# THE ROLE OF PULP AND PAPER INDUSTRY IN THE EUROPEAN TRANSITION TO LOW CARBON ECONOMY

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## SUMMARY

Climate change mitigation requires significant efforts from all industrial operators. The pulp and paper industry has a notable role with its energy-intensive processes and as a significant user and producer of energy, especially bioenergy. This paper offers an overview of the European pulp and paper industry and its possibilities to promote low carbon economy. The sector has ambitious aims to substitute fossil fuels and products with renewable alternatives and contribute to the carbon-neutrality targets of the European Union. Depending on the mill type, several routes towards the targets exist. Energy efficiency improvements enable reduction of both emissions and costs. Surplus energy can be sold. Industrial operation with excess energy makes the pulp and paper units attractive option for new process integration. The society will require substitutes for fossil-based commodities, and pulp and paper side-streams offer a partial solution. The sector has the obligation to transform, but it can also be seen as a possibility. A fossil fuel-free and energy efficient mill with a widening product portfolio can contribute to the environmental targets and be a successful business. The changing operational environment and transformation into multi-product biorefineries requires co-existence with new partners as well as policy stability and predictable regulation.

**Keywords:** Carbon capture and utilisation or storage CCUS, Climate targets, Decarbonization, Energy intensity, Sustainable production.

## INTRODUCTION

The pulp and paper industry (PPI) is responsible for about 2% of global industrial carbon dioxide ($CO_2$) emissions [1], even though it is the fourth largest industrial user of energy in Europe [2]. The energy-intensive production processes and the increasing demand on the products, especially paperboard, urge the sector to act.

The sector is affected by product price volatility especially after the COVID pandemic and the more recent rapid increase in natural gas price, which affects most paper grades in Europe [3]. Securing energy supply and maintaining industrial competitiveness adds an additional incentive to look for low carbon solutions. The sector aims at climate neutrality along with the European Union (EU) target by 2050 [2]. In 2022, the REPowerEU Plan [4] called for fast-forwarding the clean transition to reduce the dependence on Russian fossil fuels. Climate change mitigation requires long-term structural changes in the industrial processes, and the PPI has several possible pathways towards higher sustainability and a low carbon economy.

New mills improve the sector's energy efficiency by adopting new, efficient technologies, but energy efficiency has significantly improved in the existing mills because of smaller but numerous improvements in the processes [5]. Energy efficiency improvement is a way towards higher sustainability, but it also improves the economics of the energy-intensive processes. The PPI is a large user of biomass energy as the mills utilize residual biomass for energy generation [6]. Compared with other energy intensive industries, the PPI has a high share of renewables in its fuel mix, but fossil fuels are still widely used in European mills [7]. Further fuel switching is an important measure to reduce fossil-based emissions. Biomass energy has a notable role also outside the mill gates as the society struggles to reduce fossil fuel use. Some pulp and paper mills produce excess biomass energy [6] and can contribute in reducing fossil fuel use in the surrounding communities. As large users and producers of energy, the PPI units can participate in balancing the electricity markets. Rapidly increasing amount of intermittent renewable energy, such as wind energy, requires demand side management. This is a new source of additional income and already in use in some mills [8].

Novel added value products are in the core of the development of the PPI. These make use of the existing side streams such as biomass residue, lignin, tall oil, and sludge. The need to replace fossil-based products with renewable alternatives is rapidly growing in the society, and the PPI can offer a partial solution by widening its product portfolio. The future pulp and paper mill can be a biorefinery producing, along with the main products, for example textiles, pharmaceuticals, cosmetics, or composite materials. This is likely to require company collaboration; process and business integration with companies developing the new products. $CO_2$ capture with utilization or storage (CCUS) offers many benefits when applied to bioenergy production. It is an opportunity to reduce emissions and even make the mill a carbon sink [9]. Captured $CO_2$ can be used to produce renewable hydrocarbons, such as fuels or chemicals, to substitute for the currently used fossil ones [10].

