Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management
Research group of Renewable Energy

Philosophiae Doctor (PhD)
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Assessments of the future role of bioenergy in the Nordic energy and forest sectors

Vurderinger av den fremtidige rollen til bioenergi i den nordiske energi- og skogsektoren

Eirik Ogner Jåstad

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Ås, August 2020

Eirik Ogner Jåstad

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Summary

This thesis presents studies that describe different consequences of increased use of forest resources for energy purposes. Forest biomass is widely used in many different applications; in recent years, biofuel has been one of the products that has increasingly received attention. In order to produce forest-based biofuel, forest resources are needed. Either these resources have to be taken from sources that are currently not economical to harvest or biofuel producers have to compete with existing industries to get biomass. This thesis presents the positive and negative effects of increased production of forest-based biofuel within the Nordic countries for the heating, power, and forest sectors. Three different models are used to describe the effects of implementing biofuel production in the Nordic countries: two forest sector models, the Norwegian trade model (NTM) and the Nordic forest sector model (NFSM), and the energy sector model Balmorel. While in the last paper, an integrated model is developed to combine the strengths of NFSM and Balmorel.

In paper I, NTM was used to quantify major market uncertainties in the Norwegian forest sector and analyse their impacts on the results of a forest sector model study for Norway. The uncertainties were derived from historical time series of prices and exchange rates for international forest products, and their impacts were addressed using a Monte Carlo approach. The results show that the relative standard deviation for modelled harvest levels varies from 15% to 45%, while for forest products the standard deviations vary from 30% to 80%. The paper concludes that the most important factor for the Norwegian forest sector is the development of international forest product markets.

In paper II, NFSM was used to quantify how large-scale production of forest-based biofuel would affect forest owners and forest industries in the Nordic countries. The implications were studied using five scenarios covering a 0–40% biofuel share of fuel consumption. The results show that the sawmill industry increased their profit slightly due to increasing prices for their by-products, while pulp and paper producers saw their yearly profit reduced by up to 3.0 billion €, corresponding to 8% of their annual turnover, due to the increased pulpwood prices. Forest owners

increased their revenue by up to 31% due to a 15% increase in harvest at the same time as pulpwood prices increased. The study concludes that the traditional forest sector will change substantially with huge production of forest biofuels.

In paper III, NFSM was used to quantify the effects on the forest sector of different policy schemes that promote Nordic forest-based biofuel. This study assessed six different support schemes that might increase the attractiveness of investing in forest-based liquid biofuel facilities. The results show that the necessary subsidy level is in the range of 0.60–0.85 €/L (82–116% of the fossil fuel cost in 2030) for realistic amounts of biofuel production. The feed-in premium is the subsidy scheme that gives the lowest needed subsidy cost for production levels below 6 billion litres (25% market share) of forest-based biofuel, while quota obligations are the cheapest option for production levels above 6 billion litres.

In paper IV, Balmorel was used to quantify the role of woody biomass in the production of heat and power in Northern Europe towards 2040. The study focuses on GHG emissions from fossil fuel in the heat and power sectors under different carbon price scenarios, comparing the results with biofuel production. The results show that the use of woody biomass can reduce the direct emissions from the power and heat sector with 4–27% in 2030 compared to a scenario where woody biomass is not available for power and heat generation. At a low carbon price, the use of natural gas, wind, and coal power increases when biomass is not available for power and heat generation, while at higher carbon prices, solar power, wind power, power-to-heat, and natural gas become increasingly competitive; consequently, the use of biomass has a lower impact on emissions reductions. If forest-based biofuel is produced from the same amount of biomass as is used for heat and electricity production, we will get reduced fossil carbon emissions, but the total system cost will increase.

NFSM and Balmorel were integrated in paper V in order to increase our understanding of the combined forest and energy sectors. The paper discusses the strengths and weaknesses of the integration procedure using a scenario that reduces the fossil emissions in the Nordic countries by 73% compared to 2017. The results show that it is likely that the integrated model presents the connection between heat and electricity production better than standalone models. One of the conclusions is that the Nordic countries have enough forest biomass to fulfil the demand within the industrial sector and for biofuel, heat, and power production.

The results from this thesis show that in the forest sector it is likely that forest owners will be the main winners if large amounts of forest-based biofuel are produced, while forest industry, especially pulp and paper producers, will face reduced market share and profitability. Simultaneously, woody biomass contribution to lower the fossil emissions from heat and power, and the transition to low carbon energy systems will likely be more costly if biomass is excluded from energy generation.

Sammendrag

Denne avhandlingen inneholder flere studier som beskriver forskjellige konsekvenser av økt bruk av skogressurser til energiformål. Skogsbiomasse har mange forskjellige bruksområder, de siste årene har biodrivstoff vært et bruksområde som i økende grad har fått mye oppmerksomhet. For å kunne produsere skogsbasert biodrivstoff trengs store mengder tømmer, enten må tømmeret hentes fra kilder som ikke er økonomiske drivverdige i dag, eller så må produsentene konkurrere med eksisterende næringer for å få den nødvendige biomassen. Denne avhandlingen presenterer positive og negative effekter av økt biodrivstoff produksjon i Norden for varme-, kraft- og skogsektoren. Tre forskjellige modeller er brukt for å beskrive effekten av biodrivstoffproduksjon i Norden, skogsektormodellene som er brukt er Norwegian trade model (NTM) og Nordic forest sector model (NFSM), og energisektormodellen Balmorel. I arbeidet med artikkel V ble det utviklet en kombinert modell for å utnytte styrkene til både NFSM og Balmorel.

I artikkel I ble NTM brukt til å kvantifisere hvordan usikkerheten i markedspriser påvirker produksjonsnivåer i Norge, samt å analysere effektene usikkerhetene har på resultatene fra skogsektormodellen. De historiske usikkerhetene ble estimert fra historiske tidsserier for priser på internasjonale skogsprodukter og valutakurser, virkningene av disse ble funnet ved hjelp av Monte Carlo simuleringer. Resultatene viser at det relative standardavviket for hogstnivået varierer fra 15 % til 45 %, mens standardavvikene for sluttprodukter varierer fra 30 % til 80 %. Studien konkluderer med at den viktigste faktoren for norsk skogsektor er utviklingen av internasjonale markedspriser.

I artikkel II ble NFSM brukt til å beregne hvordan storstilt utbygging av skogbasert biodrivstoff vil påvirke skogeiere og skogsindustri i Norden. Implikasjonene ble studert ved bruk av fem scenarier for biodrivstoff produksjon tilsvarene 0–40 % av det nordiske drivstofforbruket i 2017. Resultatene viser en svak økning av overskuddet i sagbruksnæringen, dette skyldes økte priser på sagbrukenes biprodukter. Mens masse- og papirprodusenter fikk redusert sitt årlige overskudd med inntil 3,0 milliarder euro, tilsvarende 8 % av deres årlige omsetning, dette

skyldes økte massevirkepriser. Samtidig økte skogeiere sine inntekter med opp mot 31 % på grunn av 15 % økning i avvirkningen samtidig som prisene på massevirke økte. Studien konkluderer med at konsekvensene av storstilt biodrivstoff produksjon i Norden vil endre den tradisjonelle skogsektoren betydelig.

I artikkel III ble NFSM brukt til å kvantifisere effektene for skogsektoren av forskjellige politiske støtteordninger som fremmer nordisk skogbasert biodrivstoff. Denne studien undersøkte seks forskjellige støtteordninger som kan øke investeringene i flytende skogsbaserte biodrivstoffanlegg. Resultatene viser at det nødvendige subsidienivået ligger i området 0,60–0,85 €/L (82–116 % av den antatte prisen på fossilt drivstoff i 2030) for realistiske produksjonsnivåer. Den støtteordningen som behøvede lavest støttenivå for å gi lønnsom biodrivstoff-produksjon var innmatingstariff for produksjonsnivåer under 6 milliarder liter (25 % markedsandel), mens et innblandingskrav trenger lavest støttenivå for produksjons-nivåer over 6 milliarder liter.

I artikkel IV ble Balmorel brukt til å estimere rollen skogsbiomasse har for produksjonen av varme og strøm i Nord-Europa fram mot 2040. Studien setter søkelys på klimagassutslipp fra fossilt brensel i varme- og kraftsektorene under forskjellige karbonprisscenarier, og sammenligner resultatene opp mot biodrivstoff-produksjon. Resultatene viser at bruk av biomasse kan redusere de direkte utslippene fra kraft- og varmesektoren med 4–27 % i 2030 sammenlignet med et scenario hvor biomasse er ekskludert fra kraft- og varmesektoren. Når biomasse ikke er tilgjengelig for kraft- og varmeproduksjon øker bruken av naturgass, vind og kullkraft hvis karbonprisen er lav, mens ved høyere karbonpriser øker bruken av solenergi, vindkraft, kraft-til-varme og naturgass, og følgelig har bruken av biomasse en lavere innvirkning på utslippsreduksjonene enn ved lav karbonpris. Hvis den samme mengden biomasse blir brukt til biodrivstoff vil vi få reduserte de fossile karbonutslipp, men systemkostnadene vil samtidig øke.

