, which has modified product portfolios and production rates. Table 1 shows production volumes at the beginning and end of the decade. Production of printing and writing paper has decreased following the global trend. A main factor is the lowered demand for newsprint and magazine paper as a result from online publications. The production of paperboard has instead increased. As the level of wellbeing, especially in Asia, has risen, the demand for pulp and paper is increasing there [10]. Higher global pulp demand and favorable prices have increased chemical pulp production in Finland [26].

Table 1. Pulp and paper production in Finland in 2010 and 2017. Data from [20].

Grade	2010 (1000 t/a)	2017 (1000 t/a)	Change (%)
Paperboard	2830	3622	33
Other paper	1462	1232	−4
Printing and writing paper	7466	5422	−26
Chemical pulp	6733	7703	14
Mechanical and semi-chemical pulp	3775	3141	−13

Finnish pulp and paper industry consists currently of 17 paper mills, 14 paperboard mills, and 18 pulp mills [23]. Only few stand-alone pulp mills produce dried pulp that is delivered to paper mills. Over 80% of the pulp, as well as over 90% of the paper, is produced in integrated mills, as can be seen in Table 2. Integrated mill means that both pulp and paper are produced at the same site. Integration rate affects significantly the energy usage and the energy efficiency. Integrated mills produce pulp more energy efficiently than stand-alone mills, because they have no need for pulp drying and re-pulping and secondary heat can be used to preheat water needed in the paper machine. Practically all mechanical and recycled pulp units in Finland are integrated with a paper mill.

Table 2. Division of pulp and paper production in Finland. Elaborated from [9].

Category	Share of Pulp Production (%)	Share of Paper Production (%)
Bleached chemi-thermomechanical pulp	4	-
Integrated recycled pulp and paper	2	3
Stand-alone chemical pulp	13	-
Stand-alone paper	-	6
Integrated mechanical pulp and paper	20	35
Integrated chemical pulp and paper	60	55

2.2. Energy Usage

Finnish forest industry consumed 19.7 TWh electricity in 2017, which is about one fifth of Finnish total electricity consumption [8]. Total energy consumption in Finland was 1352.3 PJ in 2017 [27]. Forest industry used 217 PJ fuels [8], which is a significant share of the total fuel usage. Forest industry is renewable-intensive, and it accounts for 45% of production and consumption of Finnish bioenergy [10]. During the 2010s, consumption of primary energy decreased only 0.3% Fuel consumption development towards fossil fuel-free operation is a significant change. The share of biofuels increased from 76% to 85% whereas the share of fossil fuels (natural gas, heavy fuel oil, and coal) decreased from 17% to 10%. Primary energy consumption in 2010 and 2017 is presented in Table 3.

Table 3. Primary energy consumption of Finnish forest industry in 2010–2017. Elaborated from [8].

Primary Energy Usage (1000 TJ)	2010	2017	Change
Biofuels, liquid	13,534	14,984	11%
Biofuels, solid	29,787	35,468	19%
Natural gas	30,820	13,248	−57%
Peat	12,649	7875	−38%
Heavy fuel oil	6217	5454	−12%
Coal	1048	2536	142%
Others	1910	2685	41%
Total	217,774	217,115	−0.3%

Table 4 presents electricity consumption development of Finnish forest industry in 2010–2017. Data utilized in the table is presented in Supplementary material. Pulp and paper industry consumes over five times more electricity than mechanical forest industry and production of bioproducts combined. That is because chemical forest industry utilizes processes with a high energy-intensity. On the other hand, chemical pulp mills produce a lot of energy from the combustion of their sidestreams. Modern pulp mills are able to produce much more heat and over double the electricity than their processes require [28]. The surplus energy can be sold. In addition to electricity consumption, pulp and paper industry is a significant heat consumer. It is challenging to study the heat consumption of Finnish forest industry. Mills do not record or inform their heat consumption precisely because heat is not as valuable a product for mills as electricity. Therefore, this paper does not present development of heat consumption for the lack of data, but heat saving due to structural changes will be calculated.

Table 4. Electricity consumption of Finnish forest industry in 2010 and 2017.

Electricity Consumption (GWh)	2010	2017	Change	Share of Total Consumption in 2017
Bioproducts	382	667	74%	3%
Mechanical forest industry	956	1138	19%	6%
Pulp and paper	20792	17819	−17%	91%
Total	22130	19624	−13%	

Finnish forest industry electricity consumption has been slightly decreasing during the last decade. The annual electricity consumption has decreased during 2010–2017 by 2506 GWh. Reduced production of paper has decreased electricity use. At the same time, the higher amounts of bioproducts, pulp, and mechanical forest industry products have increased the total electricity consumption. In addition, changes in the end products have affected the energy consumption. The part of the electricity consumption that is not attributed to production changes can be assumed to be caused by energy efficiency improvements.

Available high-quality data restricts the reviewed period to 2011–2017. Only electricity consumption statistics, including consumption of the total forest industry, are available [8]. Therefore, the consumption of pulp and paper industry must be calculated. The most accurate way for defining electricity consumption of pulp and paper industry is to subtract electricity consumptions of mechanical forest industry and bioproducts manufacturing from the total consumption. The electricity consumption (Figure 1) is estimated using several sources, which are introduced in Supplementary material. Annual electricity usage was 2336 GWh higher in 2011 than in 2017. A significant reason for electricity consumption decrease is the reduction of production rate and evolved product palette. Even if the chemical pulp production has increased, the paper production has decreased more, and consequently total electricity usage is currently lower than at the beginning of the decade. Based on gathered production data (Supplementary material) and typical electricity consumption values [29], the decrease caused by lower production rates and changed products is 1004 GWh (~5%). Therefore, an approximate

1332 GWh (~7%) decrease must be attributed to other reasons. The major factor for this decrease has been the energy efficiency improvement.

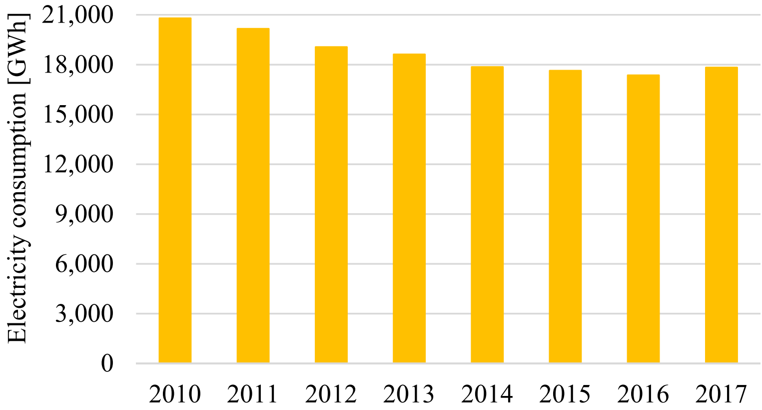

Figure 1. Pulp and paper industry electricity consumption in 2011–2017.

2.3. *Structural Changes*

Structural changes have been manifested in unit closures, unit start-ups and unit conversions to produce more profitable grades [9,29,30]. Changes in demand have led to significant reductions in pulp and paper production capacity [31]. In addition to whole mill closures and start-ups, major capacity increases and single machine upgrades have been taken into account in this study. In cases of conversions, old product is counted as a closure and new product is counted as a start-up. Table 5 presents closures during reviewed period. Paper production capacity removals have been 2,600,000 tons. Pulp capacity closures account to 530,000 tons. The largest wave of closures has occurred in printing and writing paper mills.

Table 5. Unit closures in Finland in 2011–2017 [9].

Unit	Capacity Decrease (t/a)	Product	Year of Closure
Myllykoski (UPM)	600,000	Magazine paper	2011
Myllykoski (UPM)	213,000	Groundwood	2011
Ääneskoski (M-Real)	200,000	Fine paper	2012
Rauma (UPM)	245,000	Magazine paper	2013
Veitsiluoto (Stora Enso)	190,000	Magazine paper	2014
Lohja (Loparex)	68,000	Other paper	2014
Kaukas (UPM)	270,000	Magazine paper	2014
Jämsänkoski (UPM)	270,000	Magazine paper	2014
Kauttua (Jujo Thermal)	10,000	Other paper	2015
Varkaus (Stora Enso)	285,000	Fine paper	2015
Kotka (Kotkamills)	185,000	Magazine paper	2016
Tervasaari (UPM)	100,000	Other paper	2016
Kyrö (Metsä Board)	105,000	Other paper	2016
Kyrö (Metsä Board)	74,000	Groundwood	2016
Äänekoski (Metsä Fibre)	500,000	Chemical pulp	2017

Table 6 shows the start-ups during reviewed period. During the 2010s, significant forest industry investments have been made in Finland: Reforms mainly concern enlargements in chemical pulp and paperboard production, but also biofuel mills have been built [32]. The increased demand for paperboard can be seen in the table. The number of unit start-ups is lower than the number of unit closures. There are three mills that were converted to produce paperboard, one totally new pulp mill, and three mills with a significant capacity growth. The capacity increase of paper and pulp has been 880,000 tons and 1,570,000 tons, respectively.

Table 6. Unit start-ups in Finland in 2011–2017 [9].

Unit	Capacity Increase (t/a)	Product	Year of Start-Up
Simpele (Metsä Board)	80,000	Paperboard	2011
Imatra (Stora Enso)	20,000	Paperboard	2015
Varkaus (Stora Enso)	380,000	Paperboard	2015
Kymi (UPM)	170,000	Chemical pulp	2015
Kotka (Kotkamills)	400,000	Paperboard	2016
Äänekoski (Metsä Fibre)	1,300,000	Chemical pulp	2017
Kymi (UPM)	100,000	Chemical pulp	2017

3. Methods

In this study, a method for analyzing structural energy efficiency changes was developed. Utilizing the method required gathering a high amount of individual mill energy consumption data from various sources. Both electricity and heat consumption data were gathered, verified, and analyzed.

3.1. Statistical Analysis

The study was executed as a statistical analysis. We derived energy utilization for Finnish pulp and paper sector as reference scenario one. Two additional energy consumption scenarios were made. The second scenario assumes that no units were closed but new ones were started. The third one assumes no new units were started but old ones were closed. Yearly production of all grades in each scenario was kept constant. Used method is presented step by step in Figure 2. Firstly, mills' heat and electricity consumption data, as well as mills' production rates, were collected and validated. To facilitate product division, all mills were categorized to groups introduced in Table 7. Mills' heat and electricity consumptions were decomposed to different products to enable comparing similar products. Energy consumptions of closed and started mills were compared with average existing ones. The average existing mill was defined using consumption values of at least five Finnish pulp and paper industry mills producing similar products as certain changed mill. Changes in energy consumption were calculated by assuming that average mills would replace the production of changed mills. Mills never operate with full capacity during the whole year due to maintenance stoppages etc. Calculations are done utilizing production rates 85% of the maximum capacity. Finally, obtained yearly energy consumption values were compared with statistical values.

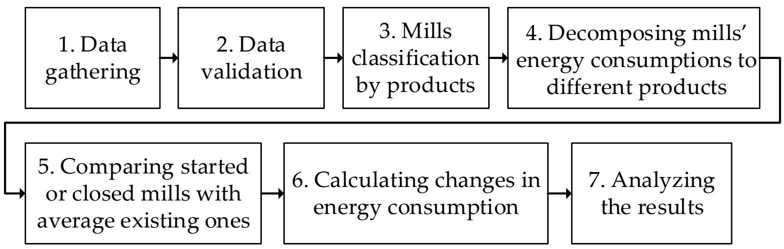

Figure 2. Utilized methodology step by step.

Table 7. Pulp and paper categorization groups.

Pulp	Paper
Chemical pulp	Paperboard
Groundwood	Magazine paper
Refiner	Fine paper
Semi-chemical pulp	Other paper
Chemi-mechanical pulp	
Recycled pulp	

Many Finnish mills are integrated, which makes evaluating energy consumption challenging. Mills reports usually the consumption of the whole mill, and therefore the consumption must be divided to different processes and products. The total energy consumption consists of the sum of consumption of every pulp and paper grade produced in the same mill:

$$E_{tot} = \sum_{i=1}^{n} P_i \cdot e_i \tag{1}$$

where E_{tot} is total energy consumption of the mill, P_i is production rate of the product and e_i is a weighting factor. The weighting factor is a typical specific energy consumption of the product. To be able to divide the consumption values to different pulp and paper grades, weighting factors presented in Table 8 are utilized.

Table 8. Weighting factors for dividing consumptions for different products. Data from [29].

Grade	Electricity Consumption (GJ/t)	Heat Consumption (GJ/t)
Chemical pulp	2.4	11.2
Groundwood	6.5	0
Refiner	5.5	−2.4
Semi-chemical pulp	1.6	3.6
Recycled pulp	1.4	0.2
Magazine paper	2.5	4.6
Fine paper	3.1	4.9
Fluting	1.2	5
Paperboard	2.4	5.6
Newsprint	2.1	4.7
Other paper	2.5	7.5

3.2. Data Gathering

Verifying and analyzing the results requires gathering reliable heat and electricity consumption data from every Finnish pulp and paper mill. In addition, the products and production rates of every mill must be known. The focus was on closed and started mills and mills similar with changed ones. Finding energy consumption data is difficult because most companies like to keep their consumption and production values as a trade secret for commercial purposes. A high number of sources, mainly environmental reports and permits, university theses dealing with energy use of individual mills, articles, and other publications, were utilized for assigning heat and electricity production and consumption values for each mill and each product. Gathered data and sources are presented in Supplementary material. Most of this work was started in a project for the Finnish Ministry of Environment [30]. Annual production rates for 2011–2017 were obtained from Finnish Forest Industries [33]. Occasionally, there was a high statistical difference with some of the values when compared with other similar mills. Clearly incorrect values were left out of the study or corrected to more reasonable ones.

Gathering statistical data includes known sources of error. Mills do not necessarily measure and report their production and consumption values in a same way and the measurement devices and practices can be different. In addition, specific energy consumption in a certain mill varies significantly, for example due to capacity utilization rate or climate conditions (winter/summer). Some gathered values were reported several years ago which also increases the possibility of errors. However, utilization of individual mill values instead of statistical averages allows one to study the structural changes.

4. Results

Calculated results are shown in Figure 3a,b. Positive values define years with electricity or heat energy savings due to structural changes. Negative values indicate years when average of existing mills have been more energy efficient than started mills or less efficient than closed mills, and therefore the total energy consumption has increased. Figure 3a presents the impacts of unit closures on heat and electricity consumption. Heat is saved every year excluding 2013 when only one, relatively energy-efficient, paper machine was closed. Between 2015 and 2017, heat was saved but electricity consumption increased somewhat. Total heat and electricity savings due to closures were 193 GWh and 109 GWh, respectively. Figure 3b presents the effects of unit start-ups. New start-ups seem to improve the energy efficiency. The most significant savings occurred in 2017 when a modern pulp mill with a high capacity was started. In 2012–2014, no new mills were started. Total heat and electricity savings due to start-ups were 383 GWh and 191 GWh, respectively. Closures and start-ups together saved heat and electricity 577 GWh and 299 GWh, respectively. As many factors, especially the accuracy of data reported by mills, affect the results, they should be viewed as the best estimation with the gathered data and used assumptions.

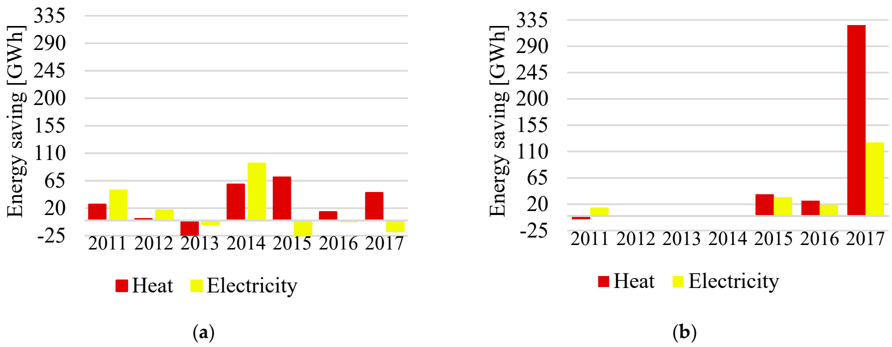

Figure 3. (**a**) Energy savings due to unit closures. (**b**) Energy saving due to unit start-ups.

Figure 4 presents the changes in Finnish pulp and paper electricity consumption. Changed production volumes are the main reason for changes in electricity usage. The black line estimates electricity consumption of chemical pulp and paper industry if the units present in 2011 would have continued to produce each year's production. It can be seen that both unit closures and start-ups have decreased the electricity consumption. Therefore, it seems safe to say they have increased the energy efficiency.

Figure 5 sums up the results of the development of electricity usage over the studied period. Decrease of annual consumption in pulp and paper industry during reviewed period was 2336 GWh. Approximately 1004 GWh was accounted for by decreased production rate and changed production portfolio. Therefore, decrease of 1332 GWh has been due to various energy efficiency improvements. Structural changes have decreased the annual electricity consumption by 299 GWh, and therefore almost 22% of the energy efficiency improvement is accounted by unit closures and start-ups. The respective shares of the start-up and closures were about 8% and 14%. The majority, almost 80%, of the improvement is derived from other energy efficiency improvement projects. It was previously mentioned that production of changed mills is 85% of the total capacity. If the total capacities had been used instead, the structural changes' share of the energy efficiency improvement would have been 26%. These results are valid only with the assumptions used here. If production volumes or the mix of different products change, the results would change.

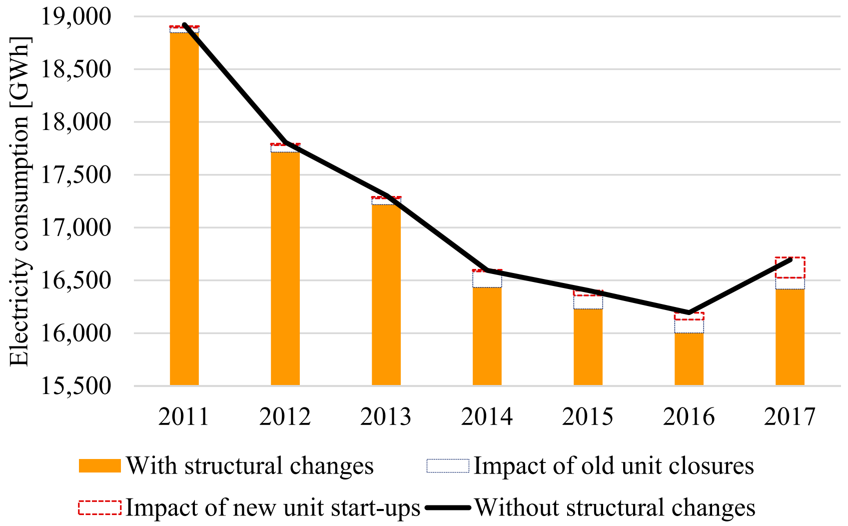

Figure 4. Effect of structural changes on electricity consumption.

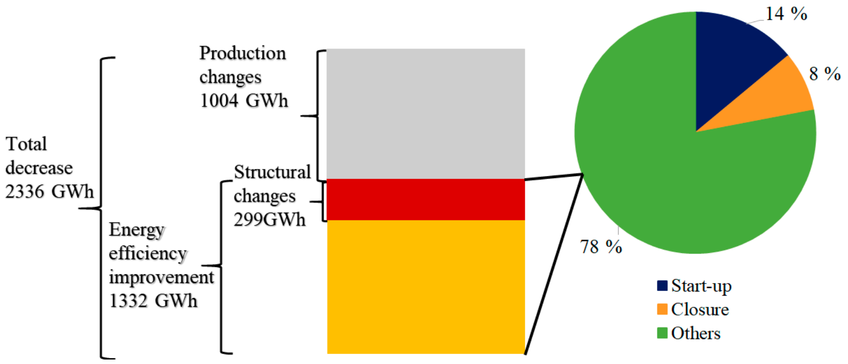

Figure 5. Division of electricity consumption changes in Finnish P&P industry in 2011–2017.

5. Discussion

The results indicate that, considering electricity, the structural changes had about 20% effect on the total energy efficiency improvement. With a moderate to high certainty, it can be stated that structural changes have improved the energy efficiency of Finnish forest industry. However, the structural changes explain only one-fifth of the improvement, and the remaining four-fifths must be explained with other factors. These major factors are changes in used technology and improved modes of operation. These technology changes include both small and large energy efficiency investments. Large investments, like modernizations of individual departments, improved utilization of secondary and waste heat or water cycle closures, can have significant impact on energy consumption.

