

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Forest biomass in the energy transition

Modelling industrial flexibility and inter-sectoral dependencies

SIMON INGVARSSON

Department of Environmental and Energy Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026

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ISBN 978-91-8103-499-8

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Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 5956

ISSN 0346-718X

<https://doi.org/10.63959/chalmers.dt/5956>

Department of Environmental and Energy Sciences

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Printed by Chalmers Digitaltryck

Gothenburg, Sweden 2026

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Abstract

Sustainably sourced forest biomass is a renewable but limited resource that can substitute for fossil carbon in many applications. As the energy transition adds demands for transportation fuels, flexible electricity generation, and negative emissions, the challenge is to allocate the biomass across competing uses, so as to increase its economic value and its contribution to climate change mitigation. This thesis explores how technologies and process configurations within the forest biomass system (defined as the value chain from harvested wood to end products), where chemical pulp mills currently play a central role, can contribute to achieving these goals during the transition. Two optimisation models are applied, representing a single pulp mill and the Swedish forest biomass system within the wider energy system.

Assuming that fossil carbon is phased out and that the demand for biogenic carbon increases, the results show that the investments and operational strategies that become rational in the near future depend on policy and market developments in sectors outside the traditional forest industry. The main contribution of the pulp mill (beyond pulp) may, thereby, shift from base-load electricity to flexibility, and eventually to replacing fossil feedstocks through lignin extraction or bioenergy with carbon capture and utilisation (BECCU), or to negative emissions through bioenergy with carbon capture and storage (BECCS). For the individual mill, carbon capture becomes the most profitable option if negative emissions are priced high enough. At the system level, however, gasification plants producing renewable methanol, in which CO₂ is a by-product of the syngas, deliver negative emissions at a lower cost when there is also a demand for methanol. The outcome of a policy for negative emissions therefore depends on whether biogenic carbon is also in demand for fuels and chemicals.

As new demands are placed on forest biomass, the interplay between the forest biomass system and the wider energy system changes at both the mill and the system level. Flexible operation of processes and boilers in the pulp mill increases the value of the mill's surplus electricity and reduces the cost of lignin extraction, which is dominated by the foregone electricity generation. BECCU, where captured CO₂ is combined with hydrogen generated by electrolysis, raises the product yield further, but at an even higher cost in electricity. At the system level, targets for methanol and negative emissions reallocate biomass away from combined heat and power (CHP) plants, whose electricity generation is lost, while the heat pumps that replace them in the heating sector increase further the electricity demand.

Under the studied conditions, the role of forest biomass shifts from that of a fuel supplying heat and electricity towards that of a source of carbon, whose refinement into products or more valuable energy carriers is paid for with heat and electricity. The value of the biomass then varies with time and location, depending on which alternative it replaces.

Keywords: Biomass allocation, Chemical pulp mill, BECCS, BECCU, Lignin extraction, Industrial flexibility, Negative emissions, Biofuels, Energy system modelling, Sector coupling

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

- I. Ingvarsson, S., Odenberger, M., & Johnsson, F. (2023). The chemical pulp mill as a flexible prosumer of electricity. *Energy Conversion and Management: X*, 20, 100401. <https://doi.org/10.1016/j.ecmx.2023.100401>
- II. Ingvarsson, S., Odenberger, M., & Johnsson, F. (2024). Lignin extraction in chemical pulp mills: The role of flexible operation. *Sustainable Chemistry for the Environment*, 7, 100137. <https://doi.org/10.1016/j.scenv.2024.100137>
- III. Ingvarsson, S., Odenberger, M., & Johnsson, F. (2025). Chemical pulp mills in future energy markets with variable electricity prices and increased demand for biogenic carbon. *Biomass and Bioenergy*, 199, 107903. <https://doi.org/10.1016/j.biombioe.2025.107903>
- IV. Öberg, S., Ingvarsson, S., Odenberger, M., & Johnsson, F. (2026). Synergies and trade-offs for forest biomass use under joint BECCS and renewable methanol targets in Sweden. Manuscript.

Author contributions:

Simon Ingvarsson is the principal author of Papers I–III and was mainly responsible for the method development, modelling, analysis, visualisation, writing and discussions in these papers. For Paper IV, Simon Ingvarsson wrote the original draft and contributed to modelling, analysis and discussions. Dr Simon Öberg contributed to modelling, analysis, visualisation, writing and discussions in Paper IV. Associate Professor Mikael Odenberger contributed to method development, editing and discussions in all the papers. Professor Filip Johnsson contributed to editing and discussions in all the papers.

Declaration on the use of generative AI

Generative AI tools were used in preparing the introductory chapters of this thesis. They were used to edit language and terminology, to suggest changes to the structure, and to check that the aim, research questions, results and conclusions agree with each other and with the appended papers. For some passages, such as parts of the related work section, the tools wrote draft text based on the author's existing text and the appended papers. The tools also suggested literature, summarised articles and checked statements in the text and tables against the cited sources. The author reviewed and revised all suggested edits and drafts, and decided which sources to include.

The tools did not produce the research ideas, models, data, results or conclusions, which come from the research presented in the appended papers. The author developed the overall storyline of the introductory chapters, including the research questions and how the results of the papers are brought together. All content and decisions in the thesis were made, verified and approved by the author, who is fully responsible for its accuracy and integrity.

Acknowledgements

I would like to express my sincere gratitude to my supervisors, Mikael and Filip. Thank you for your guidance and support throughout the work on which this thesis is based. I appreciate that you both trusted in my ability and remained curious about the topic over the years, and that you, Mikael, stayed involved in the project until the end, even after your career change. I also wish to thank Simon Ö, not only for being a good friend, but also for helping me reach all the way to the nationwide system level in our joint study. I really enjoyed our collaboration on the paper, not least during the early stages of shaping the research idea. Furthermore, I wish to thank Elin and Johanna for valuable assistance at different stages of my research journey, and Sven, Stefan and your colleagues at Södra for sharing knowledge and for our discussions.

On a more personal level, I wish to thank my fellow PhD students at the Division of Energy Technology for many memorable moments in and outside of the workplace. I know that several of you will remain my friends long after my time at Chalmers has ended. Finally, to Matilda, thank you for supporting me in this endeavour, but maybe even more for helping me keep perspective on everything else in life. I will remember the years we lived in Gothenburg not only as the years I spent at Chalmers, but as a time when we explored the city and the surrounding nature together, and, above all, got married and welcomed little Doris into the family.

Looking back, I am truly grateful for everything these years have given me, both at work and at home.

Simon Ingvarsson
Göteborg, October 2026

List of abbreviations

ADt	Air-dry tonne (of pulp)
BECCS	Bioenergy with carbon capture and storage
BECCU	Bioenergy with carbon capture and utilisation
CHP	Combined heat and power
CO ₂	Carbon dioxide
ELLI	Electricity Long-term Investment model
EU	European Union
EU ETS	EU Emissions Trading System
LP	Linear programming
MILP	Mixed integer linear programming
PEMO	Pulp mill Energy and Materials Optimisation model
PV	Photovoltaic
RED III	Renewable Energy Directive, as amended by Directive (EU) 2023/2413
RFNBO	Renewable fuel of non-biological origin
SE3	Swedish electricity bidding zone 3
VRE	Variable renewable electricity
WAM	With additional measures (projection pathway)
WEM	With existing measures (projection pathway)

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1 Introduction

1.1 Background

The world is in the midst of an energy transition that is driven by climate change; rapidly declining costs for wind power, solar PV and batteries; and a growing emphasis on security of supply in a highly uncertain geopolitical situation [1,2]. In the EU, the pace of the transition is set by the European Climate Law, which requires that net greenhouse gas emissions be reduced by 55 % by Year 2030 and by 90 % by Year 2040 relative to Year 1990; and climate neutrality be reached by Year 2050 [3]. Achieving net-zero CO₂ emissions in the energy system will require a substantial reduction in overall fossil fuel use and minimal use of unabated fossil fuels [4].

Forest biomass is a renewable source of carbon that can directly or indirectly substitute for fossil carbon in many of its current applications, such as transportation fuels, peak capacity in the electricity system, and building blocks for plastics and other chemicals [4]. The CO₂ emissions originating from biomass are generally considered carbon neutral as long as the total carbon stock is not depleted, and any net changes are accounted for in the land-use sector [5]. However, since all sectors of the economy must be de-fossilised in a relatively short time period and access to sustainably sourced biomass is limited, the challenge arises to allocate this limited resource efficiently between different uses, so as to maximise its economic value and its contribution to climate change mitigation [6].

In climate change mitigation, there is a trade-off between using the forest as a carbon sink and the substitution effect of forest products, i.e., the emissions reductions obtained when forest products replace fossil fuels or more emission-intensive materials, such as concrete and steel. Leaving forest lands unharvested increases the carbon stock in the short term, whereas the carbon released from harvested wood may take decades to be re-bound in the growing forest. At the landscape level, however, the forest as a whole remains a carbon sink as long as the level of growth exceeds the amount harvested [7]. The size of the substitution effect is uncertain, as it depends on which products are actually replaced [8]. Whichever role the forest is assigned, the demand for timber is likely to remain, and a reduced harvest in one country is, at least partly, offset by increased harvesting elsewhere [9], and as long as trees are harvested for sawn timber, there will also be pulpwood, logging residues and industry residues available for other uses.

Harvested biomass can also contribute to carbon removal through bioenergy with carbon capture and storage (BECCS). Trees absorb CO₂ from the atmosphere as they grow, and if the biogenic CO₂ is captured from the flue gases when the biomass is combusted and thereafter stored permanently, this yields so-called negative emissions. If implemented on a large scale, and without depleting the biogenic carbon stock, BECCS can compensate for residual emissions in hard-to-abate sectors, and will eventually bring the economy as a whole to net-negative emissions [10]. The European Climate Law states that the EU shall aim for negative emissions after Year 2050 [3]. Alternatively, the captured CO₂ can be used as feedstock for products, e.g., electro-fuels (e-fuels), if combined with hydrogen generated by electrolysis, in so-called bioenergy with carbon capture and utilisation (BECCU).

How forest biomass should be allocated is addressed in EU policy through the cascading principle in the Renewable Energy Directive (RED III) [11]. Member States shall design their support schemes for bioenergy so that woody biomass is used according to its highest economic and environmental added value, in the following order of priority: wood-based products; extending the service life of wood-based products; re-use; recycling; bioenergy and disposal. In addition, Member States shall not grant direct financial support for energy produced from saw logs, veneer logs, industrial-grade roundwood (including pulpwood), stumps and roots.

The cascading principle points to the principal solution to the allocation challenge: biomass that is currently used in lower-valued applications should be upgraded to higher-value applications where possible, and used and recycled for as long as possible [12]. However, a fixed order of priority does not capture the differences across the broad category of bioenergy. Bioenergy is traded in the form of heat on local markets and in the form of electricity on regional markets, while liquid biofuels are traded on global markets. The value levels of heat and electricity also vary with both time and location, and electricity generated at peak load can be worth considerably more than base-load electricity generated from the same biomass [13]. Finally, BECCS has no assigned place in the order of priority: while the economic value of negative emissions may be high, it also implies a linear flow of carbon, which reduces the amount of biomass available for other uses.

How the value of forest biomass develops during the energy transition depends largely on the demand from three areas. In the electricity sector, a growing share of variable renewable electricity (VRE) shifts the role of biomass-based generation from base load towards flexibility. In the transport sector, fossil fuels must be replaced by renewable fuels including biofuels or electricity. Through BECCS, the biogenic CO₂ from large point sources, such as pulp mills, attains a new value in the sector of negative emissions. In all three areas, the new demand for biogenic carbon is largely created by policy, from the EU Emissions Trading System (EU ETS) to sector-

specific fuel mandates, and the tightening of EU ETS already legislated for is substantial within the studied period (although the revision proposed in July 2026 would slow it down after Year 2030). Relevant EU and Swedish policies in relation to these three areas are listed in Table 1.

In the transport sector, road transport is expected to be comprehensively electrified, whereas aviation and shipping will likely require liquid fuels. If the biomass available for biofuels is limited, these sectors will also need e-fuels [14]. ReFuelEU Aviation includes a separate mandate for e-fuels, and FuelEU Maritime counts their emissions reductions twice until Year 2033 (Table 1). Candidate fuels for shipping include bio-diesel, as well as bio-methanol and e-methanol [15].

In a scenario with substantial electrification of industry and transport, the demand for electricity in Sweden is projected to more than double by Year 2050 [16], while several nuclear plants and a large share of the transmission grid will reach the end of their lifetimes [17]. A cost-optimal supply mix would be dominated by VRE, such as wind and solar power [18], which would increase price volatility and the need to manage variations in the electricity system [19].

Rapid variations can be managed cost-efficiently with batteries [20], whereas longer variations call for a broader set of measures, including supply control, demand-side management, and integration with the heating sector [21]. Beyond short-term variations, wind and solar power output also show variations with durations of several days and between years, and some winters bring rare but extreme periods of low output and high demand, so-called *dunkelflaute*, which may last for several weeks and establish the need for long-duration storage [22].

In such a VRE-dominated system, biomass-based generation can complement the variable output by supplying electricity during hours of high residual load [13]. Even in a model of the entire European energy system, in which biomass is also in demand for fuels, materials and negative emissions, flexible bio-based electricity is the biomass use that is most costly to replace when biomass use is restricted [23].

Table 1. Main EU and Swedish policy instruments affecting the demands for forest biomass in the transport sector, the electricity and heat sector, and for negative emissions, as of September 2026.

Instrument	Main requirement
Transport	
RED III, transport targets [11]	By 2030, a 14.5 % reduction in the greenhouse gas intensity of transport fuels or a 29 % renewable share, including at least 5.5 % advanced biofuels and renewable fuels of non-biological origin (RFNBOs), of which at least 1 % RFNBOs.
ReFuelEU Aviation [24]	Minimum share of sustainable aviation fuel supplied at EU airports of 2 % (2025), 6 % (2030), 20 % (2035), 34 % (2040), 42 % (2045) and 70 % (2050), including a sub-mandate for synthetic fuels of 1.2 % (2030), 5 % (2035) and 35 % (2050). Crop-based fuels are excluded.
FuelEU Maritime [25]	Greenhouse gas intensity of the energy used on board ships above 5,000 gross tonnage reduced by 2 % (2025), 6 % (2030), 14.5 % (2035), 31 % (2040), 62 % (2045) and 80 % (2050), relative to 2020. The emissions reductions of RFNBOs are counted twice until 2033, and a 2 % RFNBO sub-quota applies from 2034 if their share is <1 % in 2031.
Electricity and heat	
EU ETS [26] Proposed revision [27]	Cap for stationary installations reduced by 4.3 % per year (2024–2027) and 4.4 % per year from 2028, which would bring it to zero around 2039. Proposed revision, under negotiation: 3.7 % per year (2031–2035) and 1.7 % per year (2036–2040).
RED III, forest biomass for electricity [11]	No new support, and no renewal of existing support, for electricity from forest biomass in electricity-only installations, unless the installation applies carbon capture and storage, is located in a region identified in a territorial just transition plan, or is located in an outermost region.
Energy taxation, Sweden [28]	Electricity tax of 36.0 öre/kWh from 2026, and 0.6 öre/kWh for electricity used in manufacturing industry. Biomass fuels used for heat production are exempt from energy and carbon taxes.
Negative emissions	
EU ETS [26] Proposed revision [27]	Biogenic CO ₂ is zero-rated, and permanently stored CO ₂ carries no surrender obligation. Capture and storage of biogenic CO ₂ , therefore, generates no revenue. Proposed revision, under negotiation: the European Commission would purchase certified permanent removals from BECCS and direct air capture, and increase the cap by the same volume.
Reverse auction for bio-CCS, Sweden [29]	State support for the lowest bid per tonne of captured and permanently stored biogenic CO ₂ . First auction: SEK 20 billion for more than 11 Mt CO ₂ over at most 15 years, on average about SEK 1,800 per tonne.

Negative emissions can be rewarded in several ways: through state purchase guarantees, quota obligations on selected sectors, trade between states under the Paris Agreement, voluntary purchases by companies, or BECCS credits within the EU ETS [30]. Since capturing and storing biogenic CO₂ generates no revenue under the current EU ETS (Table 1), BECCS must rely on other routes to revenue, such as national support schemes and voluntary purchases. In Sweden, BECCS is supported through a reverse auction. With the revision of the EU ETS proposed in July 2026 (currently under negotiation), the European Commission would purchase certified removals from BECCS and direct air capture, while tightening of the cap would be eased after Year 2030 (Table 1).

Since a removed tonne of CO₂ has the same climate mitigation effect as an avoided tonne, the EU ETS price is a natural reference for the value of negative emissions. Removals that cost more than the allowance price, however, depend on additional funding, as in the Swedish reverse auction, where the first contract corresponds to about SEK 1,800 (roughly 160 €) per tonne [29], which was about twice the EU ETS price at the time [31]. In addition to the investment and operation costs for the capture technology itself, the funding must cover costs for the transport and storage. For most Nordic sources, ship transport is the least costly transport option, while inland sources depend on trucks or pipelines connecting to a harbour [32].