I artikkel V ble NFSM og Balmorel integrert, med mål å øke forståelsen for den kombinerte skog- og energisektoren i Norden. Ved bruk av et scenario som reduserer fossile utslipp i Norden med 73 % sammenlignet med 2017 diskuteres styrker og svakheter ved integrasjonsprosedyren. Resultatene synliggjør at den integrerte modellen beskriver samhandlingen mellom varme- og strømproduksjon bedre enn de frittstående modellene. En av konklusjonene er at de nordiske landene mest sannsynlig har nok skogsbiomasse til å oppfylle etterspørselen fra industrisektoren og fra biodrivstoff-, varme- og kraftproduksjon.

Resultatene fra denne avhandlingen viser at det er sannsynlig at skogeiere vil ha mest å tjene av at store mengder skogbasert biodrivstoff produseres i Norden, mens skogsindustrien og spesielt masse- og papirprodusenter vil få redusert lønnsomhet. Samtidig kan biomasse bidra til å senke de fossile utslipp fra varme- og kraftproduksjon, og overgangen til et energisystem med lave karbon utslipp vil trolig bli mer kostbart hvis biomasse blir ekskludert fra bruk til energiproduksjon.

1 Introduction

1.1 Background

Forests have always been important in the Nordic countries and were likely a premise for people settled there. Forests provide shelter, food, and energy. During the last several centuries, the forest industry has been in almost constant transition. During this time, there have been several significant innovations, notably the introduction of sawmills in the 16th century and pulp and paper mills in the 19th century (Store Norske Leksikon, 2020). Those innovations gave us the main actors in the traditional forest sector that still play a significant role in the Nordic forest sector. Today there is an increasing interest in new forest products. In particular, there is an increasing interest in including different chemicals in the value chain of traditional forest industries. One of the products that has garnered the most interest, both among the public and in the scientific community, is biofuel made from forest resources. This thesis discusses how the traditional forest sector and the energy sector will adapt to the production of biofuels and bioheat in the Nordic countries.

The Nordic economy is relatively small, open, and depends on import and export of goods. This makes the Nordic countries to price takers in the world market. Forestry and forest industries have historically been an important part of the Nordic economy (figure 1), but interest in the forest sector has declined, as has its share of the entire economy. Today the forest sector accounts for around 3% of the total gross domestic product (GDP) in the Nordic countries (Eurostat, 2020b). Figure 1 shows the forest sector's historical share of the total economy in each of the Nordic countries. In Sweden after 1990 and in Finland after 2000, the forest sector's share of total GDP dropped to half of its historical value, but in the last ten years the share has been almost constant. Concurrent with the end of this marginalizing trend, the world has started to struggle with moving away from fossil fuel; this gives the forest sector an opportunity to increase its role in the total economy in the future. In the coming years, the Nordic countries may start to use more of the available forest resources for building materials, energy, transport fuel, and chemicals; even food and clothing may

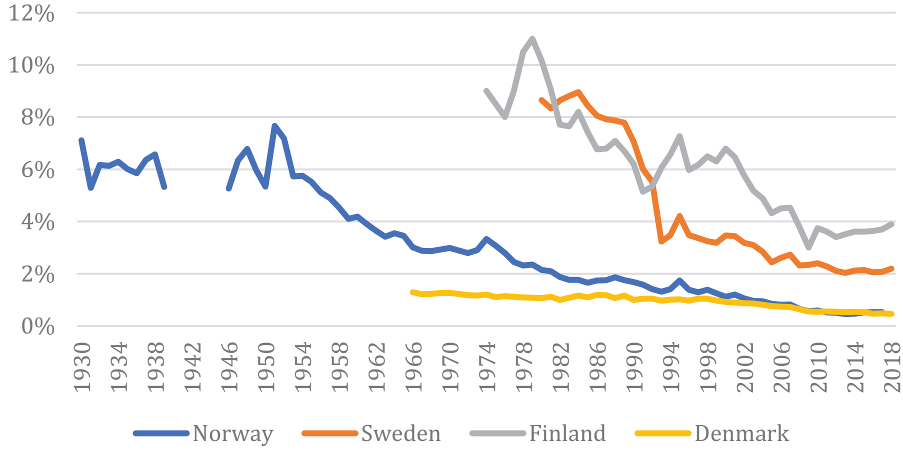

Figure 1. The forest sector's share of the total gross domestic product (GDP) in Norway, Sweden, Finland, and Denmark. Source: (Luke, 2019; SCB, 2020; SSB, 1965; SSB, 2007; SSB, 2020b; SSB, 2020c; Statistics Denmark, 2020a).

be important new forest products. This thesis investigates the possible consequences of increased biofuel and bioheat production in the future forest sector.

Another factor that will put pressure on the use of forest resources is climate change. Climate change will increase pressure on the economy to lower carbon emissions and reduce the carbon concentration in the atmosphere. The European countries have set a goal to reduce their total GHG emissions by 40% compared to 1990 by 2030 (European Commission, 2020). This will make it imperative to figure out how to best use the available forest resources. To reduce global warming, governments have introduced different restrictions and subsidies, some of which may increase the use of forest resources and others of which may reduce the use of forest resources. It is not obvious what the net effects of policies and public opinion will be. This thesis shines a spotlight on some realistic policies and explores their possible effects on the forest sector.

1.2 Objectives

Considering the uncertainty surrounding future developments in the forest sector, political regulations, and climate change, it is important to understand the economic and physical impacts of the introduction of massive forest-based biofuel production on the roundwood balance in the Nordic countries. The topic under study in this thesis is therefore the role of biofuel within the energy and forest sectors. Specifically, we answer the following research questions:

1. What are the main drivers of uncertainty within the Norwegian forest sector?
2. What are the implications for the Nordic forest sector of various levels of biofuel production?
3. Which actors in the forest sector will have increased and reduced profitability with large-scale production of biofuel?
4. Where will biofuel production be most cost competitive?
5. Which subsidy scheme is most profitable for increasing biofuel production?
6. What are the market effects for the forest sector of subsidies on forest-based biofuel production?
7. What is the role of forest biomass in the North European heat and power sector?
8. What are the strengths and weaknesses of an integrated energy sector model and a forest sector model?

The research conducted in this thesis is presented in five research articles:

I. Modelling of uncertainty in the economic development of the Norwegian forest sector.
II. Large-scale forest-based biofuel production in the Nordic forest sector: Effects on the economics of forestry and forest industries.
III. Modelling effects of policies for increased production of forest-based liquid biofuel in the Nordic countries.
IV. The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector.
V. Integration of forest and energy sector models – new insights in the bioenergy markets.

The first question is answered in paper I. Questions 2 and 3 are answered in papers II and III. Question 4 is answered in papers II and V. Questions 5 and 6 are answered in paper III. Question 7 is answered in paper IV and partly in paper V. Finally, question 8 is answered in paper V.

1.3 Thesis outline

The thesis begins with a synthesis describing the background for the studies, followed by a presentation of the five scientific papers that comprise the thesis. Chapter 2 presents the main background for the papers with an introduction to the Nordic forest sector, the Nordic heat and power sector, and the potential for forest-based biofuel production in the Nordic countries. The chapter also includes a review of the existing literature. Chapter 3 explains the models used and the basic theory behind partial equilibrium models. Chapter 4 introduces the papers and presents a broader discussion of the results. For detailed results and discussion, I recommend reading the specific papers. The synthesis is completed in chapter 5 with a presentation of the main conclusions from the thesis. The thesis also includes one appendix, which describes the forest sector input data used in paper V.

2 The Nordic forest and energy sectors

2.1 Forestry and the forest sector

Forestry and the forest industry have long traditions in the Nordic countries, and the sector has always been able to adapt to the current market situation. The annual growth in the Nordic forest sector increased from 134 million m^3 in 1960 to 230 million m^3 in 2015 (figure 2). There are many reasons for this growth, but as Henttonen et al. (2017) pointed out, a longer growing season, increased temperatures, and changes in forest management have been the main drivers of the increased growth. In the same period, the harvest has been relatively stable with a 113 million m^3 in 1960 and 156 million m^3 in 2018. The harvest is divided evenly between sawlogs and pulpwood and the fraction has been more or less constant for the last 20 years. The increased growth and the slower increase in harvest have led to an increase in the total growing stock in the Nordic forests from 3.8 billion m^3 to 6.1 billion m^3 (figure 2) over the last 60 years. Consequently, the biomass in the Nordic forests has also increased. According to the proposed forest reference level (FRL) the Nordic countries might harvest on average up to 163 million m^3 each year between 2021 and 2030 without exceeding than the sustainable level[1] (Johannsen et al., 2019; Jord- och skogsbruksministeriet, 2018; Klima- og miljødepartementet, 2019; Miljödepartementet, 2019). This will make it possible to increase the future harvest within certain limits without going beyond the sustainable limit, and hence increase LULUCF emissions. As pointed out by Rytter et al. (2016) the forest increment could be almost doubled by 2050 with the introduction of other faster-growing tree species, increased fertilisation, and increased afforestation. Moreover, climate change could extend the growing season even more. This is supported by Härkönen et al. (2019), who conclude that the stock of biomass in Northern Europe may increase by up to 30% towards 2030 as a result of longer growing seasons. This biomass might be available for energy production in the future. It has to be noted that

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[1] Sustainable, in this context, means the long-term harvest level that does not reduce the uptake of carbon in the forest more than it would naturally be reduced due to the age dynamics of the forest.