This paper evaluates the PPI's routes towards low carbon economy from two viewpoints: firstly, how do they affect the PPI, and secondly, what could the role of the PPI be in the transition towards a more sustainable Europe. The study utilises statistics, scenarios, mill data, and previous modelling results to gain a better understanding of the prospects of clean transition in the PPI. The sector has a wide selection of products, and the emission and energy intensities vary greatly in their production. For example, virgin pulp production is notably more energy-intensive than production using recycled fibre, and there is wide variation between different paper grades. Thus, it is not easy to make detailed estimation on the sector [11]. In this study, we have chosen a general approach and look at the sector as a whole without considering the detailed differences in the varying production processes.

## METHODS AND MATERIAL

### *The pulp and paper industry and its energy procurement in the EU*

The pulp and paper industry produces various everyday-life products, and their demand, especially that of packaging materials, is expected to continue to increase. The EU countries produce various paper and paperboard grades, as Table 1 shows. Pulp production is largely divided between chemical pulp, of which 94% is sulphate (kraft) pulp, and recovered paper. In paper and paperboard production, increasing demand for packaging materials can be seen while demand for paper has declined. Energy use and supply, as well as $CO_2$ emissions vary based on mill-specific details, such as product type, mill location and age, access to raw materials, and available sources of energy.

**Table 1. Pulp and paper production by grade in the EU 27 in the year 2021. Data from [12].**

| Pulp grades | Production (1000 t) | Paper and paperboard grades | Production (1000 t) |
|---|---|---|---|
| Mechanical and semi-chemical pulp | 8.4 | Newsprint | 2.7 |
| Chemical pulp | 28.3 | Printing and writing papers | 20.7 |
| Dissolving pulp | 1.8 | Household and sanitary papers | 6.8 |
| Pulp from fibres other than wood | 1.0 | Case materials | 32.0 |
| Paper for recycling | 50.9 | Cartonboard | 11.4 |
| | | Wrapping papers | 5.3 |
| | | Other papers mainly for packaging | 3.9 |
| | | Other paper and paperboard | 4.5 |
| Total | 90.4 | Total | 87.4 |

High share of biomass-based fuels is typical for PPI units. In 2020 in Cepi (Confederation of European Paper Industries) countries, 61% of fuel use was biomass-based [7]. Electricity supply can roughly be divided in three categories: electricity purchase especially outside natural gas grid and in processes where electricity demand compared to heat demand is high, own natural gas-based electricity generation, and biomass residue-based electricity especially in kraft pulp mills where heat demand compared to electricity demand is high [6].

Figure 1 presents the pulp, paper, and paperboard production by country in the largest producer countries in the EU in the year 2021, and the related fossil and biogenic $CO_2$ emissions. Sweden and Finland produce 60% kraft pulp in the EU. The kraft pulp process produces significant amounts of biomass energy as about half of the wood raw material ends up in black liquor, which is incinerated in a recovery boiler as a part of the chemical recovery process. Black liquor is the most important biofuel in the PPI. Additionally, a kraft mill typically has an additional biomass boiler and the lime kiln, which emits both fuel-based and process-based $CO_2$. The kraft mills are thus large sources of biogenic $CO_2$, approximately 2.5 t $CO_2$ per air-dry ton of pulp [9]. A paper mill integrated with a kraft pulp mill typically receives all or most required heat and electricity from the pulp mill.

Paper production uses large amounts of energy, most of it for paper drying. Many mills, especially those processing recycled fibre in Central Europe, use natural gas-fired combined heat and power (CHP) units to generate the needed energy for the processes. Germany, France, and Italy are the largest countries using recycled fibre for paper production. Substitutes for natural gas are even more urgently needed now that the recent REPowerEU Plan [4] calls for rapid reduction of the use of Russian fossil fuels.