In Sweden, these new demands for transport fuels, flexible electricity and negative emissions coincide with one of the world's largest exporters of forest products [33]. In Year 2024, the Swedish forest industry produced 17.8 million m³ of sawn timber, 8.3 Mt of paper and board, and 3.6 Mt of market pulp, most of which were exported [33]. Forest biomass in the form of residues is also an important fuel in the Swedish district heating systems, which supply about 60 % of the heat demand in buildings, with biomass alone accounting for about half of the heat supply [34]. Part of this heat is produced in combined heat and power (CHP) plants, whose share of the heat supply is expected to decrease as the use of large-scale heat pumps expands [35,36], particularly with higher biomass prices [36]. Sweden's biogenic CO₂ emissions of 47 Mt CO₂ in Year 2025 are currently as large as its fossil territorial greenhouse gas emissions (about 46.7 Mt CO₂-eq) [37,38], and about 47 % of them originate from the pulp and paper industry, corresponding to roughly 22 Mt of biogenic CO₂ per year [37]. The new demands come on top of these established uses: by Year 2050, the additional demand for forest biomass in Sweden for energy and chemicals has been estimated at 30–100 TWh per year, depending mainly on the pace of electrification, whereas the sustainable harvest of logging residues could only be increased by about 20 TWh [6].

In this thesis, the whole value chain from harvested wood to end products, including the actors that compete for the same biomass, is referred to as the forest biomass system. Within this system, this thesis has its main focus on the chemical pulp mills, which, as large processors of biogenic carbon and industrial-scale prosumers of electricity, are central actors in the current system and may take on several new roles in the energy transition. In a typical chemical pulp mill, only around 40 % of the carbon in the wood ends up in the pulp, while the remainder is used for generating steam and electricity and emitted as CO₂ from the recovery boiler, the bark boiler and the lime kiln [39]. Thus, the mills are close to self-sufficient in terms of energy [40,41] and, if the carbon stock in the forest is maintained, almost carbon neutral in their operations. Nonetheless, the mills may assume the following new roles during the energy transition: (i) as flexibility providers in the electricity system [42]; (ii) as producers of

biofuels, materials and chemicals from side streams, such as lignin or via BECCU, substituting for fossil-based products [43,44]; and (iii) as suppliers of negative emissions via BECCS [45,46].

It has long been proposed that pulp mills could develop into biorefineries, possibly being integrated with the oil refining and petrochemical industries (see, e.g., [47,48]). High wood prices and low pulp prices in recent years [49,50], together with expectations that global competition will continue to press forest product prices downwards, might now accelerate such a development, as diversification into bioenergy and biomaterials becomes increasingly necessary [51].

Diversification, however, means that new products and services compete for the same resources within the mill. Thus, lignin extraction reduces the fuel to the recovery boiler, carbon capture requires steam that would otherwise generate electricity, and flexibility depends on how steam can be shifted between processes and turbines. Similar competition appears at the system level, where forest biomass is shared between sawmills, pulp mills, heat and power plants and new biorefineries, and where the value of the by-products depends on the alternatives available in the electricity and heating systems.

Which of the competing options is least costly can often be traced back to thermodynamics. Lignin extraction may be economically viable for applications in which the molecular structure of lignin is utilised, e.g., as a phenol substitute in resins and adhesives [52]. If the lignin is instead broken down in a thermochemical process and rebuilt into new molecules, its structure adds no value, and it competes as a carbon source with other low-grade biomass forms, such as bark and sawdust, which do not have to be first extracted in a costly process. The same rationale applies to BECCU, where the biomass is combusted to CO_2 and then rebuilt into complex molecules through energy-demanding processes. For example, comparing two routes for the production of aviation fuel via methanol: the route based on captured biogenic CO_2 and hydrogen from electrolysis has a considerably lower exergy efficiency than the route via biomass gasification, and ends up with more than double the production cost [53]. Solutions that are not optimal from the strictly technical perspective may still prove to be relevant in the near future, however, when capital is locked into existing industries, infrastructures and the socio-technical systems built around them [54].

This thesis examines how the economic value of forest biomass and its contribution to climate change mitigation can be increased during the energy transition up to mid-century. It addresses which investments and modes of operation become economically rational as market and policy conditions develop, and what these choices imply for the wider energy system, both for an individual chemical pulp mill and for the

Swedish forest biomass system as a whole. Related work is reviewed in Section 1.2, and the aim and research questions are stated in Section 1.3 before the outline for the rest of the thesis is presented in Section 1.4.

1.2 Related work

Previous studies of forest biomass in the energy transition can broadly be divided into two groups. Studies at the site level represent a single plant, in most cases a pulp mill, in technical detail and take the surrounding markets as given. Studies at the system level represent the markets for biomass, energy and/or carbon but describe the individual plants in an aggregated way. Tables 2 and 3 arrange the two groups by the measure or sector studied and by how it has been analysed.

1.2.1 Studies at the site level

The site-level studies in Table 2 concern measures that a pulp mill can adopt, meaning a technology or a mode of operation. They either model the operation of a given mill under time-varying energy prices or assess investments under given market conditions, assuming steady-state operation.

The operational studies show that for a chemical pulp mill, the internal steam system provides industrial flexibility that can be valued in the electricity market. Sarimveis et al. and Marshman et al. [55,56] showed that steam can be shifted between turbines and pressure-reducing valves as fuel and electricity prices vary, and Panuschka and Hofmann [57] found that thermal storage can reduce the operating cost by a few per cent.

In mechanical pulp mills, Helin et al. and Herre et al. [58,59] showed that the grinders and refiners can provide reserve capacity and regulating power together with electric boilers and steam accumulators. Helin et al. [58] found, however, that this requires bids well above the spot price, since reducing the electricity consumption in these processes entails losing pulp production which must be made up for later.

The value of this flexibility depends on how much the prices vary. For Swedish chemical pulp mills, Jannasch [42] found that shifting load in existing process units saves more with simulated prices for Years 2030 and 2040 than at the prices of Years 2015–2017, and Mechleri et al. [60] showed that flexible operation of carbon capture at power plants is likewise rewarded more where prices vary more.

The investment studies, which form the larger part of the literature, mostly assess one measure at a time. Olsson et al. [61] showed that the profitability of lignin extraction depends on the ratio between the prices of electricity and lignin, since the extracted lignin would otherwise have been combusted in the recovery boiler, generating

electricity. Where the recovery boiler limits production, Välimäki et al. and Lindgren et al. [62,63] found that lignin extraction can instead serve to increase the pulp capacity.

Onarheim et al. [64] showed that carbon capture at a pulp mill requires heat for regenerating the solvent, which increases the steam demand and reduces the power generation of the mill. In a recent review and case study, Klüh et al. [46] found that the lost revenue from electricity sales dominates the capture cost, and that the amount that can be captured is limited by the energy available in the mill. Capture is therefore most promising at market pulp mills, which have more excess heat than integrated mills [65,66]. Kupařinen et al. [67] showed that, since the emissions of a market pulp mill are almost entirely biogenic, capturing even a small share of them would make the mill carbon-negative.

Where measures are combined, they may either compete or complement each other. Skoglund et al. [68] showed that carbon capture and lignin extraction compete for the heat from the recovery boiler, whereas Granacher et al. [69] found that producing fuels from the residue streams of a chemical pulp mill could increase the share of the carbon in the wood that leaves the mill in products.

Whether an investment in a new measure pays off also depends on how the mill is operated over the year. Svensson showed that a model based on annual averages can significantly misjudge the equipment loads and the economic result compared with one that resolves the seasonal variations [70], and that the poor part-load performance of turbines can make lignin extraction preferable to condensing power even at moderate lignin prices [71]. Optimising investments and daily operation together, Svensson et al. [72] found that varying the rate of lignin extraction can provide flexible power production, but only if the mill also invests in condensing turbine capacity. Granacher [73] added power-to-fuel and carbon capture to the fuel routes at a chemical pulp mill under varying prices and demands, raising the share of the carbon that leaves the mill in products or is stored to over 90 %. Flexible operation of carbon capture has been studied for power plants by Mechleri et al. [60] and for CHP plants by Saint-Pierre and Mancarella [74], but, to the author's knowledge, not for pulp mills.

Table 2. Previous modelling studies of pulp mills, by measure (i.e., technology or mode of operation) and methodology.

Measure	Operation under time-varying energy prices	Investment under given market conditions	Investment and time-varying operation together
Flexibility in steam system or production processes	Steam supply dispatched against contracts and hourly prices [55–57] Seasonal fuel storage against monthly prices [76] Reserves and regulating power from mechanical pulp mills [58,59]	Use of excess heat internally, for district heating or for power generation [75]	Turbines and heat deliveries at monthly resolution or seasonal and diurnal time steps [76,77]
Lignin extraction	–	Model mills and case studies with constant prices or a few scenarios [61,78, 79] Capacity increase in recovery-boiler-limited mills [62,63] Combination with carbon capture [68]	Combination with boiler and turbine investments, daily resolution [70–72]
Gasification and fuel production	–	Comparison with recovery-boiler-based concepts [80] Drop-in fuels from black liquor and bark [81,82] Combination of several fuel routes at a chemical pulp mill [69]	Combination with power-to-fuel and carbon capture at a chemical pulp mill, typical periods of prices and demand [73]
Carbon capture	Flexible capture at coal- and gas-fired plants [60,74]	Capture cost at existing pulp mills of different types, including a review of capture technologies [46,64, 65,67] Conditions for capture across Swedish pulp mills and CHP plants [83] Combination with lignin extraction [68]	–

1.2.2 Studies at the system level

At the system level, the studies concern how forest biomass is allocated between sectors and how the forest biomass system and the energy system affect each other. They use energy system models, forest sector models or the two coupled, which form the columns of Table 3. The energy system models treat the forest industry as an exogenous demand, as a supplier of fuel or as a choice of technologies for given production volumes [84,85], while the forest sector models represent the forest industry and its

feedstock markets, but the energy system only as a demand. Using forest sector models, Bryngemark and Hu et al. [86,87] showed that large-scale biofuel production and trading of negative emissions, respectively, raise the prices of pulpwood and sawmill by-products and can end the production of fibre- and particleboard.

Coupling the two, Jåstad et al. [88] showed that a forest sector model alone underestimates the use of biomass for heat production and the electricity prices facing the forest industry, whereas Mustapha et al. [89] found that an energy system model with fixed biomass prices may overestimate the use of biomass for heat and power when biofuel production competes for it.

The coupled Nordic studies resolve biomass supply and electricity prices by region but do not include carbon capture, whereas the coupled study by Charles et al. [90] includes capture for the pulp and paper industry in the United States but represents the country as a single region. Yet the conditions at individual sites have been shown to matter, both for carbon capture and for fuel production. The conditions for capture at Swedish pulp mills are site-specific, with the availability of low-pressure steam and the electricity price as recurring factors [83], and which sites are chosen for capture depends also on the distance to transport hubs [32]. Large biofuel plants are best located near large harvests or harbours and railway terminals, where they raise the local prices of pulpwood [91], and the benefit of integrating biofuel production with district heating depends on the local heat demand [92]. The studies that resolve such conditions within a country either cover a single part of the value chain at a time [32,91,93] or take the production of the forest industry as given [85]. None of them combines the competition between the existing forest industry and new uses of biomass with carbon capture, fuel production and the effects on electricity and heat.

Turning to the results, in a study of the European energy system, Millinger et al. [23] found that biomass is more valuable as a source of biogenic carbon, for fuels, chemicals and negative emissions, than as a source of energy. Fuel production and carbon capture can also complement each other. Technology routes with large flows of vented CO₂, such as gasification of black liquor or bark, have a low abatement cost when the CO₂ is captured and stored [94], and a gasification plant that can alternate between BECCS and BECCU is preferred to less flexible designs in a time-resolved electricity system model [95]. In a national energy system model of Sweden, Sandberg and Krook-Riekkola [84] found that biofuel production integrated with the forest industry, notably through black liquor gasification, was favoured in all scenarios, and that capture from the fuel production provided low-cost negative emissions, since the fuel carries the cost of separating the CO₂. Combining the CO₂ with hydrogen from electrolysis into e-fuels requires large amounts of electricity, and the production of e-fuels is therefore limited by the availability of electricity rather than of biogenic CO₂ [42,96].

Table 3. Previous studies at the system level, by sector and by which part of the system is represented in detail.

Sector	Forest sector in detail	Energy system in detail	Both, coupled
Fuels and biogenic carbon	Second-generation biofuels, Sweden [86] Biorefinery supply chains, Sweden, spatially explicit [100] Road biofuels, Nordic countries [99] Siting of biofuel plants, 356 regions in Norway [91]	Biomass use in a net-zero Europe, 37 regions [23] Methanol as an alternative to hydrogen, Europe [101] Gasification switching between BECCU and BECCS, European regions [95] Integrated biofuel production and capture in the forest industry, Sweden [84] CO₂ from pulp mills and biomass plants for e-fuels, seven regions in Finland, hourly [85]	Biofuels and heat and power, Nordic countries [89]
Heat and power	District heating as a buffer for biomass, Nordic countries [87]	Heat pumps and CHP, district heating systems, Swedish cities [35,36] Biomass in electricity systems, three European regions [13] Forest-based bioenergy, Quebec and Czechia [102, 103]	Forest sector and heat and power, Nordic countries and Northern Europe [88,89]
Negative emissions	BECCS and competition for biomass, Nordic countries [87] Supply of residues for capture, Swedish regions [93]	BECCS and direct air capture, Europe [23] Capture in district heating systems, Swedish cities [97,98] CO₂ capture and transport chains, Swedish point sources [32]	BECCS and electrification in the pulp and paper industry, United States as one region [90]

The heating sector, currently the largest user of low-grade forest biomass, is challenged from several directions. Large heat pumps reduce the role of biomass-fired CHP in district heating [35,36], while carbon capture at the remaining CHP plants would add a demand for heat and biomass [97,98]. When new demands make biomass scarcer, the district heating sector acts as a buffer in the biomass market, giving up part of its biomass and turning to lower-grade residues instead [87,99].

1.2.3 Research gap

The literature reviewed above leaves gaps at both the site and system levels, which motivate the work presented in this thesis. At the site level, the flexibility of chemical pulp mills has only been studied in detail in the boilers, turbines and steam system,

without the connection to the production processes that supply their fuel. Lignin extraction has been studied with regard to power flexibility at a daily resolution, but not with hourly operation including the detailed dynamics with other processes of the mill. The investment studies mostly assess one measure at a time under steady-state operation, and few compare electricity generation, lignin extraction and carbon capture across market conditions with time-varying operation.

At the system level, forest sector models represent how new demands for fuels and negative emissions compete with the forest industry for biomass, but not the energy system. Energy system models capture the synergies between fuel production and carbon capture and the effects on electricity and heat, but take the production of the forest industry as given. The coupled studies either leave out carbon capture or represent a whole country as a single region, although site conditions, such as access to CO₂ transport and heat demand, have been shown to matter.

Taken together, previous studies have mostly assessed the measures within the mill one at a time, and the forest industry and the energy system separately. This leaves out the interactions that determine which investments and modes of operation become economically rational as external conditions develop, and what they imply for the wider energy system.

1.3 Aim

The overarching aim of the work presented in this thesis is to improve our understanding of how different technologies and process configurations can be used to increase the economic value of forest biomass and its contribution to climate change mitigation, in particular during the transition from the current system, where chemical pulp mills play a central role.

Which of the available technologies and process configurations is most attractive depends on the value of forest biomass, which in turn depends largely on developments in the transport and electricity sectors, as well as on the need to achieve negative emissions. How these drivers translate into demand for forest biomass is determined by external market and policy conditions that are inherently uncertain and expected to change substantially over the studied time period. These conditions include the prices of competing products, the levels and variability of electricity prices, and the design of climate and industrial policies.

Developments in the forest biomass system also feed back into the wider energy system. Flexible operation may allow industries to take on new roles as providers of flexibility to the electricity system, while new processes for upgrading biomass by-products may increase the demands for heat and electricity from industries. Finally, as by-products are increasingly upgraded to higher-value uses, some of the biomass

that is currently used to meet internal energy demands in the industry or to supply society with heat and electricity (as surplus energy from the industries or in separate heat and power plants) may instead be directed to other, competing end uses.

These two perspectives — what determines the choices made within the forest biomass system, and what those choices imply for the wider energy system — are addressed through the following two research questions:

- How does the development of external market and policy conditions determine which choices for industry investment and operation in the forest biomass system become economically rational in the near future?
- How may the interplay between the forest biomass system and the wider energy system change as new demands are placed on forest biomass?

Both questions are addressed at two levels: at the site level, where the operation of and investments in an individual chemical pulp mill are optimised (Papers I–III), and at the system level, where the mills compete with other users of forest biomass within the wider energy system (Paper IV). Economic rationality is thus assessed both from the perspective of the individual mill and from a system cost perspective, and the difference between the two is a central result. In this thesis, the near future refers to the transition period from the present until mid-century, and the interplay between the forest biomass system and the wider energy system refers to the exchange of electricity, heat, biomass and CO₂ between them.

The thesis contributes (i) a mill model (PEMO) that jointly optimises flexibility in steam supply, steam demand, electricity demand and products at hourly resolution; (ii) a quantification of how flexible operation reduces the cost of lignin extraction; (iii) analytical tipping points between electricity generation, lignin extraction and carbon capture; and (iv) a regionally resolved representation of the Swedish forest biomass system within an energy system model, showing how BECCS and methanol targets interact and when capture at pulp mills is displaced by new plants.