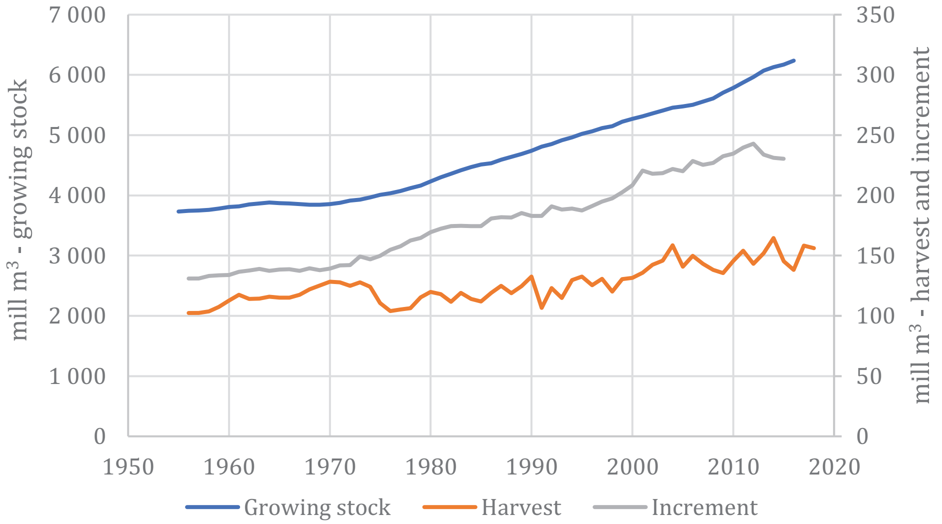

Figure 2. The Nordic (Norway, Sweden, and Finland) growing stock (left axis), yearly harvest (right axis), and increment (right axis). Source: (Luke, 2020a; Luke, 2020b; SLU, 2020a; SLU, 2020b; SLU, 2020c; SSB, 2020e; SSB, 2020f).

the future amount of available roundwood is uncertain; for instance, drought, bark beetle, and fire can substantially reduce the stock available for harvest.

Sawmills and sawnwood are the main contributors to profit-making in the forest sector (Rørstad et al., 2019), and thus are important for the entire forest value chain. Since the 1960s, Nordic sawnwood production has almost doubled from 18 million m^3 in 1961 to 33 million m^3 in 2018 (figure 3). Considering efforts to reduce carbon emissions from the construction sector, it is likely that the production of sawnwood will continue to increase in the future (Hildebrandt et al., 2017). But as Hetemäki and Hurmekoski (2016) note, the per capita consumption of traditional sawnwood has decreased from the 1990s to the 2000s. The main reason for this is the competition from alternative construction materials, including wood panels. Meanwhile, the economic and population growth in the same period has led to a total increase in the sawnwood consumption. Hetemäki and Hurmekoski (2016) also foresee a rapid increase in new sawnwood products such as cross laminated timber (CLT).

During the last 50 years, the forest industry has undergone major changes with a large expansion of pulp and paper production until 2006 (figure 3). From 1960 to 2006

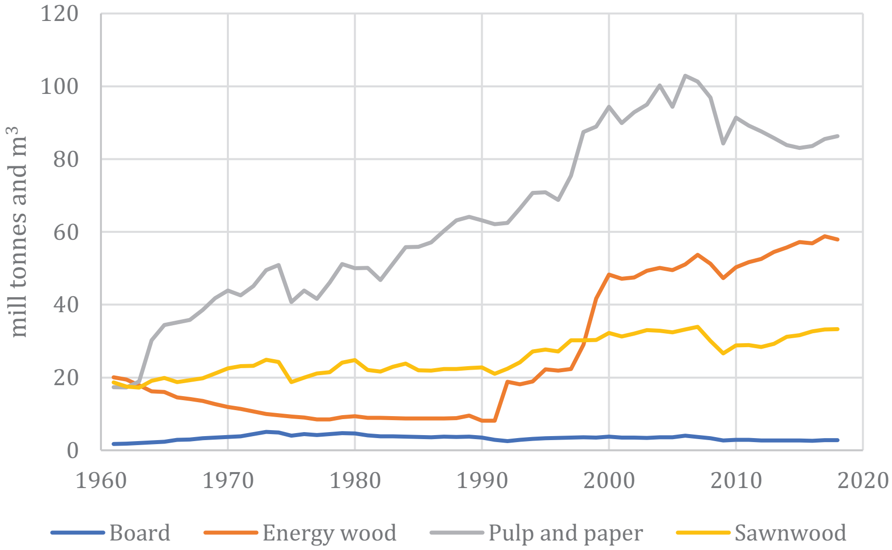

Figure 3. Nordic industrial production of board, pulp and paper, sawnwood, and energy wood. Source: (FAOSTAT, 2019).

pulp and paper production increased from 17 million tonnes to 102 million tonnes (FAOSTAT, 2019). Since 2006 the total production of pulp and paper has declined by 16%. In particular, the segments of newsprint, printing, and writing paper have seen several closures due to increased competition from digital media (Bolkesjø et al., 2003; Hänninen et al., 2014; Latta et al., 2016). At the same time, we now see new investment in the production of wrapping paper, packaging paper and cardboards, tissue, and new by-products from the traditional pulp mills (Midttun et al., 2019). This is supported by Hurmekoski et al. (2018), who investigated new wood-based products that may become important in the future forest sector; they foresee a general increase in roundwood usage because of increased demand from the construction sector, as well as from textile and biofuel production. Summing up, we see a change within the pulp and paper sector with more varied production and a broader spectrum of products, increasing the opportunity for new forest products to get a share of the market.

2.2 Heat and electricity production

In the Nordic countries, heat and electricity are produced from many different sources, some renewable – such as hydropower, wind power, solid primary biofuels, biooil, biogas, and renewable waste – some fossil-based – such as coal, peat, natural gas, and fuel oil – and other sources – such as nuclear power and non-renewable waste. Solid primary biomass comes from many sources, but mostly from by-products and waste, which are of low value and have few if any other applications besides power and heat generation. In a Nordic context, solid biomass is mainly forest biomass, with chips, pellets, and firewood being the dominant products. Nuclear, hydro, and wind are only used for electricity production, while the other sources are used in thermal plants, either in heat-only plants or in combined heat and power (CHP) plants. In Norway, most of the thermal plants are heat only, while in the other Nordic countries CHP is used more frequently (Sandberg et al., 2018). Electricity is also used to a large extent for heat generation in electrical boilers and in heat pumps.

The production of heat and electricity in the Nordic countries is to a large extent decarbonised, with hydropower (39%) and biomass (17%) being the most important energy sources (figure 4). In 2018, 72% of the heat and power produced in the Nordic countries came from a renewable source (Eurostat, 2020a). This is above the European average of 32%, and all of the Nordic countries are on the list of the top 10 countries with the highest share of renewables in the EU, with a renewable share of 98% in Norway, 76% in Denmark, 68% in Sweden, and 49% in Finland. The total share of renewables used in Nordic heat and power generation has increased from around 55% in 1990, mainly due to increased use of biomass, wind power, and waste incineration heating plants. The potential for new hydropower production has already been tapped to a large extent, so increased production in the future is likely to come from other energy sources. On-shore wind power has a great deal of potential but is the source of much debate in Norway; it is less controversial in the other Nordic countries (Bolwig et al., 2020). This leaves some doubts about future investment in wind power, at least with a short time frame. In a longer time frame, it is likely that wind power generation will increase in all the Nordic countries due to the large potential and the introduction of new technologies. This suggests that bioenergy may

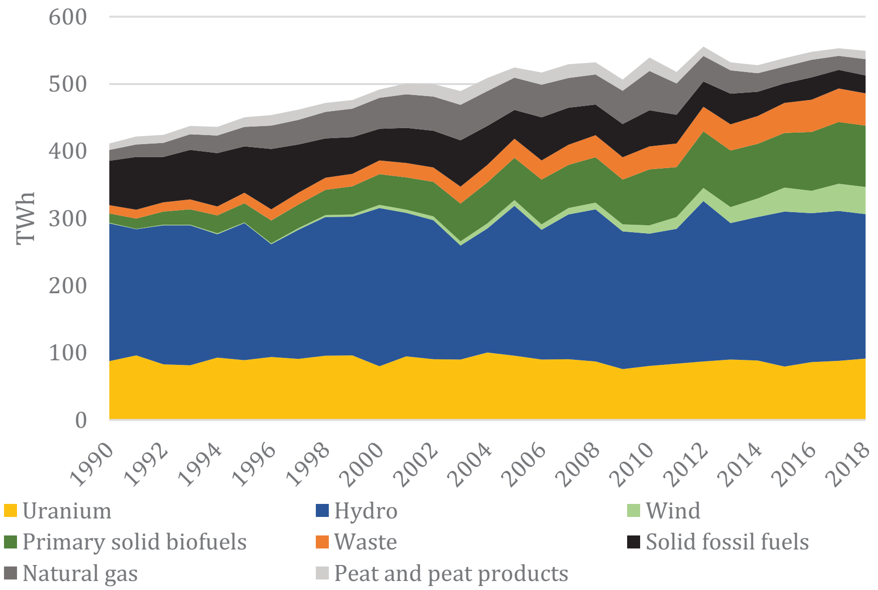

Figure 4. Production of electricity and heat for the main fuel categories in the Nordic countries. Source: (Eurostat, 2020a).

be even more important in the future since biomass can be transported, stored, and regulated and does not depend on weather conditions. Forest biomass is accessible all over the Nordic countries, making it easy to use in both remote and central areas.