Small changes, like repairing defective components or correcting operating practices, also have a clear influence on energy efficiency. Improvements in modes of operation consist of education and motivation of personnel as well as ensuring reliable data from processes is collected.

The results suggest that the size of heat savings was almost twice the size of the savings in electricity consumption. That finding meets the current trends. New technologies, for example, improved pressing and drying technologies, have increased the electricity consumption while they have decreased heat consumption [9]. In addition, modern devices for environmental protection have typically higher electricity consumption than older ones [10]. In summary, heat consumption of modern mills should clearly be lower than the heat consumption of older ones, and on the other hand, electricity consumption might be similar or even higher in modern mills in comparison to old ones.

Another interesting finding is that start-ups seem to improve energy efficiency more than closures. Start-ups have saved 70% more heat and electricity than closures, even if the amount of closed capacity was 30% higher than the started one. This finding can be explained by a high-level maintenance and regular upgrades of old mills in Finland. With good care, operating mills are kept in a good shape and the energy efficiency of them is thus not significantly lower than an average Finnish mill. On the other hand, this study indicates that modern mills have a high potential to reduce energy consumption of pulp and paper industry.

This study is valuable for policy makers, legislation, and industries. It indicates that structural changes have only a minor impact on the total energy efficiency and therefore results highlights importance of improving existing mills. Efforts used for energy efficiency improvement during recent decades have realized as significant results. On the other hand, a new large-size mill started in 2017 operates with high energy efficiency but its impact on total energy efficiency is low. The results encourages actors to invest in existing mills' improvement and maintenance. The Finnish pulp and paper industry has changed significantly during 2010s. The change has affected production rates and portfolio as well as energy usage and efficiency. Change will likely continue in the future. It is probable that new bio-based products reach an important position and even more printing and writing paper will be replaced with paperboard [29]. The changes will lead to modifications of pulp and paper making units. The results of this study can be used for estimating energy efficiency changes also in the future.

In further studies, it would be interesting to define the shares of other factors of energy efficiency improvement. Studying this topic would be difficult because a high amount of data about changes done in the mills, operational modes of the mills and energy consumptions should be made available. Also, the impact of structural changes on a global level should be examined. Varying structure of pulp and paper production as well as mill age will lead to changes in the presented results in every country. For example, countries with old mills operating with original processes probably save a high amount of energy by closing these old mills.

6. Conclusions

Finnish pulp and paper industry has gone through a large structural change that has manifested itself as several unit closures and a few new unit start-ups. In addition to changing production rate and product portfolio, structural changes have affected energy efficiency of the Finnish pulp and paper industry. The study was executed by collecting a high amount of mills' operational data and creating three scenarios. With the scenarios, energy efficiency improvement due to structural changes was estimated. Between 2011 and 2017, annual electricity consumption has decreased due to reduced production rate, changed products, and energy efficiency improvements. Energy efficiency improvements consist of several factors, such as structural changes, improved technology and processes, and more optimal operational choices. This study estimates that approximately 20% of the energy efficiency improvement is a result of structural changes. The remaining 80% is a sum of the other factors. The study also indicates that modern mill start-ups have a greater effect on energy efficiency than old mill closures. However, improving existing mills has a higher effect on total energy efficiency than closing old and starting new mills.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/19/3689/s1, Table S1: Products and production rates of Finnish pulp and paper mills. Table S2: Electricity consumption of Finnish pulp and paper mills. Table S3: Heat consumption of Finnish pulp and paper mills. Table S4: Specific electricity consumption of Finnish pulp and paper production. Table S5: Specific heat consumption of Finnish pulp and paper production. Table S6: Production rates of mechanical forest industry products. Table S7: Electricity consumption of mechanical forest industry products. Table S8: Production rates of bioproducts. Table S9: Electricity consumption of bioproducts. Figure S1: Electricity consumption of Finnish forest industry in 2010s.

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Publication III

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Effect of polysulphide pulping process on the energy balance of softwood and hardwood kraft pulp mills

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Chemical pulping

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Effect of polysulfide pulping process on the energy balance of softwood and hardwood kraft pulp mills

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Abstract: Polysulfide pulping is a method to increase the pulp yield in a kraft pulp mill. Higher production is in the core of pulp mill process development, but modifications in cooking raise questions on their effects on the other parts of the process. This study focuses on the impacts of polysulfide pulping on the energy use and production of kraft pulp mills. The impacts are estimated by calculating and analyzing the steam and electricity balances of reference softwood and hardwood mills. Energy generation using residual biomass is an essential part of the operation of a kraft pulp mill, and often a notable source of income. The results show that implementation of polysulfide cooking affects both energy consumption and production. Higher hemicelluloses content of pulp cooked using polysulfide liquor means that less organic material ends up in the black liquor. Subsequently, the recovery boiler energy production suffers. The reduced steam production together with increased steam consumption decreased electricity production, corresponding to a decline in sellable electricity of 22.4 % in the hardwood mill and 28.4 % in the softwood mill. The study shows that increasing the pulp production by investing in polysulfide cooking in stand-alone kraft pulp mills can be economically feasible.

Keywords: bioenergy; kraft pulp mill; polysulfide pulping; process efficiency; pulp yield.

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Introduction

The primary advantage of polysulfide (PS) pulping is the increase of pulp yield. Carbohydrate loss during the cooking process is one of the main drawbacks of the traditional kraft pulping process. Lower wood usage for the same production leads to higher cost-effectiveness, especially when larger amount of sellable pulp can be produced using less feedstock and chemicals. Pulp yield can increase about 1–3 % when polysulfide, anthraquinone (AQ), or both are used (MacLeod 2007). In addition to yield increase, polysulfide pulping enables a lower kappa number without yield loss, which allows a reduction in the use of bleaching chemicals (Colodette et al. 2001, Dobson and Bennington 2002, Tench et al. 1999).

Polysulfide cooking is not commonly used, although the technology has been available for long (Kleppe and Minja 1998). Growing demand for more efficient processes can be expected to increase the interest in polysulfide pulping in the near future. Energy efficiency is in the core of the development of kraft pulping process, process scale-up and environmental concerns as an obvious part of the progress. Implementation of the polysulfide process affects the pulp quality as well as the pulping process. Effect on for instance pulp strength, recovery cycle operations, corrosion, and costs have been matters of concern (Colodette et al. 2001, Kleppe and Minja 1998). These concerns can be addressed by publishing practical experiences from operating units and research results on the impacts of the technology.

Previous studies agree that polysulfide process increases the pulp yield (Copur and Tozluoglu 2008, Hakanen and Teder 1997, Jiang et al. 1994, Luthe and Berry 2005, MacLeod 2007, Vaaler and Moe 2001). The yield increase is based on retention of higher amount of hemicelluloses in pulp, because polysulfide compounds decrease the dissolution of hemicelluloses in cooking. Consequently, less hemicelluloses end up in the recovery boiler with black liquor, which reduces the dry solids load of the boiler. When the recovery boiler is the bottleneck of the pulping process, polysulfide pulping can be used to increase the pulp production without need for expensive modifications to the boiler. Lower amount of organics in the black liquor decreases steam generation in the recovery boiler. This leads to decrease in electricity generation.

This study aims at a deeper understanding on the effects of polysulfide pulping on the energy balance of a modern large eucalyptus kraft pulp mill. Previous studies on PS cooking have focused on the chemistry of the process as well as the impacts on the pulp quality primarily in softwood (SW) mills. PS process has been utilized in softwood mills, but there is a lack of published practical experience from eucalyptus kraft pulp mills. The objective of this study is to estimate how implementation of PS changes the steam and electricity balances of the reference mill producing kraft pulp using eucalyptus wood. The study is made by using mill measurements to model the changes in the processes of a reference softwood mill and then utilizing these changes in a hardwood (HW) mill model. Based on the results and earlier studies, the advantages and drawbacks of the implementation are discussed. Economic analysis is made by calculating payback periods for polysulfide cooking investments to evaluate economic feasibility.

Materials and methods

Energy generation in a modern kraft pulp mill

A modern kraft pulp mill produces heat and power by combusting residual biomass from its own processes. Typically, modern pulp mills are energy-independent apart from fossil fuels used in lime kilns and during start-up, shutdowns, and upsets. Heat and power are often produced in excess of own requirements (Vakkilainen and Kivistö 2014). Bio-based heat or power sale is an additional source of income for many pulp mills.

Steam is generated in the recovery boiler, where black liquor is combusted as a part of the chemical circulation of the pulping process. In many mills, especially in Northern Europe, there is also a power boiler where bark and residual biomass from the wood handling process is combusted for additional steam generation. Steam is used in the pulping process for heating purposes as well as in a steam turbine for power generation. The efficiency of steam use in the mill processes affects the amount of electricity for sale, because excess steam can be used to increase condensing power generation. Power is needed in the mill processes, but typically in modern mills, it is generated in excess of own requirements. The surplus is often sold or used in an integrated paper mill. Changes in the efficiency of steam production or consumption will affect the mill's operational costs.

Polysulfide pulping process

Polysulfide pulping as a method to increase pulp yield has been known since the 1940's (Kleppe and Minja 1998). Polysulfides, such as Na_2S_2 or Na_2S_3, decrease hemicellulose degradation in the early stage of cooking, when temperature range is from 100 °C to 120 °C and profuse dissolution of hemicelluloses occurs (Gustafsson et al. 2011). Pulp yield increases due to larger amount of hemicelluloses in pulp (Gellerstedt 2009). The yield increase results mostly from retention of hemicelluloses, but also from protection of cellulose chains (Colodette et al. 2001). Polysulfide compounds stabilize especially glucomannan and xylan when used in softwood pulping (Copur and Tozluoglu 2008). In eucalyptus pulping tests, half of the yield increase was found to result from xylan content increase, while in pine pulping the majority of yield gain resulted from retention of mannans (Colodette et al. 2001).

Along with higher yield, increased capacity of the recovery boiler due to lower black liquor amount is included in the benefits of polysulfide pulping. The recovery boiler is often the bottleneck of the kraft pulping process. Polysulfide pulping can be seen as a way to increase production without expensive retrofit to the recovery boiler. On the other hand, decreased amount of organics in black liquor will lead to decrease in steam and power generation.

The implementation of polysulfide pulping includes both the production of polysulfide that changes the properties of the alkaline cooking liquor and modifications in the cooking process to enable the maximum utilization of polysulfide. Polysulfide can decompose to thiosulfate if temperature or pH is too high and therefore changes in the cooking temperature profile are usually required (Szepaniak 2014). However, some mills have been able to operate using existing cooking parameters when changing to PS cooking (Hara 1991). The quality of pulp is one of the main issues whenever the PS pulping process is used. Minor changes in the pulp composition or quality have been noticed in earlier studies on polysulfide pulping (Copur and Tozluoglu 2008). The studies show that pulp tear strength may be affected due to higher hemicellulose content, but it can typically be expected to meet customary requirements. Increased hemicellulose content in PS pulp typically leads to better beatability (Hakanen and Teder 1997). Therefore, beating energy consumption of polysulfide pulp to given tensile index can be expected to be lower.

In polysulfide pulping, white liquor oxidation is used to convert a part of sulfide sulfur into elemental sulfur. The PS cooking liquor is called orange liquor due to its color in comparison with white liquor in traditional cooking process (Hakanen and Teder 1997). The most used industrial polysulfide generation method is the Moxy (Mead Oxidation) process that was first implemented in the year 1973 in Mead Corporation Chillicothe mill (Kurittu 1998). The Moxy process is a partial oxidation process of white liquor, where clarified white liquor is filtered and led to a reactor. There the sulfide is oxidized and converted to polysulfide sulfur in the presence of carbon catalyst (Kleppe and Minja 1998). In the reactor, 60 % to 70 % of sodium sulfide (Na_2S) oxidizes, of which approximately two thirds forms polysulfide while one third reacts to form thiosulfate and caustic, following reactions 1 and 2 (Arpalahti et al. 2008).

$$4\,Na_2S + O_2 + 2\,H_2O \longrightarrow 2\,Na_2S_2 + 4\,NaOH \tag{1}$$

$$2\,Na_2S + 2\,O_2 + H_2O \longrightarrow Na_2S_2O_3 + 2\,NaOH \tag{2}$$

Other commercial polysulfide processes are Chiyoda and Paprilox, which bear resemblance to the Moxy process (Eriksson and Bennington 2003, Kleppe and Minja 1998, Luthe and Berry 2005, Tench et al. 1999). Chiyoda process uses carbon as catalyst. To increase the lifetime of the catalyst, white liquor filtration is required before the reactor, as well as in the Moxy process (Kleppe and Minja 1998). Paprilox process is another catalytic white liquor oxidation process, and it can be retrofitted into an existing causticizing system (Luthe and Berry 2005, Tench et al. 1999). It is also possible to produce polysulfide using electrochemical oxidation (Watanabe et al. 2001). In this electrolytic process, white liquor is oxidized at anode to produce polysulfide, and NaOH is generated at cathode. High PS concentrations can be reached using electrolytic process.

Reference mill processes and operation

In this study, two reference mills are modelled to analyze the effects of polysulfide pulping on the steam and power balances of the mills. The studied reference mills are:

- **Mill A:** A modern softwood kraft pulp mill located in Northern Europe, pulp production 600 000 ADt/a
- **Mill B:** A modern eucalyptus kraft pulp mill located in South America, pulp production 1 500 000 ADt/a

The mass and energy balances of the reference mills have been calculated using an updated *MillFlow* program. *MillFlow* is a mill spreadsheet that has been introduced in more detail in earlier studies (Hamaguchi et al. 2011, Kuparinen 2019, Vakkilainen and Kivistö 2008). The model Mill A is updated from a model that was used in an earlier study where it was checked against actual mill operation (Vakkilainen and Kivistö 2008). Mill B was introduced in more detail in previous studies (Hamaguchi et al. 2011, Ku-

Table 1: The main process values of the reference mills in the base case.

	Unit	Mill A	Mill B
Production			
Operating hours	h/a	8400	8400
Bleached pulp production	ADt/a	600000	1500000
Wood handling			
Wood required	m^3 sob/d	7960	16710
Residue generated	BDt/d	607	1274
Cooking			
Yield	%	45	53
Polysulfide concentration	gS/l	–	–
White liquor flow to digester	m^3/d	6485	12242
White liquor dry solids	%	13.9	15.6
White liquor sulfidity	%	38.7	32.0
Active alkali charge as Na_2O	%	17.5	17.1
Active alkali as NaOH	gNaOH/l	129	140
Effective alkali as NaOH	gNaOH/l	104	118
Causticity	%	84	83
Kappa after cooking	–	30	18
Recovery boiler and evaporator			
Evaporator load	t_{H2O}/h	566	1286
Black liquor dry solids flow	tDS/ADt	1.93	1.46
HHRR (boiler load)	MW/m^2	2.85	3.43
Black liquor HHV	MJ/kgDS	13.97	13.65
Net steam flow	t/h	454	859
RB steam/BL solids virgin	kg/kg	3.44	3.54
Steam generation	MJ/ADt	21350	16280
Reduction	%	95	94
RB flue gas	Nm^3/ADt	6743	5590
Organics in BL	%	69.8	65.2
Reduction	%	95	94
Heat consumption			
Cooking	MJ/ADt	2780	1829
Bleaching	MJ/ADt	870	580
Evaporation	MJ/ADt	5199	2988
Drying	MJ/ADt	2410	2100
Recovery boiler	MJ/ADt	1780	977
Miscellaneous	MJ/ADt	1168	707
Steam consumption, total	MJ/ADt	14210	9180
Electricity			
Steam for power generation	MJ/ADt	3697	3380
Power generation	MW	69	157
Power consumption	kWh/ADt	739	602
Excess power for sale	MW	16	49

HHRR = Heart heat release rate; HHV = Higher heating value; RB = Recovery boiler; BL = Black liquor.

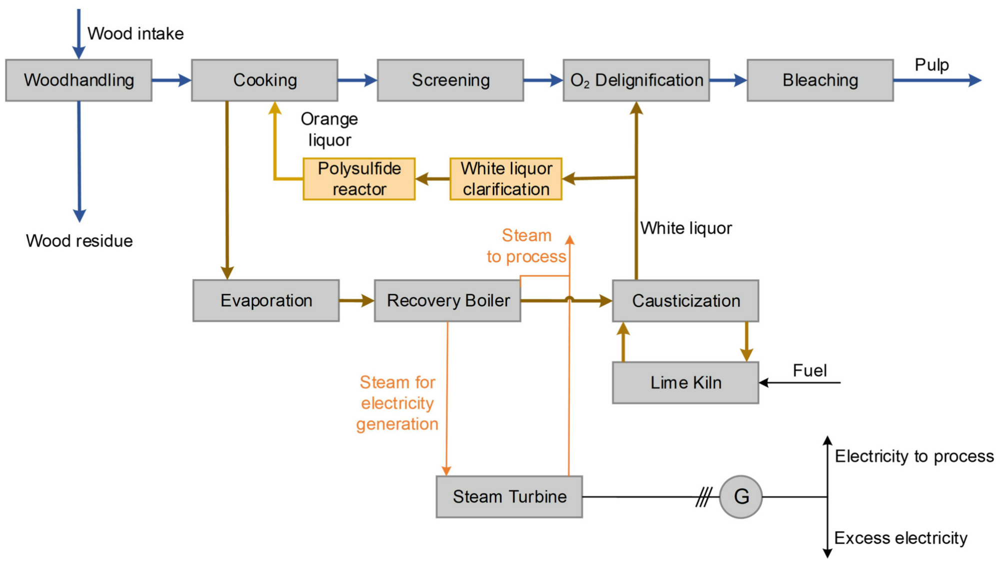

Figure 1: Polysulfide process in a kraft pulp mill.

parinen 2019, Kuparinen and Vakkilainen 2017). The main process values of the reference mills in the base case are presented in Table 1. At both mills, steam during normal operation is produced only in the recovery boiler and no separate power boiler is used.

Implementation of polysulfide pulping to the reference mill operations

Figure 1 presents a simplified block diagram of a pulp mill including a polysulfide process. The implementation of the polysulfide process requires installation of a white liquor clarification process and the actual PS reactor. Also changes in piping and process optimization, especially in cooking, are needed.

The polysulfide process was modelled using literature data (Hara 1991, Jiang et al. 1994, Nishijima et al. 1995) and vendor data. The effect of PS on the softwood mill operation was compared with the literature and mill operating data. The experience from softwood mill model was utilized with the PS eucalyptus mill model.

PS concentration in orange liquor varies from mill to mill. It was set at 5 gS/l for both studied mills based on literature. Pulp yield increase in the SW mill was 1 % based on the actual mill data. The previous experiments have suggested yield increases up to 3 % (Demuner et al. 2020) or even higher with a large dosage of sulfur (Copur 2007). The relatively low yield increase in the example mill resulted from the already high yield before PS cooking and the requirement to retain pulp strength. In previous trials, PS process was shown to increase the pulp yield also in eucalyptus pulp mills (Colodette et al. 2001). Based on laboratory experiments (Demuner et al. 2020, Zanão et al. 2019) and reported trials producing eucalyptus pulp using PS process and the knowledge on SW pulp processes, the yield increase was estimated at one percentage unit also in the HW mill case. For eucalyptus mill, there is a lack of published data of mill trials, but the used 1 % yield increase is a reasonable estimate of a possible industrial level. In an existing mill, this increase can be estimated observing the changes in the amounts of produced pulp and generated steam. Varying moisture content of incoming wood makes accurate measurements of utilized wood challenging in the mill environment.

Orange liquor concentration differs from that of white liquor. Based on experiences on Japanese mills, the amount of active alkali decreases while the amount of effective alkali increases (Nishijima et al. 1995). Also sulfidity is typically low. The composition of orange liquor was calculated using white liquor from base case mills which oxidizes according to reactions (1) and (2) so that the targeted polysulfide concentration is achieved.

Polysulfide pulping increases the amount of pulp, which causes a decrease in the organics to be burned in the recovery boiler. In the studied cases, wood input was kept the same, which means an increase in pulp production. The decrease in the load of the recovery boiler means lower amount of combustion air and consequently, lower flue gas flow and lower specific emissions per ton of product, if the flue gas emissions can be kept the same.