1.4 Outline of the thesis

This thesis consists of this introductory essay and four appended papers. The method chapter describes the approach used in the study, including the models, assumptions, and data used in the analysis. The results and discussion chapter presents the results of the appended papers and discusses them in relation to the research questions and previous work. The conclusions chapter summarises the main findings of the study and reflects on their implications for industry, policy and academia, and potential directions for future research.

The scope for each of the appended papers is illustrated in Figure 1, and the respective contributions are described below:

- **Paper I** serves as a proof-of-concept study for the Pulp mill Energy and Materials Optimisation (PEMO) model used in **Papers I–III**. In Paper I, the technical and economic potentials of flexibility measures in a chemical pulp mill with current technology are assessed, and the technical limitations are analysed.
- **Paper II** focuses on the implementation of a lignin extraction technology, addressing how lignin extraction can be used to increase the production of the mill and how flexibility measures can reduce the trade-off between selling electricity and selling lignin.
- **Paper III** explores the future role of the chemical pulp mill in the energy system, considering the potential demands for electricity, transportation fuels and negative emissions. In this study, the investment options for a condensing turbine, a lignin extraction plant, and a carbon capture unit are compared.
- **Paper IV** presents an expansion to the Electricity Long-term Investment (ELLI) model and examines how the allocation of biomass and the energy system are affected by targets for methanol production and negative emissions, aiming towards climate change mitigation and increased self-sufficiency in energy supply. Furthermore, the impact of local conditions on technology choices and localisation of new investments is examined, including the availability of biomass, location of current industry, electricity system composition, CO₂ transport and storage opportunities and access to district heating to make use of waste heat.

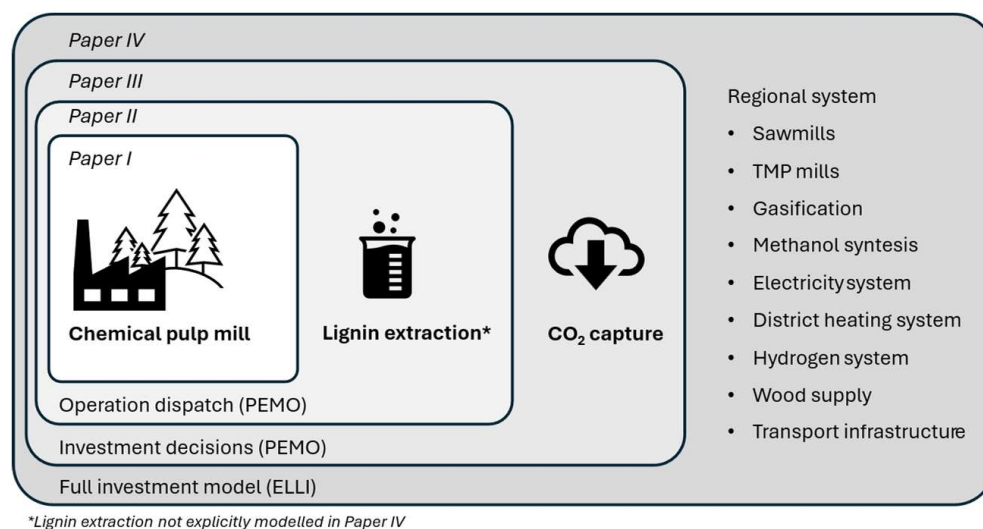


Figure 1. Overview of the technical scope and model types covered in the four appended papers.

2 Method

The work presented in this thesis applies techno-economic modelling methods, in order to address the gaps identified in Section 1.2. Two different models are used in this thesis, one at the level of the individual mill, and one at the level of the energy system. The Pulp mill Energy and Materials Optimisation (PEMO) model was developed for the work presented in this thesis, and the Electricity Long-term Investment (ELLI) model was expanded with a module that represents the biomass system. The outputs of the models are further processed to derive economic indicators, such as the product value generated at the mill and the price tipping points for profitability when comparing different options.

The models are used to explore mechanisms, trade-offs and conditions, rather than to predict outcomes or to assess the feasibility of specific projects. The results are therefore of three kinds: mechanisms that hold irrespective of the simplifications, price thresholds that a mill can apply with its own data, and illustrative magnitudes that apply to the studied cases. Site-specific dimensioning, operational risk, permitting, contracts, financing, and sustainability aspects beyond climate change mitigation, such as biodiversity, are outside the scope of the analysis.

2.1 PEMO model

The PEMO model, developed and applied in **Papers I–III**, represents a reference chemical pulp mill based on a type mill description [39], representing the best available technology at the time of its publication (Year 2010)¹. The PEMO model is a linear optimisation model that optimises the operational dispatch, i.e., the load of all the processes, boilers and turbines at each time step, while maintaining all the energy and mass balances within the system. In **Papers I and II**, the dimensioning of all processes in the mill is given exogenously to the model, whereas in **Paper III**, the investments in certain units (i.e., the condensing turbine, lignin extraction plant, and carbon capture system) are also optimised. In specific scenarios described in **Paper I**, where the mill alternates between processing softwood and hardwood, a mixed integer linear programming (MILP) version of the model is used to optimise the timing of the operational campaigns. Although the PEMO model was developed for the chemical pulp mill, the modelling framework has broader applicability. The

¹ The *PEMO* acronym does not appear in the papers since it was established after the papers were written.

fundamental dynamics, including the drivers and restrictions for flexible operation, should be applicable to most process industries, with the highest relevance for those with integrated energy supply units. For example, the framework has been adapted and applied to a sawmill with an internal boiler [104].

Figure 2 shows an overview of the objective function, input parameters, constraints, and result variables included in the PEMO modelling. A detailed mathematical description of the model is given in **Paper I**, and further refinements to the model are described in **Paper II** and **Paper III**.

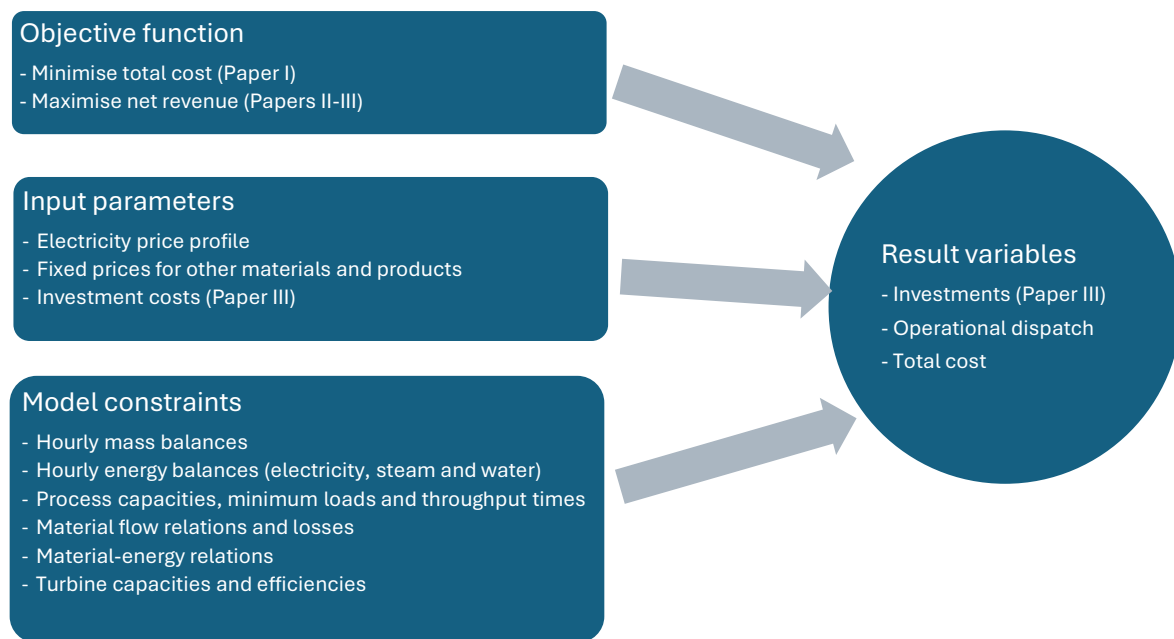


Figure 2. Overview of the objective function, input parameters, constraints and result variables included in the PEMO model.

Figure 3 depicts an overview of the model mill, including the connections between production processes, boilers and storage units. In addition to the illustrated material flows, the model covers the flows of steam and electricity. Steam production takes place in the recovery boiler, which combusts the black liquor, as well as in a separate bark boiler. Steam is converted to electricity in one back-pressure turbine and, in some cases, one condensing turbine. The generated electricity and steam are supplied to industrial processes throughout the mill, and any surplus or deficit electricity is traded with the electricity market, which is included as an unlimited market with an exogenously given price profile, under the assumption that the mill is a price-taker.

In **Paper II**, modifications to the model are described that represent an installed lignin extraction process based on acid precipitation as an extra intermediate step within the evaporation plant. The unit representing the evaporation plant process is split into

two parts, with the lignin separation process in between, as illustrated in Figure 4, which shows the evaporation plant and recovery boiler of the model mill in Figure 3 in more detail. The remaining lignin and the non-lignin parts of the black liquor are kept separate in the model, even though in reality they comprise a single physical flow.

Extracting lignin from the black liquor reduces the load in the recovery boiler, which the model can use either to increase the overall throughput of the mill (if the recovery boiler is a bottleneck to begin with) or to enable flexible operation of the recovery boiler. Three factors limit how much lignin can be extracted in the model: (i) the momentary maximum, as limited by the extraction process; (ii) the lowest lignin content of the black liquor for which it is assumed to be still combustible; and (iii) the overall steam balance of the mill.

In **Paper III**, the model mill is further extended with a carbon capture module that is connected to the three flue gas stacks: the recovery boiler, the bark boiler, and the lime kiln, as depicted in Figure 5. The module represents a post-combustion system that is based on chemical absorption, with separate absorbers for each flue gas stack, albeit with a joint stripper and liquefaction unit. For flexibility in relation to electricity price variations, the absorbers and the stripper can be operated independently of each other to the extent allowed by the sizes of the absorbent storage units.

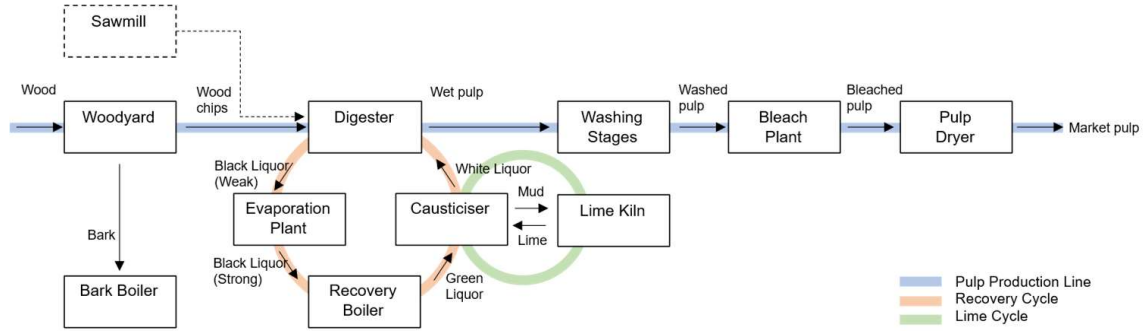


Figure 3. Schematic overview of the model mill. Source: **Paper I**.

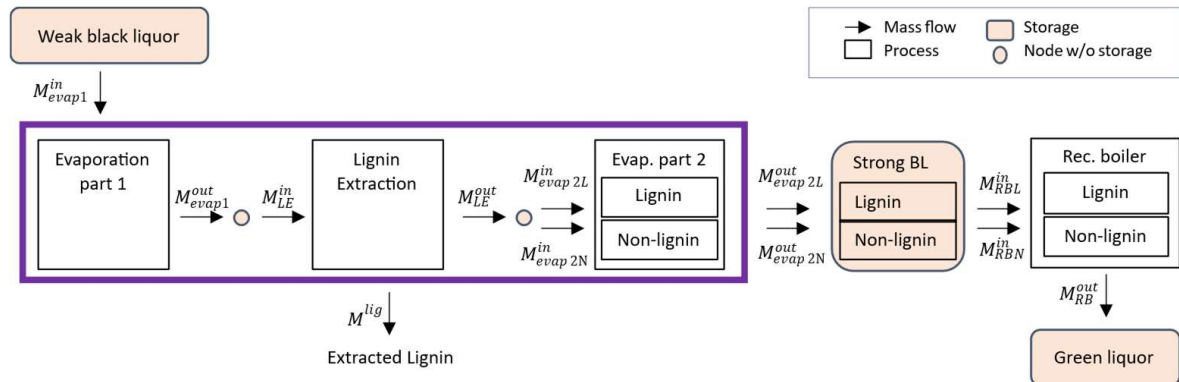


Figure 4. Schematic of the modelled evaporation plant and recovery boiler, where the evaporation plant includes an integrated lignin extraction process. BL, black liquor. Source: **Paper II**.

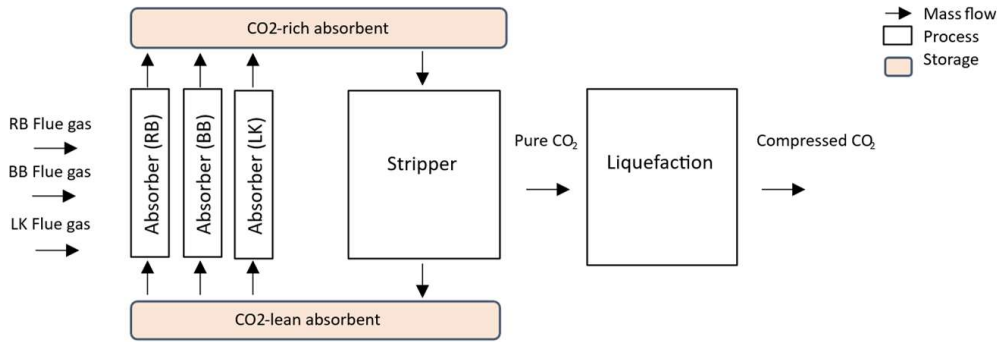


Figure 5. Schematic of the modelled carbon capture system. RB, recovery boiler; BB, bark boiler; LK, lime kiln. Source: **Paper III**.

2.2 ELLI model

ELLI is a linear investment and dispatch optimisation model of the Northern European energy system. Investments are made for each five-year period, and the dispatch within each modelled year is represented by 730 time steps, corresponding to an average resolution of 12 hours. For **Paper IV**, ELLI was expanded with a module that represents the forest biomass system, as shown in Figure 6. This module covers the feedstock supply, product delivery, conversion processes in the forest industry, heating and methanol sectors, and carbon capture, as well as transport between regions.

The objective is to minimise the total system cost while meeting exogenously set demands for electricity, hydrogen, district heating, methanol and negative emissions. Sawn timber and pulp, which are mainly produced for export, yield an income that is subtracted from the total system cost. For the version of the model applied in **Paper IV**, Sweden is divided into 26 regions, each of which is connected to one of the four Swedish bidding zones, while neighbouring countries are represented by their bidding zones. The electricity balance is resolved per bidding zone, and the balances for heat, hydrogen and forest industry materials are resolved per region. Feedstock and product markets, primary industry and transport are modelled on a yearly basis, while the energy and carbon capture technologies follow the finer time resolution.

Technologies for heat and power generation and hydrogen electrolysis are inherited from the ELLI main model, while the supply of biofuels to CHP plants and heat-only boilers is endogenised within the forest biomass module. Transport of feedstocks, methanol and CO₂ between regions follows the method established by Karlsson et al. [32]. This transport is represented by investments in and variable costs for ships, trains and trucks, depending on the available transport modes and distances.

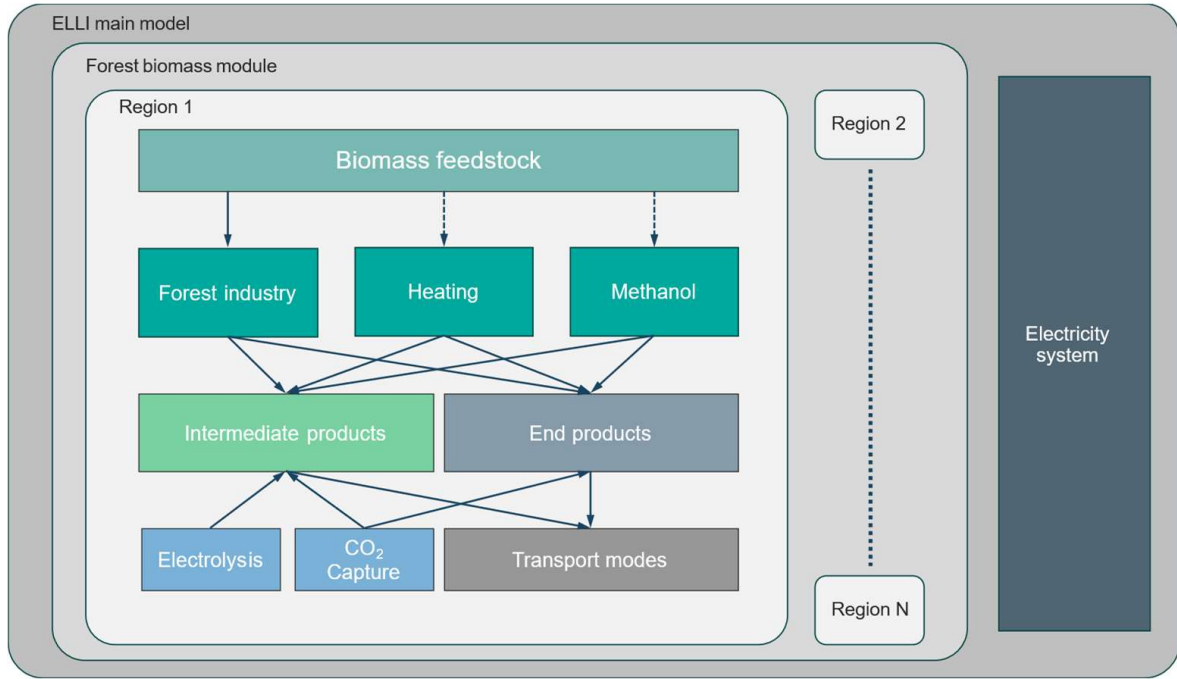


Figure 6. Overview of the forest biomass module. The arrows represent the main variables in the model and the boxes represent the main balances. Transport links the regions to each other, and electricity generation and consumption link the forest biomass module to the main ELLI model.

