Finnish Forest Industry and Its Role in Mitigating Global Environmental Changes

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1. Introduction

Climate change is currently one of the greatest global threats. Mitigating global warming requires a significant reduction in greenhouse gas (GHG) emissions either by reducing emission sources or enhancing the sinks to remove these gases from the atmosphere. To succeed, long-term structural changes are needed for different sectors, thus creating more balanced and sustainable patterns of energy supply and demand. The forest industry is an energy-intensive sector that emits approximately 2% of industrial fossil carbon dioxide emissions worldwide. Considering the high share of biofuels already used within this sector, the forest industry may shortly become a significant user of bio-based carbon capture technologies. The possibility to implement these technologies can transform pulp and paper mills into negative CO_2 emitters. Moreover, the forest industry can also contribute to GHG emission mitigation outside the mill gates by producing biomass-derived heat, electricity and liquid biofuels, and by providing wood-based products, such as packaging materials, textiles and chemicals, which will substitute the fossil-based alternatives.

The global forest industry has managed to decrease its dependence on fossil fuels as a result of energy efficiency improvement, fuel switching and structural changes, and thus its fossil CO_2 emissions have decreased substantially in the 21st century (International Energy Agency 2020). However, the paper demand is expected to increase from the current 400 Mt/a to 750–900 Mt/a by 2050, and thus there is a huge need to develop towards more sustainable operation in order to avoid an increase in CO_2 emissions. Therefore, more understanding of the possibilities of the forest sector is essentially required. In Europe, the forest sector has ambitious targets to contribute to the mitigation of GHG emissions (CEPI 2011). The sector aims to emission reduction from the 1990 level of 60 $MtCO_2$/a to 12 $MtCO_2$/a in 2050 with an increasingly significant role of generated wood-based materials in substitution of fossil materials in different applications. This book chapter considers the forest industry's possibilities to contribute to the mitigation of environmental change using Finland as a target country. The Finnish Forest Industries have recently presented a roadmap towards low-carbon operation (Finnish Forest Industries 2020a). The roadmap takes into account CO_2 reduction from increased annual forest growth, increased production of bio-based materials and reduction in fossil fuel use in industrial processes, transportation and off-site production of energy. However, there is a lack of academic studies that discuss extensively the CO_2 mitigation possibilities of the forest sector.

Finland is an important producer of pulp, paper, and sawn wood. Besides these traditional goods, Finnish mills are generating a range of innovative wood-based products that will be discussed in this study. Even though the Finnish forest industry is an important energy producer on a national level, it has currently only 13% of fossil fuels in its fuel mix, and therefore fossil CO_2 emissions are already relatively low. The previous reports, however, claim that the Finnish forest industry can become fossil-free by 2035. Finland's government confirmed the National Energy and Climate Strategy for 2030, which should help to achieve a long-term goal of a carbon-free society and keep the stable course for reach 80−95% reduction in GHG emissions from the level of 1990 by 2050 (Ministry of Employment and the Economy 2014). Finland is among the world leaders in the utilization of renewable energy sources, especially bioenergy. The substantial forest resources, developed forest industry and the well-established forest infrastructure mean that wood-based bioenergy has a significant place within the renewable energy sector in Finland. According to Statistics Finland (2020a), the total consumption of energy in Finland amounted to 1362 petajoules (PJ) in 2019 with 38% covered by renewables. Figure 1 provides a historical trend on the total energy consumption from 1970 to 2019 (ibid.). The shift from fossil fuels towards renewable alternatives continues in different spheres, with a significantly increasing increased share of the latter ones in total consumption from the 2010s.

The energy-transition tendencies and general development in the Finnish pulp and paper sector have been analysed in a few recent papers. The efficiency of the Finnish pulp and paper industry has been evaluated and compared to the EU average level (Koreneff et al. 2019). The results of this study showed that while the production efficiency is on a high level, the dominancy of kraft pulp production leads to the notably higher energy intensity of the production process. Lipiäinen et al. (2022) have evaluated the main steps towards decarbonization in Finnish and Swedish pulp and paper industries, highlighting the essential steps performed there to reduce fossil CO_2 emissions and at the same time maintain competitiveness on a high level. While previous works limited their scope to the pulp and paper sector, the current study aims to help in better understanding of the general picture and provides the most updated knowledge on the situation with forest industry in Finland: structure, characteristics, fuel consumption and GHG emissions. In addition, we identify important research directions to facilitate the transition towards a sustainable future.

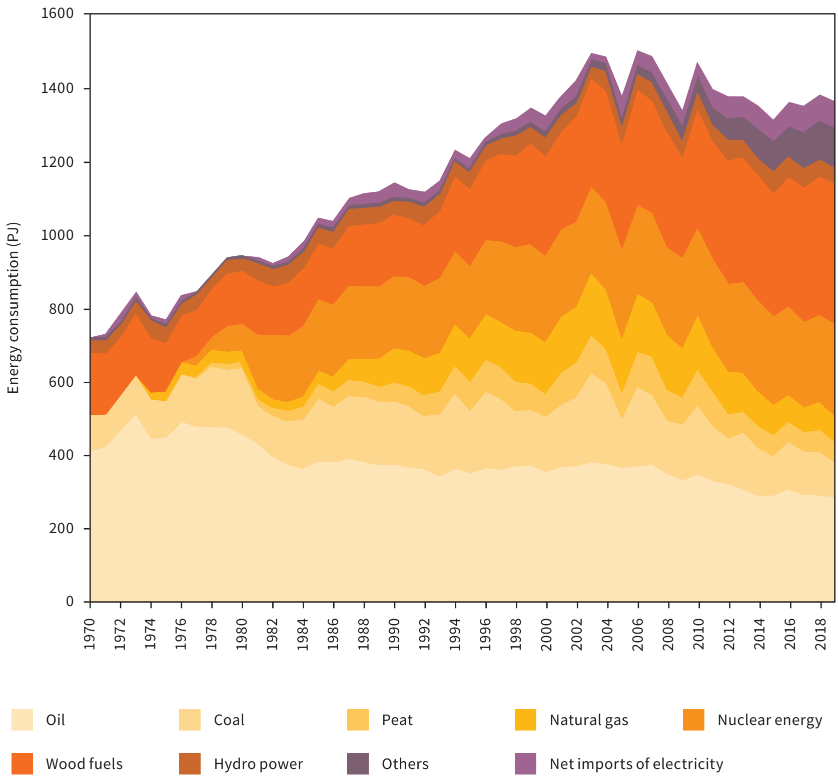

Figure 1. Total energy consumption in 1970–2019 in Finland. Source: Graphic by authors based on data from Statistics Finland (2020a).