The Nordic district heating sector delivers around 140 TWh each year (Eurostat, 2020a), with about 45% coming from solid biomass. In addition, around 14.7 million m^3, or 29 TWh, of firewood is used in households (Energimyndigheten, 2020; Luke, 2018; Nord-Larsen et al., 2018; SSB, 2020g). In total, 55 million m^3 of forest products are used for district heat production or burned in wood stoves in the Nordic countries. This shows that heat production is an important part of the entire forest sector value chain, with heat producers normally using low quality roundwood, which is currently not profitable to use in other sectors.

Electricity and heat production in the Nordic countries uses a rather large share of renewables, but if we instead look at the entire energy balance, we find that the “real” share of renewables is 37% (Eurostat, 2020a). The most dominant primary energy source in the Nordic countries is crude oil, which accounts for 36% of the primary energy in the Nordic countries. Crude oil, together with liquid biofuel and electricity, is the main energy source in the transportation sector. The Nordic countries have increased the share of renewables in the total energy supply from 25% in 1990 to 37% in 2018, while the amount of electricity and heat produced from solid biomass has increased 6.5 times in the same period. Heating sector in Sweden and Finland has the most dominated increase.

2.3 Biofuel

In 2018, the Nordic consumption of bioethanol was 3.3 TWh (0.56 million m^3) while the consumption of biodiesel was 23.7 TWh (2.6 million m^3) (Eurostat, 2020a); this is around 13% of the total energy consumed in the road transportation sector that year. For comparison, the total world production of biofuel was around 1540 TWh (154 million m^3) in 2018 (IEA, 2019b). This means that the Nordic countries use around 2% of the annual world production of biofuel. Most of the biofuel used comes from agricultural crops (IEA, 2019a), but it is technically feasible to use forest biomass instead of other biomasses. Several different conversion routes from forest resources to liquid biofuel exist, some of which are more mature than others. This has been described in many previous studies (Cherubini, 2010; de Jong et al., 2017; Dimitriadis & Bezergianni, 2017; Dimitriou et al., 2018; IRENA, 2016; Mawhood et al., 2016; Navas-Anguita et al., 2019; Sacramento-Rivero et al., 2016; Serrano & Sandquist, 2017). All the different technologies have different maturation levels, efficiency, and other technical parameters and biofuel production may be the main product or part of a side stream; some technologies produce biofuel that needs to be upgraded before it can be used as fuel, while others do not. This shows that liquid biofuel production from forest biomass is a relatively new technology that is far from economically mature. The choice of production route may be important when examining the economical and physical potential of the conversion. For this reason, in this thesis I mainly use a generic technology with an assumed conversion efficiency in the middle of the reported range. In this way I ensure that the results are valid for all technologies as long as the plants use the same amount of raw materials.

Forest biomass may be used to produce different qualities of liquid fuel. The quality determines whether or not the fuel can be used in an ordinary vehicle without any modifications; this is the case not only with forest-based biofuel but also, and perhaps more relevantly, for first generation biofuel. Some conversion routes produce ethanol that can be used as fuel when mixed with fossil fuel. European fuel standards allow up to 10% ethanol and 7% FAME to be mixed into the fuel (European Commission, 2016), but most of the projects in the Nordic countries plan to produce synthetic fuel, which has the same properties as fossil fuel. Most of the biofuel plants in the Nordic countries plan to produce biocrude, which will be blended into ordinary crude oil before further refining. Bioenergi Tidningen (2019) has identified 39 different forest-based biofuel projects in the Nordic countries with a total production capacity of 32 TWh biofuel, but at least 12 of the projects are considered uncertain. Twelve of the projects were producing biofuel in 2019, together producing around 2.1 TWh biofuel.[2] Five projects (3.3 TWh) plan to use lignin as a raw material, 16 projects (14.5 TWh) plan to use pulpwood or wood chips, 12 projects (5.4 TWh) will use sawdust, and 5 (5.3 TWh) will use tall oil, while only one project (14 GWh) plans to use black liquor as raw material (figure 5).

The use of biofuel will significantly reduce the fossil carbon emissions from road transportation. According to the renewable energy directive (RED) (European Commission, 2019), forest based biofuel may reduce the carbon emissions by 90-95% compared to fossil fuel. This shows that forest biofuel plays an important role in reducing emissions from existing vehicles and airplanes. In order to make forest-based biofuel competitive, policies and subsidies are important. The different Nordic countries have slightly different approaches when it comes to promoting biofuels. Norway, Finland, and Denmark have quota obligations as the main policy tool, while Sweden has obligations to reduce emissions compared to fossil fuel. The current Norwegian biofuel quota is 20% by volume, and at least 4% has to be advanced biofuel (Miljødirektoratet, 2020a). Finland has a quota of 20% by energy (Res Legal, 2020), while Denmark requires at least 5.75% biofuel by energy, and at least 0.9% has to be advanced (Res Legal, 2020), while Sweden has obligations of at least 4.2% GHG reduction for gasoline and at least 21% for diesel (Res Legal, 2020). The Nordic

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[2] Synthetic biofuel has approximately the same energy content as its fossil-based counterpart. The assumption in this thesis is that the energy content of biofuel is 10 MWh/m^3.

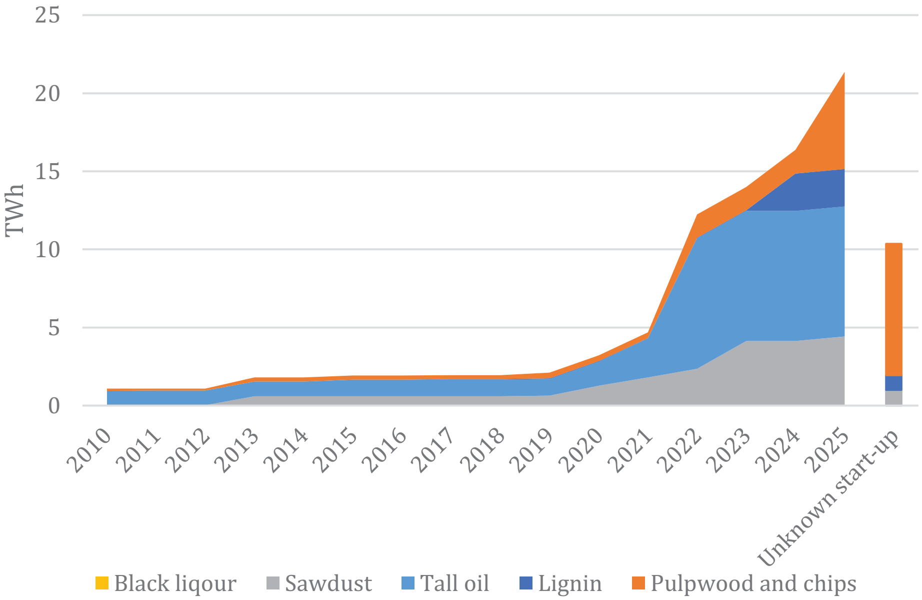

Figure 5. Identified liquid forest-based biofuel production capacity (accumulated) in Norway, Sweden, and Finland for the period 2010-2025 and additional production capacity in projects with unknown start-up date that may be regard as uncertain. Source: (Bioenergi Tidningen, 2019).

legalisation has created a market for biofuel, but as Midttun et al. (2019) have shown, the Nordic policies have not been able to promote forest-based biofuel produced in the Nordic countries as much as intended; instead, the Nordic countries import most of the biofuel they consume to fulfil the policy-driven demand.

Transportation sector and biofuel ambitions

The EU has a goal of reaching a 10% share of renewable fuel for transportation in 2020. Eurostat (2020c) estimated the share of renewables to be 8% in 2018; this means that the EU will only reach the target if we assume exponential growth based on the shares in the period 2004–2018. Even as the EU members struggle to transition the transportation sector to renewable energy, the Nordic countries have a higher share of renewables than the EU target. In 2018, the share of renewables in the transportation sector was 20% in Norway, 30% in Sweden, 15% in Finland, and 7% in Denmark (Eurostat, 2020c). These figures show that the Nordic countries are ahead of the rest of Europe when it comes to emissions reduction in the transportation sector.