2.3 Case studies

In the four papers, the models are applied to case studies to investigate various aspects of higher-value utilisation of forest biomass in the energy transition. The various methodological set-ups differ with respect to the system boundary, the time horizon, and the type of model-optimised decision, as summarised in Table 4.

The case studies presented in **Papers I–III** share the same reference mill: a stand-alone, bleached softwood market pulp mill of 2,000 ADt/d located in electricity bidding zone SE3, which is self-sufficient with respect to heat and a net exporter of electricity. Since process over-capacities and storage volumes vary considerably between real mills, the cases in **Paper I** span a range of conditions rather than representing one specific site.

The system-level analysis in **Paper IV** is a case study of Sweden, which combines a large forest industry with a largely fossil-free electricity system and widespread district heating. The quantitative results at the system level are therefore specific to Swedish conditions, whereas the mechanisms behind them are expected to be relevant also for other energy systems.

All of the appended papers investigate several scenarios and/or cases, with different assumptions made along one or several parameter dimensions. **Paper I** varies the degree of operational flexibility and **Paper II** varies the extent of lignin extraction.

In **Paper III**, the mill configuration becomes an outcome of the modelling, and the cases are instead defined by the market prices of lignin and CO₂. **Paper IV** turns the question around by prescribing targets for BECCS and renewable methanol production, rather than prices, and then letting the model determine how the biomass is allocated between sectors. The electricity price follows a similar progression. **Papers I and II** contrast the moderate prices of Year 2019 with the high and volatile prices of Year 2022. **Paper III** uses modelled future price profiles, whereas in **Paper IV** the price emerges from the system optimisation itself.

Table 4. Overview of the four case studies in the respective appended papers.

	Paper I	Paper II	Paper III	Paper IV
Model	PEMO (LP/MILP)	PEMO (LP)	PEMO (LP)	ELLI with forest biomass module (LP)
System boundary	Single model mill	Single model mill	Single model mill	Swedish forest biomass system within the Northern European energy system
Geographical resolution	–	–	–	26 Swedish regions connected to four electricity bidding zones and four forest price areas
Time horizon and resolution	One year, hourly	One year, hourly	One year, hourly	Years 2030–2050 divided into five-year periods, with 730 time steps per year
Optimised decisions	Dispatch, timing of campaigns	Dispatch	Dispatch and investments in the mill	Dispatch and investments in the whole system
Scenario/case dimensions	Six levels of operational flexibility, three campaign cases	Lignin extraction capacity (bottleneck scenario), lignin extraction target (balanced mill scenario)	Four market scenarios for the prices of lignin and CO ₂	25 combinations of BECCS and methanol targets; additional cases with fixed timber and pulp production
Electricity price profile	Historical, Years 2019 and 2022	Historical, Years 2019 and 2022	Historical Year 2017, modelled Years 2030 and 2040	Endogenous

2.4 Assumptions and data

The input data for the PEMO model are mainly based on steady-state descriptions obtained from the literature, complemented with assumptions regarding the dynamic aspects, mainly the storage sizes and process throughput times, which were obtained through discussions with industry personnel. The conventional mill processes are

represented using a description of a bleached softwood market pulp mill, the lignin extraction process is assumed to be of the LignoBoost type [105], and the carbon capture process is a post-combustion, amine-based system with a maximum capture rate of 90 % [64,65]. Since the model mill represents best available technology (in Year 2010), it should be noted that older and less energy-efficient mills have less surplus energy, which tightens the limits for lignin extraction and carbon capture.

For the forest biomass module of the ELLI model, the technical and cost parameters for the conversion technologies are obtained from the Danish Energy Agency [106]. The prices of sawn timber and pulp are based on historical market data, and the feedstock supply is described by cost-supply curves, dividing Sweden into four wood-supply zones according to [107].

The cost-supply curves cover timber, pulpwood and logging residues, so that larger volumes can be extracted at a rising marginal cost. In addition, imported biomass is available at a fixed price, although the magnitude of the imports is limited by an exogenous volume constraint, chosen to represent a scenario with a high degree of self-sufficiency. Industry residues are not extracted but arise endogenously as by-products of sawn timber and pulp production; residues from sawmills may in turn be used as feedstocks in pulp mills before being used further downstream.

2.5 Complementary analyses

In **Papers II and III**, the optimisation modelling is complemented by idealised calculations based on the mass and energy balances of the model mill, disregarding some of the technical constraints of the optimisation model. Since these analyses depend on fewer assumptions than the optimised cases, they provide more general results and provide reference points for interpreting the modelling output.

In **Paper II**, the modelled marginal cost of lignin extraction is compared with two hypothetical references: a steady-state case based on the annual average electricity price; and an ideal, fully flexible case with fewer technical limitations (ignoring, for example, capacity limits, storage volumes and time delays). Together, they indicate how much of the potential value of flexibility is captured by the modelled mill configurations.

In **Paper III**, price tipping points are derived analytically as the combinations of market prices at which two investment options (condensing turbine, lignin extraction or carbon capture) yield equal net revenues. This extends the analysis beyond the specific price levels assumed in the modelled scenarios.

The sensitivity of the results to the key assumptions is tested in all four papers. In **Paper I**, the model is also run with Year 2022 electricity prices, which were unusually

high and volatile. In **Paper II**, the lignin extraction cases are recalculated with overcapacity present in the lignin extraction process and with increased black liquor storage volumes. In **Paper III**, the tipping points are recalculated for a 50 % increase in the investment cost of each technology. In **Paper IV**, the effect on the system when pulp and timber production is locked to the reference level is examined.

The thesis provides only limited results on the climate impact of the studied measures. Indirect effects, such as the substitution effect of the methanol produced in the Paper IV scenarios, would require a larger system model to quantify. In Paper III, the carbon efficiency of the mill, i.e., the share of the input carbon that leaves the mill as products or as captured CO₂, is used as a transparent indicator, but it treats captured carbon and carbon in products as equivalent regardless of their further processing and end use.

3 Results and discussion

Taken together, the appended papers show that the optimal path to higher-value utilisation of forest biomass depends on the geographical perspective (system scope), temporal perspective, and assumptions made as to the developments in sectors that historically have been separate from the forest industry. The results are not site-specific investment appraisals. Rather, they identify the mechanisms, price thresholds and system conditions under which the studied options become attractive, which can be used to screen investment options in the forest industry and inform policymakers on the possibilities and limitations to the use of forest biomass.

This chapter is organised into seven sections. Sections 3.1–3.4 address the first research question, examining how the development of external market and policy conditions determines which choices with regard to investments and operation in the forest biomass system become rational in the economic sense in the near future. Sections 3.5–3.7 address the second research question, examining how the interplay between the forest biomass system and the wider energy system evolves as new demands are placed on forest biomass. Section 3.5 also informs the operational part of the first research question. Results are attributed to the paper in which they are presented, whereas passages without such attribution represent the synthesis and discussion of this thesis.

3.1 The evolving role of the chemical pulp mill

The study explores the near future between the present and mid-century situations. In the near term, currently active industries can be expected to remain in their current locations and with only minor adaptations to the existing technology. Towards the end of this period, however, many facilities will have reached their respective end-of-life, and it is relevant to consider relocations, technology shifts and potential divisions of, and mergers between, established sectors. Furthermore, the policy landscape will change during this time period, due to built-in adjustments in established policies (e.g., the EU Emissions Trading System, the ReFuelEU Aviation and FuelEU Maritime regulations, and the renewable fuel quotas of the Renewable Energy Directive; see Table 1) and new policies. Regarding the technological development within the time frame studied in Papers III and IV, it is likely that emerging technologies will have reduced costs due to learning effects, and that some technologies that are only demonstrated on a small scale can be scaled up to commercial level. However, it is

unlikely that completely new, unknown, technologies within energy and biomass conversion will emerge during this period.

In **Papers I and II**, the near-future perspective is implicitly considered in that the electricity system is assumed to have larger variations in the electricity price. The temporal aspect is more explicit in both **Paper III** and **Paper IV**; **Paper III** considers changes in the policy landscape and market pull from external sectors, while **Paper IV** considers that existing technologies reach the end of their lifetimes and that the costs for emerging technologies decrease. Compared to **Papers I–III**, the fourth study (which also presents the results all the way to Year 2050) comes closer to answering the question as to how an ideal future system would be designed. Nonetheless, the focus is on the transition period and it is accepted that a limitation of the methodology is that the industrial units of the forest industry (i.e., sawmills and pulp mills) have infinite lifetimes, while the heat and electricity sectors are phased out according to the construction year and assumed lifetime of each site.

Taken together, **Papers I–III** illustrate how the role of the chemical pulp mill in the electricity system could develop over the coming decades. This assumes that the electricity system will evolve towards having an increasing share of variable renewable sources, while an increased demand for biogenic carbon will drive pulp mills towards investments in integrated biorefinery concepts.

In **Paper III**, the PEMO model is applied to a set of scenarios in a case study of a possible development in which the value of the biogenic by-products of the mill over time increases compared with the reference scenario, while electricity prices become more variable. Figure 7 shows the carbon balances over the mill, the carbon efficiency (defined as the share of the input carbon that leaves the mill in the form of products or as captured CO₂), and the net level of electricity generation from the mill.

The results obtained from the reference scenario, representing historical conditions, show that it has historically made economic sense to invest in an additional turbine for increased electricity generation, but not to invest in processes for the production of lignin or CO₂. In the reference scenario, the mill contributes to the energy system, mainly as a supplier of base-load electricity. However, the results in **Paper I** show, as discussed further in Section 3.5, that already with conventional mill processes, the mill can adopt a more-active role in the electricity market than it has done historically, now acting as an industrial-scale prosumer.

In the Year 2030 scenario in **Paper III**, an assumed demand for a lignin-based biofuel from the maritime fuel sector sets the price for lignin. As discussed in the paper, such a demand is in line with FuelEU Maritime, which requires the greenhouse gas intensity of the energy used on board ships to be reduced by 6 % by Year 2030 and by 31 % by Year 2040 (Table 1). In this scenario, there is an economic incentive for the

mill to invest in both lignin extraction and a condensing turbine, thereby slightly increasing the carbon efficiency while still maintaining a substantial electricity surplus, which supports the transition of the electricity sector (and, indirectly, the electrification of the heating, transportation and industry sectors) during this period.

In the Year 2040 scenarios, the energy transition is assumed to have reached the hard-to-abate sectors (in line with, e.g., ReFuelEU Aviation and FuelEU Maritime; Table 1), which raises the prices of both lignin and captured CO₂. With these prices, the mill invests in lignin extraction and/or carbon capture at the expense of electricity generation, since supplying biogenic carbon becomes more profitable than supplying electricity. This indicates that the most valuable role of the forest industry in the wider energy system shifts towards that of a supplier of biogenic carbon for hard-to-abate sectors (e.g., aviation, maritime transport and plastics) and/or of negative emissions.

In the Year 2040a scenario, lignin and CO₂ are valued according to the demands from biofuel and e-fuel applications, respectively (assuming that the need for e-fuels drives up the price also for biofuels). This creates an incentive for the mill to prioritise increased carbon efficiency over electricity generation, which stimulates investments in lignin extraction and carbon capture. In this scenario, lignin extraction is favoured over carbon capture, although it is limited by technical constraints, which opens up possibilities for a combination of the two technologies. In the combined case, carbon capture is dimensioned according to the steam surplus that remains after lignin extraction, which illustrates that the two technologies compete for the same steam, as also shown by Skoglund et al. [68].

In the Year 2040b scenario, CO₂ is priced according to its value in generating negative emissions via BECCS. This assumption implies a much higher price for CO₂ than in the Year 2040a scenario, such that lignin extraction cannot compete with carbon capture. In this scenario, the mill imports bark, in order to increase further the output of captured CO₂.

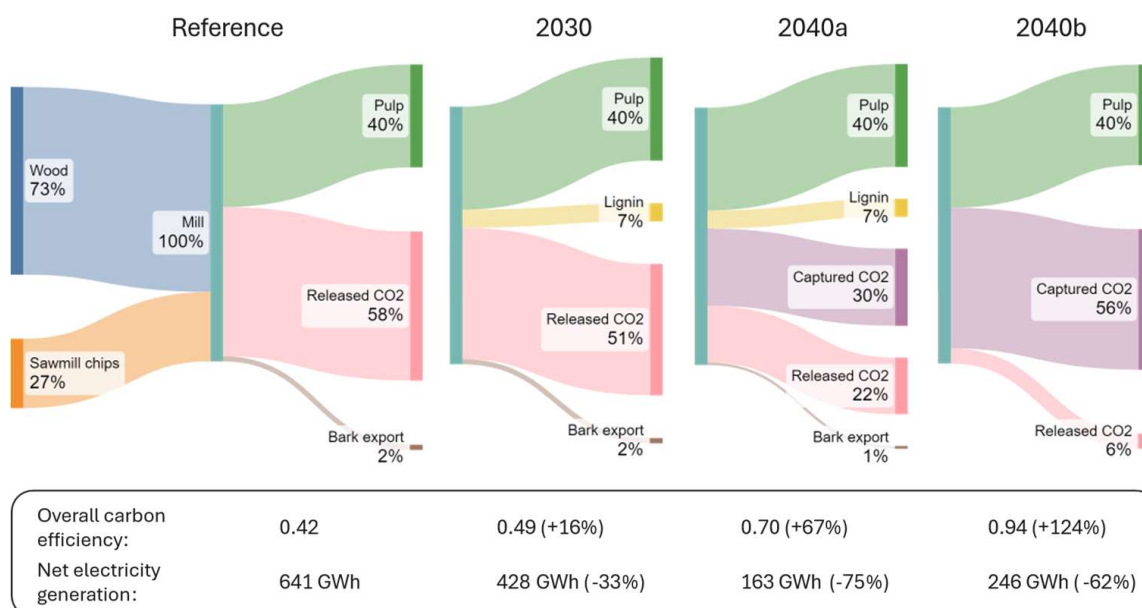


Figure 7. Carbon balances, carbon efficiencies (shares of the input carbon that leave the mill in products or as captured CO₂), and net levels of electricity generation from the mill in the four modelled scenarios. The percentages shown in parentheses indicate the differences compared to the reference scenario. Source: **Paper III**.

3.2 Comparison of options for pulp mill by-product utilisation

This section compares the studied options for the chemical pulp mill with respect to increasing the value of its biogenic by-products, i.e., lignin extraction, carbon capture for storage or for utilisation, and electricity generation, and identifies the price levels at which the economically rational choice changes from one option to another.

The results reported in **Paper II** indicate the combinations of lignin price, electricity price, and investment cost for the lignin extraction technology for which there is an economic incentive for the mill to invest in lignin extraction. A rule-of-thumb emerges that, with steady operation, for lignin extraction to be more economically attractive than the corresponding electricity generation, lignin prices (€/t) must be 1.8 times the electricity price (€/MWh) plus the non-energy operational costs of lignin extraction (assumed to be 40 €/t).

Paper III presents analogous calculations for the comparison between carbon capture and electricity. Thus, for each tonne of CO₂ captured, 1.4 tonnes of low-pressure steam (1.08 MWh) are required, which could otherwise have been used to produce 0.17 MWh of electricity in the condensing turbine. In addition, the CO₂ liquefaction process requires 0.12 MWh of electricity per tonne of CO₂. Therefore, the willingness to pay for CO₂ (€/tCO₂) must be at least 0.29 times the electricity price (in €/MWh)

plus the non-energy costs, for carbon capture to be more economically favourable than the corresponding electricity generation.

Figure 8 illustrates the tipping points for investment decisions based on the trade-offs presented above, together with the assumed capital costs. The literature suggests that if kraft lignin is valued according to its equivalent fossil counterparts as a feedstock for green chemicals, such as aromatic monomers and phenol-formaldehyde resins, its market value will rise from the current value of around 100 €/t to up to 350 €/t [52] or even as high as 500 €/t [108]. Figure 8a shows that, at such lignin prices, investments in lignin extraction are favoured over investments in electricity generation if the average electricity prices remain around the Year 2019 level for bidding zone SE3 (shown in the figure for comparison), whereas at the current lignin value of around 100 €/t they are not.