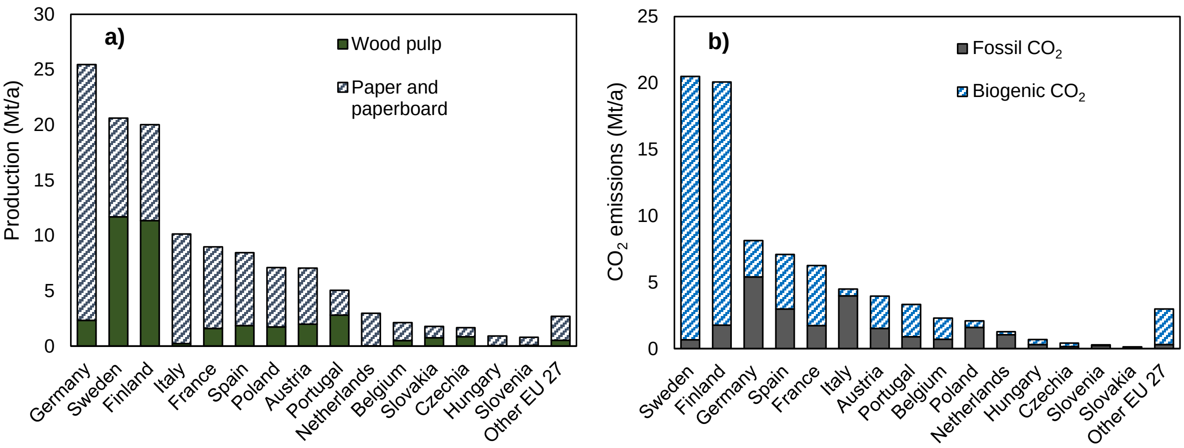


**Figure 1. The largest pulp and paper producers in the EU 27 in the year 2021 (a) and the related $CO_2$ emissions (b). Production data from [12], fossil $CO_2$ data from [13], biogenic $CO_2$ estimated based on [14].**

### *Pathways towards low-carbon operation*

The transformation towards low carbon economy requires both reduction of $CO_2$ emissions and enhancing carbon sinks. A single solution does not exist, but a wide variation of solutions is needed to tackle the climate change. The PPI has several possible pathways towards low-carbon operation, including energy efficiency improvement, switching from fossil fuels to renewables, biomass energy for own processes but also as a sellable product, valorisation of side-streams to produce value-added products, CCUS, and along with increasing amount of intermittent renewable electricity production, the PPI can also contribute to balancing the electricity market. Some of these methods, such as fuel switching, are widely used and well-known, while others, such as balancing the electricity market, are novel options.

***Energy efficiency improvement and fuel switching***

Energy efficiency improvement reduces emissions but also improves profitability. The PPI units have notably improved their energy efficiency in the last decades. A study from the Finnish PPI showed that large structural changes such as mill closures and new mill start-ups improve energy efficiency, but mostly the improvement results from changes in used technology and improved modes of operation [5]. These include for example modernized departments and equipment, efficient use of secondary heat streams, closed water cycles, developed monitoring of operation, and education and motivation of personnel. For example improved use and maintenance are highly feasible measures due to their low cost and risk level [6]. Implementation of modern technologies does not straightforwardly improve energy efficiency, but they also change the energy consumption profile, as for example new paper drying methods often use less heat but more electricity [5]. Modernization also often means commissioning new devices for environmental protection that can even increase energy consumption compared with the old ones [6]. Examples from Sweden and Finland indicate that the PPI has untapped potential to improve energy efficiency, and that for example voluntary agreements on energy efficiency can be successful in realizing it [15].

Energy efficiency improvement is often understood as decreased specific energy consumption, but it can also be increased energy production. Modern technologies can enhance energy generation, as has been seen for example in the development of the recovery boilers in the last decades [6,16].

The largest part of fossil-based emissions reduction can be expected to come from substituting fossil fuels with renewables [17]. The fossil $CO_2$ emissions in the PPI are energy-related, which makes their reduction relatively easy as it does not affect the actual process. The chemical pulp industry is a large energy user and producer of bioenergy, and its $CO_2$ emissions are thus largely biogenic. In modern kraft mills the lime kiln is often the only fossil fuel user during normal operational process. Lime kilns have traditionally combusted natural gas or oil, but switching to renewables is often a feasible possibility [18]. Several mills in Sweden and Finland already use renewables in their lime kilns; typically gas from biomass gasification, but also for example lignin or pulverized wood.