2. Methods

2.1. Data Gathering

Data were gathered from several sources to evaluate both the current state and the development of the Finnish forest sector. The main sources for energy consumption, production and emissions were Finnish Forest Industries and Statistics Finland databases (Finnish Forest Industries 2020b; Statistics Finland 2020c). During the study, a large number of previous studies were reviewed and the Finnish forest sector's possibilities to participate in mitigation of climate change were evaluated.

Moreover, the emerging forest industry projects, such as the production of new bioproducts in Finland, have been identified and introduced.

2.2. Energy Efficiency Index Method

Energy efficiency development in the Finnish forest industry was studied using the energy efficiency index method. The method was applied in the previous study for assessing energy efficiency development in the pulp and paper industry (Lipiäinen et al. 2022). The present work follows the same method and uses the same reference-specific energy consumption values.

3. Finnish Forest Industry

The forest industry is a globally important industrial sector. Several wood-based products, such as paper, paperboard and sawn wood participate in people's everyday life. The forest industry can be divided into the chemical forest industry that produces mainly pulp and paper, and the mechanical one that focuses on producing sawn wood and wood-based panels. The global forest industry produced 188 Mt of wood pulp, 409 Mt of paper, 493 Mm^3 of sawn wood and 408 Mm^3 of wood-based panels in 2018 (Food and Agriculture Organization of the United Nations 2019).

In 2019, Finland produced 30%, 11% and 7% of European pulp, paper and board, and sawn wood, respectively (CEPI 2019; Food and Agriculture Organization of the United Nations 2019). 73% of produced pulp was kraft (sulphate) pulp. The rest consists of mechanical, chemi-mechanical, and semi-chemical pulp. Within paper production, the major shares had printing and writing papers (47%), and packaging materials (45%). A minor amount of newsprint and hygiene papers were produced. The Finnish forest industry has been recently going through a structural change (Kähkönen et al. 2019). The development of information technology has led to a decrease in the consumption of printing and writing papers (Johnston 2016), whereas the demand for packaging materials has increased globally (Hetemäki et al. 2013). The changes in the production volumes between 1990 and 2019 are presented in Table 1. Production of newsprint, printing and writing papers has declined and several mills have been closed, while substantial growth in volumes of chemical pulp, packaging materials and sawn wood has taken place. The role of new products, such as chemicals, biofuels, and energy, is increasing, and forest industry companies are looking for new product opportunities, which will be discussed later.

Table 1. Production volumes in the Finnish forest industry.

Grade	1990	2019	Change
Domestic wood usage [Mm^3]	44	61	+38%
Imported wood usage [Mm^3]	6	10	+66%
Chemical pulp [Mt]	5.16	8.72	+69%
Mechanical pulp [Mt]	3.73	3.28	−12%
Newsprint [Mt]	1.43	0.27	−81%
Printing and writing paper [Mt]	4.68	4.60	−2%
Packaging materials [Mt]	2.32	4.44	+91%
Household and sanitary papers [Mt]	0.16	0.20	+22%
Other paper and paperboard [Mt]	0.37	0.20	−46%
Sawn wood [Mm^3]	7.50	11.39	+52%
Wood-based panels [Mm^3]	1.34	1.29	−4%

Source: Data from Food and Agriculture Organization of the United Nations (2020) and Nature Resource Institute (LUKE) (2020).

The forest industry, especially the pulp and paper industry (PPI), is an energy-intensive sector. The PPI is the fourth largest industrial energy user and globally it consumed 7 EJ of energy in 2018 (International Energy Agency 2018). The share of biofuels was 48%, which is 18% higher than at the beginning of the 2000s. Energy demand per ton of produced paper has decreased substantially, and fuel switching together with increased efficiency has led to lower fossil CO_2 intensity. In Finland, the manufacturing of forest industry products is by far the largest industrial energy consumer, which accounts for more than half of total industrial energy use: 316.8 PJ in 2019 (Statistics Finland 2020b). The forest industry is also a significant energy producer: it can cover a major share of its heat demand and about half of its electricity demand. This highlights the importance of efficiency improvement and cost-efficient reduction in GHG emissions along with the promotion of clean and sustainable technologies for this energy-intensive sector. The characteristics of energy use and emissions in the Finnish forest industry are presented in Table 2.

Table 2. Energy and emissions in the Finnish forest industry in 2019.

Energy and Emissions	Finnish Forest Industry	Share in Total Domestic Values
Electricity consumption	19.3 TWh/a	22.4%
Electricity production	10.1 TWh/a [1]	15.3%
Energy consumption	316.8 PJ/a	23.3%
Dominant energy sources	Biomass 87%, NG 5% [2]	-
Fossil CO_2 emissions	2.7 Mt/a [2]	5.1%
NO_x	17.5 kt/a	10.9%
S	1.7 kt/a	10.9%

[1] 2016 electricity production used due to lack of data. [2] Include only on-site fuel use. NG = natural gas. Source: Data from Finnish Forest Industries (2020b) and Statistics Finland (2020c).

4. Climate Change Mitigation Opportunities in the Forest Industry

Climate change mitigation requires both reducing GHG emissions and enhancing carbon sinks. There is no single solution to solve the problem of climate change, but a wide range of solutions is needed, some of which are more mature than others. The forest industry has a significant role in promoting these in Finland. Sustainable forest management enables not only the efficient utilization of forest resources but also their increase thus enhancing the role of forests as carbon sinks. Many changes and challenges have already transformed the forest industry in Finland in recent years and there should be more developments to come to adapt to the rapidly changing global situation. Modern pulp mills are expanding the traditional concept of pulp mills by introducing the combination of multifunctional biorefineries and energy plants that utilize wood resources to produce not only pulp but also energy as well as new high-value products from side-streams and residues.