Figure 8b compares investments in CO₂ capture and electricity generation. For the economic value of negative emissions, the future cost of emission allowances in the EU ETS scheme should be a good proxy (Section 1.1). However, the future trajectory of allowance prices is highly uncertain, being dependent upon policy decisions that have not yet been taken. In the scenario assumptions that the European Commission supplies to the EU Member States, the allowance price for emissions included in ETS1 reaches 100 €/tCO₂ by Year 2040 under the pathway with existing measures (WEM) and 290 €/tCO₂ under the pathway with additional measures (WAM), with these values increasing to 190 €/tCO₂ and 490 €/tCO₂, respectively, by Year 2050 [109]. Thus, if the captured CO₂ at the mill gate is valued according to the credit price for emission allowances within the EU ETS minus the costs for CO₂ transport and storage (assumed to be 100 €/t in **Paper III**), a mill-gate price well above 100 €/t is not unlikely by Year 2040 if allowance prices follow the WAM pathway (around 190 €/t), whereas the WEM pathway gives close to zero.

In Figure 8c, investments in carbon capture are compared with investments in lignin extraction². The comparison shows that if CO₂ is sold at its production cost (around 50 €/t) the corresponding lignin price (150 €/t) is well within the price range for lignin applications. If, however, CO₂ is priced in line with the EU ETS, CO₂ prices (minus the costs for CO₂ transport and storage) following the WAM pathway would clearly outcompete the full estimated price range for lignin by Year 2040, while the CO₂ prices following the WEM pathway would transit this range between Years 2040 and 2050.

² In the corresponding figure in **Paper III** (Fig. 5), the Year 2024 ETS allowance price is marked as a reference level on the CO₂ price axis. Since the axis represents the value at the mill gate, the marked level corresponds to an actual ETS price that is higher than the Year 2024 price by the cost of CO₂ transport and storage. The comparisons made against this reference level in the associated analysis should be interpreted accordingly.

The capture costs in Paper III (around 46–91 €/t at the recovery boiler with the electricity prices of Year 2040) are in line with the literature, where costs for capture and compression at pulp mills range from 8 to 263 €/t, with a median of 65 €/t [46]. However, they do not include the higher costs of first-of-a-kind plants, so the tipping points in Figure 8 should be read as lower bounds. **Paper IV** gives a considerably higher marginal cost for BECCS of around 225–300 €/t when post-combustion capture at pulp mills is the marginal technology. Unlike the costs in **Paper III**, this figure includes the transport of CO₂, is based on different cost assumptions (which is natural, given the wide range reported in literature), and, as a shadow price of the BECCS target, also reflects opportunity costs in the system, for example for the production of heat and electricity. If these costs are transferred to the breakpoint analysis in Paper III (subtracting transport costs), CO₂ prices following the WAM pathway still out-compete lignin extraction by Year 2040, while those following the WEM pathway may not be competitive even by Year 2050. Early projects are therefore likely to depend on additional revenue, for example from national support or voluntary carbon markets (Section 1.1).

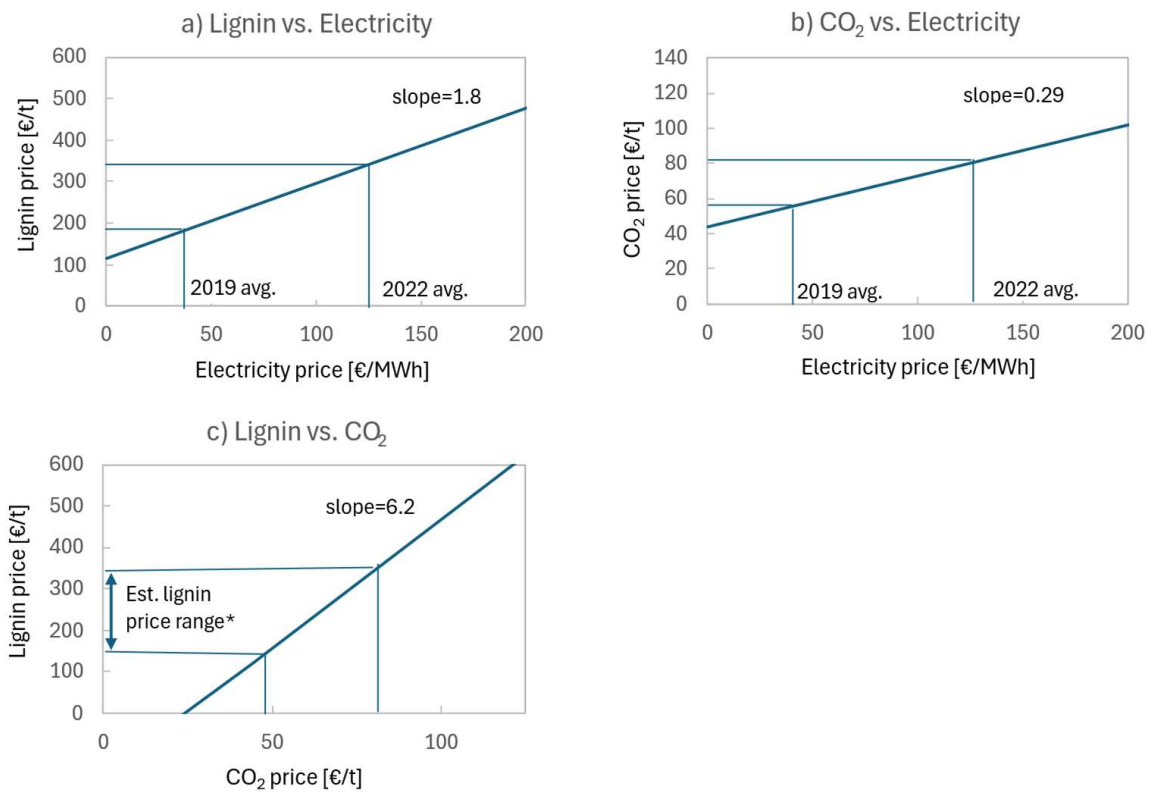


Figure 8. Tipping points for decisions to invest in a) a condensing turbine versus a lignin extraction plant; b) a condensing turbine versus a carbon capture system; and c) a carbon capture system versus a lignin extraction plant. The solid lines indicate the price combinations at which the economic incentives for both investment options are equivalent. All prices are considered at the mill gate. * Estimated range for the selling price of kraft lignin depending on market conditions and policy according to [52]. Adapted from **Paper III**.

As stated in the *Method* section, there are several technical limits linked to how much lignin can be extracted. In **Paper II**, the overall steam balance of the mill is not the limiting factor, mainly because the mill is energy-efficient as a whole (with high temperature and pressure levels in the steam system) but also because a surplus of bark remains available to replace the energy content of the extracted lignin. If the mill is less energy-efficient, it would be relevant to assess the possibility of supplementing with a low-grade biomass fuel, e.g., by mixing sawdust into the black liquor, in order to push the steam balance limit. This may be a realistic scenario if the lignin is destined for a niche product where the chemical structure of the lignin is valued, whereas if lignin is subjected to a thermochemical process, e.g., to produce a transportation fuel, fractions such as surplus bark and sawdust have likely been used for that purpose already, such that the surplus assumed in **Paper II** would no longer be available. Furthermore, the model mill in Papers I–III is a stand-alone market pulp mill. Integrated pulp and paper mills, which are typically net consumers of electricity, would need additional energy input for lignin extraction or carbon capture, for example from an additional biomass boiler or high-temperature heat pumps, as discussed in Paper III.

The scenarios in **Paper III** are defined by assumed demands for renewable maritime fuels and negative emissions, with a timeline for the maritime fuels that is consistent with FuelEU Maritime (Table 1). The Year 2040b scenario also assumes that negative emissions are credited in the EU ETS at the allowance price, based on forecasts of around 250 €/t by Year 2040. Under the legislation in force, however, the allowance cap would reach zero around Year 2039, so the conditions assumed for Year 2040 could arise already in the 2030s, whereas the revision proposed in July 2026 would slow down the reduction of the cap after Year 2030 (Table 1). If other political decisions allow for the continued use of fossil alternatives, the willingness to pay for bio-based fuels and products may be much lower than assumed in this thesis, and a voluntary market for carbon-neutral products at a premium price may not be sufficient to motivate transformative changes in the pulp and paper sector.

Furthermore, the evolution of the pulp mill suggested by the results of **Paper III** would be difficult to accomplish in practice, since the market conditions would change faster than it would take for the industry to modify its roles, considering that investment cycles in the basic industries usually extend over decades. Thus, if the markets develop as suggested, it will be difficult for any actor in the system to take on the optimal role at every stage. Nevertheless, if decision-makers in the forest industry want to create the largest-possible value and contribute as much as possible to reaching climate targets, it is important that they understand how the markets and policy landscape are developing, not just in their own traditional value chain, but across all sectors of the economy.

3.3 The economic value of low-grade biomass

The system price for residual biomass, in the forms of industry residues (bark, wood chips, sawdust and/or lignin), is examined in the appended papers on all levels, from the individual mill to the national system. **Papers I and II** address the supply cost in the individual mill. **Paper III** adds demand price signals as an exogenous assumption, and **Paper IV** includes both supply and demand aspects.

In **Papers I and II**, the price of electricity is the only price input to the model, meaning that all internal prices are set in relation to this price signal. Specifically, the shadow price of bark is in **Paper I** obtained for each hour, accounting for the conversion efficiency from bark to electricity. In the non-flexible case, the value is proportional to the electricity price for each hour, and the more storage capacity that is made available, the more the variations in the bark value are smoothed over the year. For the more-flexible scenarios, the resulting steady values are close to the average Swedish market value for solid biomass by-products during the period of 2012–2021 (16 €/MWh) [108]. Whether there is a value associated with trading bark on the external market, rather than using it internally, therefore depends on the storage possibilities within the mill and on the price variations in the market.

When several alternative end-products are introduced in **Paper III** and **Paper IV**, the value of residual biomass is no longer linked in a straightforward way to the electricity price. Instead, it is linked to the sector where the willingness to pay is highest during the specific time step and at the specific geographical location. This illustrates the point made in Section 1.1, that a fixed order of priority such as the cascading principle [11] does not capture the differences in value within the category of bioenergy, which depend on the energy carrier and on when and where it is delivered. In the cascading principle, bioenergy also includes biofuels, so that bio-methanol used as a fuel ranks below material uses, whereas the same bio-methanol used as a feedstock for chemicals would arguably count as a material use, as the directive does not specify whether chemicals are included among the wood-based products.

For lignin, its chemical structure makes it suitable for a number of niche applications, although the markets for these are small in relation to those within the energy and base chemical segments. The focus of this work is, therefore, mainly on applications related to energy and base chemicals, where lignin competes with other low-grade fractions of wood, such as the pyrolysis-derived biodiesel depicted as an intended end use in the case study of **Paper III**. With the national perspective applied in **Paper IV**, it is also shown that transportation costs affect the value of low-grade biomass, creating cost discrepancies between geographical regions.

Figure 9 shows how the value of industry residues (wood chips, sawdust and bark), obtained as the marginal cost of the residue balance in each region from the ELLI

model, varies across the Swedish regions included in the case study in **Paper IV**, for nine combinations of BECCS and methanol targets. Since these residues are modelled with the same properties as logging residues and (unspecified) imported wood, it can be regarded as the willingness to pay for any locally available low-grade wood fraction. In the reference case (Figure 9a), the marginal cost is set according to the value of heat and power as delivered by CHP plants or auxiliary boilers in pulp mills. The marginal cost increases as the target levels become more ambitious, partly because residues are used in processes that produce higher-value products, and partly because a re-allocation of the primary feedstock (as discussed further in Section 3.7) reduces the total volume of industry residues that arises in the first place. The direction is consistent with the forest sector studies by Bryngemark and Hu et al. [86,87], in which large-scale biofuel production and trading of negative emissions, respectively, raise the prices of pulpwood and sawmill by-products.

Across the scenarios depicted in Figure 9, there are large differences between the regions as can be seen from the distribution across regions. In the inland regions without harbour access, neither the marginal cost nor the use of industry residues is affected by higher target levels, as the cost of transporting products out of these regions is prohibitive. In the model, access to transport infrastructure, rather than proximity to the feedstock, is what determines whether a region is exposed to the new demands. This partly agrees with Jåstad et al. [91], who found that large biofuel plants in Norway are best located near large harvests or at harbours and railway terminals, where they raise the local pulpwood prices. For CO₂, ship transport is the least costly option for most Nordic sources [32].

The models and case studies in this work are carried out with the perspective of either the individual mill or the national system. While heat and electricity are traded on more-or-less local markets, biomass feedstock and products are shipped world-wide. Therefore, the global perspective is of great importance to understanding the implications and limitations of the study.

In the case study reported in **Paper IV**, the feedstock import volume is limited in order to assess a scenario with a high degree of self-sufficiency. With unlimited biomass imports, the import price would establish a limit for the domestic price of biomass (although it would remain subject to local differences due to transportation costs and logistical bottlenecks). The marginal values shown in Figure 9 fall both below and above the marginal value of the import restriction (if the assumed cost of import at 22 €/MWh is added on top of the line shown), whereas, with unlimited imports, the import price plus the cost of transport from the harbour would define a ceiling for the value of the industry residues in each region.

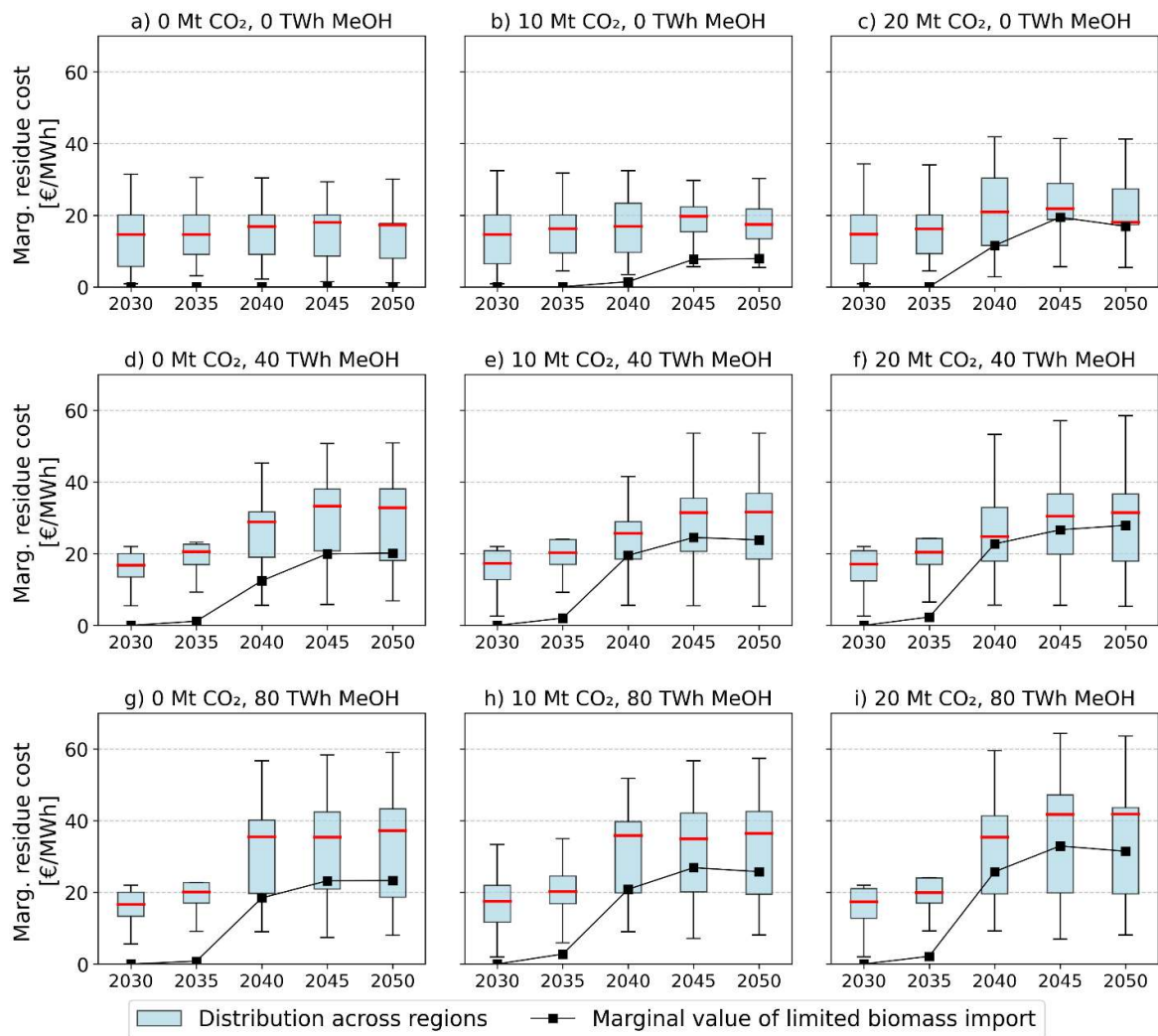


Figure 9. Box-plots of the distribution across regions of the marginal costs for industry residues for nine modelled scenarios, spanning different combinations of BECCS and methanol targets, from Year 2030 to Year 2050. The red lines indicate the median costs, and the boxes represent the 25th to 75th percentiles of the regions. Source: **Paper IV**.