The recent increase in fossil fuel prices has made the renewable options more attractive. Based on results from the Finnish and Swedish PPIs, we can assume that fossil fuel use has closely followed energy prices [15]. Thus, for example taxation can be an efficient driver for fuel switching, however the policymakers need to consider the risk for carbon leakage.

While the PPI produces heat and electricity primarily for its own use, especially the modern kraft pulp mills typically produce excess heat and electricity that can be sold. Heat can be used in other industrial process or for district heating, which can utilise also low-temperature heat streams. Surplus electricity can be sold to the grid. Energy efficiency improvements further improve the possibility of the PPI units to sell surplus energy to the surrounding communities, where it can substitute for fossil energy.

***From a pulp and paper unit to a multi-product biorefinery***

The PPI produces various side streams that are only partly utilised today. In addition to the secondary heat streams, these include for example biomass residue, sludge, and lignin, and $CO_2$. Modern mills are widening their product portfolio aiming both at higher material efficiency and at higher profitability via value-added products. Integration of new processes enables production of biomass-based substitutes for products that currently are fossil-based. This includes many materials, chemicals, and fuels. Many new methods for example for textile production are in a verge of a commercial breakthrough [19]. Examples of routes to produce new products from side streams are depicted in Fig. 2.

Woodhandling residues enable production of solid, liquid, and gaseous fuels that can be used for energy purposes onsite or outside the mill gates, or further converted into more advanced bioproducts. Sludges originate from the wastewater treatment processes. Primary sludge consists mainly of fibres and other solids, biosludge forms in the biological water treatment, and tertiary (chemical) sludge comes from the chemical treatment of wastewater. Currently, sludges are often mixed and incinerated in the mill boilers. Biosludge is difficult to dewater, and its heating value is low, even negative. Separate handling opens new possibilities for sludge utilization, as the properties of the sludge streams vary. Primary sludge can relatively easily be used for example for soil management. New treatment possibilities like hydrothermal carbonization (HTC) [20] or anaerobic digestion can be used to produce usable products, such as biochar or gas from biosludge.

Kraft pulping produces black liquor, which includes the cooking chemicals but also half of the wood raw material, mainly hemicelluloses and lignin. Currently these are combusted in the recovery boiler, but they are also valuable raw materials that could be separated from the process for further processing, see e.g. [21].

The PPI has a high potential for carbon capture from the combustion processes [9]. CCUS has been highlighted as one of the key technologies to mitigate the climate change [10,22,23]. Especially capturing biomass-based carbon from the kraft pulp mills is an attractive option for two reasons: firstly, it enables making the mills carbon sinks and secondly, the mills are large $CO_2$ point sources with existing steam or heat surplus steams [9,24,25]. The potential to integrate CCUS depends on mill-specific details, such as type of pulping process, geographical conditions, and proximity to potential $CO_2$ storage or users [26]. Jönsson and Berntsson [26] estimated the potential to capture bio-$CO_2$ in Europe at 60 $MtCO_2$/a.

CCUS offers also an option for novel products, as the captured $CO_2$ can at least partly be utilised either in the mill operations [9] or to produce new products, such as fuels and chemicals [10]. Production of e-fuels or chemicals from $CO_2$ and renewable hydrogen enables large-scale $CO_2$ utilization [27], but requires significant amounts of electricity and, to become economically feasible, low electricity price, compensation for negative emissions, or a green premium in the product price. The large pulping units could be attractive locations for these processes due to $CO_2$ availability and possibility for efficient heat integration, as unit size and energy costs have a significant role in the costs of carbon capture [28,29]. $CO_2$ also has numerous uses in the industrial processes outside the PPI [30] and could be a sellable product. The climate benefits depend on the chosen usage or storage option, as for example fuels do not bind $CO_2$ permanently but release it when combusted. Thus, the climate effect of the fuel depends on the lifecycle emissions but also from the alternative; if a renewable $CO_2$-based fuel replaces a fossil one, indirect emission savings are achieved.