Previous studies have estimated the contribution of the forest sector to mitigation of climate change by direct or indirect CO_2 emission reduction (e.g., Finnish and Swedish roadmaps). Based on the results from the previous studies, the main possibilities for the forest industry are addressed in the present work:

- Direct CO_2 emissions reduction;
- Green energy production
- Bio-based materials.

The present study does not consider forest management but assumes that wood used by the forest industry is sustainably harvested.

4.1. CO_2 Emissions and the Reduction Possibilities

The Finnish forest industry emitted 2.7 Mt of fossil and about 22 Mt of biogenic CO_2 in 2019 (Finnish Forest Industries 2020b). The mechanical forest industry is a minor energy user and CO_2 emitter in comparison to the chemical forest industry. A large part of CO_2 produced in a pulp and paper mill comes from biomass combustion and can be considered carbon-neutral when the wood is from a sustainable origin. The fossil CO_2 emissions from the PPI are energy-related, which makes their reduction easier compared with for example the cement industry, since it does not require direct process modifications. The lime kilns also produce process-related CO_2 emissions, but they are largely biogenic. The fossil CO_2 emissions have decreased by 44% over the last 20 years (1999–2019) (Figure 2). Emissions per ton of product decreased by 37% from 194 to 122 kg_{CO2}/ton. The industrial strike in 2005 and the economic crisis around 2009 decreased absolute emissions strongly due to a significant drop in production volume. During those crises, emissions per ton of product did not change significantly. The reforms in energy taxation around 2003 and 2011 have most probably contributed to the drops in emissions. The European Union (EU) introduced Emission Trading System (ETS) in 2005. It may have affected the fossil CO_2 emissions, but it has been argued that ETS has had only a limited effect on the PPI due to excess emission allowances (Gulbrandsen and Stenqvist 2013). After a period of steady emission levels between 2012 and 2016, the emissions have been declining again. The emissions are expected to continue to decline in the future as the Finnish forest industry is aiming towards net-zero emissions. A recently published report argues that nearly zero emissions can be achieved in 2035 (Pöyry 2020).

The primary means to reduce CO_2 emissions of the PPI are switching to low-carbon fuels, electrification, and energy efficiency improvement. Carbon capture and storage (CCS) technologies that initially had been aimed mainly at the power sector, have significant potential in the PPI. In Finland, the role of the forest industry in mitigating environmental change and meeting the national carbon neutrality target by 2035 is not limited to emissions reduction in the mills (Lipiäinen and Vakkilainen 2021). The PPI supplies green electricity to the grid and produces other renewable energy carriers. Moreover, it has been evaluated that products of the Finnish forest industry can annually mitigate 16.6 Mt of CO_2 emissions (Finnish Forest Industries 2020b). However, forests are a significant carbon sink, and therefore they must be managed sustainably to achieve emission reductions.

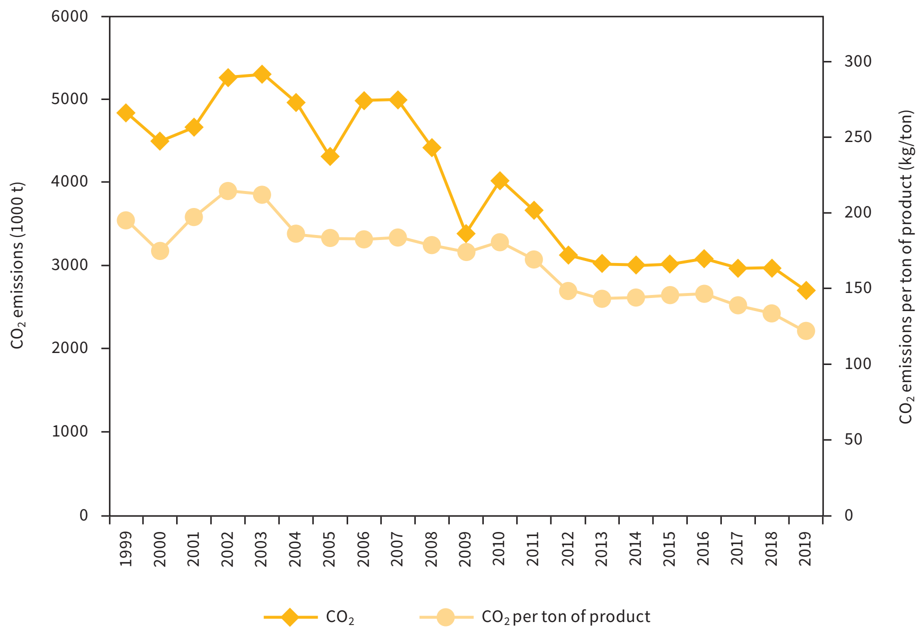

Figure 2. Trends in fossil CO_2 emissions in the Finnish pulp and paper industry. Source: Graphic by authors based on data from Finnish Forest Industries (2020b).

4.1.1. Fuel Switching

The largest part of fossil-based CO_2 emission savings is expected to come from replacing the current use of fossil fuels with renewables (Moya and Pavel 2018; Metsäteollisuus ry 2020). The forest industry typically meets a large share of its energy demand by its own production. A modern stand-alone pulp mill can even surpass its heat and electricity demand by combusting wood residues (IRENA et al. 2018). Black liquor, a side-stream from kraft pulping, is the most important biofuel in the PPI. Mills combust it in the recovery boilers, and many mills have an additional power boiler for combusting wood residues. The boilers supply steam for the processes and for turbines to generate electricity. In the modern stand-alone pulp mills, fossil fuel consumption can be limited to start-ups, shutdowns, and other exceptional situations, but many mills still combust fossil fuels in the lime kilns, mainly natural gas or oil (Kuparinen et al. 2019). Stand-alone paper mills and some integrated pulp and paper mills cannot meet their energy demand by combusting their own residues. These mills either combust fossil fuels or purchase energy. Many kraft pulp mills produce an excess of electricity that is typically sold but can be also used for hydrogen or e-fuels generation. However, the role of electrification is estimated to be minor in the emission reduction within the Finnish forest industry, mainly it is expected to substitute for natural gas use.