Whether the domestic options studied here would remain competitive in face of such a limit is not addressed in the appended papers, although the cost estimates that they provide give an indication. Bark and sawdust, as well as some fractions of logging residues, which are today generally regarded as free by-products, will likely remain competitive as feedstocks even when global alternatives are available. The use of lignin in energy applications is debatable in this regard. The results from **Papers II** and **III** suggest that lignin can be extracted from chemical pulp mills at a cost of around 22–35 €/MWh, of which 10–15 €/MWh are annualised capital costs and 12–20 €/MWh are variable costs, in cases where 10 %–30 % of the lignin is extracted and flexibility measures are applied. These numbers fall within the system value of residues in most regions in the high-target scenarios with limited imports (see Figure

9), but they can hardly compete with the historical prices for imported wood pellets at around 22 €/MWh [110].

However, if also the demand for biomass (or carbon atoms) increases in a global system where all countries phase out fossil feedstocks, it is uncertain whether biomass will be available for import at the same cost as it is today. Assessing this would require an analysis that addresses the issues of global land use, land-use change, and forestry, which fall outside the scope of this thesis.

3.4 Incentives for BECCS and synergy with methanol production

The demand for negative emissions via BECCS is a question of policy rather than one of economics. Although the markets for electricity, heat and fuels are also affected by policy, the BECCS market differs in that negative emissions represent a policy-driven product. As shown above, with a strong incentive for BECCS (150 €/t at the mill gate in the Year 2040b scenario of Paper III), the captured CO₂ needed to achieve negative emissions is valued higher at the mill gate than both the extracted lignin and CO₂ for BECCU applications. From the local perspective applied in **Paper III**, a sufficiently high value attached to BECCS makes it optimal for the mill to invest in a carbon capture technology. **Paper IV** shows that this conclusion survives at the system level only as long as there are no other options for providing negative emissions at a lower cost.

Figure 10 shows the amounts of emitted and captured CO₂ from the three main sources across the scenarios modelled in **Paper IV**. Where a target is set for negative emissions alone (the panels in the top row), the captured CO₂ is mainly obtained through post-combustion capture at pulp mills, which is in that case the cheapest option available to the model. However, once a target for domestic methanol production is added the gasification process supplies CO₂ as a by-product of the syngas, and post-combustion capture from pulp mills is progressively phased out as the methanol target becomes more ambitious.

Even in the scenarios in **Paper IV** that have only a BECCS target, post-combustion capture is not always superior to gasification. Part of the explanation of this follows directly from the input data, where the investment cost per unit of captured CO₂ is lower for capture from a gasification unit than for post-combustion capture at an existing mill [106]. In addition, it is assumed in **Paper IV** that the mill is fixed at its current location, whereas a new gasification plant can be located wherever the conditions for capture are optimal.

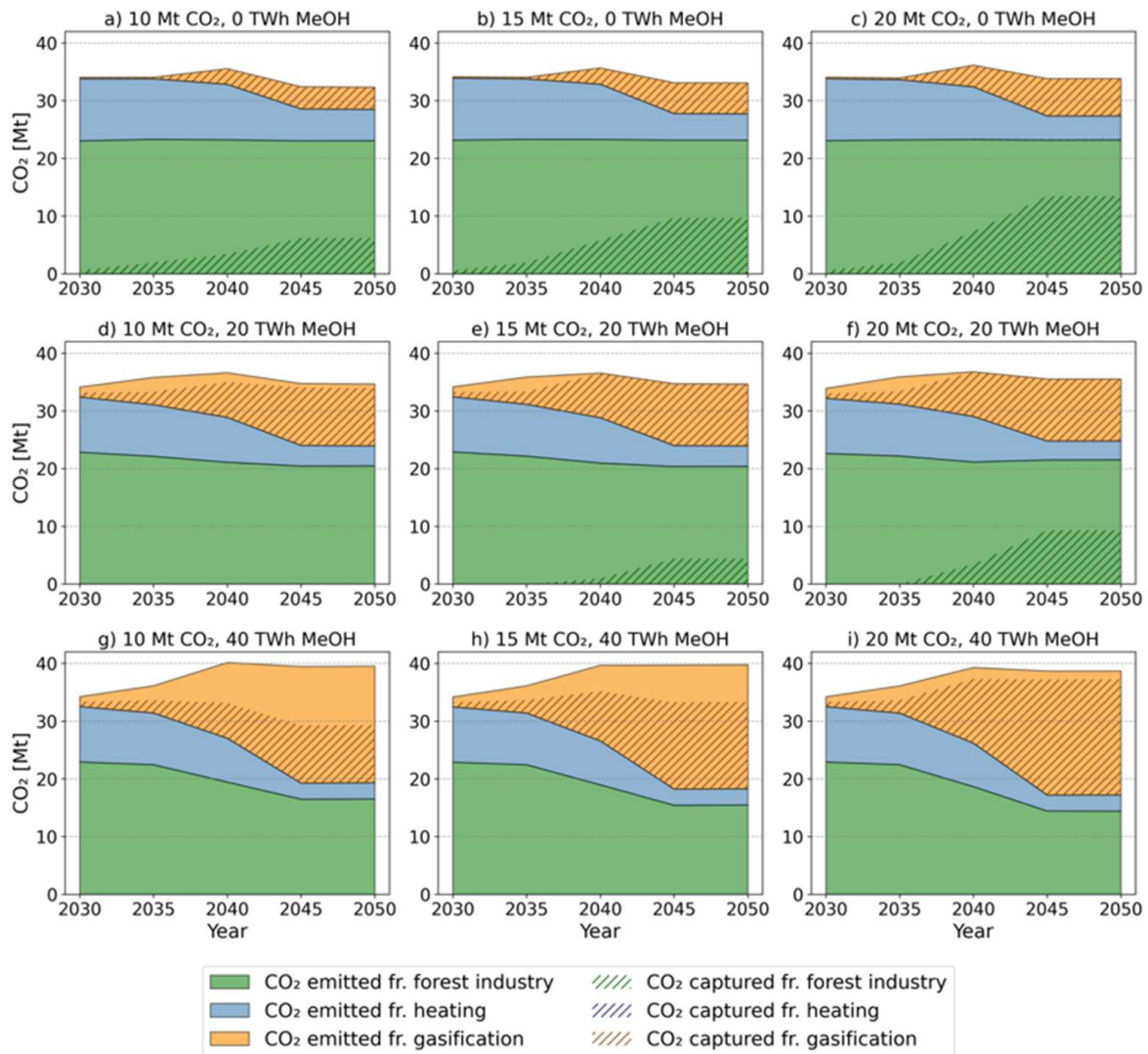


Figure 10. Amounts of emitted and captured CO₂ from the three emission source types between Years 2030 and 2050 across nine selected scenarios from **Paper IV**, spanning different combinations of BECCS and methanol targets. Source: **Paper IV**.

Three features work in favour of the gasification-based carbon capture, the first two of which are related to location. First, since land-based transport of CO₂ is prohibitively expensive, capture is less costly when located in regions that have access to a harbour. Second, post-combustion capture consumes both heat and electricity, while gasification with capture is a net producer of heat, which can thereafter serve the regional heating demand. Thus, the same tonne of captured carbon carries a different energy penalty (in economic terms) depending on where it is captured. Third, where there is also a demand for methanol, the CO₂ from a gasification plant acts as a by-product of a syngas stream that is itself sold, whereas CO₂ captured at the mill must carry its full cost alone. Sandberg and Krook-Riekkola [84] found the same mechanism in a national energy system model of Sweden, where capture from fuel production provided low-cost negative emissions. In that study, however, the favoured route

was biofuel production through black liquor gasification, which is not included as an option in **Paper IV**.

Working in the opposite direction, the gasification route requires a new biomass feed-stock flow, which is limited in volume and priced according to the use from which it is taken. This is the reason why capture at the existing point sources of the forest industry appears in the cost-optimal mix as long as negative emissions are pursued on their own. For capture at the pulp mill to remain competitive once methanol is also in demand, the value of the pulp that the gasification route would displace must outweigh not only the methanol revenue foregone, but also the advantages in terms of capital cost, locational flexibility and energy balance. Unlike models that represent each country by one or a few regions [23,84,90], **Paper IV** thus shows how location, infrastructure and co-production determine where the CO₂ is captured within a country.

Figure 11 shows the resulting marginal costs for targets set for negative emissions (left panel) and methanol production (right panel), across the scenarios studied in **Paper IV**. Where no methanol target is set (green area) or where the target for negative emissions substantially exceeds the methanol target on a carbon basis (dashed black and red lines), the marginal cost of negative emissions is approximately 80 % higher than under the combined targets, which reach a median of around 150 €/tCO₂ by Year 2045 (a cost that includes capture and transport to the storage site, but excludes storage). Similarly, the marginal cost of methanol is heavily reduced under high BECCS targets (black and red lines), where the syngas required for bio-methanol production becomes a by-product of the captured CO₂.

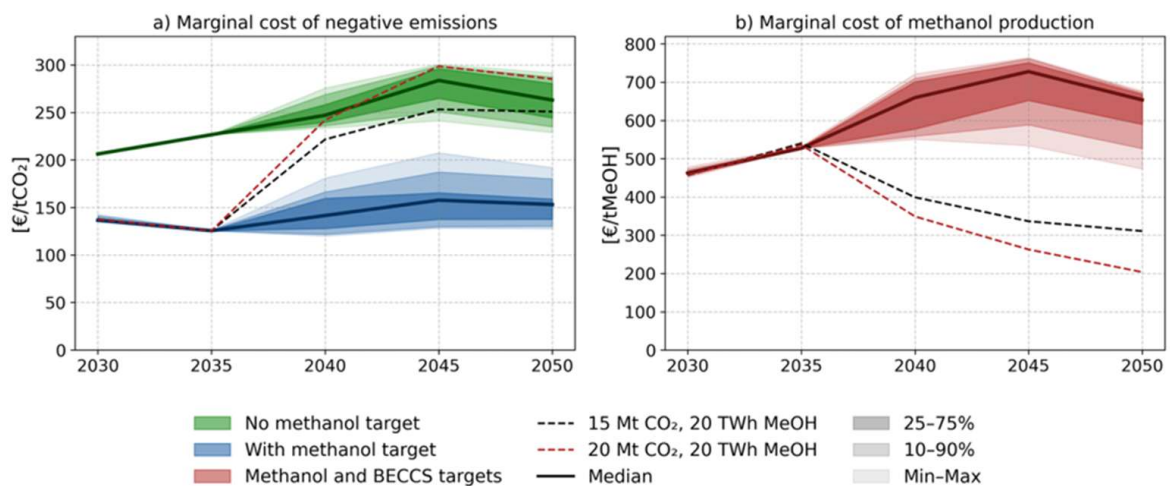


Figure 11. Marginal costs for targets related to negative emissions (a) and methanol production (b), across 25 scenarios spanning different combinations of BECCS and methanol targets. Source: **Paper IV**.

The modelled BECCS costs can be compared to the two BECCS price pathways introduced above (based on the forecasts for emissions allowances). A price that follows the WEM pathway would only cover negative emissions in Year 2050, and then only through the cheaper combined route, whereas a price that follows the WAM pathway lies within the range of the scenarios in which post-combustion capture is on the margin already in Year 2040. (The comparison should be treated with caution, since the modelled costs cover capture and transport to the storage site but not the storage itself.) Thus, according to the results shown in **Paper IV**, whether an incentive linked to the allowance price delivers BECCS from the forest biomass system, and if so, which technology and timing become viable, depends on which one of the two pathways is realised.

Gasification also produces net heat, and where a plant is sited close to a large district heating demand, the residual heat can supply a substantial share of that demand, e.g., around 20 % of the heat supply in Stockholm with targets of 20 Mt of negative emissions and 80 TWh of methanol per year. How much heat is available depends on how much CO₂ is captured at the plant, since a substantial share of the residual heat is required to operate the capture unit.

In **Paper IV**, no climate targets are imposed on the system, and the geographical scope of the biomass module is limited to Sweden, although neighbouring countries are included to account for trading in electricity. Millinger et al. [23] have shown that if climate targets are imposed on the system, the value of biogenic carbon is so high that the biogenic CO₂ from pulp mills is never released to the atmosphere. This raises the question as to how such an outcome could be achieved.

It is possible that, in the long term, if chemical pulp mills are completely re-designed for the purpose of providing low-cost BECCS, for example by replacing conventional boilers with black liquor gasification [80,84] or chemical looping combustion [111], BECCS could become more cost-competitive than capture at new gasification plants. Such technologies are not examined in this thesis, due to the near-future perspective with the focus on solutions that can be fitted to existing industry. Furthermore, studies that find such concepts competitive, such as that by Sandberg and Krook-Riekkola [84], typically assume the costs of mature (Nth-of-a-kind) plants, whereas first-of-a-kind projects usually come with higher costs.

Since the model minimises the total system cost, a given target for negative emissions is, by construction, met by the least costly combination of capture sites. Which sites these are, however, depends on whether there is also a demand for methanol, so that the same BECCS target leads to different outcomes with and without a methanol target. With a methanol target, the quantity is filled by gasification plants in which

capture shares its cost with methanol production, so that negative emissions and the use of biogenic carbon in products are complementary. The CO₂ from the pulp mills is then released, since the remaining biogenic emissions carry no cost: at a target of 20 Mt per year, 10–15 Mt of capturable biogenic CO₂ remains uncaptured. If this CO₂ should not be released, as Millinger et al. find under climate targets [23], a BECCS policy that aims for a given quantity of negative emissions at the lowest price, such as a reverse auction, may not be sufficient on its own. Without a methanol target, a larger share of the capture instead takes place at the pulp mills (Figure 10), at a marginal cost that is around 80 % higher (Figure 11). High incentives for BECCS then risk locking in processes that convert biomass to CO₂, even where the carbon could be valorised upstream: carbon capture outcompetes lignin extraction at the mill (Section 3.2), the same applies to biomass in the heating sector (Section 3.7), and a BECCS policy tailored to pulp mills would subsidise pulp production even if biofuels compete for the same pulpwood. Which of these outcomes a BECCS policy leads to therefore depends on whether there is also a demand for biogenic carbon in fuels and chemicals.

The revision of the EU ETS proposed by the Commission in July 2026 (Table 1) is relevant for this in two ways. First, the slower reduction of the cap, by 3.7 % per year in Years 2031–2035 and 1.7 % per year from Year 2036, makes allowance prices along the WAM pathway less likely, which weakens the case for capture at the pulp mills (Section 3.2). Second, the proposal would make the Commission a central buyer of certified permanent removals, financed by 250 million additional allowances. If these removals are purchased at the lowest cost per tonne, the instrument shares the property of the reverse auction discussed above.

3.5 The potential, value and limits of flexible operation

So far, this chapter has considered how external market and policy conditions determine which investment and operational choices in the forest biomass system become economically reasonable. The following three sections examine how the interplay between the forest biomass system and the wider energy system may change as new demands are placed on forest biomass. Flexible operation is the most-immediate form that the interplay takes, since it requires neither a new product nor a new process. The mill continues to produce pulp and electricity, although it schedules its material, steam and electricity flows with respect to the electricity price rather than supplying a steady base load, thereby becoming a resource for an electricity system that has a growing share of variable generation. This section examines the technical potential for such flexible operation, its value to the mill, and the limits to which it is subjected.

Paper I investigates the technical potential of, and the limitations to, flexible operation of conventional mill processes, for a range of cases, spanning from the less-flexible to the more-flexible. Figure 12 presents a duration curve of the net electricity production from the model mill (producing 2,000 ADt/d of pulp) for the modelled cases, together with a reference case with steady-state operation. The results show that the mill remains a net producer of electricity during most of the operational hours, even with flexible operation. The span between the maximum and minimum net electricity production increases from 17 MW in the least-flexible scenario to 105 MW in the most-flexible scenario. Aggregated over the modelled year, 25–111 GWh of electricity are shifted from low-value hours to high-value hours.

To place these results in the context of the Swedish electricity system as a whole, the potentials are scaled by a factor of 10 to represent the 20 largest chemical pulp mills in Sweden (based on data in the ChICaSP database [112]). The resulting potential is in the range of 200 MW to 1 GW in terms of capacity, or 250 GWh to 1.1 TWh of shifted electricity per year. For comparison, the installed capacity of grid-scale batteries in Sweden was around 1 GW in Year 2025 [113]. It should also be noted that this flexibility is obtained from storage volumes that are already part of the process, and that these volumes allow electricity to be shifted over hours to days (and in the case of the bark storage, over seasons). This is a longer time perspective than that of flexibility services covered by batteries, the cost structure of which is better suited to variations of shorter duration. If the numbers at the higher end of the range could be realised, the proposed measures could at least be of importance locally, or during those hours when it is especially difficult to match supply with demand.