It can be assumed that PS does not affect the fate of the inorganic matter in the cooking liquor. The organic/inorganic relation changes, as the amount of organics in black liquor decreases and the amount of inorganics remains stable. This may change the heating value of black liquor. In practice, the heating value has been found to decrease, but the change is small (Parkko 2013). The change in the dry matter of the black liquor is more significant. Other effects on the combustion operations include e. g. possible increase in SO_2 emissions from the recovery boiler, because polysulfide process increases the amount of reactive sulfur in black liquor. In long-term use, SO_2 causes corrosion in the boiler equipment. In mills where PS process has been used, neither higher sulfur emissions nor increased corrosion have been reported.

The viscosity of black liquor from polysulfide cooking is typically slightly lower than that of traditional black liquor, which can make the evaporation process easier (Hara 1991). The changes in BL composition can lead to fouling of evaporator and therefore in a mill trial, a more frequent need for washing (Szepaniak 2014). In addition to the changes in the chemical cycle, PS cooking may affect bleaching and drying. Possible changes in residual lignin might affect bleaching chemical consumption and steam usage. PS pulp most probably means changes in the operation of drying machine, and in its steam consumption. If the required dryer capacity exceeds the nominal capacity, an increase in the drying steam pressure or an additional infrared drying equipment is often required.

Results and discussion

Polysulfide pulping can be used to increase pulp yield in kraft pulp mills. Utilization of PS affects the mill operations, including the mass and energy balances of the mill. Based on literature data, the implementation and effects of PS in a softwood kraft pulp mill were modelled using *MillFlow* Excel spreadsheet. The results were compared with literature data. The model was then used to estimate the effects of PS in a eucalyptus pulp mill.

When polysulfide pulping is implemented in an existing pulp mill, the process is optimized to gain the maximum benefit from the changes. Some of the changes in reported trials and experiences from existing mills may result from other simultaneous modifications in addition to the actual PS process. This should be considered when the reported results are used to estimate the effects of the PS process.

Softwood mill results

The results of the softwood mill calculations using *MillFlow* are largely consistent with earlier results in literature and mill trials. The main process values before and after PS implementation are collected in Table 2. The chosen PS concentration of 5 gS/l in the produced orange liquor led to increase of one percentage unit in pulp production, namely from 45 % to 46 %. When wood input was kept the same in both cases, pulp production increased 2.0 %. The cooking liquor flow per produced pulp ton decreased due to different composition of the cooking liquor, but the daily use of cooking liquor remains the same because of the increased yield.

The changes in cooking affect the recovery cycle. In the example mill, changes in the washing stage were implemented at the same time with the polysulfide cooking project. The improved washing increased the dry solid content of weak black liquor, which can be seen as a decreased load in the evaporators. The load decreased 3.5 % from 566 t_{H2O}/h to 546 $t_{H2O/}$h, and the heat consumption per pulp ton was 5.6 % lower in the PS pulping case. The results suggest that mill's power consumption is lower when PS pulp is produced compared with traditional kraft pulping, mainly due to decreased evaporator load.

The amount of organic material ending up in BL from cooking decreased as expected, which can be seen as a reduced heating value (−0.8 %). Daily black liquor flow remained practically the same but the black liquor flow per produced pulp ton decreased. The changes in the BL flow led to a steam production decrease of 3.2 %. Only few of the earlier trials have reported the change in steam production. The decrease was approximately 4 % at Hachinohe mill (Hara 1991). Munro et al. (2002) reported 8.3 % increase in steam production per BL dry solids. A small increase (2.7 %) in the dry solid content of black liquor was reported but the result is nonetheless unexpected. Electricity is produced using excess steam. Less excess steam is available after PS implementation due to the lower steam

Table 2: The main process values of the SW mill in the base case and after the implementation of the PS process.

	Unit	SW mill, base case	SW mill, PS case	Change
Production				
Operating hours	h/a	8400	8400	0.0 %
Bleached pulp production	ADt/a	600000	613334	2.2 %
Wood handling				
Wood required	m^3 sob/d	7960	7960	0.0 %
Residue generated	BDt/d	607	607	0.0 %
Cooking				
Yield	%	45	46	2.2 %
Polysulfide concentration	gS/l	–	5	–
White liquor flow to digester	m^3/d	6485	6485	0.0 %
White liquor dry solids	%	13.9	14.4	3.0 %
White liquor sulfidity	%	38.7	26.3	−32.4 %
Active alkali charge as Na_2O	%	17.5	16.2	−7.2 %
Active alkali as NaOH	gNaOH/l	129	120	−7.2 %
Effective alkali as NaOH	gNaOH/l	104	104	0.0 %
Causticity	%	84	84	0.0 %
Kappa after cooking	–	30	30	0.0 %
Recovery boiler and evaporator				
Evaporator load	t_{H2O}/h	566	546	−3.5 %
Black liquor dry solids flow	tDS/ADt	1.93	1.89	−2.1 %
HHRR (boiler load)	MW/m^2	2.85	2.83	−0.7 %
Black liquor HHV	MJ/kgDS	13.97	13.87	−0.8 %
Net steam flow	t/h	454	449	−1.0 %
RB steam/BL solids virgin	kg/kg	3.44	3.40	−1.1 %
Steam generation	MJ/ADt	21350	20670	−3.2 %
Reduction	%	95	95	0.0 %
RB flue gas	Nm^3/ADt	6743	6601	−2.1 %
Organics in BL	%	69.8	68.9	−1.2 %
Reduction	%	95	95	0.0 %
Heat consumption				
Cooking	MJ/ADt	2780	2980	7.2 %
Bleaching	MJ/ADt	870	1150	32.2 %
Evaporation	MJ/ADt	5199	4909	−5.6 %
Drying	MJ/ADt	2410	2580	7.1 %
Recovery boiler	MJ/ADt	1780	1790	0.1 %
Miscellaneous	MJ/ADt	1168	1157	−0.9 %
Steam consumption, total	MJ/ADt	14210	14570	2.5 %
Electricity				
Steam for power generation	MJ/ADt	3697	3406	−7.9 %
Power generation	MW	69	65	−5.8 %
Power consumption	kWh/ADt	739	731	−1.1 %
Excess power for sale	MW	16	12	−28.4 %

generation and increased steam consumption, and therefore electricity production decreases. Electricity generation decreased 5.8 %, which led to 28.4 % decrease in sellable electricity. However, the example mill can still cover its electricity demand by own production.

Combustion air requirement depends on the amount of organic material of fuel. Decreased air flow into the recovery boiler in relation to BL flow indicates that the amount of organic matter in BL has decreased. Change in combustion air flow leads to change in the amount of flue gas. Flue gas production per pulp ton decreased 2.1 %. Absolute flue gas flow did not change notably due to increased pulp production. Emissions in relation to production decrease because less energy per pulp ton is produced. Formation of some emissions such as SO_2 are out of the focus of this study.

Eucalyptus mill results

The effects of adopting polysulfide pulping in the reference eucalyptus pulp mill were studied by modelling the process using the *MillFlow* Excel spreadsheet. The model is based on the earlier model on South American eucalyptus pulp mills. The PS process changes were based on the effects in mills as reported in mill trials and literature studies as well as the reference SW model used in this study. Table 3 shows the process values of the eucalyptus mill in the base case and after PS implementation, based on the *MillFlow* calculations.

Properties of the cooking liquor change when polysulfide cooking is implemented. Active alkali decreases notably whereas effective alkali remains unchanged. Less active alkali is needed for cooking, and white liquor dry solids content increases. There is practically no change in the cooking liquor flow for unit of wood used. Less liquor is needed per produced pulp ton because the total production has increased. Changes to cooking are similar with the case of softwood mill. It was assumed that pulp drying capacity was adequate to handle the additional pulp production without modifications.

Effects of PS cooking on the evaporator operation differ from the softwood mill case. In the reference softwood mill, washing stage was renovated, which affected notably on the dry solids content of the weak black liquor. It was assumed that washing is not modified in the hardwood mill case. The evaporator load increased 1.1 % because of slightly increased weak black liquor flow. However, the steam consumption of evaporator per produced pulp ton decreased 0.7 %.

Higher heating value of black liquor decreased 0.7 % due to the lower share of organics in the dry solids of black liquor. Black liquor dry solids flow per pulp ton decreased 2.0 % due to less organics ending up in the black liquor. The decreased heating value and lower flow of organics to recovery boiler led to a decrease of 1.1 % on the net steam flow. Therefore, even if the heat production per ton of pulp decreased 2.9 %, the implementation of PS cooking did not have a great effect on the absolute steam production. Increased production and decreased organics in the black liquor led to decrease of 2.0 % in recovery boiler's flue gas flow per produced pulp ton. Absolute amount of flue gases changed only slightly.

The results suggest that total steam consumption increases 4.7 % Together with the lower steam generation, the increased consumption led to a decrease in electricity production. The power generation dropped 6.2 %. Mill's power consumption did not change significantly. Excess power for sale decreased 22.4 %. In the case of southern hardwood mills, it should be noted that excess power may not be a valuable product due to lack of distribution network.

Economic analysis and discussion on the feasibility

The economic analysis was made by calculating a payback period for polysulfide process investment for both Nordic softwood mill and Southern hardwood mill. The key variables were prices for electricity, pulp, and wood. Selling electricity can be a notable source of income especially in the case of Northern softwood mill. As both mills are energy self-sufficient, changes in energy consumption affect only the amount of excess electricity. Expected yield increase from running the polysulfide process leads either to saving in wood input or increase in pulp production. Investment cost of 15 Me is used for the softwood mill (Partanen 2012). The cost is scaled for the hardwood mill using Equation (3).

$$\frac{C}{C_{ref}} = \left(\frac{M}{M_{ref}}\right)^n \qquad (3)$$

where C stands for investment costs and M for capacity of a mill. Scaling factor n is 0.67 in this study. The capacity and the investment cost of the SW mill are used as a reference. Used values for the lifetime of the investment and interest rate are 25 years and 7 %, respectively. The annual operation and maintenance costs of the PS process are estimated at 5 % of the investment. Based on the chemical balance of the mill and costs presented in Onarheim et al. (2017), cost for additional bleaching chemicals in case of increased pulp production was set at 35 e/ADt. Other minor variables such as changes in water use or effluents were excluded.

The results show that if the polysulfide process is used for increasing the pulp production, the investment is economically feasible in most of the cases (Figure 2). Some previous trials have reported yield increases up to 3 % for softwood mills, and therefore two additional cases for higher yield increase (2 %) were calculated. If the higher yield increase can be reached, the payback period drops significantly. Electricity price affects the payback period if it is assumed that the excess electricity is a source of income for the mill. It should be noted that especially in remote areas electricity cannot be always sold. This is the case in many southern hardwood mills that have no or only a restricted access to the national distribution network. The economic analysis highlights the fact that polysulfide cooking should be used for increasing the pulp production instead of saving on wood cost.

Table 3: The main process values of the eucalyptus mill in the base case and after the implementation of the PS process.

	Unit	HW mill, base case	HW mill, PS case	Change
Production				
Operating hours	h/a	8400	8400	0.0 %
Bleached pulp production	ADt/a	1500000	1528300	1.9 %
Wood handling				
Wood required	m^3 sob/d	16710	16710	0.0 %
Residue generated	BDt/d	1274	1274	0.0 %
Cooking				
Yield	%	53	54	1.9 %
PS concentration in WL	gS/l	–	5	–
White liquor flow to digester	m^3/d	12242	12245	0.0 %
White liquor dry solids	%	15.6	16.0	2.5 %
White liquor sulfidity	%	32.0	20.1	−37.1 %
Active alkali charge as Na_2O	%	17.1	15.9	−6.6 %
Active alkali as NaOH	gNaOH/l	140	131	−6.6 %
Effective alkali as NaOH	gNaOH/l	118	118	0.0 %
Kappa after cooking	–	18	18	0.0 %
Causticity	%	83	83	0.0 %
Recovery boiler and evaporator				
Evaporator load	t_{H2O}/h	1286	1301	1.1 %
Black liquor dry solids flow	tDS/ADt	1.46	1.43	−2.0 %
HHRR (boiler load)	MW/m^2	3.43	3.41	−0.8 %
Black liquor HHV	MJ/kgDS	13.65	13.55	−0.7 %
Net steam flow	t/h	859	850	−1.1 %
RB steam/BL solids virgin	kg/kg	3.54	3.42	−3.4 %
Heat generation	MJ/ADt	16280	15810	−2.9 %
RB flue gas	Nm^3/ADt	5590	5478	−2.0 %
Organics in BL	%	65.2	64.3	−1.3 %
Reduction	%	94	94	0.0 %
Steam consumption				
Cooking	MJ/ADt	1829	1960	7.2 %
Bleaching	MJ/ADt	580	767	32.2 %
Evaporation	MJ/ADt	2988	2966	−0.7 %
Drying	MJ/ADt	2100	2248	7.1 %
Recovery boiler	MJ/ADt	977	963	−1.4 %
Miscellaneous	MJ/ADt	707	706	−0.1 %
Steam consumption, total	MJ/ADt	9180	9611	4.7 %
Electricity				
Steam for power generation	MJ/ADt	3380	3113	−7.9 %
Power generation	MW	157	147	−6.2 %
Power consumption in mill	kWh/ADt	602	598	−0.6 %
Excess power for sale	MW	49	39	−22.4 %

The mill type affects the feasibility of the polysulfide process. Integrated pulp and paper mills require more heat and electricity than stand-alone mills, and typically they are not energy self-sufficient. Therefore, decrease in steam and electricity production due to implementation of polysulfide cooking leads to increasing demand for purchased energy and can thus decrease the attractiveness of the investment.

Polysulfide cooking has several effects on the kraft cooking. Many of them are attractive but also some drawbacks have been documented. The results of previous studies including the current study are collected in Table 4. The purpose of PS cooking is to increase yield, and the studies agree that the PS addition leads to higher yield, but the magnitude of the increase varies within different wood species, polysulfide and anthraquinone charges, and cooking conditions. General opinion is that the PS cooking can be used for decreasing kappa number without impairing the yield, but a few studies have documented increased kappa numbers. Copur (2007) suggested that

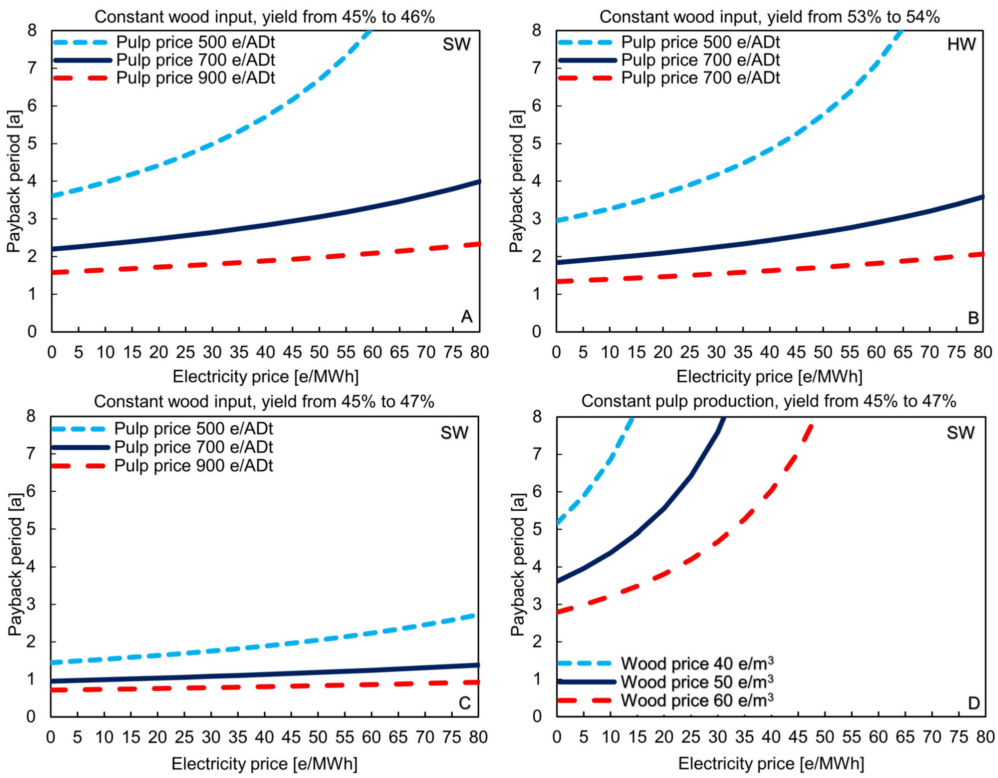

Figure 2: Economic analysis of polysulfide cooking process investment. (A) a softwood mill with a yield increase of 1 percentage point and a constant wood input; (B) a hardwood mill with a yield increase of 1 percentage point and a constant wood input; (C) a softwood mill with a yield increase if 2 percentage points and a constant wood input; (D) a softwood mill with a yield increase of 2 percentage points and a constant pulp production.

increased kappa number may be a result of high sulfidity. Most of the studies found that PS pulping increases tensile and burst index while tear index reduces. However, Demuner et al. (2020) did not observe any changes in physical, chemical, or morphological properties. Some studies, for instance (Kleppe and Minja 1998), also stated that the reduce in tear strength is usually not harmful for paper making.

Only few studies have investigated the effect of PS cooking on the recovery cycle, energy production, and energy consumption. The current study provides detailed information of the effects of PS cooking on the energy use and production in Northern softwood and Southern hardwood pulp mills. The findings are in line with the previous results. Employing PS cooking increased steam demand and reduced energy production but did not lead to demand for additional steam production in the studied mills. The results suggest that revenues from increased pulp production can easily cover losses from reduced electricity production and capital costs.

PS cooking has not become a popular cooking method even though it has been known approximately eight decades and a few mills have reported encouraging experiences. As there seems to be no crucial barriers, it is possible that increasing demand for high material efficiency will promote the adoption of PS cooking in the future.

Conclusions

This study evaluated the implementation of polysulfide cooking in a modern hardwood mill based on its perfor-

Table 4: Effects of polysulfide cooking on the kraft process.

Advantage	Reference	Disadvantage	Reference
Yield increase	(Colodette et al. 2001, Copur 2007, Copur and Tozluoglu 2008, Demuner et al. 2020, Griffin et al. 1995, Hakanen and Teder 1997, Hara 1991, Jiang et al. 1994, Kleppe et al. 1998, Kleppe and Minja 1998, Luthe and Berry 2005, Minja et al. 1997, Molin and Teder 2002, Paananen and Sixta 2015, Rahman et al. 2017, Tench et al. 1999, Vaaler and Moe 2001, Watanabe et al. 2001, Zanão et al. 2019)	Lower tear index	(Copur 2007, Hakanen and Teder 1997, Jiang et al. 1994, Kleppe and Minja 1998, Luthe and Berry 2005, Minja et al. 1997)
Lower kappa number	(Colodette et al. 2001, Dobson and Bennington 2002, Griffin et al. 1995, Tench et al. 1999)	Higher kappa number	(Copur 2007, Copur and Tozluoglu 2008)
Higher tensile index	(Copur 2007, Hakanen and Teder 1997, Kleppe and Minja 1998, Luthe and Berry 2005, Zanão et al. 2019)	Lower opacity	(Zanão et al. 2019)
Higher burst index	(Copur 2007, Zanão et al. 2019)	Decrease in steam production	(Hara 1991)
Better beatability	(Kleppe et al. 1998, Kleppe and Minja 1998, Luthe and Berry 2005, Zanão et al. 2019)	Need for process optimization	(Szepaniak 2014)
Lower alkali consumption	(Hara 1991, Tench et al. 1999)	Higher steam consumption	(Szepaniak 2014)
Attractive payback period	(Kleppe and Minja 1998)	Decrease in electricity production	(Szepaniak 2014)
Reduced boiler load	(Hara 1991, Tench et al. 1999)	Sulfur emissions[1]	(Kleppe and Minja 1998)
Lower H-factor	(Luthe and Berry 2005, Vaaler and Moe 2001, Zanão et al. 2019)	General uncertainty on the effects of PS cooking	(Colodette et al. 2001)

[1]Particularly in case of elemental sulfur addition.

mance on a reference Nordic softwood mill using a process balances calculation tool called *MillFlow*. The results suggest that polysulfide cooking affects the energy balance of both types of mills. Steam consumption rises due to changes in process mass flows and conditions. Cooking conditions are typically modified to avoid detrimental decomposition of polysulfide. Changes to operation are also needed in bleaching and drying stages. The net steam flow from recovery boiler dropped approximately 1 % for 1 percentage point increase in yield in both mills, if the wood input was kept the same during kraft cooking and polysulfide cooking. Less organics ended up in the recovery boiler during polysulfide cooking which decreased the load of the boiler. This enables higher pulp production if the recovery boiler is a bottleneck of the process. The increased steam consumption together with decreased steam production led to a decrease in electricity production. This decrease corresponds to 28.4 % and 22.4 % declines in sellable electricity in the softwood and hardwood mills, respectively. Despite the implementation of polysulfide cooking, both modern mills were able to meet their steam and electricity demand.