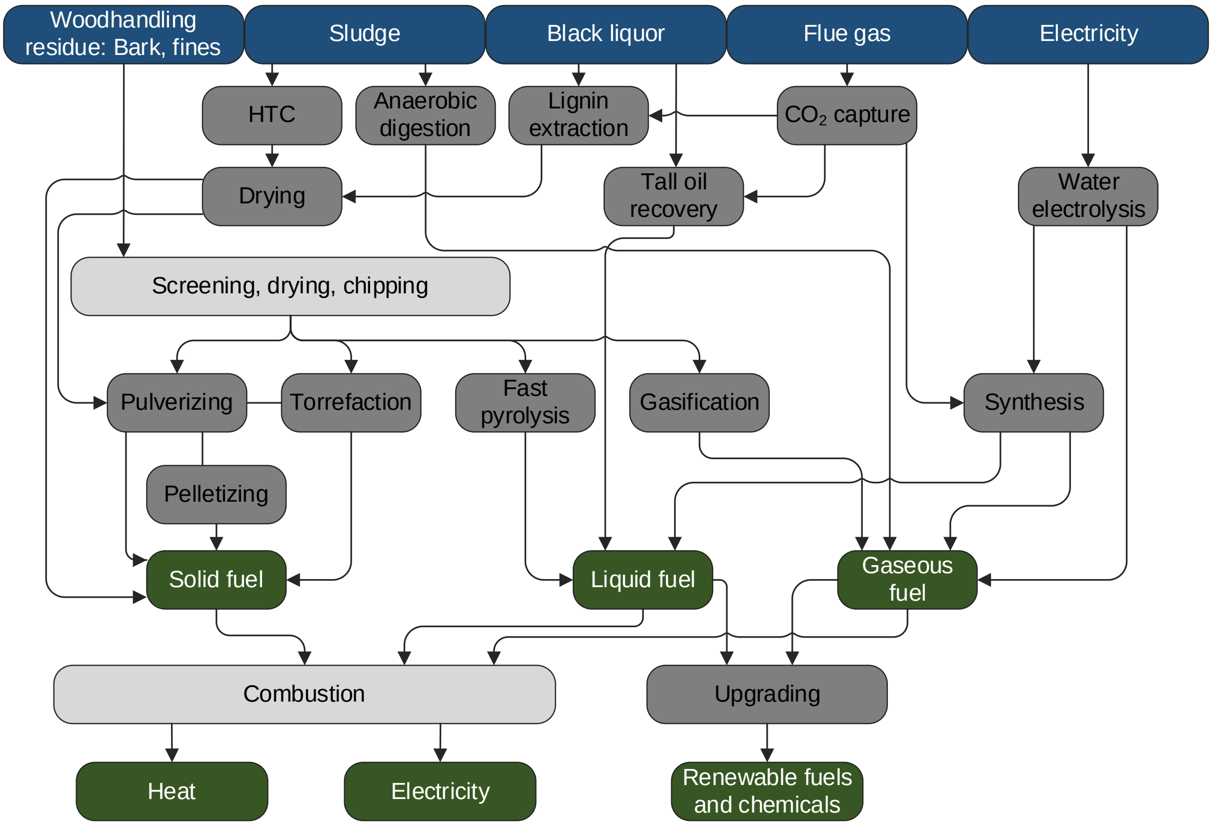


**Figure 2. Possible routes to produce advanced renewable products by utilizing pulp and paper mill side streams.**

***Balancing the electricity markets***

Rapidly increasing amount of intermittent renewable energy production, such as wind and solar energy, requires balancing the electricity grid. This requires engagement from the energy consumers and a new way of thinking. Electricity storage possibilities and adjustment of power consumption based on the situation in the electricity markets are needed to balance power production and consumption. The volatility in the electricity prices offer an additional source of income for consumers, who can adjust their processes in times of low or high-cost electricity. The pulp and paper industry as a large energy user can participate in the balancing markets via careful operational planning. The tools to optimize for example paper production considering also the power price already exist and are in use in some mills; the primary hindrance is people's readiness to adapt to new ways of working [8].