Biomass has been an important fuel in the Finnish forest industry for a long time, but the fuel mix includes also natural gas, oil, coal, and peat (Figure 3). In 1990, the share of biofuels was 64%, natural gas covered 15%, and oil, coal, and peat stand for approximately 7% each. In 2019, the share of biofuels had increased to 87%, and the shares of natural gas, peat, oil, and coal were decreased to 6%, 3%, 2% and 1%, respectively. Peat is a specific fuel in Finland that is typically co-fired with biomass in power boilers. The recent political decisions in Finland promote the replacement of coal and peat by biomass. Increased volumes of chemical pulp have increased the use of biofuels, but many mills have also actively looked for solutions to decrease the use of fossil fuels. Currently, biomass has been seen as the most potential alternative for fossil fuels in the Finnish forest industry, and other renewables have not played a large role. The possibility to use wind power for covering paper mills' energy demand has been recently realized with a long-term Wind Power Purchase agreement of Finnish company UPM with German wind park development company (wpd) (UPM Communication Papers 2020). This agreement will enable the decrease in CO_2 emissions by 200,000 tonnes annually starting from 2022 and help to achieve the company's ambitious 65% CO_2 emission reduction target by 2030. In addition, UPM is utilizing hydropower sources and upgrading the performance of the existing hydropower plants (UPM Energy 2021).

The lime kilns are the primary fossil fuel users in chemical pulp production. CO_2 is produced from both the combustion and the actual lime regeneration reaction during the calcining process. The CO_2 from the reaction originates mainly from wood and is thus biogenic. The lime kiln process requires stable combustion conditions and easily controllable hot-end temperature. Consequently, fuel characteristics and quality should be consistent (Isaksson 2007). In addition to fossil fuels, alternative fuels such as methanol, tall oil, strong odorous gases, tall oil pitch, hydrogen, and turpentine are often co-fired in the lime kilns. Technically, it is also possible to utilize existing side-streams to substitute for fossil fuels there (Kuparinen and Vakkilainen 2017). However, biomass fuels typically have lower adiabatic flame temperature and lower energy content than fossil oil or natural gas. Therefore, higher firing rates are required to maintain the kiln capacity in the case of biomass supply. Another problem is that the impurities that originated from the solid biomass tend to accumulate in such a closed cycle process. These non-process elements can cause, e.g., corrosion and ring formation in the kiln and decrease the lime quality. The use of alternative fuels can thus lead to increased use of make-up lime and should be evaluated thoughtfully.

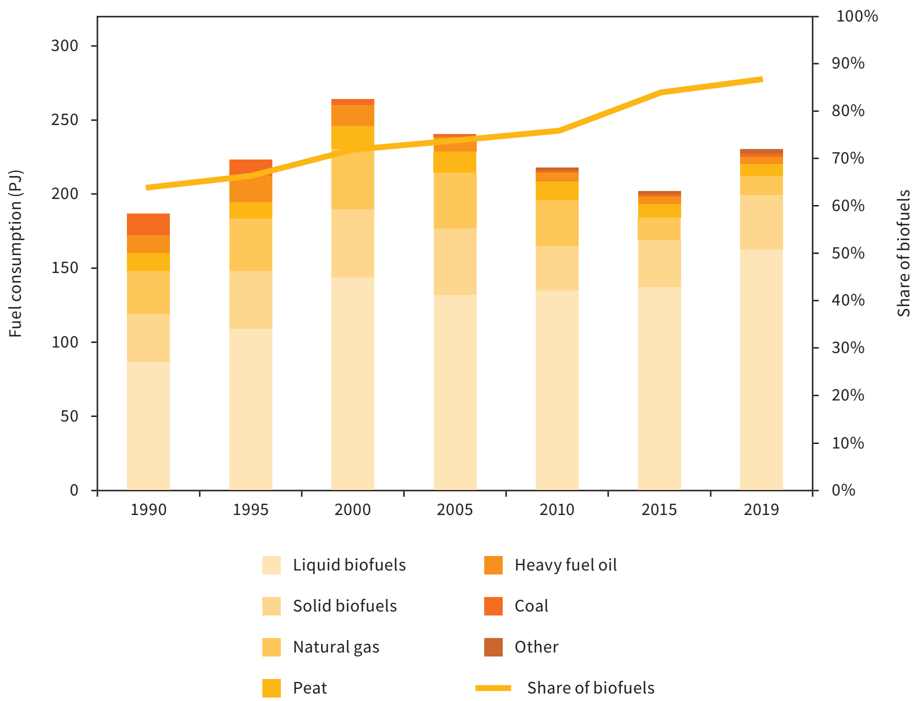

Figure 3. Development of fuels use in the Finnish forest industry. Source: Graphic by authors based on data from Finnish Forest Industries (2020b).

4.1.2. Energy Efficiency Improvement

Improvement of energy efficiency has played a notable role in the reduction in CO_2 emissions so far (European Commission 2018). Efficient reduction in heat losses, recovery of process heat and process optimization offer further possibilities for emissions reduction but require other concurrent actions to achieve the climate goals. The Best Available Technologies (BAT) reference document (European Commission 2015) presents state-of-the-art technologies. Energy efficiency is however not a straightforward concept. It is often measured by specific energy consumption (SEC), i.e., the energy consumed for the production of a unit of product. However, a change in SEC may result for example from increased utilization rate instead of improvements in energy efficiency. The forest industry is a heterogeneous sector with a diverse product portfolio and highly energy intensive production processes.

No uniform practice on collecting process information exists. The collection of reliable process information is necessary for efficiency improvement. While in general, the increased energy efficiency leads to a decrease in CO_2 emissions, an energy-efficient mill is not necessarily CO_2 efficient due to different products, process alternatives, and mill configurations. Stenqvist and Åhman (2016) noticed that the benchmark-based emission allowance allocation of the EU ETS does not result in the best performance in a heterogeneous sector like the PPI due to, e.g., lack of benchmark curves and biased reference values.

Energy efficiency within the forest industry can be improved by new technologies but also new modes of operation. Energy audits, motivated and competent employees, and process monitoring and control advance energy efficiency (Vakkilainen and Kivistö 2014). Finland has a long history of energy auditing, and both mandatory and voluntary energy auditing schemes are carried out to measure energy consumption and identify energy-saving opportunities (Ministry of Economic Affairs and Employment of Finland 2021). The Finnish know-how on energy audits has also been relied upon in other countries building their own audit schemes (Motiva Ltd. 2019). Enhanced process integration typically improves energy efficiency. The pulp and paper production processes result in secondary heat streams, whose further utilization would improve the total efficiency. The ongoing transformation from traditional pulp and paper mills to modern multi-product biorefineries offers a possibility to utilize these in the production of advanced bioproducts. Another viable option is improved drying techniques that help to reduce emissions from one of the most energy-intensive process stages.