The economic analysis shows that the profits from the increased pulp production are notably higher than losses from the decreased energy production, and therefore polysulfide cooking can be economically feasible. No crucial drawbacks in polysulfide pulping have been reported. Thus, implementation of polysulfide cooking in kraft pulp mills seems practical. However, changes in the pulp quality may be an issue for some mills, and if the polysulfide cooking is implemented in mills with high energy consumption, for instance in integrated pulp and paper mills, maintaining the energy supply can be a concern. As there are no modern large eucalyptus polysulfide kraft pulp mills operating currently, the detailed verification of the hardwood polysulfide processes of this study might be addressed in future studies.

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Publication IV

Lipiäinen, S., and Vakkilainen, E.

Role of the Finnish forest industry in mitigating global change: energy use and greenhouse gas emissions towards 2035

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ORIGINAL ARTICLE

Role of the Finnish forest industry in mitigating global change: energy use and greenhouse gas emissions towards 2035

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Abstract
The objective of this paper is to analyse role of forest industry in meeting energy and climate targets that aim to mitigating global change. Finland as an important forest industry country with the ambitious target of becoming carbon neutral by 2035 is selected to a target county. This study aims to present a plausible assessment of the future of the Finnish forest industry until 2035 based on literature and a scenario building approach. The focus is on energy use and fossil carbon dioxide (CO_2) emissions. The results suggest that electricity consumption will decrease, whereas electricity production will increase, which indicates that forest industry can provide more renewable electricity to the grid. Heat consumption may even increase as a result from building new biorefineries, but those mills can most probably meet their heat demand by combusting biofuels. Changes in forest industry's direct fossil CO_2 emissions can reduce Finnish fossil CO_2 emissions 2–4% in comparison to 2018. Biofuels production is likely to rise, but the extent remains to be seen. It is concluded that the Finnish forest industry can contribute significantly to meeting national climate policy targets, and forest industry in general can play a role in mitigating global change. Additionally, it was found that development of the Finnish forest industry will probably be limited by the requirement for sustainable wood harvesting, which may also be a problem for other forest industry countries.

Keywords Forest industry · CO_2 emissions · Energy use · Climate change mitigation · Climate policy · Scenario building

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1 Introduction

Climate change is one of the greatest global challenges of the twenty-first century (Solnørdal and Foss 2018), and mitigation of climate change–related threats requires a substantial reduction in global greenhouse gas (GHG) emissions. World leaders and international organizations are leading efforts to promote a change towards more sustainable development, and the European Union (EU), for example, has set demanding energy and climate targets for 2030. Key EU objectives are a 40% reduction in GHG emissions compared to 1990, a 32% share for renewable energy and a 32.5% energy efficiency improvement (EEI) (European Commission n.d.). In line with EU policy, the Finnish government has included in its programme the strategic objective of becoming a completely carbon neutral society by 2035 (Ministry of the Environment 2020). Additionally, Finland aims to increase the share of renewable energy in final energy consumption to 50% and to replace 40% of fossil transportation fuels with renewable alternatives (Ministry of Economic Affairs and Employment 2017).

Industry is a major energy user and an emitter of fossil CO_2. Energy efficiency improvement and decarbonising different industrial sectors are crucial for meeting energy and climate targets in global, EU and national levels (European Commission 2019). Forest industry, especially pulp and paper industry, is an energy-intensive sector. Pulp and paper industry is the world's fourth largest industrial energy user and accounts for 2% of industrial direct CO_2 emissions (Trudeau et al. 2011). Finnish forest industry has been promoting reduction of CO_2 emissions, and majority (85%) of fuels used in Finnish forest industry are bio-based (Finnish Forest Industries 2018). However, it still accounts for about 5% of total fossil CO_2 emissions in Finland (Statistics Finland 2019b; Energy Authority). If forest industry aims to reach carbon neutrality, as Finnish forest industry does, fossil fuels must be replaced with bio-based alternatives. Moreover, forest industry can contribute to emission reduction by production of bio-based materials, fuels and renewable energy. In Finland, forest industry is the major player in the industrial sector, which covered 47% (148 TWh) of final energy consumption in 2018 (Statistic Finland 2019a). At 22%, the share of total electricity consumption is also high (Finnish Energy 2020). As the forest industry is both the main producer and consumer of bioenergy (Finnish Forest Industry 2018), it can play an important role in meeting political targets regarding the use of renewable energy.

Forecasting the future of forest industry is challenging because several drivers for change, such as climate change, population growth, demographic changes, development of information technology (IT), structural changes of global economy, growing energy demand and increasing scarcity of biodiversity and resources, are affecting the business environment. Demands for different products are changing, and continuing demands to reduce energy use and emissions require existing mills to improve energy efficiency. Among the drivers for change, availability of wood resources affects the development of forest industry in Finland. In 2018, 78.2 Mm^3 of roundwood was harvested for industrial and energy use (Natural Resource Institute Finland (Luke) 2018), whereas the estimated sustainable annual harvesting rate is only 80.5 Mm^3 (Natural Resource Institute Finland (Luke) 2020). Moreover, forests absorb CO_2 and act as carbon sinks (Siljander and Ekholm 2018). There have been a lot of discussions whether forests must be protected instead of used by industrial and energy sector. This study assumes that Finnish forest sector can continue harvesting as long as forests are sustainably managed and annual harvesting rate does not surpass the growth rate.

Several studies have considered the future of the forest industry, of which most focus primarily on production development (Buongiorno et al. 1998; Bolkesjo et al.

2003; Buongiorno 1996; Johnston 2016) or innovative technologies and products (Möllerstein et al. 2006; Kong et al. 2016; Hamaguchi et al. 2012; Hämäläinen et al. 2011). A small number of studies considering future directions of the forest industry have taken energy and climate issues into account. Johnsson et al. (2019), Fleiter et al. (2012) and Szabó et al. (2009) evaluated energy saving and greenhouse gas mitigation potential. Nyström and Cornland (2003) reviewed the potential role of the Swedish forest industry in reducing CO_2 emissions, and Ericsson et al. (2011) studied the role of climate and energy policies in the prospective development of the Swedish pulp and paper industry. The future of the Finnish forest industry has been the subject of some recent studies and reports (Pöyry 2016; Koljonen et al. 2019; Kivistö et al. 2013). However, the role of the Finnish forest industry in meeting EU and national energy and climate policy targets that aims to mitigate global change remains unclear.

Hurmekoski and Hetemäki (2013) evaluate several methods used for outlook studies in the forest sector. Each method has benefits and weaknesses, and typically method selection depends on the specific case studied. This study uses a scenario building approach because it enables several alternative futures to be reviewed and consequently gives a broad view of possible outcomes. None of the forecasts can describe the future perfectly, and the results should therefore be considered indicative. The review period of this study is moderate, under 20 years, and the reviewed area is limited to Finland. Therefore, detailed assumptions and some mill-by-mill analysis can be done.

The aim of this paper is to examine role of forest industry in mitigating global change. Finland is chosen as a target country as it has been a forerunner in the bioeconomy producing a large variation of bioproducts and having a renewable-based fuel mix and sustainably used forest resources (Finnish Forest Industry 2010). The main question is how energy use and fossil CO_2 emissions in the Finnish forest industry will develop to 2035. Role of Finnish forest industry in reducing energy consumption, contributing to fossil CO_2 emissions mitigation and producing renewable energy is evaluated.

This paper consists of five sections. After this introduction, section 2 presents used materials, describes the scenario building method and introduces assumptions and initial values. Section 3 shows the results of scenario building presenting how electricity and heat consumption, electricity production and CO_2 emissions could develop to 2035 and considers how forest industry can contribute to mitigation of global change. Section 4 discusses about possible uncertainties and limitations, compares the study to previous ones and provides future research topics. Finally, section 5 presents the conclusions of the results.

2 Methods and materials

The method employed in this study uses a scenario building approach to evaluate development of energy use and fossil CO_2 emissions in Finnish forest industry to 2035. Development of wood use is included as availability and use of wood resources are an important issue. Literature review is completed to find out what is the initial stage of Finnish forest industry and what kinds of trends are affecting it. Previous studies investigating future of Finnish forest industry and publications of forest industry companies are reviewed. Trends are used in scenario building.

2.1 Finnish forest industry: current situation and future

Finnish forest industry is a major producer of pulp, paper and mechanical forest industry products (FAO 2019). In 2017, it produced 3.1 Mtons of mechanical pulp, 8.0 Mtons of chemical pulp, 5.4 Mtons of printing and writing papers, 3.6 Mtons of packaging materials, 1.2 Mtons of other papers, 1.4 Mm^3 of wood-based panels, 11.8 Mm^3 of sawnwood, 0.4 Mtons of solid biofuels and 0.2 Mtons of liquid biofuels. Total fuel use was 226 PJ and fossil fuel use 35 PJ (Statistics Finland 2019a). Approximately 2.6 Mtons of fossil CO_2 was emitted (Energy Authority 2019). Electricity consumption and production were 20 TWh and 10 TWh, respectively (Finnish Forest Industries 2018). Historical development of Finnish forest industry is presented in Appendix Fig. 3.

Previous studies (e.g. Hänninen et al. 2013; Pöyry 2016; Koljonen et al. 2019) have investigated development of Finnish forest industry. The Finnish forest industry is going through a structural change. Several printing and writing paper and mechanical pulp mills were closed, and new packaging paper and chemical pulp mills were built in 2010s (Kähkönen et al. 2019). The change is continuing, and many forest industry projects are in the design phase. Major projects include three large pulp mills and several mills that would produce advanced biofuels from wood. The total capacity of the planned pulp mills is high, approximately 2.6 million tons per year (Metsä Fibre n.d.-b; Kaicell Fibers 2020; Boreal Bioref 2019). Fulfilment of all the project plans would increase chemical pulp production capacity by almost 30%. Thus, if all these projects are realized, it is very likely that significant existing capacity will be closed.

It is to be expected that new bioproducts, such as biofuels, nanocellulose, textile fibres, intelligent packages, hemicellulose and lignin, will become increasingly important in the forest industry product mix (Hurmekoski et al. 2018). In recent years, Finland has become a forerunner in the field of integrated biotechnology in forest industry mills. For example, the Sunila pulp mill produces 50,000 t/a of lignin, the Kaukas biorefinery produces 130,000 t/a of biodiesel from tall oil, the Enocell mill produces dissolving pulp for textiles, and the large Äänekoski pulp mill based biorefinery produces several bioproducts from its side streams (Stora Enso n.d.-a, b; Metsä Fibre n.d.-a; UPM Biofuels 2020). Moreover, a mill in Kajaani uses sawmill residues as a raw material for transportation fuel (St1 2019).

In addition to production changes, energy use and consequently CO_2 emissions are likely to change. The motivation of mills to implement energy savings and emission reductions can be affected by political means such as CO_2 taxes and emissions trading. In Finland, the use of coal for energy production will be banned from May 2029 (Finnish Government 2019). Additionally, there has been a lot of debate about banning peat combustion. Use of peat will probably end during the 2030s due to high taxation (Wahlström et al. 2017). In addition to political means, technological development, especially biomass-based carbon capture and storage or utilization (BECCS, BECCU) technologies, may accelerate reductions in emissions in the future forest industry (Kuparinen et al. 2019).

2.2 Choosing the scenarios, initial values and assumptions

The purpose of scenarios is to analyse possible futures. In this study, building the scenarios starts with analysing the most crucial factors affecting the energy use and CO_2 emissions. Sector's activity, structure and energy efficiency define sector's energy consumption (Stenqvist 2015), and therefore, those factors were identified as key variables.

Based on literature, two main development paths for development of production were identified. The first path follows current trends: decreasing grades (mechanical pulp, printing and writing papers, wood-based panels) continue their decrease, whereas currently increasing grades (chemical pulp, packaging and other papers, sawnwood, bioproducts) will increase also in the future. The second one assumes that new biorefinery projects will be realized, and therefore, pulp production is strongly increasing as well as production of biofuels and new bioproducts.

As energy efficiency has an important impact on energy use, it is included in the scenarios. Energy efficiency improvement is impossible to predict accurately as several factors such as technology, operational modes, energy management and prevailing policies are affecting it. In this study, the uncertainty is managed using two different energy efficiency improvement rates. The two different development paths for production are combined with high and low energy efficiency improvement rates forming four scenarios. These scenarios assume that forest industry will be increasing. However, it is possible that factors such as tightening competition about raw materials or changes in global competitiveness may weaken Finnish forest industry. Therefore, scenario with decreasing production rates is created to complete palette of scenarios. These five scenarios describe effect of different development paths of production and energy efficiency on energy use of Finnish forest industry in many ways.

The state of forest industry in 2017 is used as a reference scenario. Development of forest industry's fossil CO_2 emissions is not directly related to energy use because changes in energy use may not lead to a change in fossil fuels use but to change in use of biofuels or purchased energy. Thus, studying development of fossil CO_2 emissions needs more assumptions. Those and other assumptions are introduced in the following sections. The assumptions and initial values are based on literature review and values presented in previous studies when applicable.

2.3 Production rates and wood consumption

Changes in production volume and structure have a major contribution to development of energy use. Grade changes have an important impact, because specific energy consumption varies between different grades. In this study, three possible development paths for production rates are established to be able to consider alternative futures (Table 1). Production rates in scenarios I–IV are own evaluations that are based on literature (e.g. Hänninen et al. 2013; Pöyry 2016; Koljonen et al. 2019; FAO 2019). Production rates for scenarios I and II follow current trends. No new pulp and paper mills are built in these scenarios, but renovations and capacity increases are carried out in existing mills. Scenarios III and IV take into account biorefinery projects that are currently in a design phase, which can be seen as a high growth rate of chemical pulp. Paper industry is doing better than in scenarios I and II as well as production of biofuels and new bioproducts. It is assumed that increasing competition about wood leads to decrease in production of wood-based panels and sawnwood. In scenario V, growth rates are chosen to predict decline in Finnish forest industry. Production of conventional forest industry products is decreasing, but production of biofuels and new bioproducts is slightly increasing. The model excludes replacement of old mills with new ones except in case of chemical pulp mills. In this study, chemical pulp capacity is restricted to 10 million tons per year due to wood availability and pulp demand issues. Building the new chemical pulp mills in scenarios III and IV leads to decrease in old capacity.

In addition to production changes, changes in roundwood consumption are estimated. Used specific wood consumption values for mechanical pulp, chemical pulp, sawnwood and wood-

Table 1 Growth rates of forest industry products in Finland until 2035 in the different scenarios

Grade	Unit	Scenarios I & II Change	Scenarios III & IV Change	Scenario V Change
Mechanical pulp	%/a	−1.7	−2.0	−2.5
Chemical pulp	%/a	0.5	1.2	−0.5
Other papers	%/a	0.5	0.7	−0.5
Packaging paper	%/a	0.3	0.5	−0.5
Printing & writing paper	%/a	−2.0	−1.5	−3.0
Wood-based panels	%/a	−0.2	−0.5	−2.0
Sawnwood	%/a	0.3	−0.1	−2.0
Biofuels (s)	%/a	1.0	3.0	0.5
Biofuels (l)	%/a	5.0	11.0	2.0
New bioproducts	1000 tons	100	400	50

based panels are 1.10 tons/ton, 2.17 tons/ton, 1.15 tons/m^3 and 1.22 tons/m^3, respectively. It is assumed that other products do not use roundwood as raw material. Values are calculated using data provided by FAO (2019) and Natural Resource Institute Finland (Luke) (2019).

2.4 Energy use

According to Fracaro et al. (2012), average annual energy efficiency improvement (EEI) of the Finnish chemical forest industry between 1979 and 2009 was 0.39% per year. As the value is relatively low, it is used as lower energy efficiency improvement rate. The higher production rate is set to be twice as high than the lower rate, 0.78%/a. In many cases, literature states higher EEI rates. For example, Odyssee-Mure (2015) reports that industrial energy efficiency improved 0.9%/a between 2007 and 2013. Therefore, both selected values are moderate to avoid too optimistic results. The energy efficiency improvement term in the equation applies only to old mills. Energy efficiency improvement of new mills is included using specific energy consumption values (Table 2). Development of energy consumption is calculated using Eq. (1).

Table 2 Specific energy consumption values of old and new mills. Evaluated using data from Nature Resource Institute Finland (Luke) (2019), Kähkönen et al. (2019) and Pöyry (2016)

Product	Unit	SEC, electricity		SEC, heat	
		Old units	New units	Old units	New units
Mechanical pulp	MWh/t	1.92	1.60	0.17	−0.19
Chemical pulp	MWh/t	0.67	0.53	3.19	2.83
Printing & writing paper	MWh/t	0.82	0.61	1.37	1.21
Paperboard	MWh/t	0.57	0.52	1.48	1.26
Other paper	MWh/t	1.25	0.85	2.41	1.81
Sawnwood	MWh/m^3	0.08	0.08	0.31	0.31
Wood-based panels	MWh/m^3	0.16	0.16	0.61	0.60
Biofuels (s)	MWh/t	–	0.25	–	0.72
Biofuels (l)	MWh/t	–	1.33	–	1.47
New bioproducts	MWh/t	–	1.00	–	1.00

$$E = E_0 + \overbrace{\left(1 - \frac{\Delta P_x}{P_{tot,x}}\right)}^{Share\ of\ old\ capacity} \overbrace{\left[E_0 (1-\varepsilon)^{(v_x - v_0)} - E_0\right]}^{Energy\ efficiency\ improvement} + \overbrace{\sum_{i=1}^{n} \left(w_{n,i} P_{n,i} - w_{o,i} P_{o,i}\right)}^{Structure\ and\ volume\ change} \quad (1)$$

where E is energy consumption of the Finnish forest industry in a certain year [GWh], E_0 is initial energy consumption in a reference year [GWh], ΔP_x is new capacity in a certain year [tons], $P_{tot,x}$ is total capacity in a certain year [tons], ε is energy efficiency improvement [%/a], v_x is the year reviewed, v_0 is a reference year, $w_{n,i}$ is specific energy consumption of new capacity of a certain grade [GWh/ton], $w_{o,i}$ is specific energy consumption of old capacity of a certain grade [GWh/ton], $P_{n,i}$ is new capacity of a certain grade [tons], and $P_{o,i}$ is closed capacity of a certain grade [tons].

Specific energy consumption (SEC) values are chosen separately to old and new mills as it is assumed that new mills are more energy efficient than older ones. The values are based on previous studies. No specific old energy consumption values are presented for production of biofuels or new bioproducts as it is assumed that mills producing those products will not be closed during studied period.

Development of electricity production in the Finnish forest industry is estimated using the logic presented in Eq. (1). It is assumed that the lion's share of the electricity is generated by market chemical pulp mills and integrates. Reference mills for new and old units are chosen based on Finnish pulp and paper mill electricity production data (Table 3). All forest industry mills are different with unique characteristics, and therefore, evaluating future electricity production using reference mills is challenging. No data about annual energy production efficiency improvement rates was available. However, the technology will most probably develop, and therefore, energy production efficiency improvement rates are set to 0.10%/a and 0.20%/a.

2.5 Greenhouse gas emissions

This study considers only CO_2 emissions from use of fossil fuels in forest industry mills. Emissions of energy companies that locate in the same site and produce energy for the mills are excluded, because typically their major task is to produce energy for external use, and therefore, it is challenging to allocate emissions to forest industry and energy sector. Those emissions that are produced when energy company produces energy for forest industry mill are classified as indirect emissions. The amount of CO_2 emitted is related to the energy consumption and fuel mix.

$$CO_2 = \sum_{i=1}^{n} P_i \cdot SEC_i \cdot F \cdot I \quad (2)$$

Table 3 Specific electricity production values of old and new capacity. Evaluations based on data from previous study (Kivistö et al. 2013)

Electricity production (MWh/ton)			
Type of capacity	Market chemical pulp mill	Integrated mechanical pulp and paper mill	Integrated chemical pulp and paper mill
New	1.38	0.58	1.27
Old	0.84	0.28	0.92

where CO_2 is total emissions of the forest industry [tCO_2/a], P_i is annual production of a certain product [tons/a], SEC_i is specific energy consumption of a certain product [GJ/ton], F is share of fossil fuels [GJ/GJ], and I is CO_2 intensity of the fossil fuels mix [CO_2/GJ]. This study considers only changes in amount of used fossil fuels as it is assumed that forest industry companies aim to reduce use of fossil fuels and CO_2 emissions significantly (e.g. UPM 2020).