Recently, many paper mills have planned electric boilers to replace fossil fuels, especially natural gas, see e.g. [31]. Electric boilers use electrical energy to generate thermal energy, namely heat or steam, and are more flexible and energy efficient than combustion processes. In addition to fossil fuel-based emissions reduction, the boilers enable more flexible heat production and improve security of heat supply. They also improve the possibilities to participate in balancing the electricity markets by providing demand-side flexibility.

## RESULTS AND DISCUSSION

The PPI consists of different types of mills and production processes and all routes to low carbon operation are not suitable for all mills. Most likely, the future of the PPI is a combination of the presented routes. Modernization and energy efficiency improvement is eventually compulsory for all mills, as old equipment cannot feasibly be used forever, but the other choices depend on the mill details and the visions the decision-makers have.

The kraft pulp mills can improve energy efficiency, implement CCUS, and utilize side-streams and surplus energy to produce novel products. For paper mills, fossil fuel replacement, electrification, energy efficiency improvement, and participating in the electricity grid balancing offer the most promising options. The recovered paper processes can replace fossil fuel-based heat production with electric boilers or biomass processes. Electricity grid balancing is a novel option for mills where processes can be adjusted based on electricity prices or where electricity storage options can be implemented.

When choosing low carbon pathways for a single mill it is important to consider how the choices affect the mill operation and the further opportunities. Interaction between different low carbon pathways for the PPI is a little studied subject, although it is clear that a chosen pathway is likely to affect the mill operations and change the possibilities for further options. For example, lignin extraction from black liquor affects the recovery boiler operation and reduces steam production [32], and carbon capture processes increase energy consumption. Sometimes a chosen pathway can support other low carbon targets, for example in the concept presented by Svensson et al. [33], electrification of the calcination process in example kraft pulp mills enabled low-cost carbon capture and reduced primary steam demand. Further research is needed to study the interactions between different concepts.

The combat against climate change changes the operational environment of the PPI. The sector already has reduced its emissions by switching from fossil fuels to renewables and improving energy efficiency and this development needs to continue in all the mill types. Increasing demand on products, especially paperboard, together with the environmental targets calls for further reduction of emission intensity of the production processes. The surplus energy generation and many side streams of the processes, such as lignin, tall oil, sludge, and biogenic $CO_2$ can be used to produce novel, sellable products that can substitutes for fossil fuels, chemicals, and materials also in the surrounding community. For the PPI, this is a challenge but also an opportunity.

The trailblazers in the industrial transformation towards low carbon economy need policy stability and a predictable regulatory framework. Sweden has been in the frontline in developing capture of especially biogenic $CO_2$, and Lefvert et al. [34] found three main reasons for that: increased awareness on the urgency for climate change, negative emissions potential seen as a new framing for carbon capture, and improved prospects of $CO_2$ storage. The EU Emission Trading System (ETS) is the main policy instrument to achieve the climate targets related to fossil energy use [17], but it has been argued to have only a limited effect on the PPI due to excess emission allowances [35]. Moreover, it does not yet contemplate biogenic $CO_2$ emissions [17]. The lack of political prioritization and subsequently, the lack of policy incentives have been considered the main barriers preventing investments in capturing biogenic $CO_2$ [36].

Widening product portfolio and implementation of new production processes require special knowhow and is not an easy task for the pulp and paper companies. Simultaneously, small startups are developing novel processes, but do not have the means to for example handle the logistics and follow the strict environmental regulations. Many new PPI units have practiced co-existence with chemical plants operating on the same site. Transition to a low carbon economy means that the PPI units need to learn a new operation model and extend the co-existence model to other products.

The PPI needs a fundamental transformation to answer to the increasing demand for higher sustainability. A single mill needs to choose its path to maintain industrial competitiveness and fulfil the climate targets. Various solutions promoting carbon-neutrality are in or near the commercial stage and could be implemented, given that the knowhow and resources meet and the regulatory framework supports investments.