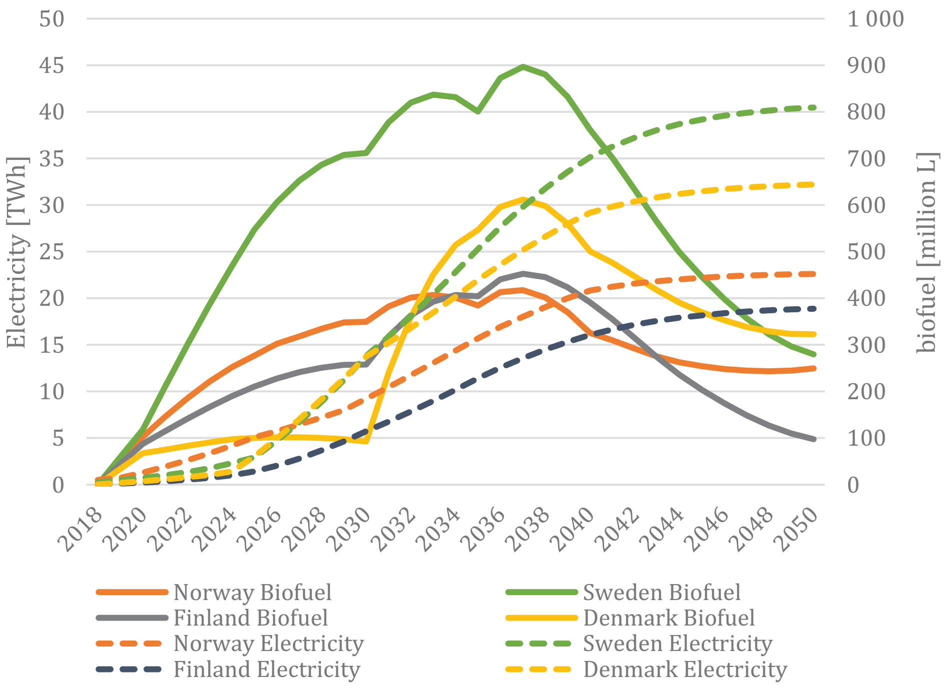

Figure 6. Forecast of second-generation biofuel demand and electricity demand in the transportation sector based on extrapolation of existing policies and trends. The salient points in 2030 and 2035 are the result of the transition from one policy period to another. Source: (Avinor, 2020; Energistyrelsen, 2018; Lovdata, 2018; Miljødirektoratet, 2020b; Petroleum & Biofuels, 2018; Regeringskansliet, 2018; SSB, 2020a; SSB, 2020d; Statistics Denmark, 2020b; Statnett, 2019; Svenskt Näringsliv, 2020; Tilastokeskus, 2020a; Tilastokeskus, 2020b; Transport Analys, 2020) and my own estimates.

Although the Nordic countries have already implemented policies to reduce transportation sector emissions, they plan to reduce fossil fuel emissions from transportation even more. Figure 6 shows my estimation of future demand for liquid second-generation biofuel and electricity in the transportation sector in the Nordic countries. Figures until 2030 are based on likely trends, established policies, and planned policies, while figures after 2030 are mainly based on extrapolation and harmonisation of Nordic goals; a 100% renewable transportation sector within 2050 is assumed. The biofuel demand follows two main trends: 1) When an old vehicle is retired, the probability that it will be replaced with an electrical vehicle increases as a function of year; consequently, the electric share of the transportation fleet will increase over time. 2) The blend-in obligation, or willingness to buy renewable biofuel, increases with time with an upper limit of 100% second-generation forest-based biofuel. These two trends together give an estimated peak in biofuel demand in the mid-2030s, which will then decrease until 2050. It is likely that the demand for biofuel will not reach zero due to the need for liquid fuel in some sectors, such as long-distance aviation. The assumption behind figure 6 is described below.

The total number of vehicles and the total driving distances are based on historical figures (SSB, 2020d; Statistics Denmark, 2020b; Tilastokeskus, 2020a; Transport Analys, 2020) and it is assumed that they remain constant throughout the period in question. It is assumed that the vehicle retirement age follows historical figures (SSB, 2020a) and each retired vehicle is replaced with either an electric or a fossil fuel-powered vehicle with an estimated probability function for year of retirement (Miljødirektoratet, 2020b; Svenskt Näringsliv, 2020; Tilastokeskus, 2020b). In Norway, the stated policy is that all new private vehicles have to be electric from 2025 and the country aims to fully electrify all other new vehicles by 2035 (Miljødirektoratet, 2020b). Sweden does not have such clear goals, but Svenskt Näringsliv (2020) estimates that almost all new private vehicles from 2025 will be plug-in hybrids or electric, and the country will be close to the full electrification of all new vehicles in 2030.

For non-road transportation, it is assumed that the energy output is constant independent of whether the engine runs on electricity or liquid fuel. To convert between liquid fuel and electricity, average engine effectivity is used[3] (Miljødirektoratet, 2020b). It is assumed that railway transportation will be fully electrified by 2025 and the electricity demand from short distance marine and ferries in Norway will increase by 0.3 TWh each year between 2020 and 2025 (Statnett, 2019). Further, it is assumed that from 2025 all domestic ferries will be electric and the potential for shore supply will be fulfilled. For domestic aviation, a constant liquid fuel demand is assumed until 2030; for 2040 this demand is reduced to 80% of the 2018 values with the remainder of the energy demand being met by electricity; this is in keeping with Avinor (2020).

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[3] Efficiencies used for calculating the electrical demand are 30% for gasoline engines, 35% for diesel engines in road transportation, 40% for other diesel engines, 90% for electrical engines, and 10% electrical charge losses (Miljødirektoratet, 2020b).

As stated above, the Norwegian blend-in mandate is that 20% of the liquid fuel sold as road fuel will be biofuel in 2020; of this, we assume that 1.75% is forest-based biofuel. The volumetric share of advanced biofuel is assumed to increase to 10% by 2030 (Miljødirektoratet, 2020b); we assume all of this biofuel has to be forest based. It is also assumed that the blend-in share will increase to 20% by 2035, and further increase to 100% by 2050. We assume the same blend-in obligation for all types of transportation.

The Swedish biofuel policy is not a blend-in obligation, but a GHG reduction goal; the goal is 40% reduction for all liquid fuel for transportation by 2030 (Regeringskansliet, 2018). It is assumed that Nordic forest-based biofuel reduces the GHG emissions by 95% (Lovdata, 2018) compared to fossil fuel. With the same assumptions regarding the forest-based biofuel share of the total biofuel mix as in Norway, we get 1.2% forest-based biofuel in 2020, 10.5% in 2030, 20% in 2035, and 100% in 2050. Biofuel blend-in policies similar to those in Sweden are assumed for Finland and Denmark after 2030; before 2030 existing policies are used (Energistyrelsen, 2018; Petroleum & Biofuels, 2018).

According to the estimates in figure 6, the Nordic demand for forest-based biofuel will peak at 2.4 billion litres in 2037. It should be noted that this is an ambitious estimate for forest biofuel demand, but it assumes no increase in net energy demand from transportation. For comparison, forest-based biofuel projects of 32 TWh or approximately 3.2 billion L were found (figure 5); thus, if all projects are fulfilled, Nordic production will be higher than consumption. This means that the Nordic countries may start to export biofuel; however, it is more likely that not all the projects will be conducted.

2.4 Literature review

The optimal use of Nordic forests resources in a climate perspective is a subject of debate, but it seems relatively uncontroversial to state that sawnwood and other long-life forest products still will continue to be produced in the future since sawnwood and other construction materials will store carbon in buildings for decades (Marland et al., 2010). Nor is it controversial to use the by-products from the harvest of sawlogs and sawnwood production for other products; in a carbon perspective, however, only the very low-quality by-products will be beneficial for energy production. This means that in a GHG perspective there is a close relationship between the harvest level and the choice of products made from the roundwood. This is supported by Cintas et al. (2017), who argue that bioenergy and forest-based materials have complementary roles in reducing Swedish emissions and do not see any controversies between use of forest products and carbon storage. Dwivedi et al. (2016) studied the forest carbon storages in the United States and concluded that change in rotation age does not necessarily impact the forest carbon storage, but increased use of bioenergy would potentially reduce the rotation age due to increased prices for thinner roundwood categories. On the other hand, Havlík et al. (2011) estimated the indirect land use change of different biofuel production routes using the partial equilibrium model GLOBIOM. They found that forest biofuel from managed forests may reduce the total emissions by 27% compared to fossil fuels. However, first generation biofuel may increase emissions. This is supported by Dauvergne and Neville (2010), who question whether there is such a thing as sustainable biofuel since most biofuel is produced from agricultural crops that are grown on former rainforest land, and hence linking biofuel production to deforestation. This is not a direct problem for Nordic forest-based biofuel production, but indirect land use changes may be a challenge.