For studying the future, the major sources of fossil CO_2 emissions were identified. The main fossil CO_2 emitter in chemical pulp industry is the lime kiln, which typically uses natural gas or oil as fuel, followed by fossil fuels use in mill boilers during start-ups, stoppages and other exceptional situations (Kuparinen et al. 2019). Peat and coal are used in biomass boilers, for increasing steam production and reaching full capacity when the biomass fuel is wet. Some oil and gas are used to balance steam generation and to ensure steam supply during stoppages in auxiliary boilers. Several mills use natural gas in drying devices. The forest industry does not generate all the energy it needs, and it therefore causes also indirect CO_2 emissions, which are not included in this study.

Contributions of different fossil fuel sources to total emissions are evaluated to enable studying the future CO_2 emissions. The following assumptions have been made: an average lime kiln emits 120 $kgCO_2$/ton of pulp; average biomass boiler and recovery boiler start-up and shut-down emit 20 $kgCO_2$/ton of pulp and 10 $kgCO_2$/ton of pulp, respectively; every pulp mill has a recovery boiler; and 75% of the mills have a biomass boiler. Assumptions for CO_2 emissions are adopted from Kuparinen et al. (2019). Calculations in this study do not consider the impact of carbon capture technologies. Those technologies may have an important role in the future, but previous studies (e.g. Teir et al. 2011) state that carbon capture will not be feasible in Finnish forest industry before 2030 because of lack of financial incentives. Therefore, it is assumed that CCS will not reach a significant role during studied period.

The starting point for calculations is based on fuels used in the Finnish forest industry in 2017 and their emission intensities (Table 4). With the assumptions above, it can be calculated that use of oil and natural gas in lime kilns supports fuels of recovery and biomass boilers, and incineration of peat and coal accounts for approximately 90% of Finnish forest industry CO_2 emissions. The rest is emitted by auxiliary fuel oil and natural gas fired boilers, infrared dryers in paper drying processes, as well as other minor sources.

Use of peat, coal and fossil fuels in lime kiln is the main variable in scenarios. Literature review showed that burning coal will be banned, and use of peat will probably end during 2030s due to high taxation. Therefore, it is assumed that coal is not combusted in Finnish forest industry after 2029. Scenarios II and IV assume that Finnish forest industry is willing to invest in clean technology, and consequently both peat combustion and use of fossil fuels in lime kilns will stop. In scenarios I and III, forest industry is assumed to be less innovative, 50%

Table 4 Emissions intensity and use of fuels in the Finnish forest industry (Fleiter et al. 2012; Alakangas et al. 2016; Energy Authority; Finnish Forest Industries 2018)

Fuel	Emission intensity (tCO_2/GJ)	Use in 2017 (PJ/a)
Biofuels	0	206.1
Natural gas	0.056	14.7
Peat	0.106	8.8
Heavy fuel oil	0.078	6.1
Coal	0.094	2.8
Other	0.046	3.0

and 75% of lime kilns use biofuels, and 50% and 75% of peat combustion is replaced. In scenario V, it is assumed that forest industry is not willing to invest in new lime kilns, and the share of bio-based fuels is 50%. However, peat use is assumed to end because energy use probably decreases significantly as a result of declining production. There are no major changes in use of start-up and shut-down fuels as they are only a minor user of fossil fuels and they are relatively challenging to replace. Residual fossil fuels remain constant except in scenario IV.

2.6 Scenarios

Five scenarios are created based on own evaluations and data found from literature. The scenarios aim to estimate emissions and energy use of Finnish forest industry in 2035 considering changes in volume, structure, energy efficiency and fuel mix. Scenarios I—V and reference scenario are presented in Table 5. In addition to CO_2 emission sources listed in the table, start-up and shut-down fuels are estimated to emit approximately 0.24 $MtCO_2$ per year. However, it is assumed that there will be no major changes in the use of those fuels within the next 15 years.

3 Results

In all the scenarios studied, the structure of the Finnish forest industry will change in the future (Fig. 1). The production volume change in the whole Finnish pulp and paper industry from 2018 to 2035 is −6.3% in scenarios I and II, 0.3% in scenarios III and IV and − 20.4% in scenario V. Production volume changes in the mechanical forest industry in scenarios I and II, in scenarios III and IV and in scenario V are 4.3%, −2.4% and − 29.1%, respectively. Even though changes in total volume are moderate, the structure changes significantly. Conventional bulk products such as printing and writing paper will likely make room for innovative high-quality products. New bioproducts remain a minor forest industry product, but their production grows in every scenario. There is a lot of uncertainty in the production volume of biofuels and new bioproducts. New products should be profitable, and at the same time, they must meet sustainability criteria. Industrial scale changes occur slowly, and therefore, production of biofuels or new bioproducts may not meet the estimated production volumes.

Production changes estimated in this study will increase roundwood consumption in most of the scenarios (Table 6). In addition to forest industry's wood consumption, energy wood is harvested. If wood imports and energy wood harvesting remain at the 2018 level, scenarios I—IV will probably surpass the limit of sustainable harvesting. Achieving a balance between increasing demand for wood and limited wood resources is an issue that Finland must solve. Competition for raw material will lead to increasing prices, which will affect the competitiveness of Finnish mills.

Increasing wood use will lead to growth in the availability of wood residues that can be used in energy production or for raw material. However, demand for wood residues is likely to increase notably as biofuels production is growing and forest industry mills as well as other actors have already stated aim of replacing fossil fuels with bio-based alternatives due to factors such as increasing taxation of fossil fuels and desire to enhance corporate's image. Strategies of forest industry companies and policies regarding bioenergy and biofuels will play a key role when decisions are made whether wood residues are used as raw material or energy.

Table 5 Used scenarios and their features

	Scenario I	Scenario II	Scenario III	Scenario IV	Scenario V	REF
Name	No significant new investments	Active energy efficiency improvement	New investments	New investments and active energy efficiency improvement	Declining forest industry	Frozen situation
Production	Current trends continue	Current trends continue	New biorefineries and bioproducts	New biorefineries and bioproducts	Decreasing conventional products	2017 level*
EEI	Low	High	Low	High	Low	–
Peat	−50%	−100%	−75%	−100%	−100%	0.93 $MtCO_2$
Coal	−100%	−100%	−100%	−100%	−100%	0.27 $MtCO_2$
Lime kilns	50% bio	100% bio	75% bio	100% bio	50% bio	0.95 $MtCO_2$
Residual fossil fuels	No major changes	No major changes	No major changes	−50%	No major changes	0.24 $MtCO_2$

*Presented in section 2.1

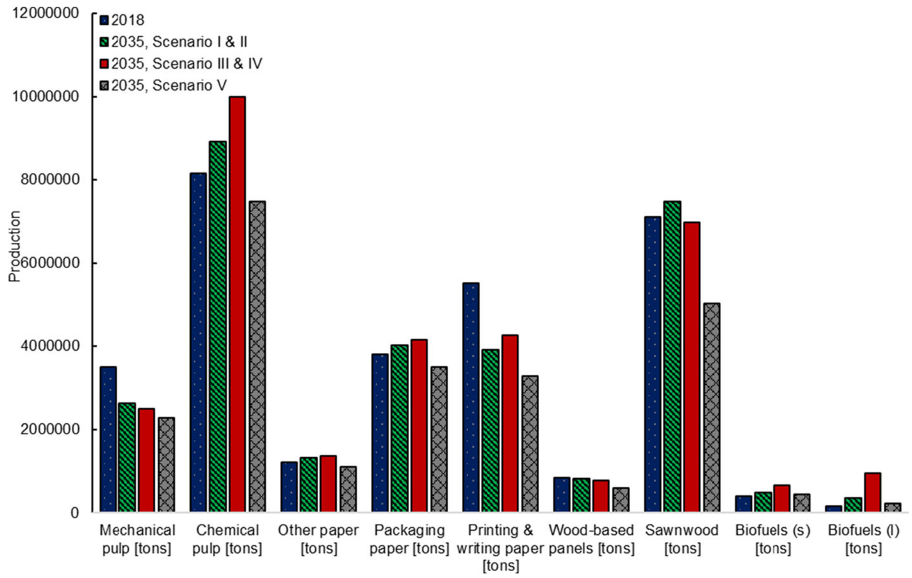

Fig. 1 Production changes in the Finnish forest industry from 2018 to 2035. Production of wood-based panels and sawnwood are converted to tons using density of 0.6 ton/m³

A trend that applies to every scenario is declining electricity consumption (Fig. 2a). A decrease in electricity use can have several impacts. Firstly, combustion of fossil fuels may decrease which would reduce forest industry's CO_2 emissions. Secondly, the electricity self-sufficiency rate of mills will likely increase. Decreased electricity demand may also lead to increase in the amount of bioelectricity available for sale on electricity markets. Thirdly, excess electricity can offer mills opportunities. For example, carbon capture and power-to-x technologies are more attractive if there is available renewable electricity in the mills. Heat demand in the different scenarios varies more than electricity demand (Fig. 2b). Scenario III predicts a 7.5% increase in heat use, whereas realization of scenario V will lead to a 22.4% decrease. Savings in final energy use will probably lead to reduction of fossil fuels and/or purchased energy. In such a case, the Finnish forest industry of the future will be more self-sufficient in terms of energy, and its fuel mix will be even more dominated by biofuels.

The results suggest that electricity production by the forest industry will increase in the future, with the exception of scenario V (Fig. 2c). Scenarios III and IV show that the construction of large pulp mills will have an important role in increasing the amount of electricity produced. Electricity self-sufficiency of new pulp mills can be over 200%, and consequently there may be excess electricity in the mills. Oversupply of electricity may have the same effects as a decrease in electricity consumption. However, changes in electricity

Table 6 Wood consumption and available wood residues in the Finnish forest industry

Year	2018	2035		
Scenario	Current	Scenarios I & II	Scenarios III & IV	Scenarios V
Wood consumption [Mm³]	73.6	76.3	78.6	59.1
Wood residues [Mm³]	23.8	25.6	27.8	20.8

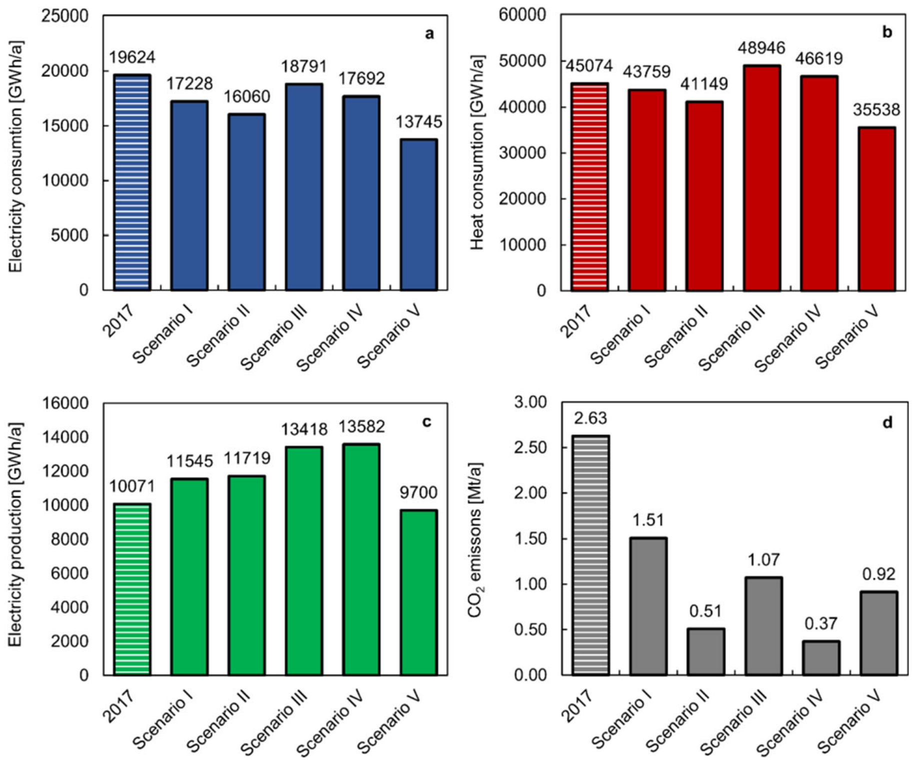

Fig. 2 Finnish forest industry development from 2017 to 2035: **a** electricity consumption, **b** heat consumption, **c** total energy consumption and **d** CO_2 emissions

production and the energy balance of Finnish mills are dependent on strategic choices, electricity prices, and competition for bio-based raw materials. A decrease in electricity consumption may lead to a notable drop in electricity production if there is no profitable use for the excess electricity. Also, decrease in heat consumption may reduce amount of electricity produced in combined heat and power plants.

Even though energy consumption may decrease and the availability of biomass from Finnish mills' own operations increases, which should help reach the target of a CO_2 emissions-free forest industry, some technical barriers may cause challenges; for example, fossil fuels used as supporting fuels during start-ups and other exceptional situations may be difficult to replace. Many mills would be forced to make significant and expensive modifications to their energy systems if all fossil fuel were to be replaced with renewable alternatives, which may discourage especially companies that cannot meet additional renewable energy demand using internal wood residues and side streams.

The results of the scenario analysis suggest that the forest industry's CO_2 emissions will decrease by 43% (scenario I) to 86% (scenario IV) by 2035, in comparison to 2017 (Fig. 2d). Replacing fossil fuels in lime kilns with bio-based alternatives and ending incineration of peat and coal will make a major contribution to CO_2 emissions reduction. Savings in electricity and heat consumption will facilitate reduction of emissions that originate from energy production. In scenarios III and IV, energy consumption rises due to increasing production, and therefore, emissions mitigation is more challenging; however, the adoption of bio-based technologies may enable significant reductions.

Even though energy consumption reductions and availability of own biomass in mills ease reaching emission-free forest industry, total elimination of fossil CO_2 emissions will need significant additional actions. Emerging technologies provide tools for moving forward on the path towards carbon neutrality, but the attractiveness of these technologies depends, among other factors, on costs and policies. Moreover, a decrease in overall energy consumption may not lead to a reduction in fossil fuels use but to a reduction in purchased energy, and a significant increase in electricity production might make reducing fossil fuels use even more challenging.

On the other hand, such a change would result in a significantly larger decrease in CO_2 emissions. It should be noted that the use of carbon capture technologies was excluded from the scenarios. Such technology has high CO_2 reduction potential, but its widespread adoption by 2035 is uncertain. Adoption of bioenergy with carbon capture and storage technologies (BECCS) can provide opportunity to transform pulp and paper industry carbon neutral or even negative emitter (Kuparinen et al. 2019). As future forest industry in Finland emits relatively low amounts of fossil CO_2 emissions, BECCS could enable reaching the carbon neutrality. Moreover, printing and writing paper production capacity and mechanical pulp production will probably lead to the closure of mills with the lowest competitiveness. In many cases, these mills have lower energy efficiency than average. Furthermore, integrated mechanical pulp and paper mills and stand-alone paper mills are typically dependent on fossil fuels. Therefore, such closures can facilitate a reduction in total CO_2 emissions.

Changes in energy consumption of the Finnish forest industry until 2035 result mainly from production volume and mix changes (Table 7). Structural changes affect the ratio of heat and electricity needed. Especially changes in production mix of pulp affect the energy use. Chemical pulp is a heat-intensive product, whereas mechanical pulping requires a lot of

Table 7 Energy saving resulting from production changes and energy efficiency improvement from 2017 to 2035

Scenario	Mechanical pulp	Chemical pulp	Packaging & other papers	Printing & writing paper	Mechanical forest industry	Biofuels & other new bioproducts	Energy efficiency	Total
Heat (2017=45,074 GWh)								
I	−0.3%	4.8%	1.0%	−4.9%	0.4%	1.0%	−6.2%	−4.2%
II	−0.3%	4.8%	1.0%	−4.9%	0.4%	1.0%	−12.0%	−10.0%
III	−0.4%	12.4%	1.5%	−3.8%	−0.3%	3.9%	−5.8%	7.5%
IV	−0.4%	12.4%	1.5%	−3.8%	−0.3%	3.9%	−11.3%	2.1%
V	−0.5%	−4.7%	−1.4%	−6.8%	−2.9%	0.4%	−6.5%	−22.4%
Electricity (2017=19,624 GWh)								
I	−8.6%	2.1%	1.0%	−6.7%	0.2%	2.0%	−6.4%	−16.3%
II	−8.6%	2.1%	1.0%	−6.7%	0.2%	2.0%	−12.3%	−22.3%
III	−10.0%	5.6%	1.5%	−5.2%	−0.2%	7.7%	−6.0%	−6.6%
IV	−10.0%	5.6%	1.5%	−5.2%	−0.2%	7.7%	−11.6%	−12.2%
V	−12.0%	−2.3%	−1.5%	−9.3%	−1.6%	0.7%	−6.7%	−32.8%
Total energy (2017=64,698 GWh)								
I	−2.8%	4.0%	1.0%	−5.4%	0.3%	1.3%	−6.2%	−7.9%
II	−2.8%	4.0%	1.0%	−5.4%	0.3%	1.3%	−12.1%	−13.7%
III	−3.3%	10.3%	1.5%	−4.2%	−0.3%	5.0%	−5.9%	3.3%
IV	−3.3%	10.3%	1.5%	−4.2%	−0.3%	5.0%	−11.3%	−2.2%
V	−4.0%	−4.0%	−1.4%	−7.6%	−2.5%	0.5%	−6.6%	−25.5%

electricity. Pulping is becoming more heat-intensive. The expected decrease in printing and writing paper production will leads to notable heat and electricity savings, whereas production of biofuels and new bioproducts may increase the energy use significantly. Energy efficiency improvement will make an important contribution to energy saving in every scenario.

The forest industry can play an important role in meeting Finland's climate and energy policy targets. The results suggest that final energy consumption in the forest industry will decrease. As bioenergy becomes even more predominant form of energy, the forest industry will probably incinerate fewer fossil fuels, which will lead to lower emissions. CO_2 emissions in Fig. 2d are equal to a 2.0–4.0% decrease in Finland's total emissions. Moreover, the results suggest that while the forest industry's electricity consumption will decrease, electricity production may increase. Thus, mills may have excess electricity, which can be sold on electricity markets and increase the amount of renewable electricity used in the economy as a whole. The forest industry may also become an important producer of advanced biofuels, which will enable Finland to meet its targets regarding the share of renewables in transportation fuels. Additionally, new bioproducts may serve as substitutes for fossil-based materials such as plastics.

4 Discussion

Some megatrends are clearly discernible and already affect social, economic and industrial developments worldwide. The size of the impact of these developments is unknown, and only rough estimates can be made. Unexpected developments can appear suddenly and require forecasts to be updated. For example, changes in the global economy have profound effects on the Finnish forest industry, and the economic crisis of 2008–2009 caused several unit closures in Finland. Most future studies done before the crisis were unable to account for such a sudden and dramatic change in economic activity. Within the context of this study, possible political actions by EU in the energy and climate sector could change the Finnish forest industry dramatically, which may affect the validity of the scenarios developed. Moreover, the Finnish forest industry is in transition. Many conventional products have lost their overwhelmingly dominant position and new innovations and product groups are emerging. The forest industry's transformation towards a biorefineries concept with innovative products in addition to the core products of sawn goods, pulp and paper has been expected for a number of years. Currently, however, the Finnish forest industry is still predominantly focused on the production of conventional products with few new products being produced in commercial volumes. Pressure to produce more sustainable products and fuels may accelerate the transformation, but far-reaching change will probably still take time. At the moment, it is impossible to predict with certainty which of the new innovations will break through to become high volume products.