## CONCLUSIONS

The PPI has the obligation to transform towards higher sustainability, but this can also be considered a possibility. The sector can reduce its emissions in various ways and simultaneously, contribute to the societal transformation outside the mill gates. The means to reduce $CO_2$ emissions include for example energy efficiency improvement, switching from fossil fuels to renewables, electrification, and carbon capture. Novel products from side stream utilisation can substitute for fossil-based alternatives also outside the mill gates, and new modes of operation can for example enable participation in balancing the electricity market. For individual mills and companies, the transformation into modern multi-product biorefineries require investments in modern technology, new ways of thinking and co-existence with new business partners, which asks for a forward-looking attitude and bold decision-making. A fossil fuel-free and energy efficient mill with a widening product portfolio can contribute to the environmental targets and be a successful business. For the PPI, the ability to transform is also a question on energy security and industrial competitiveness in the future. Predictable regulation and a stable operational environment are needed to enable pathway choices towards a low carbon economy.

## REFERENCES


1. International Energy Agency (IEA), Pulp and paper – Tracking report, (2022), https://www.iea.org/reports/pulp-and-paper
2. Confederation of European Paper Industries (Cepi), 'Fit for 55' package: How to unleash the European pulp and paper industry's decarbonisation potential?, (2021), https://www.cepi.org/fit-for-55-package-how-to-unleash-the-european-pulp-and-paper-industrys-decarbonisation-potential/
3. V. Henttonen, How European pulp and paper mills adapted to the new energy transition reality, (2023), https://www.fastmarkets.com/insights/how-european-pulp-and-paper-mills-adapted-to-energy-transition
4. European Commission, REPowerEU Plan – COM(2022) 230 final, (2022), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN
5. S. Kähkönen, E. Vakkilainen, and T. Laukkanen, Impact of structural changes on energy efficiency of Finnish pulp and paper industry, *Energies* **12**(19):3689 (2019)
6. E. Vakkilainen, and A. Kivistö, Forest industry energy consumption – Trends and effects of modern mills, Lappeenranta University of Technology, Lappeenranta, Finland (2014)
7. Confederation of European Paper Industries (Cepi), Key Statistics 2021 – European pulp and paper industry, Brussels, Belgium (2022)

8. A. Särkilahti, An innovative energy management service for industrial businesses, Finnish Forest Products Engineers Association, Autumn Seminar 2022, Helsinki, Finland (2022)

9. K. Kuparinen, E. Vakkilainen, and T. Tynjälä, Biomass-based carbon capture and utilization in kraft pulp mills, *Mitig. Adapt. Strateg. Glob. Chang.* **24**(7):1213–1230 (2019)

10. J. Lehtonen, V. Järnefelt, S. Alakurtti, A. Arasto, I. Hannula, A. Harlin, T. Koljonen, R. Lantto, M. Lienemann, K. Onarheim, J.-P. Pitkänen, and M. Tähtinen, The Carbon Reuse Economy - Transforming $CO_2$ from a pollutant into a resource, VTT Technical Research Centre of Finland, Espoo, Finland (2019)

11. G. Koreneff, J. Suojanen, and P. Huotari, Energy efficiency of Finnish pulp and paper sector – indicators and estimates, Motiva, Espoo, Finland (2019)

12. Food and Agriculture Organization of the United Nations (FAO), Forestry production and trade, (2022)

13. European Environment Agency (EEA), EU Emissions Trading System (ETS) data viewer, (2023). https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

14. L. Rosa, D.L. Sanchez, and M. Mazzotti, Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe, *Energy Environ. Sci*. **14**(5):3086–3097 (2021)

15. S. Lipiäinen, K. Kuparinen, E. Sermyagina, and E. Vakkilainen, Pulp and paper industry in energy transition: towards energy-efficient low carbon operation in Finland and Sweden, *Sustain. Prod. Consum*. **29**:421–431 (2022)

16. E. Vakkilainen, Firing practices in modern recovery boilers, 55th Anniversary International Recovery Boiler Conference, Turku, Finland (2019)

17. J.A. Moya, and C.C. Pavel, Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry, Publications Office of the European Union, Luxembourg (2018)