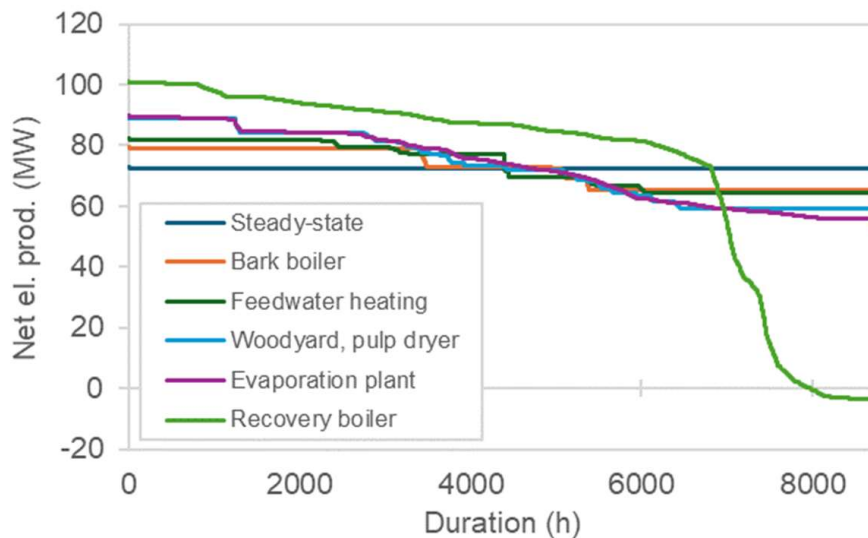


Figure 12. Duration curve of the net electricity production from the model mill (producing 2,000 ADt/d of softwood market pulp) for the modelled cases and for a reference case with steady-state operation. The legend shows the process units that are allowed to operate flexibly in each case, in addition to those of the previous cases. Adapted from **Paper I**.

Among the measures studied in **Paper I**, over-capacity of the recovery boiler has the strongest effect on the overall flexibility potential of the mill. **Paper II** shows how such an operating margin can be created in an existing mill: a lignin extraction process removes lignin from the black liquor before the black liquor enters the boiler, which reduces the boiler load and, thereby, enables flexible operation. The technology for lignin extraction is well known and has been commercially deployed in at least three pulp mills world-wide (**Paper II**). Compared with the daily-resolution study by Svensson et al. [72], the new information from **Paper II** is that, with hourly resolution and intermediate storage, lignin extraction in combination with flexible recovery boiler operation can increase the product output from the mill with only a small penalty imposed on the electricity trade, which strengthens the incentives for investments in lignin extraction.

In both **Papers I** and **II**, the main technical limitations in relation to flexibility are the capacity limits (minimum and maximum loads) of the flexible processes, turbines and boilers. The storage units for intermediate products are typically sufficiently large to handle variations on time-scales that range from hours to days, although they become limiting on longer time-scales. The flexibility is, therefore, mainly used to match the diurnal variations in the electricity price, although long-term storage of bark also enables a seasonal pattern of operation for the bark boiler.

Figure 13 shows the impacts on the mill economy of the proposed measures for flexible operation of conventional mill processes (based on the results from **Paper I**), with the electricity prices for Year 2019. The results show that already with these relatively stable electricity prices, the value of traded electricity can be increased by 1 %–8 % through increased integration with the electricity market. For the model mill, producing 2,000 ADt/d of pulp, the economic gains correspond to 0.2–2.0 M€ per year. As discussed in Paper I, these values represent the willingness to pay for flexibility from a system perspective, excluding taxes and fees, rather than the savings that a specific mill would realise. While these gains are small in relation to the total income from the net export of electricity (around 26 M€ for the model mill) or the revenue from pulp sales (around 730 M€), it should be borne in mind that the benefits are achieved without investments in additional process capacity and without any impact on pulp production.

Figure 13 distinguishes between the contributions to the value linked to having flexibility in the boilers (*Steam supply*), steam consumption in the production processes and turbines (*Steam demand*), and electricity consumption in the production processes (*El. demand*). In the most-flexible scenario, where over-capacity is available in the recovery boiler, steam supply flexibility dominates the value of the traded electricity. In the other two scenarios, where flexibilities of the steam supply, steam

demand, and electricity demand are all available, they contribute around 40 %, 40 %, and 20 % of the value, respectively.

These results not only imply an economic synergy between the mill and the electricity system, but also show how additional value can be generated from the same biomass resource, even without shifting to alternative products. This is in line with the value of biomass-based electricity in a system dominated by VRE, where electricity generated at peak load can be worth considerably more than base-load electricity from the same biomass [13]. Millinger et al. [23] also found that flexible bio-based electricity is the biomass use that is most costly to replace in the European energy system. If the shifting of electricity generation from low-price hours to high-price hours results in reduced use of fossil fuels for peak electricity production, the measures will also contribute to reducing greenhouse gas emissions from the electricity sector.

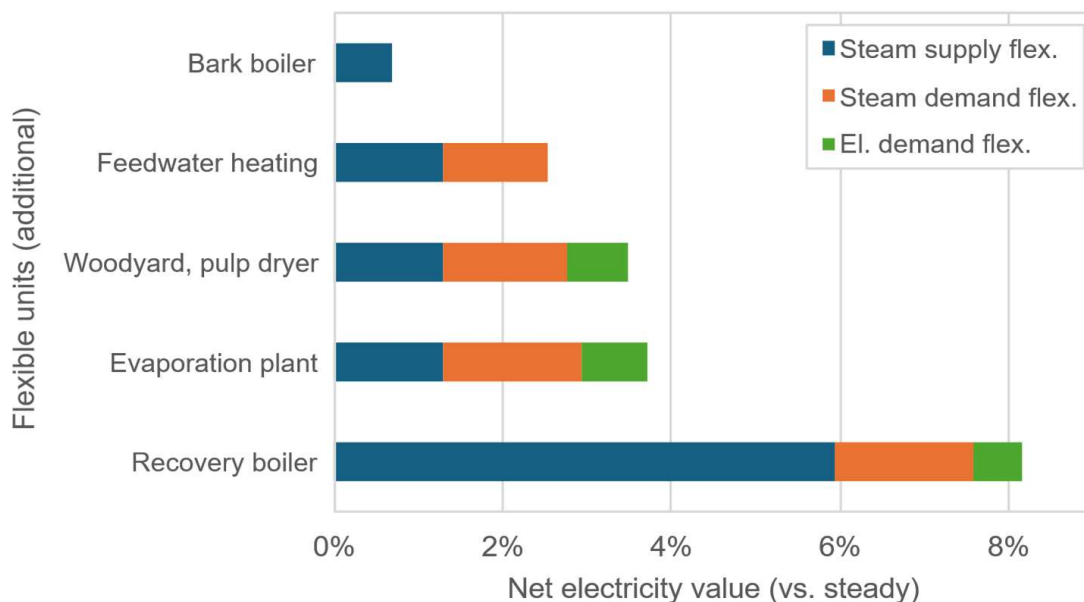


Figure 13. Impacts on the mill economy of the proposed flexibility measures for the cases modelled with the electricity prices for Year 2019. The flexibility measures are categorised as steam supply flexibility, steam demand flexibility, and electricity demand flexibility. The y-axis lists the unit(s) in which that flexibility is introduced in each case, in addition to the previous cases. Adapted from **Paper I**.

It should be noted that the modelled cases are stylised, in the sense that they assume similar conditions for flexibility throughout the year. In reality, a level of capacity that allows flexible operation may be available only during parts of the day or year. This may be due to different product campaigns (as shown in the additional cases in **Paper I**), seasonal variations (e.g., variations in heat demand due to climatic variations), or operations that are undertaken intermittently, such as knife-changes in wood choppers or soot-blowing in boilers. Svensson [70] showed that seasonal variations significantly affect the economic potential for flexible operation.

While the aim of **Paper I** was to study the potential and incentives for operating the processes in a flexible manner when capacity and storage volumes are already available, a separate question that arises is whether flexible operation can also motivate additional investments in process capacity or storage. According to the results presented above, the economic gains from the flexibility measures are small relative to the typical sizes of investments in production units, boilers and turbines. This suggests that spot market variations are, in general, not sufficiently large for flexibility to be a decisive factor at the investment stage. However, when the model was run with the high and variable prices of Year 2022 (also presented in **Paper I**), the economic gains were 10 times higher, although the average electricity price was only three times higher. This supports the hypothesis that flexibility measures will be increasingly valuable in a future that has more-volatile electricity prices. While the electricity prices projected for Years 2030 and 2040 are not as high and volatile as those recorded in Year 2022, it is not inconceivable that future prices will turn out to be similar to those in the Year 2022 profile, at least for some period of time during the transition of the energy system in the coming decades. Whether such variable electricity prices are indeed enough to motivate investments in additional capacity for a specific process is a question that requires a site-specific investigation.

In **Paper III**, investment optimisation is explicitly conducted for a condensing turbine, a lignin extraction plant, and a carbon capture plant, under projected assumptions regarding electricity and product prices in Years 2030 and 2040. The model mill makes use of the flexibility that is inherent to existing mill processes, and benefits from the flexibility in the recovery boiler when lignin extraction is installed. However, in none of the modelled cases does the model invest in additional capacity for the purpose of part-time utilisation, apart from a minor investment in the condensing turbine in one case. Spot prices similar to those recorded for Year 2022 would, as shown in the paper, dramatically change the calculations, motivating investments in combinations of lignin extraction and electricity generation or carbon capture and electricity generation, for part-time utilisation in response to the variable electricity prices, for a broad range of lignin and CO₂ prices.

3.6 Trading electricity for biogenic carbon

The higher-value utilisation of forest biomass means, in addition to the flexibility discussed above, that carbon that would otherwise have been combusted is instead directed into products. Since the biomass is the energy carrier as well as the source of carbon, every such shift comes with an energy cost. It appears either as generation that is foregone as a lower amount of fuel being burnt in the pulp mills' recovery boilers or in power plants, or as heat and electricity that are consumed, when CO₂ is captured and converted into fuels or chemicals. **Papers II** and **III** quantify this

exchange for the individual mill, and the results reported in **Paper IV** show that the same trade-off governs the system level. Thus, biomass that is allocated to gasification and methanol production is biomass that no longer generates heat and electricity in the district heating systems, and if products are instead to be made from the captured CO₂ and hydrogen, the electricity demand of the system increases substantially. Taken together, the results describe a gradual reversal of the role that forest biomass plays in the energy system: from a fuel that supplies heat and electricity, towards becoming a source of carbon whose refinement into products or more valuable energy carriers is paid for with heat and electricity.

This perspective of the individual mill is especially interesting for the case of lignin extraction. As discussed in Section 3.2, the exchange between electricity generation and material output is central to the economic calculations, since the majority of the operational cost of the process consists of the indirect electricity cost (i.e., the lost income from electricity that was generated from the combustion of black liquor in the reference case without lignin extraction).

Paper II shows how flexible operation of the recovery boiler can reduce this indirect electricity cost. The average cost of lignin, depending on the extraction target, is presented in Figure 14. For lower levels of lignin extraction, the indirect electricity cost is lower, since the lost electricity generation (and, less importantly, the increased consumption of electricity) can be concentrated to low-price hours. With the electricity price profile of Year 2019, the value of the flexibility is relatively low, whereas for the Year 2022 prices, flexible recovery boiler operation is shown to save 15 %–70 % of the operational cost of lignin extraction, as compared with steady-state operation. If the price ranges for future years lie somewhere in between those of Years 2019 and 2022, then the Year 2022 values can be regarded as an upper limit for the potential. It should be noted that flexible operation does not increase the value of the electricity trade compared with the original mill configuration; instead, it minimises the loss of value from electricity trading that is a consequence of lignin extraction.

Furthermore, it is shown in **Paper II** that adding up to 10 % over-capacity in the lignin extraction plant further enhances the level of flexibility, thereby reducing by up to 50 % the marginal cost of lignin, with the electricity prices of Year 2022. Increasing the size of the black liquor storage by a factor of 3 has a similar effect.

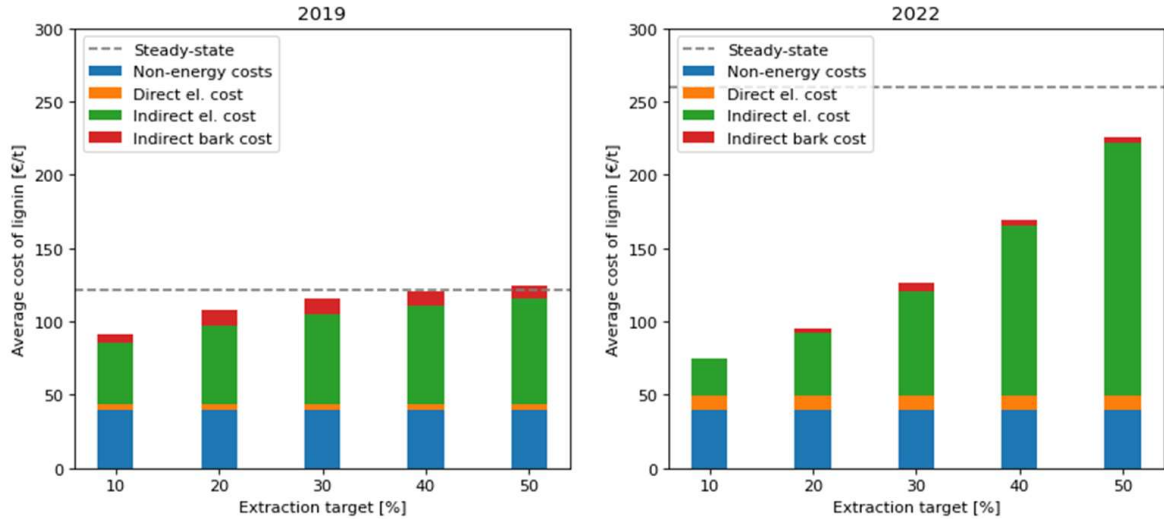


Figure 14. Average cost of lignin depending on the extraction target, for the electricity prices in Year 2019 (left panel) and Year 2022 (right panel). The indirect electricity cost (green bars) and indirect bark cost (red bars) represent the respective lost income levels from the sold electricity and bark that were generated in the reference case without lignin extraction. Investment costs are not included. Source: **Paper II**.

As described in Section 3.2, the addition of a carbon capture process to the mill reduces the electricity surplus from the mill. The trade-off is of a different character than that seen in the case with lignin extraction, since the capture and conversion processes consume heat and electricity rather than merely displacing its generation. In **Paper III**, the model has the opportunity to invest in over-capacity of the capture process, in order to respond to electricity prices, as for the lignin extraction process. However, due to the high capital costs of the capture process compared to the potential savings in operational costs, this opportunity never materialises in the cost-optimisation of investments. Flexible operation of carbon capture has been found to be rewarded under variable electricity prices at power plants by Mechleri et al. [60] and at CHP plants by Saint-Pierre and Mancarella [74]. However, these studies only optimised operations for a given investment, and, in line with the result of Paper III, Mechleri et al. [60] found that the viability of strategies that require additional equipment, such as solvent storage, depends strongly on its capital cost.

In the presented studies, the largest effect on the electricity trade from the industry site is observed when the system boundary is moved so that electrolysis for BECCU applications is included. In a stylised case (labelled 2040c in **Paper III**), where no lignin extraction is applied and 90 % of the CO₂ is captured for the synthesis of e-fuels, the 1.9 Mt CO₂ captured from the model mill would yield around 6.85 TWh of e-fuel, although around 11 TWh of electricity would be required for the electrolysis process.

As the system boundary is increasingly expanded in **Paper IV**, it becomes evident that changes to the biomass system also have implications for the electricity system as a whole. Figure 15 shows the difference in electricity generation by source in Sweden compared to the reference scenario (without targets for methanol or BECCS) across nine scenarios (including the reference, Figure 15a) from **Paper IV**. As for the individual mill, the most-substantial effects on the system level are seen in the scenarios that meet the methanol target through the use of e-methanol (BECCU). This is seen in Figure 15 in that the electricity generation increases with increasing methanol targets but decreases with an increasing BECCS target for a given methanol target, since increased BECCS targets lead to more methanol being produced via biomass gasification. The additional generation is mainly supplied by offshore wind power.