The results suggest that forest industry can contribute to climate change mitigation. Some previous studies (e.g. Lundmark et al. 2014) as well argue that forest sector can participate on CO_2 reduction. This study focused on energy-related aspects, whereas many previous studies have concentrated as well on strengthening forests' carbon sinks and evaluating what is the role of substituting fossil-based materials with wood-based alternatives. Notably, Siljander and Ekholm (2018) claim that using forests as a carbon sink would be a more cost-effective way to reduce emissions than using them as a bioenergy source, but they also agree that wood-based products can be useful for mitigating climate change. Exact role of forests as a sink, energy source and raw material is unclear, and future studies probably will shed more light on this question.

This study is limited to investigate how production, energy use, energy production and direct fossil CO_2 emissions could develop in the future. The main limitation is that the study does not estimate indirect changes, i.e. how much increasing renewable electricity production can decrease fossil CO_2 emissions of the energy sector or what is the role of new biofuels and bioproducts in reducing fossil-based material use. Moreover, the impact of forest industry on forests as a carbon sinks is out of focus. The study is limited to Finland. However, forest industry is a globally important sector, and many studied trends apply also for other countries' forest industry. The findings can be used for those countries where applicable. In addition, as the forest industry currently produces 5% of Finnish fossil CO_2 emissions, reaching national emissions reduction targets requires major reductions in other sectors. In Finland, energy sector, industry and traffic are the main emitters (Statistic Finland 2019a). Metal industry, chemical industry and pulp and paper industry are the major players in terms of CO_2 emissions. To meet Finnish climate and energy targets, other sectors should be studied as well. Further studies are needed to cover these limitations.

5 Conclusion

This study investigated development of Finnish forest industry's energy use and fossil CO_2 emissions to 2035 using five scenarios and assessed how possible changes would affect the attainment of climate and energy targets that aim to mitigate global change. Forest industry has the opportunity to promote low-carbon society and bioeconomy as it is a major user and producer of bioenergy, biofuels and bioproducts. Impact of bioproducts on reduction of national fossil CO_2 emissions was out of the focus of this study. Forest industry is an energy-intensive sector, and when there are fossil fuels in fuel mix, a significant amount of fossil CO_2 emissions can be emitted. Finnish forest industry has been a forerunner in decarbonizing the forest sector, but it still has potential to reduce fossil CO_2 emissions notably. The reduction requires replacements of peat and coal in power boilers, and oil and natural gas in lime kilns with renewable alternatives. The scenario analysis results indicate that the drop in fossil CO_2 emissions from changes in the forest industry could lead to a 2–4% reduction in Finland's total emissions compared to 2018. Possible carbon capture (BECCS) was not included in the scenarios due to current lack of incentives. The CO_2 reduction potential may therefore be notably higher. If new biorefinery projects are realized, production of renewable electricity will probably increase notably. Energy efficiency improvement and changes in production mix decrease forest industry's electricity consumption, and consequently a larger share of produced electricity can be sold to the grid. The role of the Finnish forest industry in advanced biofuels supply is still unclear. The industry already produces some biofuels, and their production is likely to increase in the future, but the extent remains to be seen. The results suggest that wood resources are a limiting factor for Finnish forest industry. Four of the scenarios indicate that domestic roundwood consumption could approach or surpass the limit of sustainable harvesting especially if harvesting of energy wood remains at the 2018 level. Moreover, debate about forests protection creates uncertainties for forest industry.

Appendix. Trends in Finnish forest industry

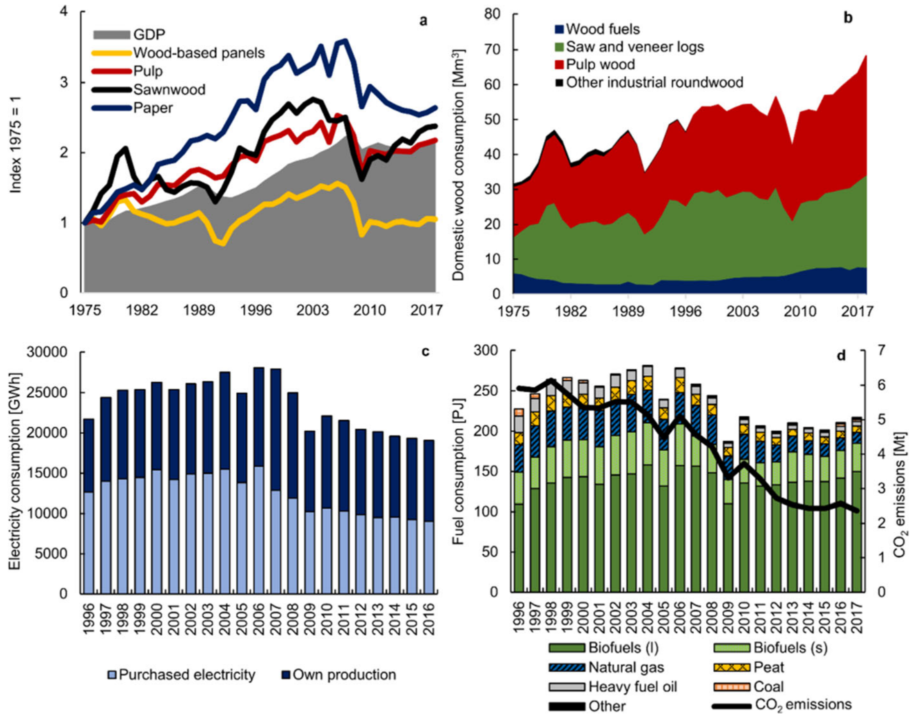

Fig. 3 Development of the Finnish forest sector: **a** Gross domestic product (GDP) and production rates, **b** domestic wood consumption, **c** electricity production and consumption and **d** fuel consumption and fossil CO_2 emissions. Data from FAO (2019), Statistic Finland (2019c) and Finnish Forest Industries database. Emissions evaluated using emission intensities in Table 4

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Research paper

Future of forest industry in carbon-neutral reality: Finnish and Swedish visions

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ABSTRACT

The forest industry is a significant emitter of CO_2 and thus it needs to transform toward a more sustainable operation in order to contribute to tackling climate change. This paper looks at the progress, tools, possibilities, and barriers of Finnish and Swedish forest industries in achieving deep decarbonization. Finland and Sweden have set ambitious national targets to reach net negative greenhouse gas emissions. The role of the forest industry in reaching national targets in these countries remains unclear even if significant fossil CO_2 emission reduction and efficiency improvement has occurred. If the forest industries in these countries fulfill their planned future visions, their contribution to meeting the targets will be substantial. This study identified the largest CO_2 emitting sectors in the forest industry. They are for both countries, arranged by size, transport including non-road mobile machinery, on-site energy production, fossil fuel use in processes (lime kilns and dryers), and purchased electricity. Viable decarbonization measures exist for key fossil CO_2 emissions sources, but several technical, economic, and political barriers are hindering their implementation. Fuel switching from fossil energy sources to bio-based alternatives is the main tool in the decarbonization of the forest sector in both countries, but also electrification of e.g. transport, provides emission reduction opportunities. The forest industry has a high and sustainable potential to become carbon-negative by investing in bioenergy with carbon capture and storage (BECCS) but achieving net-zero emissions might not be realistic without changes in policies and suitable incentives.

1. Introduction

The European Union (EU) is aiming to achieve carbon neutrality by 2050 and to decouple the economic growth from resource utilization (European Commission, 2020). EU Member States are now revising and implementing national long-term strategies for reducing greenhouse gas (GHG) emissions to meet their stronger commitments under the EU objectives and the Paris Agreement. The Nordic countries, i.e. Denmark, Norway, Sweden, Finland, and Iceland, take joint action in transition to a low-carbon economy by developing their advanced cross-border electricity market and promoting utilization of renewable sources (Bird, 2017). The ambitious climate and energy policies implemented within the Nordic region for the past decades have already led to impressive results (Kofoed-Wiuff et al., 2020; Wråke et al., 2021). In 2019, approximately 90% of Nordic electricity was carbon-free and over 40% of the total energy supply was covered by renewables (IEA, 2021a,b). However, the GHG emissions per capita in the Nordic countries are still higher than the European average due to several regional factors, such as cold climate, long transportation distances, and energy-intensive industry (Bird, 2017). Decarbonization is currently progressing faster within power and heat generation as well as in reducing direct emissions from buildings in comparison with more challenging sources in industry and transport. In the Nordic countries, there are several major industrial CO_2 emission sectors: pulp and paper industry (PPI), oil and gas activities, iron and steel production, as well as cement and lime production (Kofoed-Wiuff et al., 2020). Among these, the PPI along with the forest industry in general has great potential for economically reducing fossil fuel dependency while achieving higher production efficiency and increased share of renewables (Onarheim et al., 2017).

74% of the Finnish and 69% of the Swedish land area is covered by forests (FAO, 2020a,b). The forest industries in these two countries provide excellent examples of the efficient conversion of wood-based sources to versatile products, such as green energy, different biofuels (solid, liquid, and gaseous), and other bio-products (Koponen et al., 2015). Moreover, pulp and paper mills as the large stationary sources of biogenic CO_2 provide a unique possibility to obtain negative emissions without increasing wood removals by implementing bioenergy with carbon capture and storage (BECCS) solutions (Rodriguez et al., 2021).

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Both Finland and Sweden have set ambitious climate goals: Finland is aiming to become carbon-neutral by 2035 and carbon-negative shortly after, while Sweden is targeting at net-zero emissions by 2045 (Ministry of Economic Affairs and Employment, 2019a; Ministry of the Environment and Energy, 2017). The target of Sweden is legally binding in contrast to the Finnish one. To meet these progressive goals within the energy-intensive industry sectors, significant reductions of direct and indirect CO_2 emissions are needed. Different CO_2 reduction opportunities within the Swedish PPI have been investigated by Möllersten (2002) and the results proved the essential CO_2 reduction potential. The BECCS is seen as a key technology for mitigating climate change, which however currently lacks the comprehensive understanding and acceptance needed for proper implementation (Geden and Schenuit, 2019). In a recent paper by Rodriguez et al. (2021), the importance of political support through national or international policies for BECCS technologies was highlighted. The negative effect of the uncertainties related to the future status and support of the carbon capture technologies was also underlined by Lipiäinen and Vakkilainen (2021). The results presented in the paper prove that although e.g. the Finnish forest industry has already made impressive progress in decarbonizing and efficiency increase, there is still significant potential for fossil CO_2 reduction.

Due to similarities in geographical and political conditions, forest industries in Finland and Sweden are rather comparable as well as the ambition in their national climate targets. Both countries are targeting to become the world's first fossil-free developed country (Ministry of Economic Affairs and Employment, 2019b; Ministry of Infrastructure of Sweden, 2020). Forest sector companies in these two countries were pioneers in efficiency and sustainability development, which was mainly caused by increased competition in the global market along with more stringent regulations on pollutants and emissions, and increased electricity prices (Hetemäki and Hänninen, 2009; Kumar et al., 2021). At the same time, significant differences in climate change policies exist (Ylä-Anttila et al., 2018). The future of Finnish and Swedish forest industries largely hinges on several essential factors such as the development of global demand and business opportunities apart from the previously mentioned political support.

Achieving carbon neutrality has become an important target for several countries and regions creating the need for comprehensive studies on how fossil CO_2 emissions can be almost eliminated. This paper is evaluating the current state of the forest industries and the possible solutions that need to be implemented to reach carbon-neutrality in the relatively near future. The paper consists of four parts. Firstly, greenhouse gas emissions and climate targets of Finland and Sweden are introduced. Secondly, the status of the Finnish and Swedish forest industries regarding energy use, CO_2 emissions, and decarbonization actions are analyzed. The purpose is to establish the major sources of fossil CO_2 emissions. Thirdly, the visions introduced in the national low-carbon roadmaps are presented, and finally, the measures and barriers for deep decarbonization are evaluated. While many studies limit the analysis on emissions that originate inside the mill gates, this study broadens the view on the overall emissions of the forest industry, namely the production of purchased electricity, transportation, and non-road mobile machinery. International transportation, as well as emissions related to inputs other than wood, are excluded. Even though the study focuses on the Finnish and Swedish forest industries, several lessons learned can be applied to the forest sectors in other countries as well as other industry sectors. Improved understanding of forest industry decarbonization possibilities and challenges provides useful insights for industrial operators as well as policymakers.

2. Literature review

Several countries are aiming at reducing fossil CO_2 emissions from the forest industry. The business environment i.e., national climate policies and transport distances, as well as the current status of the forest industry affect significantly the decarbonization opportunities. This section provides a brief review of previous studies on the decarbonization of the forest industry and focuses on analyzing the business environment and the state of the Finnish and Swedish forest industries.

2.1. Previous studies on the decarbonization of the forest industry

Möllersten et al. (2003) studied CO_2 reduction possibilities within the Swedish PPI and found a reduction potential of 8–14 $MtCO_2$/a. Fleiter et al. (2012) claimed that pulp and paper manufacturing in Germany can cut its CO_2 emissions by 19% (3 $MtCO_2$/a) by 2035 mainly by utilizing waste heat and improved paper drying technologies. Kong et al. (2017) estimated that the adoption of 23 energy-saving technologies in the Chinese PPI could reduce CO_2 emissions cost-effectively by 19 $MtCO_2$/a. Rahnama Mobarakeh et al. (2021) found that electrification of steam supply has great CO_2 emissions reduction potential but reaching carbon neutrality by 2050 in the Austrian PPI requires a combination of several measures. Griffin et al. (2018) argue that the United Kingdom can cut 80% of its PPI's GHG emissions by 2050 in comparison with 1990. They underline the importance of bioenergy, grid decarbonization, energy efficiency, waste heat recovery, electrification of heat, and decarbonization of the grid. Previous studies have widely investigated CO_2 emissions reduction by fuel switching and energy savings, and BECCS has recently become a popular research topic within the forest industry (e.g., Kuparinen et al., 2019; Onarheim et al., 2017b). As the forest industry is a complex sector, each producer country has its own specific features, and there is an urgent need for emissions reduction, more research is needed.

2.2. Greenhouse gas emissions and climate targets for Finland and Sweden

The natural environment and social organization of Finland and Sweden are similar in many ways, however, GHG emissions per capita in Finland have been nearly twice higher than those of Sweden continually for the past two decades (Fig. 1). Despite a notable declining trend through 2010–2019, the level of Finnish emissions is 20% higher than the EU27 average. Finnish per capita emissions are relatively high mostly due to the use of fossil fuels in its electricity mix: 19% was covered by coal in Finland in 2019 versus 2% in Sweden (IEA, 2021c). According to the IEA (2021c), the shares of renewable and low-carbon energy sources in power generation are 45% and 65% in Finland and 61% and 91% in Sweden correspondingly. GHG emissions in Sweden are currently the lowest in the Nordic region (5.2 $t_{CO2-eq.}$ per capita in 2019) (European Environment Agency, 2021). Overall, the Finnish economy is notably more energy-intensive in comparison with the Swedish and the European average levels: 168.17 kg of oil equivalent (kgoe) per €1000 GDP in Finland compared to 113.88 kgoe per €1000 in Sweden and 119.48 kgoe per €1000 in EU27 in 2019 (Eurostat, 2021a). At the same time, Sweden and Finland are responsible for the largest industrial CO_2 emissions in the Nordic region (Kofoed-Wiuff et al., 2020). Finnish industry is an extensive energy end-user, which consumed 44% of energy available for the final use in 2019, with paper, pulp, metal, and chemicals being the major consumers (Eurostat, 2021b). Swedish industry, while having similar structural characteristics, was responsible for 35% of the final energy consumption in 2019 (Eurostat, 2021b).

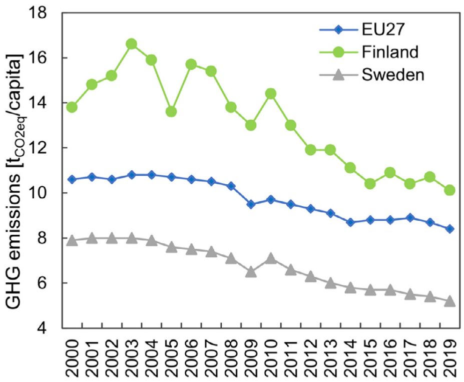

Fig. 1. GHG emissions in Finland, Sweden and EU27 (European Environment Agency, 2021).

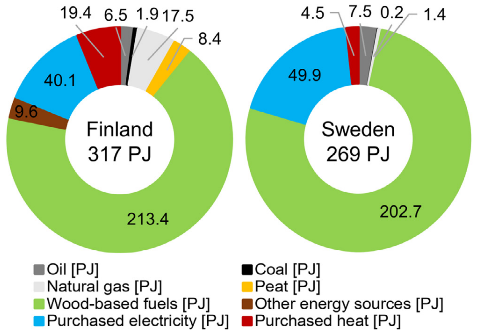

Fig. 2. Energy sources in the Finnish and Swedish forest industries in 2019. Data from Statistics Finland (2020b), Swedish Energy Agency (2020), Swedish Forest Industries (2020).

Climate Change Act is the key pillar of Finland's national climate policy. It entered into force in 2015 and was recently updated for medium- and long-term targets: 55% emissions reduction by 2030 and 80%–95% reduction by 2050 compared to 1990 level (Ministry of Economic Affairs and Employment, 2019b). The carbon-neutrality should be reached by 2035, however, it is a non-binding proposal, and the emission levels might be balanced by using forests as carbon sinks (Ministry of Economic Affairs and Employment, 2019b). Coal-fired power generation is already declining in Finland due to the approved act banning the use of hard coal for power and heat generation in 2029 (Finnish Government, 2019). While energy peat is among the main domestic energy sources in Finland (Statistics Finland, 2020a), its use in energy production should be reduced by at least a half by 2030 (Ministry of Economic Affairs and Employment, 2019b). The climate policy in Sweden is considered more ambitious than in Finland (Gronow et al., 2019). Sweden is set to have zero net GHG emissions by 2045 (85% reduction from 1990 level) with a limited share of the supplementary measures, which are the increased net CO_2 removal by forests, verified emission reductions from investments in other countries, and BECCS (Ministry of the Environment, 2020). The emissions and removals from Land use, land-use change and forestry (LULUCF) are not included directly.

2.3. Forest industry status in Finland and Sweden

Finland and Sweden are significant forest industry countries. They produce approximately 50% of the Europe's virgin pulp, and Sweden is the second largest paper producer in Europe after Germany, followed by Finland (FAO, 2019). Export orientation is common to the countries: 80% and 75% of forest industry products are exported in Sweden and Finland, respectively (Finnish Forest Industries, 2020a; Swedish Forest Industries, 2020). The integration rate of mills is high in both countries: almost 90% of paper is produced in integrated pulp and paper mills. The forest industry also plays an important role in the national energy balance because it is a large producer and consumer of both heat and electricity.

2.3.1. Production volumes

In 2018, the total production of pulp in Finland and Sweden was 11.7 Mt and 11.9 Mt, respectively (FAO, 2019). As for paper production, while the total volumes were rather comparable (10.5 Mt and 10.1 Mt in Finland and Sweden, respectively), there is a notable variation in the shares of different grades (Table 1). The Swedish forest industry is focused on producing packaging materials whereas Finland is a large producer of printing and writing papers. The production of the Finnish and Swedish forest industry relies on virgin fibers: both chemical and mechanical pulps are produced with high volumes, and only 5%–10% of raw material used by the paper industry is produced from recycled fibers (Finnish Forest Industries, 2020b; Swedish Forest Industries, 2020). Kraft (sulfate) pulping is a dominating pulping process accounting for over 60% of produced pulp.

2.3.2. Energy use

The forest industry is an energy-intensive sector and requires significant amounts of heat and electricity. In Sweden, the forest industry stood for approximately 20% (269 PJ) of total final energy consumption and 17% (21 TWh) of electricity consumption in 2019 (Swedish Energy Agency, 2020; Swedish Forest Industries, 2020). In Finland, the shares of the forest industry in total energy and electricity consumption were 23% (317 PJ) and 22% (19 TWh) in the same year (Statistics Finland, 2020b). The Finnish and Swedish forest industries cover most of the energy demand by their own production.