18. K. Kuparinen, and E. Vakkilainen, Green pulp mill: Renewable alternatives to fossil fuels in lime kiln operations, *BioResources* **12**(2):4031–4048 (2017)

19. E. Sermyagina, S. Lipiäinen, and K. Kuparinen, Finnish forest industry and its role in mitigating global environmental changes, *in*: E. Constable (ed.), Transitioning to affordable and clean energy, MDPI, Basel, Switzerland (2022)

20. J. Saari, C. Mendoza Martinez, K. Kuparinen, S. Lipiäinen, M. Hamaguchi, M. Cardoso, E. Vakkilainen, and M. Haider, Techno-economic analysis of hydrothermal carbonization of pulp mill biosludge, *TAPPI J*. **22**(3):206–2016 (2023)

21. M. Hamaguchi, J. Kautto, and E. Vakkilainen, Effects of hemicellulose extraction on the kraft pulp mill operation and energy use: Review and case study with lignin removal, *Chem. Eng. Res. Des*. **91**(7):1284–1291 (2013)

22. International Energy Agency (IEA), Special report on carbon capture, utilisation and storage: CCUS in clean energy transitions, Paris, France (2020)

23. Intergovernmental Panel on Climate Change (IPCC), Summary for policymakers, *in*: V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Cambridge University Press, Cambridge, UK and New York, NY, USA (2018)

24. K. Onarheim, S. Santos, P. Kangas, and V. Hankalin, Performance and costs of CCS in the pulp and paper industry part 1: Performance of amine-based post-combustion $CO_2$ capture, *Int. J. Greenh. Gas Control*. **59**:58–73 (2017)

25. K. Kuparinen, S. Kähkönen, E. Vakkilainen, and T. Laukkanen, Boundary conditions for economical implementation of BECCS in the Nordic pulp and paper industry, Proc. 2$^{nd}$ International Conference on Negative $CO_2$ Emissions, Gothenburg, Sweden (2022)

26. J. Jönsson, and T. Berntsson, Analysing the potential for implementation of CCS within the European pulp and paper industry, *Energy* **44**(1):641–648 (2012)

27. K. Kuparinen, S. Lipiäinen, and E. Vakkilainen, Can carbon capture be a new revenue opportunity for the pulp

and paper sector?, *TAPPI J*. **20**(8):527–540 (2021)

28. S. Garðarsdóttir, F. Normann, R. Skagestad, and F. Johnsson, Investment costs and $CO_2$ reduction potential of carbon capture from industrial plants – A Swedish case study, *Int. J. Greenh. Gas Control* **76**:111–124 (2018) https://doi.org/https://doi.org/10.1016/j.ijggc.2018.06.022.
29. D. Kearns, H. Liu, and C. Consoli, Technology readiness and costs of CCS, Global CCS Institute (2021)
30. International Energy Agency (IEA), Putting $CO_2$ to use, IEA, Paris, France (2019)
31. UPM, UPM electrifies heat and steam production at its mills in Finland and Germany, Press release (2023).
32. M. Hamaguchi, E. Vakkilainen, and P. Ryder, The impact of lignin removal on the dimensioning of eucalyptus pulp mills, *Appita J*. **64**(5):433–439 (2011)
33. E. Svensson, H. Wiertzema, and S. Harvey, Potential for negative emissions by carbon capture and storage from a novel electric plasma calcination process for pulp and paper mills, *Front. Clim*. **3**:705032 (2021)
34. A. Lefvert, E. Rodriguez, M. Fridahl, S. Grönkvist, S. Haikola, and A. Hansson, What are the potential paths for carbon capture and storage in Sweden? A multi-level assessment of historical and current developments, *Energy Res. Soc. Sci*. **87**:102452 (2022)
35. L. Gulbrandsen, and C. Stenqvist, The limited effect of EU emissions trading on corporate climate strategies: Comparison of a Swedish and a Norwegian pulp and paper company, *Energy Policy*. **56**:516–525 (2013)
36. M. Fridahl, and M. Lehtveer, Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers, *Energy Res. Soc. Sci*. **42**:155–165 (2018)