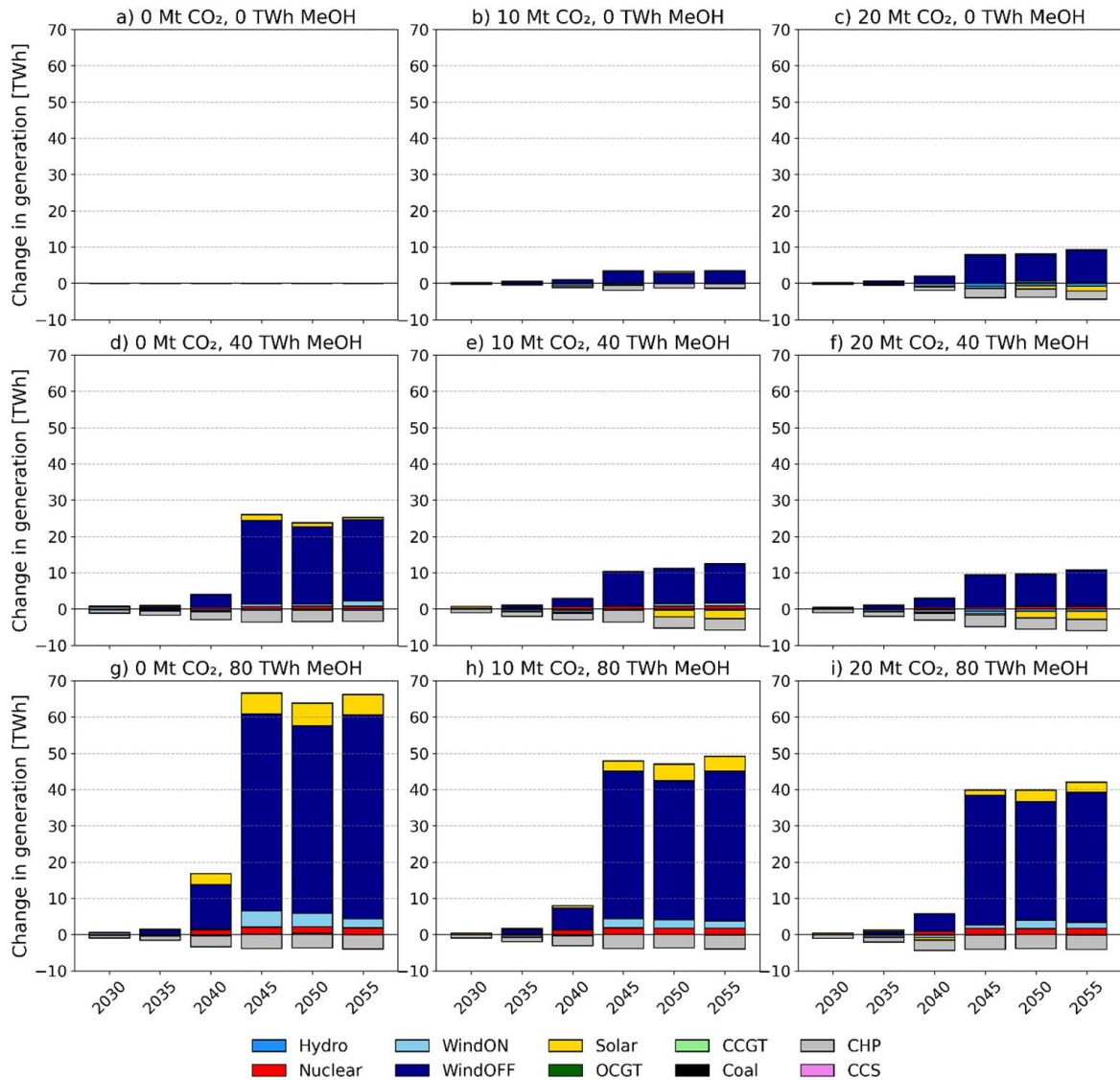


Figure 15. Difference in electricity generation by source in Sweden compared to the reference scenario (panel a) across nine scenarios. The figure is based on results from **Paper IV**.

Paper IV also shows a large difference in the consequences for the electricity system between free and fixed allocations of biomass: if pulp and sawn timber production outputs are held at their reference levels, so that the methanol target must be met with more e-methanol rather than by the gasification of pulpwood, the total electricity generation in Sweden with a methanol target of 40 TWh per year reaches 250 TWh in Year 2050, compared with 222–238 TWh under free allocation, where the lower values correspond to higher BECCS targets. This corresponds to a 48 % increase in electricity generation over the Year 2025 level, compared with an increase of 31–40 % under free allocation. The difference grows with higher methanol targets, reaching 53–77 TWh at the (explorative) target of 80 TWh per year. Notably, fixed allocation corresponds to taking the production of the forest industry as given, as is common in energy system models (Section 1.2).

An additional effect, which is present to varying extents in all the scenarios in Figure 15, comes from the heating sector and affects the electricity system in two ways: the electricity generation that is lost as biomass-fired CHP plants are phased out has to be replaced, and the heat pumps that take their place add a further electricity demand. This effect is larger with higher BECCS targets, since the capture process increases heat demand (see top row without methanol target in Figure 15). One of the reasons why heat pumps are viable in the heating sector is that they, when combined with heat storage, can utilise low-cost electricity from variable sources of electricity, such as wind power. The competitiveness of power-to-heat technologies in electricity systems with a high share of wind power aligns with the studies of district heating systems in Swedish cities in which the share of CHP decreases as large heat pumps expand [35,36].

3.7 Re-allocating forest biomass between sectors

When the supply of biomass is limited and several sectors compete for the same feedstock, the competition takes on a different form. The question then arises as to which sector the biomass should be allocated: the traditional forest industry producing pulp and sawn timber, the heat and power sector, or the production of fuels and chemicals, here represented by methanol. **Paper IV** addresses this question, since the allocation of biomass between sectors, and the resulting prices, are determined within the model rather than imposed as assumptions.

Figure 16 shows how the allocation of different segments of forest biomass between sectors changes over time, for four of the different target combinations assessed in **Paper IV**. Column *a* shows the reference case with no target for either methanol or BECCS, and columns *b–d* show cases that range from 5 Mt/year of BECCS and 20

TWh/year of methanol to 15 Mt/year of BECCS and 60 TWh/year of methanol by Year 2045 (with lower intermediate targets for earlier years).

In the reference case (column *a*), the most-notable change over time is that the importation of wood to the heating sector (light-cyan colour, top panel) is phased out as CHP plants reach the end of their lifetimes and are replaced by heat pumps in the heating sector.

For the cases shown in columns *b–d*, the general trend is that as methanol targets increase, biomass is re-allocated from the other sectors to methanol production, in order to produce bio-methanol through gasification followed by methanol synthesis. The initial response to a methanol target is an increase in biomass imports and increased extraction of logging residues, both of which activities carry a higher marginal cost. Thereafter, biomass is re-allocated from heat and electricity generation in CHP plants to gasification, and the biomass used internally in the pulp mills for auxiliary heat and electricity generation is gradually phased out.

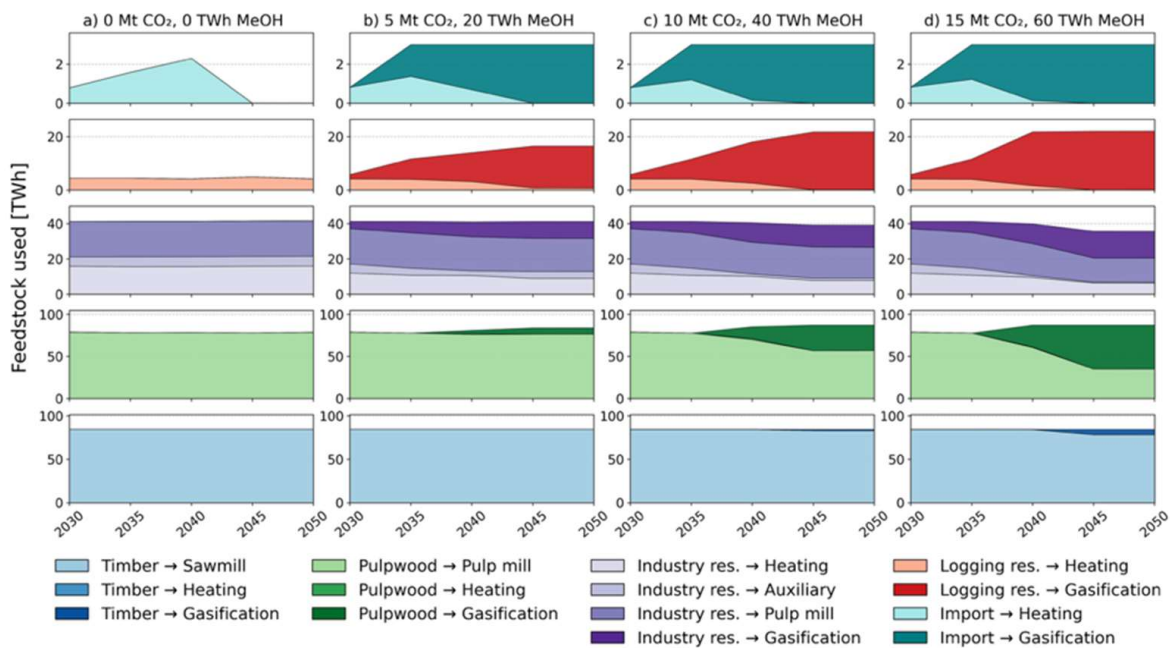


Figure 16. Progress over time for the allocation of different segments of forest biomass to different sectors across four selected scenarios in **Paper IV**. ‘Industry res. > Pulp mill’ represents wood chips from sawmills that are used as feedstocks for pulp mills; and ‘Industry res. > Auxiliary’ represents the internal transfer of industry residues to auxiliary boilers at the pulp mills. Note the different scales between the panels. Source: **Paper IV**.

With the higher targets for methanol, the production of bio-methanol eventually competes with the traditional forest sector, using the pulpwood quality of biomass as feedstock, unless the pulp price is sufficiently high to motivate investments in e-methanol production. The production of sawn timber remains stable, except for the most-extreme target combinations. The re-allocation away from heat and power plants agrees with the forest sector studies by Hu et al. and Jåstad et al. [87,99]. In those studies, however, the heating sector is represented only as a demand for biomass and responds by turning to lower-grade residues, whereas in Paper IV it turns to heat pumps. This response is in line with the coupled study by Mustapha et al. [89], in which increased biofuel production reduced the investments in biomass-based heat and CHP and made heat pumps more favourable.

The results from **Paper IV** and the discussion in this thesis jointly suggest that the heating sector can be considered as a low-value utilisation of biomass (assuming that alternative heating is available). Therefore, to make forest biomass available to higher-value applications, it is important that it is not locked into the heating sector because of a poorly designed BECCS incentive or unbalanced taxes, such as the exemption of biomass fuels used for heat production from energy and carbon tax while the electricity used in heat pumps for district heating is taxed at the full rate (Table 1), or because of bottlenecks in the electricity grid that limit the expansion of power-to-heat solutions. This, however, does not mean that present BECCS projects in the heating sector, such as that by Stockholm Exergi [29], are not important. Such projects contribute to technology development and provide large-scale demonstration of BECCS.

Also, this thesis does not provide a straightforward answer as to whether pulp and paper, transportation fuels or green chemicals are the most-valuable commodities to produce for society. All of these products are traded on global markets and subject to competition, e.g., from feedstocks based on fast-growing wood species in tropical regions or industry residues in other countries with a large forest industry. On a national or European level, policymakers should consider whether it is more important to be self-sufficient in paper products or in fuels and green chemicals. This consideration needs to be part of a broader energy strategy that also considers the advantages and drawbacks of other carbon-free alternatives in the hard-to-abate sectors, such as various forms of electrification and hydrogen-based solutions.

4 Conclusions

The combined results of the appended papers show that the optimal utilisation of forest biomass during the energy transition to maximise the economic value and the contribution to climate change mitigation depends on temporal perspective, system boundaries, and assumptions on the development in other sectors. Although certain aspects of the studied system are specific to Sweden, which combines a large forest industry with a largely fossil-free electricity system and widespread district heating, the results illustrate mechanisms that are relevant wherever forest biomass is shared between the forest industry, the energy system and new demands for biogenic carbon.

In answer to the first research question, the results show that which investments and operational strategies become rational within the forest biomass system in the coming decades will depend on policy developments and market trends in sectors that have historically been separated from the forest industry. Assuming the value of biogenic carbon increases throughout the studied period, the most valuable contribution of the chemical pulp mill beyond pulp may shift over time, from supplying base-load electricity, to supporting the electrification of other sectors through flexibility, and later to decarbonising hard-to-abate sectors by replacing fossil-based feedstocks or compensating for residual and historic emissions through bioenergy with carbon capture and storage (BECCS).

If the demand for bio-based transport fuels and chemicals rises, the value of the residue biomass from the forest industry is no longer determined by the electricity price alone, but by the sector with the highest willingness to pay in a given time period and location. Of the options for producing renewable fuels from the by-products of the chemical pulp mill, lignin extraction is more cost-efficient than bioenergy with carbon capture and utilisation (BECCU), although BECCU can raise the product yield beyond the technical limits of lignin extraction.

The demand for BECCS is fundamentally created by policy. If BECCS is priced according to the EU ETS allowance price, whether carbon capture becomes more profitable for the mill than lignin extraction or BECCU depends on where that price ends up. At high estimates for the ETS price, the lignin price needed to match carbon capture exceeds the value reported in the literature for lignin even as a feedstock for high-value green chemicals.

From a system perspective, however, carbon capture at the pulp mills is optimal only as long as there are no lower-cost options for BECCS. If there is also a demand for

renewable methanol, new gasification plants, in which CO₂ is obtained as a by-product of the syngas, deliver captured CO₂ at a lower cost and displace capture at the pulp mills. In a case study of Sweden, by Year 2045, the marginal cost of negative emissions is around 80 % higher where no methanol target is set than where the two are combined.

On the system level, the outcome of a BECCS policy therefore depends on whether there is also a demand for biogenic carbon in fuels and chemicals. With such a demand, lowest-cost procurement of negative emissions, for example through reverse auctions, favours gasification plants in which capture shares its cost with methanol production, while the CO₂ from the pulp mills is released, since the remaining biogenic emissions carry no cost. Without such a demand, a larger share of the capture instead takes place at combustion-based routes, such as the chemical pulp mills, and a high incentive may lock in biomass use in processes that convert biomass to CO₂ even where the carbon could be valorised upstream in the value chain. Ideally, a policy framework for cost-efficient biomass allocation should consider BECCS and the use of biogenic carbon in fuels and chemicals together, so that the biomass replaces the most expensive alternative across the whole system.

In answer to the second research question, the thesis shows how the interplay between the forest biomass system and the wider energy system evolves in three ways as new demands are placed on forest biomass: through flexible operation of the mills, through trading electricity for biogenic carbon, and through the re-allocation of biomass away from heat and power.

Shifting net electricity generation in time allows chemical pulp mills to move from base-load towards mid- and peak-load providers, thereby increasing the value of black liquor and bark as by-products to pulp. The incentive increases with both the magnitude and the variability of the electricity price: in the most-flexible case studied, the increase in the value of traded electricity from flexible operation, compared with steady-state operation, is 10 times higher with the prices of Year 2022 than with those of Year 2019, although the average price of electricity was only three times higher. Scaled to the 20 largest chemical pulp mills in Sweden, the flexibility potential corresponds to roughly 200 MW to 1 GW, or 250 GWh to 1.1 TWh of shifted electricity per year. Most flexibility can be achieved if over-capacity is unlocked in the recovery boiler, for example by extracting lignin from the black liquor.

An increasing demand for biogenic carbon may also motivate the mill to reduce its net electricity generation to obtain a higher product yield. For lignin extraction, the foregone electricity generation constitutes the major share of operational costs, and if it can be shifted to low-price hours, these costs can be reduced by 15 %–70 % under volatile electricity prices. The trade-off is most pronounced for BECCU, which

requires both carbon capture and electrolysis. At the Swedish national level, the same effect dominates the electricity system implications of biomass re-allocation: at a methanol target of 40 TWh per year, holding pulp and sawn timber production at their reference levels forces the system towards e-methanol and raises electricity generation from 222–238 to 250 TWh.

When new demands pull biomass away from CHP plants, their electricity generation is lost, and the large-scale heat pumps that replace their heat supply add further to the electricity demand. Where these changes take place is determined largely by regional conditions: since land transport of methanol and CO₂ is costly, investments in methanol production and carbon capture are made mainly in regions with harbour access, while inland regions remain less affected.

The results also show why a fixed order of priority, as in the cascading principle, is not sufficient to guide the allocation of forest biomass: the value of electricity from biomass depends on when it is delivered, and the value of residues on where they are available. An allocation principle based on the opportunity cost of biomass, which varies with time and location, would capture these differences. Together, the results of the thesis suggest that a forest biomass strategy in line with the EU target of climate neutrality by Year 2050 must account for both the drivers reshaping the value of different products and the industry's evolving role in the energy system, rather than treating these as separate issues.

4.1 Future work

The following directions, which fall outside the scope of the appended papers, would help address some of the open questions identified above:

- Represent process integration of biofuel production, both with pulp mills and with refineries and petrochemical industries, in the system model. In **Paper IV**, the options at the mill are limited to BECCS and BECCU, and new methanol plants are stand-alone units. Since the optimal technology choice depends partly on the possibilities for process integration, for example the use of waste heat [47], integrated biofuel production could be favoured either at pulp mills, e.g., through lignin extraction or black liquor gasification, or in the existing oil refining and petrochemical industries. Including both would show which is preferable, and whether the advantage of integration with the forest industry, found by Sandberg and Krook-Riekkola [84] for the national level, is nuanced when regional differences in biomass supply, CO₂ transport and heat demand are accounted for.
- Evaluate electrification measures at the chemical pulp mill. Once biogenic carbon becomes clearly more valuable than electricity, measures such as an

electric boiler or heat pump for steam supply, or gas-plasma calcination in place of a bark-fired lime kiln, could become economically relevant. These options could be compared with options outside the chemical pulp mill in terms of the energetic and monetary cost of biogenic carbon, in a system-scale model such as the one developed in **Paper IV**.

- Study the flexibility in electricity consumption and production of a greenfield chemical pulp mill under different electricity system compositions. In this thesis, the capacities of mill processes and storages are assumed from an existing configuration, and the flexibility studied is that inherent to existing mill processes. A full investment optimisation would clarify which flexibility measures are cost-efficient only because the relevant capacity already exists, and which would be worth investing in from scratch. Such an analysis could also cover seasonal variations in the steam demand that were not considered in the PEMO model.
- Compare policy instruments for negative emissions in the system model under a net-zero constraint, such as reverse auctions, the integration of removals in the EU ETS with central procurement as proposed in 2026, and crediting of biogenic carbon uptake. This would test the policy-related claims in this thesis.

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