Energy sources of the forest industries are illustrated in Fig. 2. The share of biofuels in the fuel mix was 96% in Sweden in 2019, and 87% in Finland (Finnish Forest Industries, 2020b; Swedish Forest Industries, 2020). For comparison, the European PPI used approximately 40% of fossil fuels in its fuel mix in 2016 (Eurostat, 2018). However, fossil fuels usage is higher in energy production processes co-located in forest industry mills (Kuparinen and Vakkilainen, 2017). The forest industry generates steam by mainly combusting black liquor and wood residues. The steam is needed for the manufacturing processes with part of it converted to electricity in co-generation units. The Finnish and Swedish PPIs cover most of their steam demand by their own production. However, some boilers are outsourced to energy companies, and thus mills, especially in Finland, purchase heat from those on-site operators. Approximately 31% and 52% of consumed electricity can be covered by mills' own production in Sweden and Finland, respectively (Finnish Forest Industries, 2020b; Statistics Finland, 2020b; Swedish Energy Agency, 2020; Swedish Forest Industries, 2020). In addition to their own energy generation, the mills purchase electricity from the grid, and a share of it is notably essential in Sweden.

Table 1
Production of Finnish and Swedish pulp and paper industry in 2018.
Source: Data from FAO (2019).

Country	Newsprint [Mt]	Printing & writing paper [Mt]	Packaging paper [Mt]	Other paper [Mt]	Chemical pulp [Mt]	Mechanical pulp [Mt]
Finland	0.3	5.2	3.8	1.2	8.2	3.5
Sweden	1.0	2.5	6.2	0.4	8.6	3.4

3. Methods

This section introduces the gathered data and methods for estimating current CO_2 emissions and future CO_2 emissions reduction potentials in the Finnish and Swedish forest industries. The previous study (Lipiäinen et al., 2021) investigated the historical development of energy use and CO_2 emissions in the Finnish and Swedish PPIs in the 21st century using decomposition analysis and the energy efficiency index method, and provides a background for the current study.

3.1. Data gathering

Several sources such as Finnish Forest Industries (2020b), Statistics Finland (2021a), Swedish Energy Agency (2020), Swedish Forest Industries (2020) provide data on energy use and CO_2 emissions of the forest sector but the data is rather aggregated. Thus, data from several sources were combined.[1] Environmental reports and permits were used as a key data source for the Finnish forest industry. Activities having a risk to pollute the environment need an environmental permit in Finland (Regional State Administrative Agency, 2021), and as forest industry mills belong to this category, the permits provide comprehensive data on the sector. Moreover, zero carbon roadmaps produced by the Finnish and Swedish forest industries (Finnish Forest Industries, 2020c; The Swedish Forest Industries Federation, 2018) offered an important data source for evaluating both the current state and the emission reduction potentials.

3.2. Estimation of CO_2 emissions

Energy sources of the Finnish and Swedish forest industries were collected (see Fig. 2), as well as data on total fossil CO_2 emissions. The magnitude of different CO_2 emission sources was estimated using CO_2 emission intensities of fuels presented in Table 2. The direct emissions, as well as indirect emissions from energy production and transport, were allocated to different sources using literature data and the following assumptions:

- All reported peat and coal are combusted in power boilers
- Natural gas that is not combusted in lime kilns is combusted in power boilers
- Lime kilns and dryers emit 100 $kgCO_2$/ADt in Finland. Due to different CO_2 intensity and data availability, CO_2 emissions of non-road mobile machinery and support fuels are subtracted from direct emissions to estimate emissions from lime kilns and dryers in Sweden
- Start-up, shutdown, and support fuels emit 30 $kgCO_2$/ADt (Kuparinen et al., 2019)
- Emission intensities for electricity are 12 $kgCO_2$/kWh for Sweden and 89 $kgCO_2$/kWh for Finland (European Environment Agency (EEA), 2021)
- Emission intensity for purchased heat is 58 gCO_2/kWh (Statistics Finland, 2019)
- Transport consumes approximately the same amount of energy in Finland as in Sweden
- Indirect emissions from the production of chemicals and other raw materials are excluded

Different emission reduction opportunities (e.g. fuel switching) were identified for the estimation of future emissions reduction potential. The magnitude of each identified opportunity was estimated based on calculated present CO_2 emissions, and carbon neutrality roadmaps created by the Finnish and Swedish forest industries (Finnish Forest Industries, 2020c; The Swedish Forest Industries Federation, 2018). Following assumptions were used to supplement information provided by the roadmaps:

- The electricity grid is practically fully decarbonized in 2050
- Climate benefit from biofuels production is 0.144 $MtCO_2$/TWh (Swedish Forest Industries, 2019)
- Climate benefits from forest growth 1.33 $MtCO_2/Mm^3$ (Holmgren and Kolar, 2019)
- The increase in annual growth for Swedish forests is 2.3 Mm^3 (2020–2050) (Ministry for the Environment, 2019)

After establishing the magnitude of the present CO_2 emission sources in the Finnish and Swedish forest industries, this study evaluates possibilities and obstacles for achieving net-zero emissions in the relatively near future. The analysis is done by critically reviewing the literature.

4. Results

The high energy intensity of the forest industry leads to large production of CO_2 emissions. In this study, fossil CO_2 emissions of Finnish and Swedish forest industries were estimated at 5.5 $MtCO_2$ and 2.6 $MtCO_2$. On-site industrial fossil CO_2 emissions are approximately 2.7 $MtCO_2$ and 0.8 $MtCO_2$ for Finland and Sweden, respectively (Finnish Forest Industries, 2020b; Swedish Forest Industries, 2020). The combustion of biofuels in the mills generates large amounts of biogenic emissions, roughly 20 $MtCO_2$ annually in both Finland and Sweden. Biogenic emissions do not increase the amount of carbon circulating in the biosphere because the sustainably growing biomass captures at least the same amount of CO_2 than is released during combustion. Thus, this study focuses on presenting how the Finnish and Swedish forest industries are aiming toward fossil CO_2-free operation.

4.1. Fossil CO_2 emissions from forest industry in Finland and Sweden

Both the Finnish and Swedish forest industries have reduced their fossil CO_2 emissions substantially during previous decades (Lindmark et al., 2011; Lipiäinen et al., 2021). Decrease in energy demand as a result of energy efficiency improvement and changes in production volume and structure as well as increased share of biofuels in the fuel mix have enabled notable cuts, but additional reductions are still needed. Current fossil CO_2 flows in the Finnish and Swedish forest industries are illustrated in Fig. 3. Most of the direct fossil CO_2 emissions of the sector are from fossil fuel use in boilers, lime kilns and dryers. Peat is not used in Sweden, but in Finland, its use for energy is responsible for 0.9 $MtCO_2$/a. Even though the direct fossil CO_2 emissions are substantial in both countries, emission intensity is lower than the European average, especially in Sweden. The specific emissions were 90 $kgCO_2/t_{paper}$

[1] The authors are willing to share their data set in Excel format with those who wish to replicate the results of this research.

Table 2
CO_2 emission intensities for fossil fuels.
Source: Data from Statistics Finland (2021b).

Fuel	Fuel oil	Diesel oil	NG	Coal	Peat	Propane	Asphaltene	Other
CO_2 intensity [$kgCO_2/GJ$]	78	65	56	96	106	64	84	74

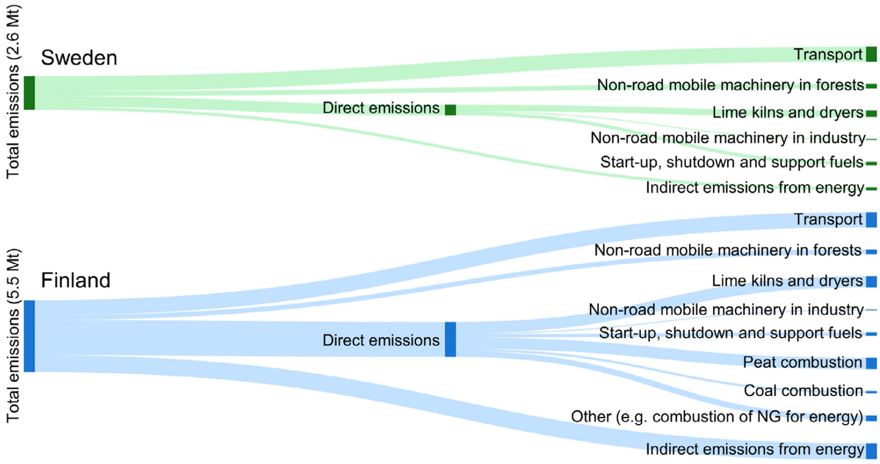

Fig. 3. Fossil CO_2 flows in the Finnish and Swedish forest industries. Calculated using authors' evaluations and data from Finnish Forest Industries (2020b), FAO (2019), Lipiäinen and Vakkilainen (2021), Swedish Energy Agency (2020), The Swedish Forest Industries Federation (2018).

and 280 $kgCO_2/t_{paper}$ in Sweden and Finland, respectively, in 2019 whereas the European average was 300 $kgCO_2/t_{paper}$ (CEPI, 2019). Production of electricity and heat purchased by the mills results in indirect emissions. In Finland and Sweden, national electricity production has a low carbon intensity because of a high amount of nuclear, hydro, and bio-based production. Thus, indirect emissions from purchased electricity are approximately 0.2 $MtCO_2$ in Sweden and 1.3 $MtCO_2$ in Finland. The transport of wood and generated products requires a substantial amount of fossil fuels. The energy demand of domestic transport of the forest sector in Sweden has been estimated at 5 TWh, which is approximately 6% of the total energy use of the transport sector (The Swedish Forest Industries Federation, 2018). In addition to fossil emissions addressed in this study, external production of chemicals and other raw material inputs emits approximately 1.1 $MtCO_2/a$ in Sweden (Swedish Forest Industries, 2019), and the figure is probably at the same magnitude in Finland.

4.2. The visions of Finland and Sweden: Carbon neutrality roadmaps

Different industrial sectors in Finland and Sweden have created roadmaps for fossil-free operation (Fossil Free Sweden, 2017; Paloneva and Takamäki, 2021). In Finland, 13 sectors have prepared the roadmaps, of which four are large and energy-intensive sectors, including energy, chemical, forest, and technology industries. In Sweden, 22 sectors that cover approximately 70% of the total fossil CO_2 emissions have created roadmaps. The purpose of the roadmaps is to enhance the understanding of needed measures, costs, opportunities, and obstacles to transform the region to carbon-neutrality. The maps improve sectors' understanding of the need for emission reductions as well as possibilities to achieve them. Both countries emphasize the importance of maintaining competitiveness as well as the role of the country as a trailblazer and an exporter of clean solutions. Most of the sectors aim at reaching carbon-neutrality by energy efficiency improvement and replacing fossil fuels with biofuels and electricity. However, currently available biomass resources will not meet the total demand of all sectors, and the capacity of the electricity grid may not be sufficient especially during peak loads.

The forest industry is in a slightly different position. It has access to bio-based energy because it can be generated from side streams of its own processes. Therefore, the forest industry has good premises to achieve carbon-neutrality. Moreover, the forest industry's biofuel production can play an important role in increasing the amount of renewable fuels in the market. Thus, it can promote the decarbonization of other sectors as well. Increasing competition for biomass and pressure to increase electrification can, nonetheless, significantly affect the business environment of the forest industry. Both Finnish and Swedish forest industries have published roadmaps toward a low-carbon operation (Finnish Forest Industries, 2020c; The Swedish Forest Industries Federation, 2018). The Finnish and Swedish visions for CO_2 emissions reduction by the forest sector are presented in Fig. 4. The diverse role of the forest sector makes the evaluation of the sector's climate effect challenging. The industry is both consumer and producer of energy. The climate effects of forest growth and bio-based products as carbon storages and substitutes for fossil materials have sparked debate, and still need further studies, e.g. Howard et al. (2021). Another important question concerns the boundaries of the forest sector, e.g. how carbon stored in exported products should be taken into account in the national carbon balance. Moreover, especially the Swedish roadmap has a lack of some exact numerical values, and therefore the figure was complemented by the authors' own evaluations. Thus, the values should be considered indicative.

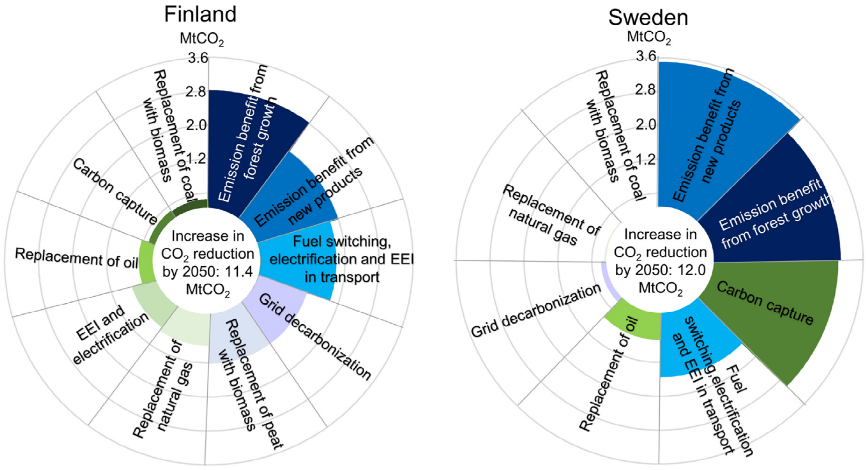

Fig. 4. The vision of the Finnish forest sector by 2050. Constructed based on Finnish Forest Industries (2020c), Holmgren and Kolar (2019), Ministry for the Environment (2019), Swedish Forest Industries (2019), The Swedish Forest Industries Federation (2018), Vasara et al. (2020), and authors' own evaluations. EEI refers to energy efficiency improvement.

Sweden targets phasing out the use of fossil energy sources in the forest industry by 2045. At the same time, the sector has a target to maintain competitiveness and increase the production of biofuels and high-value biomaterials. Finland has estimated that on-site industrial fossil CO_2 emissions can be reduced up to 90% by 2035 compared to 2017, and significant cuts in transport emissions are expected as well. The Finnish roadmap has a target to reduce CO_2 emissions, prevent carbon leakage, strengthen carbon storages, and increase the production of renewable materials that substitute fossil ones. Both countries aim to replace most of the industrial fuels with biomass. As fossil fuel use in Sweden is currently lower than in Finland, also the emission reduction potential is lower. Finland claims that energy efficiency improvement and electrification will bring cuts in CO_2 emissions by reducing the demand for fossil fuels. Swedish roadmap does not give a certain value for expected cuts from energy efficiency improvement and electrification is awaited to play a role mainly in transport. However, the effects of energy efficiency improvement are challenging to evaluate as they may have indirect effects as well. For example, reduced energy demand may release biomass to be used by other sectors. The Finnish and Swedish forest sectors anticipate that fossil fuels use is phased out in the transport sector as well as in electricity production, which lead to significant CO_2 reductions especially in the Finnish forest industry. In addition to the fossil emissions reduction, both countries highlighted that the forest sector can provide climate benefits by strengthening forests as carbon sinks and producing sustainable products that can substitute for fossil-based products. The increase in annual forest growth is very challenging to evaluate and there may be even significantly higher potential to carbon capture by forest than the presented estimate. The roadmap of the Swedish forest industry does not consider carbon capture technologies, but Sweden has stated that BECCS will have a significant role in its carbon balance in 2050, and a large share of the BECCS may be implemented in PPI (Karlsson et al., 2021). The Finnish vision does not see BECCS as a major player. The generation of green electricity will probably increase significantly in the pulp mills but the effect of it is not separated from the replacement of fossil fuels in mills and grid.

4.3. Emission reduction potential

The forest industry has several tools for CO_2 emissions reduction: fuel switching, energy efficiency improvement, electrification, and carbon capture. Additionally, the forest industry can mitigate emissions by substituting fossil-based materials with bio-based alternatives. This study focuses on the CO_2 emission reduction possibilities in energy production, processes and transportation. Indirect emissions from production of chemicals and other raw materials are excluded from the analysis.

4.3.1. Emissions related to energy production

Energy efficiency improvement has been considered as the most important measure to reduce industrial energy use and consequently emissions (Worrell et al., 2009). Our previous study suggested that even though the Finnish and Swedish pulp and paper industries have already increased energy efficiency substantially, there is still a further improvement potential (Lipiäinen et al., 2021). However, as the Finnish and Swedish forest industries already meet most of the energy demand with biofuels, the energy efficiency improvement may not have a notable impact on direct fossil CO_2 emissions. Energy savings can lead to a decrease in purchased electricity or an increase in excess energy in the mills. Furthermore, Johansson et al. (2021) suggest that energy efficiency improvement can release resources for developing new green energy products. At the same time, energy savings can lead to significant reductions in costs, and thus energy efficiency improvement can be considered as an important factor for competitiveness. Technologies that have the potential to improve energy efficiency have been introduced in several studies (e.g. European Commission, 2015; Fleiter et al., 2012; Kong et al., 2016). In addition to improved technologies, energy management can play a significant role in industrial energy saving (Andersson et al., 2021; Thollander and Ottosson, 2010). Energy efficiency improvement will play an important role in the sustainable and competitive development of the forest sector, but other measures are needed to meet the carbon neutrality targets.

The Finnish forest industry used 8.3 PJ of peat in energy production in 2019 (Statistics Finland, 2021a), which corresponds to annual CO_2 emissions of ∼0.9 $MtCO_2$. Additionally, on-site energy companies that produce energy for the forest industry use peat in multi-fuels boilers together with biomass. Many mills have stated an aim to reduce the share of peat in the fuel mix, and many of them have already achieved lower dependence on fossil fuels in energy production, see e.g. Pöyry Finland Oy (2018). At the same time, complete elimination of peat may not be technically possible in some existing boilers (Afry, 2020). Alkali chlorides in biomass tend to form a sticky mixture that causes corrosion in the boiler. Sulfur in peat reacts with the alkali chlorides and thus prevents corrosion. The addition of elemental sulfur has been used in some boilers to overcome the issue but this will generate HCl emissions. Another challenge is the lower energy content of biomass in comparison with peat. If peat is replaced with biomass, more fuel is required, and thus more flue gases are produced, which may lead to a need for modifications. The availability and price of biomass are additional matters of concern. Apart from peat, three mills in Finland are using coal in energy production (∼1.9 PJ, ∼0.2 $MtCO_2$). As combustion of coal will be banned in Finland in 2029, it will most probably end shortly.

The pulp and paper mills often use auxiliary boilers to secure steam supply during exceptional situations, such as start-ups and shutdowns. In many cases, these boilers combust natural gas or oil. In Finland, natural gas-fired boilers are responsible for energy production during the normal operation of some mills. Electric boilers can rapidly respond to demand for additional steam and thus represent potential alternatives for fossil fuel-fired auxiliary boilers (Herre et al., 2020). High electricity prices have been limiting the utilization of electric boilers. In Finland, there are two minor (10–15 MW) electric boilers that are used for heating up the mills when other boilers are not operating. In Sweden, electric boilers are more common in the forest industry. Co-firing of fossil fuels is required in many mills to ensure the complete destruction of odorous gases. Even though these are limited sources of fossil CO_2 emissions, the realization of a carbon-free forest industry requires addressing even these minor emissions. Metsä Fibre Äänekoski pulp mill in Finland has eliminated fossil fuels by only combusting biogenic pitch oil and methanol in the whole mill. Other mills as well have announced the use of pitch oil in exceptional situations (e.g. Stora Enso Oulu). However, many pulp mills still either sell the methanol and tall oil or already utilize them e.g. in a lime kiln. As fossil fuels are easy to combust and store and their use during exceptional situations plays a minor role in the total fuel usage, substituting them can be a challenge. However, achieving net-zero emissions may not require the elimination of all fossil fuels if carbon capture technologies are added to the emissions reduction portfolio.

4.3.2. Emissions related to pulping and papermaking processes

A lime kiln is a rotary kiln that converts lime mud into lime needed for kraft pulping processes. The calcination reaction of lime mud (1) requires a high temperature, typically at least 800 °C (Arpalahti et al., 2008).

$$CaCO_3 \rightarrow CaO + CO_2 \tag{1}$$

The CO_2 released through the calcination process is considered biogenic since most of the carbon in the sodium carbonate originates from wood. At the same time, the process temperature is maintained by combusting fuels, such as oil or natural gas (Miner and Upton, 2002), and it makes the lime kilns a significant source of fossil CO_2. It can be estimated that the lime kilns at pulp mills consume about 16 PJ energy in both Finland and Sweden, which accounts for approx. 7% and 8% of current fuel consumption in the Finnish and Swedish forest industries, respectively. Consequently, lime kiln fuel switching is essential to achieve a carbon-neutral forest industry. Laboratory experiments, computer modeling, as well as mill trials, have been done to find solutions for fossil fuel substitution (Gorog et al., 2015; Kuparinen and Vakkilainen, 2017; Kurian and Divya, 2015). Several viable alternatives have been suggested for meeting the lime kiln energy demand, namely crude tall oil, tall oil pitch, lignin, turpentine, concentrated non-condensable gases, stripper off-gases, and methanol (Francey et al., 2009; Hart, 2020a). In addition to these options, excess biomass and electricity generated in mills can provide the required energy for the lime kiln. The use of wood powder, gasified biomass, torrefied biomass, pyrolysis oil, and hydrogen has been investigated in previous studies (Hart, 2020b; Kuparinen and Vakkilainen, 2017). Another interesting solution is the use of electric-gas plasma that would eliminate fuel combustion (Andersson and Skogström, 2020; Svensson et al., 2021).