The Finnish forest industry has been historically an energy-efficient operator (Fracaro et al. 2012). Finnish pulp and paper production is already rather efficient, despite the need for heating due to the cold climate. Compared to the EU average, the Finnish mills are large, efficient, and modern (Koreneff et al. 2019). Nevertheless, it is still possible to increase efficiency. The development of the forest industry's efficiency is presented in Figure 4. Between 2002 and 2019, primary energy efficiency and electricity efficiency improved 1.4% and 1.2% per year, respectively. The strike in 2005 and the economic crisis around 2009 decreased the efficiency because several mills were operating only part of their capacity. Several factors, such as closures of old mills, start-ups of new mills, technology development and increase in energy prices, have contributed to the efficiency improvement (Kähkönen et al. 2019).

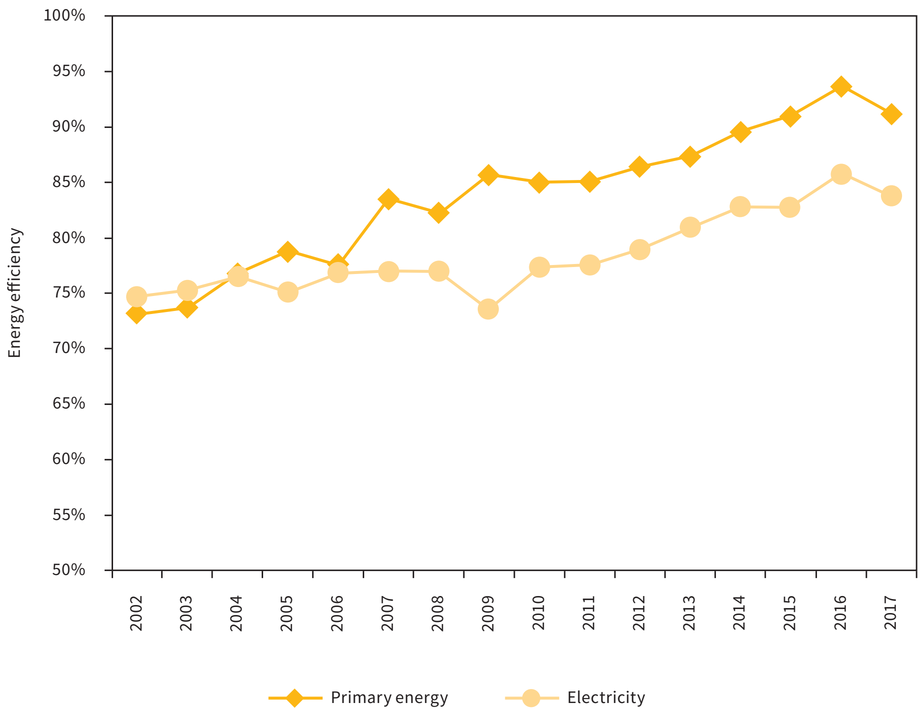

Figure 4. Trends in energy efficiency in the Finnish forest industry. Source: Graphic by authors based on data from Statistics Finland (2020c), Food and Agriculture Organization of the United Nations (2019) and Finnish Forest Industries (2020b).

4.1.3. Carbon Capture Technologies

When the target is net-zero or even negative emissions, carbon capture, utilization, and storage (CCUS) technologies have to be included in the palette. CCUS has a remarkable role in many decarbonizing scenarios, especially in the ones that include fossil fuels in the energy mix also in the future (European Commission 2018). Bioenergy with carbon capture and storage or utilization (BECCS/U) is one of the key negative emission technologies. The pulp and paper industry, being a significant bioenergy producer, has a unique possibility for the implementation of BECCS/U. The global technical capture potential from kraft pulp mills has been estimated at approximately 137 Mt_{CO2}/a (Kuparinen et al. 2019). One of the primary concerns regarding large-scale utilization of BECCS/U is increased land use since BECCS/U is often seen as promoting additional use of biomass for energy. Large existing pulp and paper units however offer the possibility to implement BECCS/U without additional biomass harvesting. The main weaknesses of BECCS/U currently are the lack of experience and political support. Public acceptance and uncertainties on the long-term behaviour of the stored carbon have also hindered their implementation in the EU (European Commission 2018). Besides, carbon capture processes require heat and electricity. Therefore, their integration into a mill affects the mill's energy balance and total CO_2 emissions.

The primary CO_2 sources in the PPI are the combustion processes, namely the recovery boilers, the power boilers, and the lime kilns. The minor CO_2 sources include, e.g., non-condensable gas destruction and biosludge treatment to produce biogas in some mills. The magnitude of the recovery process is often not fully appreciated. In 2016, the global sulphate pulp production was 137 Mt (FAO 2017). Consequently, more than 1300 Mt of weak black liquor was processed in recovery boilers globally and 206 Mt of black liquor dry solids were combusted to produce about 1.8 EJ of energy (Tran and Vakkilainen 2008). According to (International Energy Agency 2018), it makes black liquor the fifth most important fuel in the world after coal, oil, natural gas, and gasoline, and the most used biofuel globally. Therefore, the recovery boilers alone offer a notable possibility for BECCS/U.

The capture of biogenic CO_2 from the pulp and paper mill processes is a little-studied subject so far (Leeson et al. 2017). Recent publications (IEAGHG 2016; Kuparinen et al. 2019) have however indicated the technical feasibility of BECCS/U within the pulp mills. Several technologies including pre-combustion, post-combustion and oxy-combustion methods can be applied to pulp and paper mills. Many of these are in the development stage. The most studied capture method is the monoethanolamine (MEA) process (Onarheim et al. 2017; Leeson et al. 2017). The commercial MEA process is a post-combustion method and thus can be easily applied to existing mills. Based on earlier estimates, the cost of CO_2 avoided in pulp mills ranges between 20 and 92 EUR/t_{CO2} depending on the chosen processes and mill characteristics (Fuss et al. 2018; IEAGHG 2016).