It is debatable how much of the available forest resources can be harvested without going beyond sustainable levels and increasing overall emissions. In this context, the sustainable level is close to the sustained yield, which is the most it is possible to harvest without needing to reduce future harvests. Kumar et al. (2020) reviewed recent studies and estimated the availability of forest biomass in Sweden. They found that Swedish forests may continue to provide sustainable raw materials for the forest industries. Lecocq et al. (2011), who discuss the GHG effects of using forest biomass for carbon storage or producing products that substitute fossil fuel, reach the opposite conclusion using a French forest sector model. They show that forest carbon storage is the only option that is better than business as usual over a ten-year period, although they recognise that this relatively short time frame may have affected the results. Another approach is that of Kallio et al. (2018b), who used a global forest sector model to study the impacts of limiting the harvest in Europe and found that the European forest sector will observe leakage of harvest and forest industry production to the rest of the world if the harvest is restricted to the average 2000-2012 levels. Countries outside Europe will instead increase forest production, while consumers in Europe will start to use non-forest materials for constructing and reduce chemical production from forest resources, both of which will likely increase carbon emissions. According to Kallio et al. (2018b), it will not be possible to use European forests as a carbon sink if rest of the world does not do the same, since reduced harvest in Europe will lead to increased harvest other places. Simultaneously, reduced harvests may lead to increased rotation age of European forests, and younger forests have a higher uptake of carbon than older forests. The European Union has, however, introduced a forest reference level (FRL) (European Commission, 2018) to balance the LULUCF effects and carbon uptake and release from the forest. As pointed out by Grassi et al. (2018), the FRL is not a strict limit on the harvest but rather a base line for the harvest, which in practice is the highest harvest member states are allowed to have without reporting the emissions in their national carbon budget. This is done in order to ensure that the emissions from forest management are accounted for using the same methodology as other emissions.

In the future, it is likely that biorefineries will take up a larger share of the available forest biomasses in the Nordic countries. This is supported by Kumar et al. (2020), who looked at current biorefinery projects in Sweden and found that there has been a significant expansion the last decade. Biorefineries with forest raw materials produce many different final products, including chemicals, enzymes, lignin, material, textiles, proteins, and transportation fuels (Cherubini, 2010). In Norway, Borregaard (2020), a well-known biorefinery, has produced different chemicals from roundwood for many decades. Other Norwegian biorefinery projects are mainly focused on making liquid biofuel (Biozin, 2019; Silva Green Fuel, 2019). The effects of biofuel production have been studied by Mustapha et al. (2017), who used a forest sector model to study the optimal locations, production level, and raw materials for biofuel production with the Nordic countries. They found that feedstock choice has large effect on the allocation between the Nordic countries, and for some feedstocks, sawmills may have significant positive synergic effects on nearby biofuel plants, while the opposite is the case for other forest industries. Assuming high use of the heat surplus is sold as district heat, biofuel production in Sweden is more profitable because district heat is more widely used in Sweden than in the other Nordic countries.

The forest sector, biofuel production, and heat and power production from forest biomass are closely connected and will probably be even more connected in the future. For example, Mustapha et al. (2019) combined NFSM and Balmorel using a hard-link approach and found that when the biofuel share in the Nordic countries is 40% of the volume used for road transportation, the use of bioheat is reduced by 50%. A similar result is found in Bryngemark (2019) where a Swedish forest sector model was used to study the effects of 5-30 TWh forest-based biofuel production. They found a strong connection between use of forest biomass in the heat and power sector and biofuel production; at the same time, board production close down for higher amount of biofuel production due to higher raw material competition. This is supported by Trømborg et al. (2013), who, using a Norwegian forest sector model, found that some raw materials from the forest may have a higher impact on heat production than others. The opposite was found by Kallio et al. (2018a), who address the economic potential and impacts of forest biofuel production using a forest sector model, EFI-GTM. They found that different policies will have a significant impact on the competition of forest products between power, heat, and biofuel production and that the European forest sector will be marginally affected by the increased wood consumption within energy production.

The use of biomass for heat and power production is discussed in the literature, with some studies concluding that biomass increases the overall GHG emission and others concluding the opposite. For example, Welfle et al. (2017) are sceptical about the positive GHG effects of biofuel; using an LCA study with different biomass conversion pathways they found that the GHG effects are highly path dependent, concluding that locally produced products with low levels of pre-processing may have the most positive GHG effects. Booth (2018) points out that if bioenergy leads to increased harvests, more carbon will also be released in a short time frame, but the effect is small if harvest residues or by-products are used. This concern is supported by Searchinger et al. (2018), who state that the European countries have to be especially careful with using imported pellets for bioenergy purposes. Other studies have concluded that biomass is an important step towards a carbon neutral energy supply; for example, Connolly and Mathiesen (2014) present a pathway to obtaining a 100% renewable energy system following these steps: increase the use of district heating, increase the use of heat pumps, increase demand response, increase use of electric vehicles, produce biofuel, and, finally, use biogas for the remaining fossil fuel consumption. If the Nordic countries fully adopt Connolly and Mathiesen (2014) advice, they will increase energy production from forest biomass significantly. Other studies have found that it is possible to obtain a fully renewable energy system without high amount of biomass, such as Höltinger et al. (2019), who studied long term time series of hourly variable energy production combined with an energy sector model and found that Sweden may have up to 50% variable energy production with no lack of security of supply. They also found that biomass CHP is important as a backup solution, even though it accounts for only 7% of yearly electricity production. Other studies have found that increased utilisation of variable renewables leads to increased use of biomass for electricity production, e.g. Ćosić et al. (2012), Lund and Mathiesen (2009), and Mathiesen et al. (2011) for single countries and Steinke et al. (2013) for multiple countries. The main reason for this is the favourable storage and security of supply properties of biomass compared to other renewables. Mathiesen et al. (2012) found, however, that using less wind power could lead to more use of biomass. Meanwhile, Reid et al. (2020), argue that while bioenergy is an important step towards a carbon neutral energy supply, it is likely that bioenergy will be replaced with other energy technologies after 2050.

Many previous studies have pointed out aspects of biofuel and bioenergy when it comes to the forest sector, emissions reduction, and energy sector changes. The above-mentioned studies show that bioenergy and other forest products work together in order to increase the roundwood value. Considering this, bioenergy will likely increase the harvest, but the increase may take the form of segments that have low value as carbon storages, such as harvest by-products, thinning, and industrial by-products. As a consequence, this bioenergy will have a positive effect on GHG emissions when it replaces fossil fuel. Biofuel and bioenergy will likely compete for the same raw materials in the lower valued segment of forest products. It is obvious that an increase in the production from one of the sectors would affect the other, and increased production would also increase raw material prices in the rest of the forest sector.

3 Models and methodology

In this thesis, different partial equilibrium models are used and further developed. In paper I the focus was on the Norwegian forest sector and therefore the Norwegian Trade Model III (NTM3) was used. In papers II and III the focus was biofuel implications in the Nordic forest sector, so the Nordic Forest Sector Model (NFSM) was used. In paper IV the focus was the role of forest biomass in the Northern European energy sectors; therefore, we used the energy sector model Balmorel. In the paper V, a new model was introduced that combined the NFSM and Balmorel model, allowing us to look at the effects of biomass in both the forest and energy sectors. In this chapter first the theoretical rational behind partial equilibrium model is discussed, following a brief description of forest and energy sector modelling. I refer to the various papers for specific descriptions of the model versions that were used.

3.1 Partial equilibrium modelling

In this chapter I briefly explain the general theory behind partial equilibrium modelling and welfare modelling. Since NTM and NFSM are the only models that are welfare maximizing, all the theory explained below will be valid for those two models. Balmorel is a cost minimizing model with constant energy demand; for this reason, only part of the theory will be relevant for Balmorel.

The theory behind partial equilibrium models was first explain by Samuelson (1952), and the economic theory behind the models used in this thesis is well known. The term equilibrium means that the model provides prices that balance the consumptions and supply, while partial equilibrium model means that all prices besides those of the goods being studied are assumed to be fixed (Varian, 1992), hence the model only covers part of the economy. The forest sector models are models with linear constraints and a nonlinear objective. The models are welfare-maximizing, which means they maximise the sum of all areas under each of the demand functions minus the sum of all transportation costs and production costs.

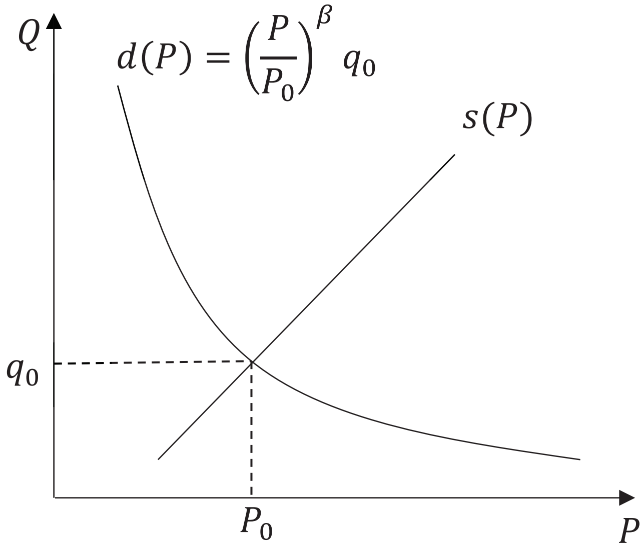

Figure 7. Connection between supply, demand, and price of a good.

These conditions are equivalent to a free competitive market, where all actors (i.e. consumers and producers) maximise their welfare given a set of constraints.