There is a range of technical challenges that have limited utilization of ''green'' fuels in lime kilns. Alternative fuels have typically lower heating values compared with oil and natural gas that leads to increased fuel demand and, consequently, higher flue gas exit temperature, flow and velocity (Francey et al., 2009). Thus, the capacity of a flue gas handling system may become a bottleneck of the process. Manning and Tran (2015) found that co-firing of alternative fuels often cause instability of operation. The increased concentration of impurities and non-process elements originating from bio-based fuels is a serious issue for kraft pulp mills trying to operate in as closed cycle as possible (Hart, 2020b). These elements can cause, for instance, scaling in evaporators, corrosion, and ring formation, and to limit the accumulation, a larger part of the lime must be replaced with fresh make-up lime. Nevertheless, even though there are certain concerns regarding the use of alternative fuels, many mills have reported promising experiences, and for example, a study conducted by Francey et al. (2011) did not observe a clear relationship between alternative fuel use and operational issues.

Finland and Sweden are the leading countries in lime kiln fuel switching, e.g. most of the wood powder- and gasifier-operated kilns are located in these countries (Valmet, 2018a), and thus the needed expertise for advanced decarbonization is already available. Among the examples, the Swedish forest products company SCA with a major focus on environmental performance has been upgrading its lime kilns with renewable alternatives, starting in 2011 with the world's first ever new-build lime kiln at Östrand's pulp mill, which operates almost completely on biofuel, and steadily continuing with Munksund mill—in 2014 and Obbola mill—expected in 2021 (Svenska Cellulosa Aktiebolaget, 2021). All three aforementioned lime kilns are primarily fueled by wood powder from ground pellets, which leads to annual cost savings and reduction in fossil CO_2 emissions. The Finnish mills have progressed in fuel switching as well (Mäkelä, 2019). Stora Enso Sunila mill in Finland successfully started to use lignin as a fuel for a lime kiln in 2015, thus decreasing the fossil carbon emission drastically (Björk, 2018). In the same year, Stora Enso Enocell mill started the combustion of wood powder. The largest lime kiln in Europe at Äänekoski bioproduct mill covers most of its energy demand with product gas from bark gasification (Valmet, 2018b). Metsä Fibre Joutseno and Stora Enso Varkaus mills as well rely on the combustion of gasified biomass in a lime kiln. Moreover, UPM Pietarsaari and Stora Enso Oulu are examples of mills that use substantial amounts of pitch oil as a lime kiln fuel.

Drying is the most energy-intensive stage of papermaking (European Commission, 2015). The largest share of water in the paper is removed mechanically, but the final dryness is reached with energy consuming thermal drying (Karlsson and Paltakari, 2009). The latter uses primarily steam from boilers, but the heat from direct fuel combustion is also utilized, especially to increase capacity for drying in the coating processes. Infrared (IR) dryers and air flotation dryers typically combust natural gas or liquified petroleum gas (LPG). The average intensity of fossil CO_2 emissions of the Finnish mills using gas-fired dryers was estimated at 36 $kgCO_2$/t of paper based on values from environmental reports and permits. While the energy-related emissions can be several hundreds of kilograms of CO_2 per paper ton, and fossil fuel-fired lime kilns produce approximately 100–250 $kgCO_2$/ADt of pulp (Kuparinen et al., 2019), the emissions from dryers can be considered relatively negligible. However, on a national and global scale, dryers emit a significant amount of fossil CO_2. In addition to paper mills, many mechanical pulp mills combust fossil fuels during drying, e.g. chemi-thermomechanical pulp (CTMP) mills use flash dryers that are typically natural gas-fired but also oil and steam coils have been used to provide the heat (Berg, 2011).

Fossil CO_2 emissions from dryers can be reduced by switching to more efficient technology, electrifying the process, or using renewable fuels. The improved mechanical pressing stage decreases energy demand during the thermal drying step, e.g. BCTMP mill in Joutseno, Finland, invested in Twinroll™ dewatering press, which decreased natural gas consumption by 20% (Valmet, 2019). The use of bio-based alternatives has been simulated but the effect of impurities is unclear (Energiforsk, 2016). The advantage of natural gas and LPG is uncontaminated flue gases that can be directly used in paper drying, and thus the replacement with biofuels can be challenging. The possibilities to improve the efficiency of IR dryers are actively studied in Sweden (Larsson and Nodin, 2013). Electrification may be the most viable option for decarbonizing the drying. Electric IR dryers already exist and are used on a mill scale. However, as dryers are a relatively minor source of emissions, mills' focus has been on the effects of drying on paper quality as well as costs instead of decarbonization (Kong et al., 2012).

4.3.3. Indirect emissions

Emissions associated with the generation of purchased electricity that is consumed in the forest industry offer additional reduction possibilities. The power sectors in Finland and Sweden involve a significant share of renewable sources and have set ambitious targets for carbon-neutrality in the short term. The electricity production in Finland is expected to be nearly emission-free by the end of the 2030s (Ministry of Economic Affairs and Employment, 2019b). The share of CO_2-neutral electricity (mainly nuclear, hydro, biomass and wind) was already at a high level of 85% in 2020 (Finnish Energy, 2021). The development of an integrated electricity market at the regional and the European levels should improve even further the market flexibility and system efficiency in general. Norway, Sweden, Finland, and Denmark have long shared a single electricity market (Nordic electricity market) that represents an excellent example of a harmonized cross-national market. The Swedish government's energy policies have also promoted the use of renewable energy, and its power sector is targeting to reach 100% renewable electricity production by 2040. In 2019, 90% of electricity came from CO_2-neutral sources (nuclear, hydroelectric and wind) (Swedish Energy Agency, 2021). The Swedish Electricity Certificate System is a market-based system that is efficiently used for supporting renewable electricity production (Swedish Energy Agency, 2015). Like in Sweden, the voluntary Green Certificate system in Finland is used to favor the generation from renewable energy sources. The net-zero operation of the forest industry requires the elimination of fossil CO_2 emissions from purchased electricity, which can be achieved by either fully decarbonizing the grid or purchasing renewable electricity certificates. The forest sector has limited possibilities to affect the emissions from the energy produced outside the mill.

Transport emissions are deemed the most challenging ones to reduce (Salvucci et al., 2019). Transport distances are long in Finland and Sweden and represent a substantial share of production costs. Rail transport covers long distances with low CO_2 emissions (The Swedish Forest Industries Federation, 2018), however, the railways are not flexible and have limited direct access to wood resources. Therefore, freight trucks are responsible for a large share of forest industry haulage. In addition to road transport, non-road mobile machinery participates in the operations of the forest industry, e.g. harvesters in forests and forklifts in mills. Lower transport emissions can be achieved by minimizing fuel consumption and switching to renewable fuels. Optimized transport, e.g. optimal use of trucks capacity, avoiding empty running, improved road conditions, higher average loads, drivers' behavior, and energy efficiency in general, can save fuel (Liimatainen et al., 2014). For example, Höök et al. (2020) found that existing corridors suitable for high-capacity transport in Sweden enable GHG saving of 5.5 $ktCO_2$ annually and 3.1 M€ cost reduction in roundwood transport. Finnish Road Administration (2005) argued that a 10% change in rolling resistance due to uneven pavement can lead to even 6.6% higher fuel consumption.

Decreasing fuel consumption has a limited effect on decarbonization, and thus fuel switching plays a more significant role. The most promising substitute fuel in heavy transport is biofuels (The Ministry of Transportation and Communications of Finland, 2021). Biodiesel can be effectively used in existing engines with current infrastructure, and several commercial conversion routes already exist (Liimatainen et al., 2014). However, feedstock availability is a severe issue. Biogas represents another viable fuel for trucks but is currently limited by gas availability and the power of existing engines. Electrification of heavy trucks can be challenging due to e.g. heavy batteries and limited range, but the concept of electric road systems (ERS) has been considered as a promising decarbonization option (Connolly, 2017). Electric roads have been actively investigated and tested in Sweden and Germany with the world's first wireless ERS installed in the Swedish island Gotland for charging electric buses and trucks (Electreon, 2021). Jelica et al. (2018) stated that extending the ERS to the several Swedish roads with the highest traffic flows can reduce CO_2 emissions by 20%, while the hourly electricity peak demand will be increased by less than 4%. The ERS concept is deemed promising in Finland, however high investment costs and uncertainties of this emerging technology are limiting its application (Finnish Transport Infrastructure Agency, 2020). Additionally, hydrogen and electrofuels have been deemed as promising future energy carriers. The non-road machinery in the industry could be electrified whereas forest machines require biofuels, and thus similar problems exist as with the transport sector (The Swedish Forest Industries Federation, 2018). The forest industry has limited possibilities to affect the emissions of transport, and thus primary transformation in society is required, but the transformation should not heavily increase the transport costs to maintain competitiveness.

4.3.4. Potential of carbon capture

Meeting net-zero emissions might be impossible without employing carbon capture technologies (IEA, 2021d). Many recent scenarios, such as the IEA Sustainable Development Scenario, include carbon capture with utilization and storage (CCUS) as a part of emission reduction measures for the PPI (IEA, 2020). Whilst CCUS is named as one of the industrial priority areas in the European Green Deal action plan (European Commission, 2019), the main policy instrument, the EU Emission Trading System (ETS), does not contemplate biogenic emissions (Moya and Pavel, 2018). At the same time, the large PPI units can offer the possibility to reduce emissions with lower costs than some smaller fossil sources (Garðarsdóttir et al., 2018). The carbon capture potential in the PPI sector in Europe is primarily in the kraft pulp mills, where it enables emission reduction and feasible transformation of a pulp mill into a negative emitter utilizing BECCS (Jönsson and Berntsson, 2012; Kuparinen, 2019; Leeson et al., 2017). BECCS is considered one of the most promising carbon removal technologies, however, lack of policy incentives is seen as the main barrier to prevent investments in BECCS (Fridahl and Lehtveer, 2018). The available technological options are still in the early stages of development (Minx et al., 2018) and the price of carbon allowances has been considerably lower than the cost of CCS (Fuss et al., 2018). However, the prices have notably increased in Europe in 2020 and 2021 (Krukowska, 2021).

The costs of carbon capture primarily depend on scale, partial pressure of CO_2 in the stream, and energy costs. The latter ones have a significant effect on the total costs of the CCUS process (Kearns et al., 2021), and thus low-cost energy and efficient thermal heat integration have a significant impact on economic feasibility. As the PPI processes often have waste heat streams that can be utilized, integrating a CCUS process in a pulp mill can offer additional benefits. The primary CO_2 sources in kraft pulp mills are the recovery boilers, multi-fuel or biomass boilers, and lime kilns. While the recovery boiler is the largest biogenic CO_2 source in a kraft mill, the lime kiln flue gas typically has higher CO_2 content including both process and fuel-based CO_2. Overall, the effect of the capture process on the energy balance of the mill needs to be evaluated.

Both Finnish and Swedish forest industries have several mills that capture minor amounts of CO_2 from combustion processes for producing precipitated calcium carbonate (PCC) that is needed for paper production (Jönsson and Berntsson, 2012); (Kaakkois-Suomen ympäristökeskus, 2005). Teir et al. (2005) estimated that PCC production could eliminate up to 200 kt of CO_2 annually in Finland, considering only the potential within the pulp and paper sector. CO_2 can also be used in several stages of the kraft pulping process, e.g. in tall oil acidulation, brown stock washing and lignin extraction (Ruostemaa, 2018). These processes offer possibilities for on-site utilization of captured CO_2, although their potential to remove CO_2 from the atmosphere is minor in comparison with CO_2 storage. The large-scale significance of utilization of bio-based CO_2 lies within the possibility to produce sustainable alternatives for fossil-based products and the subsequent reduction of fossil CO_2. Pulp and paper mills have an attractive environment considering for example production of formic acid or methanol via electrolysis and CO_2 capture (Kärki et al., 2018). These processes are promising but require further research as well as political support to become feasible.

BECCS is expected to play a large role in Sweden, contributing 1.8 Mt and 3–10 Mt of negative CO_2 emissions in 2030 and 2045 respectively (Karlsson et al., 2021). Currently, Sweden has at least two forest industry CCS projects in a design phase: one that would capture 0.8 $MtCO_2$/a from pulp and paper mill's flue gases and another that would capture 0.26 $MtCO_2$/a from a black liquor gasifier (Torvanger, 2019). If the projects were implemented, the Swedish forest industry would be free from direct fossil CO_2 emissions. In contrast, Finland's national strategy does not include BECCS (Ministry of Economic Affairs and Employment, 2019b) and CCS technologies are not used on a large scale in the forest industry. According to Teir et al. (2011), the large-scale CCS will not be feasible in Finland until 2030 due to technical challenges and lack of incentives for capturing biogenic CO_2. Finnish Forest Industries (2020c) claims that CCS can play a role in the Finnish forest industry from the 2040s. Despite the willingness of the Finnish and Swedish PPI to participate in the development of CCS, the companies press for government collaboration and are not willing to take financial responsibility (Rodriguez et al., 2021).

Large-scale implementation of CCS requires permanent storages for captured carbon. The most usable storages are porous rock formations under the seabed, where the depth of at least 800 m keeps the stored carbon in liquid form. Finland and Sweden do not have suitable underground geological formations, thus storing carbon requires pipeline and/or ship transportation as well as intermediate storages and transport hubs. The storage cost e.g. in Finland will therefore be 10%–20% higher compared with the average cost in Europe (CCSP Carbon Capture and Storage Program, 2016). The structure of the Finnish and Swedish PPI with a high share of virgin fiber raw material processed in kraft pulp mills means that BECCS offers significant opportunities for carbon capture in these countries, given that both BECCS and negative emissions will be contemplated in the EU ETS. Realization of major investments in BECCS requires a predictable operational environment, considering the whole chain from capture to storage. CCS with standardized mechanisms for storage monitoring would enable a more verified route for carbon-neutral pulp and paper products compared with the currently used emissions reduction certificates from voluntary carbon offsetting programs (Klement et al., 2021).

5. Discussion

To reach the zero-emission targets, fundamental transformation and significant technological advancement are needed within the transport, industry, and energy sectors. The EU, as one of the largest emitters globally and simultaneously a frontrunner in international climate policy, is under great pressure to meet global expectations. Over the past decades, both Finland and Sweden have shown good progress in the decarbonization of their economies, utilizing high shares of renewable and low-carbon sources. A significant part of cutting the residual emissions should come from transforming the most challenging sectors like transport and industry (IEA, 2021e). The supplementary measures, such as increased CO_2 uptake by forests or investments in the climate projects abroad, along with the conventional fuel switching and efficiency improvements should facilitate the transition and reach the ambitious targets. The bioenergy and biofuels in Sweden and Finland are currently generated mostly as side-streams of the forest sector, and thus the forest sector will play a key role in the national decarbonization targets.

The fossil CO_2 emissions of the forest industry originate from varying sources, and thus various measures are required to mitigate them. Transport together with non-road mobile machinery is responsible for one-third of fossil CO_2 emissions of the Finnish forest industry and two-thirds in Sweden. The forest industry processes, i.e. lime kilns and dryers, account for roughly one-fifth of the emissions in both countries. With current technologies, the additional use of biofuels is the most viable route to decarbonize both lime kilns and freight transportation. Moreover, biomass has been considered as the main solution for the replacement of peat in energy production in the Finnish mills. The implementation of decarbonizing visions might drastically increase the demand for biomass. Depending on the choice between electrification and bio-based energy in their future scenarios, there is significant pressure to increase and strengthen the availability of sustainable biomass sources. In addition to concerns on availability, uncertainties lie in the costs of biomass and the effects of new fuels on the processes. Side streams from existing processes can be used for internal energy production or as fuels in lime kilns, but, at the same time, they can be sold as valuable products. If more profitable routes are available, the attractiveness of the combustion of side streams will decrease. However, the expected increase in fossil fuel prices, carbon taxes as well as ETS carbon prices will most probably accelerate fuel switching.

Complete decarbonizing of the economy within a time frame of only 10–20 years is unrealistic. Most climate models include the concept of negative emissions to address already generated CO_2 emissions (Geden and Schäfer, 2016). Appropriate policy frameworks that incentivize the investment of CCS in the pulp and paper industry should be promoted and facilitated by decision-makers. The combination of the stationary biogenic CO_2 sources and the access to well-established biomass markets, supply chains, and forest management systems should successfully provide beneficial conditions for BECCS in Sweden and Finland without additional biomass utilization. Sweden is expected to be a pioneer in BECCS application (Fuss and Johnsson, 2021). However, the CCS implementation comes with a considerable investment cost and a significant effect on the plant operating cost, and large-scale implementation of BECCS may also lead to significant growth in biomass demand (Karlsson et al., 2021). In addition, the price of carbon allowances is still lower than the cost of CCS, and previous research has shown that political uncertainty can have a detrimental impact on future price developments (Fuss et al., 2018). The recent study of Rodriguez et al. (2021) indicated that a lack of customer demand for negative emissions along with a lack of supporting policies hinders the incentive to invest in carbon capture. Another important obstacle is that the companies of the forest sector do not feel that they should be expected to go beyond their current sustainability efforts since their share of fossil emissions is already on a low level (Rodriguez et al., 2021).

The forest industry in Finland and Sweden can already be deemed as a carbon-neutral sector if carbon sequestrated by raw materials and emission reduction from the substitution of fossil fuels and materials with bio-based alternatives are considered. New products, as well as bioenergy and fuels produced by the forest industry, will have an important role in the decarbonization of society even though they were out of the scope of this study. The sector has substantial potential to increase its contribution to CO_2 emissions reduction in the future, not only by producing bioproducts but also by reducing the dependence on fossil fuels in other sectors.

6. Conclusions

Climate change is undoubtedly among the most challenging issues of this century. The Nordic countries, i.e. Denmark, Finland, Iceland, Norway, and Sweden, have announced ambitious goals toward decarbonizing their energy systems before 2050. Among others, Finland and Sweden due to their environmental and social similarities offer an interesting possibility to compare the industry development pathways and highlight the most viable decarbonizing measures within them. They are the most forested countries in Europe, and thus the forest industries play an important role in these countries, especially concerning their current transition toward low-carbon societies. In spite of differences in industrial fossil CO_2 emissions and energy production, both countries' visions aim to fast decarbonization. If the countries meet their decarbonization visions, the forest sectors will play a notable role in achieving the national climate targets. Currently, the fossil CO_2 emissions of the forest industry originate from several sources. The single largest user of fossil fuels within a kraft pulp mill is typically the lime kiln, where the fuel switching to "green" fuels is technically possible and deemed a promising measure to achieve more sustainable operation. Decarbonization of the transport, as well as electricity production sector, plays a significant role in achieving the long-term climate and energy targets. The Swedish mills do not use fossil fuels in on-site energy production, but the Finnish ones still need to find alternatives for peat and natural gas. Various measures for eliminating fossil CO_2 emissions from different origins exist, but economic, political and technical barriers are still hindering the deep decarbonization. It can be expected that at least minor CO_2 sources, i.e. fossil fuels as a reserve or emergency fuels, will remain in the mills' fuel mix. However, the Finnish and Swedish forest industries' plans to eliminate industrial fossil fuels use can be considered rather realistic but the future of indirect emissions especially from the transport sector remains unclear. The forest industry has a unique possibility to become carbon negative. BECCS could participate in compensating remaining fossil emissions, but the challenge will be to establish policies that create incentives for mitigating these emissions.

CRediT authorship contribution statement

Satu Lipiäinen: Conceptualization, Investigation, Writing – original draft. **Ekaterina Sermyagina:** Conceptualization, Investigation, Writing – original draft. **Katja Kuparinen:** Conceptualization, Investigation, Writing – original draft. **Esa Vakkilainen:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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