CO_2 is typically seen as emission or waste; its value as a raw material for carbon-based products has not been recognized until recently. CO_2 conversion technologies include biotechnical and chemical or catalytic processes, a few of which have been commercialized so far (Lehtonen et al. 2019). The value of captured CO_2 as a raw material can be a push for cost-effective carbon capture. It has a wide range of potential utilization routes in industrial and chemical applications, where it currently comes mostly from fossil sources. CCU processes enable CO_2 recycling and therefore reduction in the CO_2 in the atmosphere. Net negative CO_2 emissions can be reached only if at least part of the captured CO_2 is stored or utilized in a process that permanently removes it from the atmosphere. Using it for fuel production, for instance, delays the release and enables the indirect reduction in the atmosphere, if the fuel is used to substitute for traditional fossil fuels.

The possibilities to utilize CO_2 in the PPI depend on mill-specific details. Currently, the chemical forest industry utilizes CO_2, e.g., for pH control and in brown stock washing. Instead of purchase, it can be captured from the mills (Ruostemaa 2018). Carbon capture from lime kiln flue gases and subsequent use as calcium carbonate paper filler (precipitated calcium carbonate, PCC) is a well-known and widely applied technology (Hirsch et al. 2013). In 2005, Teir et al. (2005) estimated that the potential to eliminate CO_2 emissions considering only the PCC used in the PPI in Finland would be 200 kt/a. Apart from this, softwood pulp mill typically produces tall oil as a by-product. Raw soap is separated from black liquor and converted to crude tall oil by acidulation, typically using sulfuric acid. Part of the acid, up to 50%, can be replaced by CO_2. Tall oil can be further converted to renewable fuels and used to substitute for fossil alternatives. Another relevant alternative is lignin separation from black liquor using sulfuric acid, which can be also replaced by CO_2: 150–250 kg_{CO2}/t_{lignin}.

The reduction in direct CO_2 emissions by fuel switching and energy efficiency improvement can avoid up to 2.5 $MtCO_2$ of emissions, which correspond to 5% of the Finnish total fossil CO_2 emissions. Moreover, capturing biogenic CO_2 has a significant potential to provide extended climate benefits.

4.2. Green Energy

Wood-derived energy made up 74% of total renewable energy in Finland in 2019 with the largest share covered by black liquor combustion (47.2 TWh) (Natural Resources Institute 2019). According to the Natural Resources Institute (2019), solid wood fuels used at power and heating plants accounted for 39.5 TWh, the small-scale combustion of wood comprised 16.8 TWh and other wood fuels covered 2.1 TWh in 2019. Wood energy resources for energy generation are typically used in highly efficient district heating (DH) systems and combined heat and power (CHP) plants (Alakangas et al. 2018). Several examples of biomass-fired CHP plants in Finland are given in Table 3. All presented plants rely mainly on woody biomass with a minor share of energy peat in consumption.

Table 3. Biomass-fired CHP plants in Finland.

Power Station	Location	Electricity	Heat	Fuel	Reference
Alholmens Kraft power plant	Jakobstad	265 MW	60 MW DH 100 MW process heat	forest residues peat	Alholmens Kraft (2020)
Vaasa power plant	Vaasa	230 MW	175 MW DH	wood and peat coal	Vaskiluodon Voima (2017)
Keljonlahti power plant	Jyväskylä	130 MW	260 MW DH	wood peat	Alva (2020)
Kaukaan Voima power plant	Lappeenranta	125 MW	110 MW DH 152 MW process heat	forest residues energy wood peat	Kaukaan Voima Oy (2019)
Seinäjoki power plant	Seinäjoki	120 MW	100 MW DH	forest chip swood residues recycled wood peat	Vaskiluodon Voima (2017)

Most of the bioenergy in Finland is produced in pulp and paper mills. The modern pulp and paper mills and sawmills operate with an integrated approach by using the residuals and by-products producing heat and power, biofuels and biomaterials (Kuparinen et al. 2019). Figure 5 presents some alternative technologies to produce biofuels or bioenergy by conversion of kraft pulp mill side streams. Many of these technologies are already used in Finnish mills and some, such as the production of synthetic hydrocarbons, are new possibilities.

Pulp and paper mills generate large amounts of sludges during wastewater treatment, which can be converted to renewable energy streams. Due to their high water content and poor dewaterability, pulp and paper mill sludges are extremely problematic streams, which are generally incinerated with low efficiency (Hagelqvist 2013). Anaerobic digestion is a noteworthy alternative to convert sludge into valuable commodities, i.e., biogas (mainly methane) and digestate (Bakraoui et al. 2019a, 2019b). Numerous studies have shown that most pulp and paper mill effluents can be to some extent anaerobically treated (Meyer and Edwards 2014; Bayr 2014). Hydrothermal carbonization (HTC) is another promising path to treat sludge, which has been actively studied at a laboratory scale (Saha et al. 2019; Areeprasert et al. 2015; Mäkelä et al. 2016). HTC converts sludge into hydrochar with upgraded properties that can be then combusted more effectively. World's first OxyPower HTC biofuel plant for sludge recycling is recently built by C-Green Technology in Heinola, Finland (C-Green Technology AB 2019). The facility will recycle 16,000 tons of biosludge annually at Stora Enso's fluting paper mill to reduce annual CO_2 emissions by 2500 tons.