In a partial equilibrium model is there a connection in the reference year between consumption, price, and price elasticity used to build a parametric representation of the market (demand and supply curves). When a new market condition is established, the parametric representation is used to generate the new consumptions and prices. Figure 7 shows a generic relationship between the demand (d) and supply (s), where Q is the quantity consumed/produced and P is the price. In the figure the demand function $d(P)$ is nonlinear with β as the price elasticity; P_0 is the reference price and q_0 is the reference consumption used to generate the model. In this simplified model, the supply function $s(P)$ is linearly increasing with production, but for many products the supply function may also be non-linear. The market price and quantity are found at the point where the marginal costs equal the marginal revenue.

A single-region model (figure 7) is the simplest version of a partial equilibrium model. To better represent the real roundwood market, trade between multiple regions is allowed. With multiple regions, a new equilibrium is formed. Assuming no transportation costs, the new equilibrium prices are equal in all regions. Normally when discussing ordinary goods, we have transportation costs, and in the case of

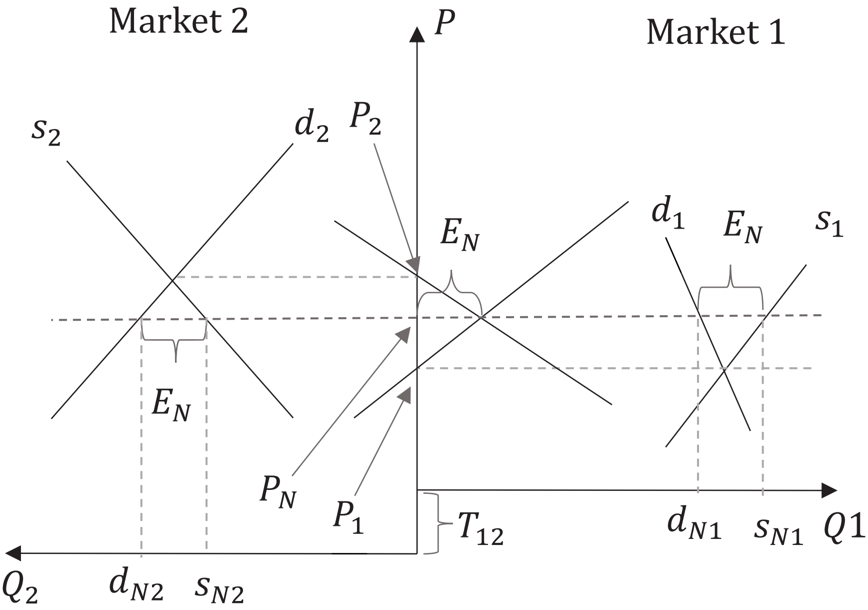

Figure 8. Outline of how the market reacts when an exporting region (market 1) and an importing region (market 2) are connected. Market 2 is shown as the inverse of market 1.

energy, losses are also relevant. The difference in price between regions will now result in one of two scenarios: 1) The original price difference is smaller than the transportation cost; this will not give any trade and the original prices will remain. 2) The original price difference is higher than the transportation cost; this will give new prices that are exactly separated by the transportation cost. The low-price regions will increase their market price, causing a reduction in consumption, and the high-price region will have reduced prices and increased consumption. How much each region must change its production depends on the amount of consumption, production costs, and willingness to pay.

Figure 8 shows how trade between an exporting region (market 1) to an importing region (market 2) affects both markets. We can see that the conditions for trade exist since $P_2 - P_1 > T_{12}$, where P_1 is the original price in market 1, P_2 is the original price in market 2, and T_{12} is the cost of transportation between the two markets. The new combined market price P_N is given by the equation $P_{N2} = P_{N1} + T_{12}$. The amount of transported goods E_N is equal to divagation from the original demand (d) and supply (s) in both markets and is explained by the equation set $E_N = s_{N1} - d_{N1}$ and $-E_N = s_{N2} - d_{N2}$, which combined will be $s_{N1} - d_{N1} = d_{N2} - s_{N2}$, where s_{N1} and s_{N2}

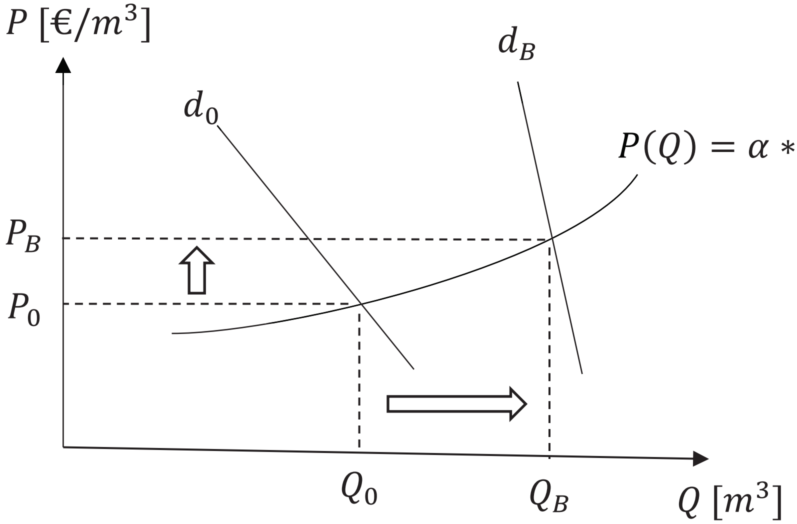

Figure 9. Change in pulpwood supply and marginal price when a biofuel plant is located in the region.

are the new production in markets 1 and 2, respectively, and d_{N1} and d_{N2} are the new demand in markets 1 and 2, respectively. When the welfare is maximised in both markets 1 and 2, the prices in the exporting region increase, while the importing region will the prices decrease. In total, the sum of the consumed and produced goods in both markets remains at the same level as it was initially, but some of the production moves from a high-cost region to a low-cost region, while the opposite is true for consumption. Combined, these results will increase welfare within the system.

Figure 9 illustrates how the pulpwood supply is affected when a biofuel plant is located in a given region. As shown, the marginal cost (P) of pulpwood is a nonlinear function, where α is an estimated parameter, β is the price elasticity of the roundwood supply, and Q is the harvest. Introducing a biofuel plant will create competition about the pulpwood and the joint demand function will change from d_0 to d_B, the consumption of pulpwood increases from Q_0 to Q_B, and the price increases from P_0 to P_B.

Revenue from consumption and cost of harvest are non-linear functions in NFSM; the functional shapes are linearized to allow the use of a linear solver. Figure 10 shows an example of a linearization of a non-linear function. The first step of linearization is to divide the x-axis into smaller segments ($S_1 - S_5$); usually the segments are of equal

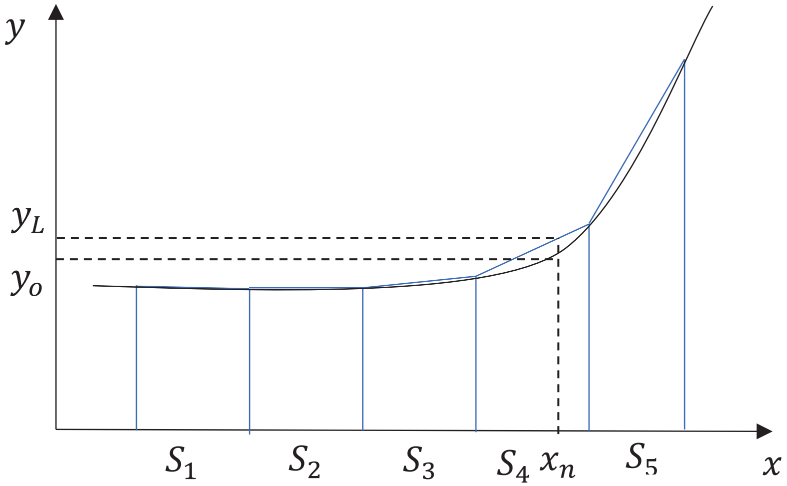

Figure 10. Schematic representation of a linearization.

length, Δx, but this is not a requirement. The second step is to calculate the y-value for the start and stop of each segment, and the third and final step is to estimate a linear function between the start and stop of each segment. When evolving the linearized model, the linearized segment that is valid for the interesting x_n-value will be used. In this example, the linearization will give a small error $y_L - y_o$. As seen in the figure, the linearization will be relatively accurate in the segments that are close to a linear part of the function, such as S_1, while in segments of the function that are distinctly non-linear, such as S_4, the linearization may be inaccurate. Most of the errors may be accounted for if the segment of the most non-linear part is divided into shorter segments than the other parts of the function. For most of the structural forms used in NFSM, the structural form is relatively linear in the most frequently used segments of the function, but for extreme scenarios the linearization may introduce some inaccuracy compared to a non-linear version.

The models used in this study are either cost minimizing (Balmorel) or welfare maximizing (NFSM). The benefit of using a welfare maximizing model is relatively obvious since forest products have a price elasticity that is strictly different from zero and infinite (Buongiorno, 2015). On the other hand, consumers in the energy sector tend to be most interested in covering their demand for energy at a certain time, rather than in short time price variations (Cialani & Mortazavi, 2018). This will give a very inelastic demand, which in Balmorel is assumed to be perfectly inelastic. On the difference between cost minimizing and welfare maximizing models, Kallio et al. (1987) write that "at any level of output, the two problems yield the same solution since profit maximization implies cost minimization". This means that cost minimaxing and welfare maximizing models are the same if the output is exogenously defined, as it is in Balmorel. In other words, it is possible to say that both Balmorel and NFSM are welfare maximizing models, although Balmorel is a simplified version.