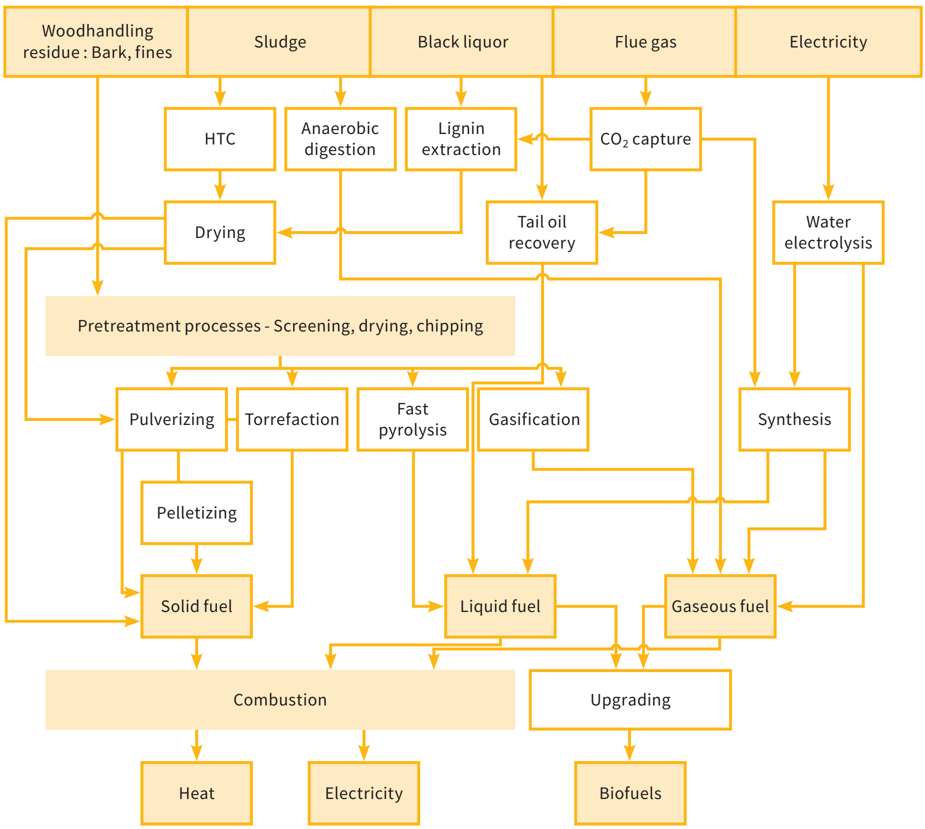

Figure 5. Alternative technologies for bioenergy and biofuel production by the usage of kraft pulp mill side streams. Source: Graphic by authors.

The most widely proposed utilization for captured CO_2 is the production of synthetic hydrocarbons from H_2 and CO_2 (Lehtonen et al. 2019). These hydrocarbons represent possible substitutes for fossil fuels in energy generation. Currently, H_2 is mostly produced from fossil fuels, usually, natural gas, using a steam reforming process, but renewable H_2 can be produced via electrolysis. Synthetic hydrocarbons produced from H_2 and CO_2 can be considered carbon neutral if H_2 is produced using renewable electricity and CO_2 originates from biomass or direct air capture. E-fuels and advanced biofuels have the significant benefit of being suitable for conventional engines and the traditional distribution infrastructure. Pulp mills offer an attractive option for integration of these processes due to their own production of renewable electricity, availability of biogenic CO_2, and abundant secondary heat streams.

Some examples of emerging technologies that may change the PPI in the future:

- Black liquor gasification is a promising technology to increase self-generation capabilities in the PPI. The process aims to replace the recovery boiler and produce energy, chemicals and fuels (Naqvi et al. 2010; Consonni et al. 2009). Despite of some technical difficulties, this technology can possibly provide significant investment returns along with energy and environmental benefits (Consonni et al. 2009; Bajpai 2016).
- Hydrogen production. The conversion of mill's streams to hydrogen-rich gases is actively studied recently. Supercritical water gasification (SWG) of black liquor is an innovative method to produce H_2-rich gases (Cao et al. 2020; Casademont et al. 2020; Özdenkçi et al. 2019, 2020). SWG is a potentially cost-effective way to improve pulp mill profitability (Özdenkçi et al. 2019). The applicability of SWG towards sludges was also intensively studied. This is a promising way to produce high-quality fuels like methane, H_2 and heavy oils (Zhang et al. 2010; Rönnlund et al. 2011).

Increased production of green electricity can contribute to grid decarbonization, and thus reduce CO_2 emissions from electricity generation. The new biofuels generated by the forest industry can play an important role in the decarbonization of other sectors. Some sectors are considered challenging or even impossible to electrify, and consequently, renewable fuels present a viable solution for their emission reduction. Decreasing the fossil fuel dependency in the heavy road, marine and air transport, for instance, most probably requires large amounts of bio-based and synthetic fuels.

4.3. Bio-Based Materials

Wood-derived materials are actively used in various applications, such as the production of paper, packaging, cosmetics, construction materials, composite and textile products. New innovative products are being constantly developed alongside the traditional ones in response to global challenges. Using wood to substitute intensive materials and fossil fuels can provide significant climate benefits (Leskinen et al. 2018). In addition, bio-based materials have a major role in climate change mitigation through temporary carbon storage (Jørgensen et al. 2015). Nowadays, besides the range of the standard products, such as pulp, tall oil, bark, turpentine, electricity and process steam, the forest industry mills can offer additional bioproducts such as textile fibres, biocomposites, fertilizers, biofuels and various cellulose- and lignin-derivatives. Finnish companies are actively expanding their product portfolio to new value chains thus allowing the Finnish forest industry to be successfully transformed into a bioproduct industry (Ministry of Economic Affairs and Employment 2017). One good example is Metsä Fibre bioproduct mill in Äänekoski, Finland (Metsä Group 2018). This unique mill is based on traditional kraft pulping technology and produces typical pulp mill products as well as a range of other commodities, such as product gas from bark gasification, sulphuric acid from odorous gases, biogas, biopellets from sludge digestion and biocomposites. The mill is highly self-sufficient in terms of electricity, producing 2.4 times more electricity than needed for mill operation.

The development of novel biomaterials from wood and produced with a reduced carbon footprint contributes significantly to the sustainable approach and brings higher flexibility to the forest industry. The most promising wood-based products for emerging markets are discussed in the following:

- Biochemicals and biofuels: Wood-based chemicals are considered as one of the main possibilities to compensate for the decline in revenues of PPI from reduced demand for graphic papers (Ignatius 2019). The main route is producing acids and alcohols by fermenting monomeric sugars from sawdust and chips (Hurmekoski et al. 2018). Biochemicals can be used for biofuels production, the need of which is expected to increase towards 2030 (Hurmekoski et al. 2018). The Finnish Parliament has approved a law that sets a gradually increasing 30% biofuels target for 2030. The tall oil-based technology route to generate renewable diesel seems effective and economically competitive (Heuser et al. 2013; UPM 2021b). The world's first UPM biorefinery in Lappeenranta, Finland uses the hy)drotreatment technology to produce UPM BioVerno diesel and naphtha from crude tall oil. The BioVerno diesel shows superior fuel properties in comparison with regular diesel and first-generation ester-type diesel fuel (Heuser et al. 2013).
- Biocomposites: A combination of biomass-derived fibres (mostly based on natural cellulosic fibers) with either virgin or recycled polymers offers a valuable alternative to oil-based plastics. Lignin-reinforced bioplastics have recently gained attention worldwide (Yang et al. 2019; Thakur et al. 2014). Finnish company Woodio has recently developed the world's first 100% waterproof wood composite of wood chips and resin-based adhesives that has a wide range of possible applications (Woodio 2021).

- Bio-based textiles: Dissolving wood pulp is a sustainable replacement for cotton and synthetic fibres in the textile and clothing industries, and its global production is increasing steadily (Kallio 2021). New textile wood-based fibre production technologies to manufacturing such materials as viscose and lyocell are actively investigated and applied. Innovation company Metsä Spring is launching a demo phase project in Äänekoski, Finland to produce the textile fibre Kuura®, which is produced by a novel direct-dissolution method (Metsä Group 2021). The carbamate, BioCelSol and Ioncell-F are sustainable and safe cellulose dissolution technologies recently developed in Finland (VTT 2017).
- Lignin-based materials: The majority of lignin is consumed as a fuel on-site, and only about 5% of lignin is currently utilized for the production of value-added products (Dessbesell et al. 2017). At the same time, lignin has potential for numerous applications: as a precursor for carbon fibers (Souto et al. 2018; Mainka et al. 2015), resins and adhesives (Cheng et al. 2011) and within different other applications (Kienberger 2019). Stora Enso's Sunila pulp mill, Finland is the largest integrated kraft lignin extraction plant in the world (50,000 tonnes of extracted lignin annually) (Stora Enso 2020). The new pilot plant to use lignin for manufacturing a graphite replacement for energy storage applications is currently under construction there.
- Nanocellulose: Cellulose nanomaterials possess a range of promising properties that enable their utilization in diverse applications, including packaging, filtering, biomedical applications, energy and electronics, construction and so forth (Lin and Dufresne 2014; Dhali et al. 2021). Stora Enso runs the world's largest micro-fibrillated cellulose (MFC) production facility at Imatra, Finland (Stora Enso 2019). MFC is used to produce an MFC-enhanced liquid packaging board New Natura™, which has extra strength and low weight. Another Finnish company, UPM, is implementing a novel method to produce wood-based cellulose nanofibril hydrogel GrowDex® for 3D cell culturing and other biomedical applications (UPM 2016). UPM is also producing a nanocellulose-based wound dressing FibDex® that provides an optimal environment for wound healing (UPM 2021a).
- Hemicellulose products: Hemicelluloses are generally burned along with lignin in the kraft pulp mills; however, the cost-effective extraction method would enable their more efficient utilization. Water solubility, biodegradability and amorphous structure make hemicellulose a promising precursor for high-value applications. It can be used as an environmentally friendly and inexpensive emulsifier to stabilize food, cosmetic and pharmaceutical products (Carvalheiro et al. 2008). Also, it can be hydrolyzed to produce biofuels and chemicals

(Hurmekoski et al. 2018). CH-Bioforce, a Finnish start-up company, has developed a method of biomass fractionation, which can be used to extract effectively biomass components (Bioforce 2020).

In addition to the aforementioned products, other concepts are being actively developed, such as advanced materials (porous cellulosic materials, coatings, films, foams), fertilizers and earthwork materials (Fabbri et al. 2018). Novel products bring additional flexibility to the mills, however, the production of new commodities may be significantly constrained by the availability of by-product flows within the mills (Hurmekoski et al. 2018).

The forest industry has significant potential to participate in the substitution of fossil-based materials in various sectors, and thus it plays a major role in creating and developing bioeconomy. The products of the Finnish forest industry already provide substantial climate benefits, but it is expected that the benefits will expand even more in the future (Finnish Forest Industries 2020a).

5. Conclusions

Climate change increases the significance of forest energy. The circular economy goals outlined globally, and within the EU, include improvements in material and energy efficiency, a realization of industrial symbiosis potential and a significant increase in the use of residues and wastes as valuable raw materials. Combining different technologies and using the potential of wood resources to the highest extent can boost energy and economic efficiency by providing fuel flexibility along with a wide range of products generated with a reduced carbon footprint.

Sustainability and life cycle thinking play a major role in the development of a circular economy in the forest sector in Finland. Finnish forest industry companies are constantly improving their energy efficiency and decreasing their dependency on fossil sources. The structural changes affecting the forest industry sector bring simultaneously new opportunities through novel outputs. The use of the best available techniques, tighter emissions regulations and emission-related costs are enabling a more effective transition of the forest industry towards effective biorefineries. Modern Finnish pulp and paper mills and sawmills operate with an integrated approach by utilizing the process residuals for producing renewable heat, power, and bioproducts. Among the most promising wood-derived products are biofuels, textile fibres, biocomposites, fertilizers, various cellulose- and lignin-derivatives. Carbon capture technologies have a remarkable potential within the PPI. While producing a significant amount of bioenergy, pulp and paper mills integrated with CO_2 capture technologies can become major sources of negative

CO_2 emissions. At the same time, as long as the political environment for bioenergy carbon capture is uncertain, the future potential is extremely challenging to evaluate.

The climate benefit from forest industry products in Finland has been estimated to be currently 16.6 $MtCO_2$, and it is expected to increase in the future. Many of the new bioproducts are in an early stage of development and thus further studies are needed to bring them to the markets. Replacement of fossil fuels used and efficiency improvement in the Finnish pulp and paper mills can lead to roughly 2.5 $MtCO_2$ emission reduction, which corresponds to approximately 5% of the domestic CO_2 emissions. An increase in demand for biomass sources might be the major challenge in the replacement of fossil fuels. While the role of forests as a carbon sink was out of the scope of this study, it is worth noting that the improved forest management can substantially enhance carbon removal from the atmosphere. As the aforementioned examples show, the possibilities of the forest industry to contribute to the mitigation of environmental changes evaluated on the Finnish example are certainly impressive. However, further studies are needed to enhance understanding of climate benefits of different solutions and to release the potential of the forest sector by overcoming technical, economic and political barriers.

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