The most significant limitation of the models applied in this study is that they are partial equilibrium models. Because these models only cover small parts of the total economy (i.e. the forest sector or energy sector), a lot of assumptions are made regarding rest of the economy. One such assumption is that the demand for products (both forest and energy) depends heavily on how the rest of the economy evolves. However, it is also a strength of partial equilibrium models that they cover only part of the economy since it allows for a detailed description of the topic of interest without too high computational costs or too many disturbances.

3.2 Forest sector modelling

Forest sector modelling started in the 1980s with the introduction of four different forest sector models: the Timber Assessment Market Model (TAMM) (Adams & Haynes, 1980), the Timber Supply Model (TSM) (Lyon & Sedjo, 1983), PAPYRUS (Gilless & Buongiorno, 1987), and the Global Trade Model (GTM) (Kallio et al., 1987). Subsequently, these models evolved in many different directions. In their review of the development of forest sector models through 2012, Latta et al. (2013) conclude that forest sector models are used for a large variety of topics and geographical areas. The forest sector models used in this thesis were developed from the GTM model.

The first version of the Norwegian Trade Model (NTM) was launched in 1995 by Trømborg and Solberg (1995), and further developed by Bolkesjø et al. (2005), Bolkesjø et al. (2006), Trømborg and Sjølie (2011), and Trømborg et al. (2013); the latest version, NTM3, was further updated and used in Paper I. NTM is a forest sector model that describes the Norwegian forest sector in relative detail with 19 Norwegian regions, one Swedish region, and a simplistic rest of the world region (ROW).

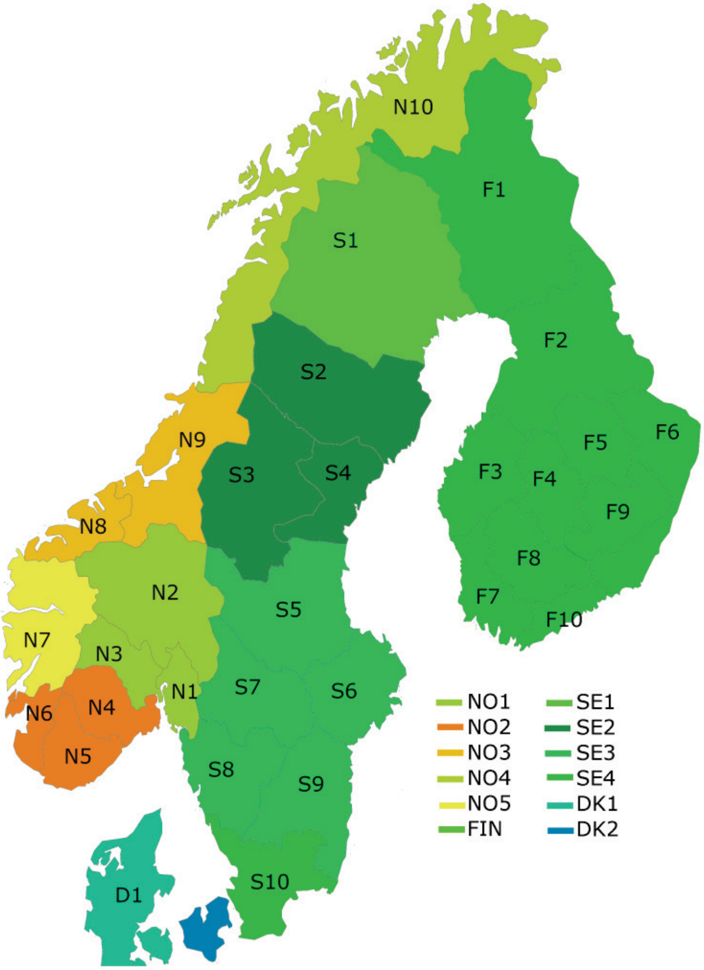

Figure 11. The regionalisation within the Nordic countries as presented in paper V. Colours represent the approximative Balmorel regions, while the border lines show the NFSM regions.

The Nordic forest sector is a highly interconnected market (Nyrud, 2002; Thorsen, 1998; Toivonen et al., 2002). To describe the cross boarder roundwood balance between the Nordic countries, Mustapha (2016) further expanded the structure of the NTM model to create the Nordic Forest Sector Model (NFSM). NFSM covers 32 regions, 10 in Norway, Sweden, and Finland, and one region in Denmark and ROW. Figure 11 shows the NFSM regions used in paper V; a slightly different regionalisation in Norway is used in papers II and III.

Both NTM and NFSM are partial equilibrium models that seek to maximise overall social welfare (i.e. consumers plus producers' surplus) in the Norwegian and Nordic

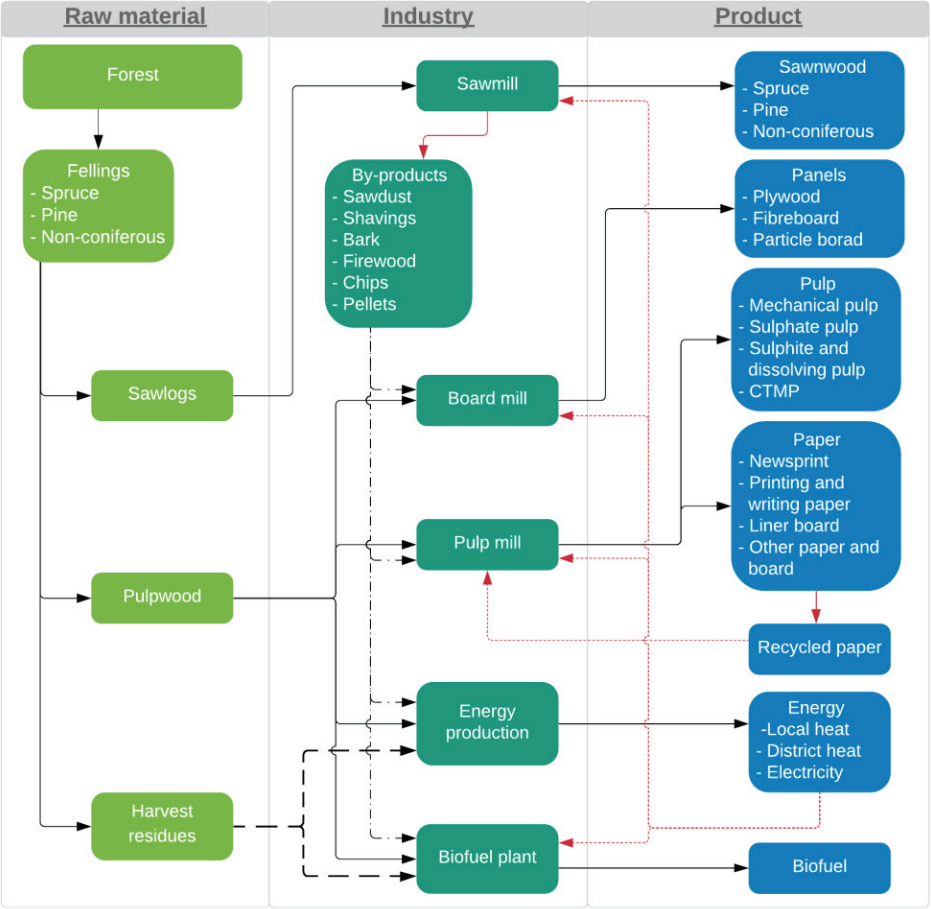

Figure 12. Schematic representation of the forest sector models as presented in paper III.

forest sectors respectively. Both models cover the main aspects of and actors in the forest sector, including roundwood supply, industrial production (including bioenergy production), consumption of final products, and trade between regions. NTM consists of 6 roundwood categories, 9 intermediate products, and 12 final products covering all Norwegian pulp and paper mills and board producers with unique technologies, sawmill technologies for spruce, pine, and non-coniferous sawnwood; finally, it includes different grades of bioenergy production. NFSM has 15 different aggregates of final produces, 15 intermediate products and by-products, and 7 forest products. Figure 12 shows a flowchart of the NFSM model used in papers II and III with minor changes in the product category valid for papers I and V as well. In general, the complexity of the model increases from paper I though paper V.

Both models are multi-periodic and recursive as they find the equilibrium for one year before solving for the next. Despite being multi-periodic, the models are static and deterministic giving equilibrium solutions that should be equal each time given equal input. The models are suitable for short- to long-term projections of changes within the forest sector, as are made in paper I (12 years into the future) and in paper V (32 years into the future). The models are also suited to validating the effects of large shocks within the forest sector, which was done in papers II and III. Because the effect of huge shocks depends on when they happen and how long they last, it was decided to only optimise a single period in papers II and III.

3.3 Energy sector modelling

Energy sector modelling appeared as early as the 1950s with the purpose of planning grid capacity expansions (Massé & Gibrat, 1957). The interest in and scope of energy sector modelling increased during the 1970s and has continued until the present (Wei et al., 2006). Today energy sector models are widely used within a wide range of topics, especially those related to the decarbonisation of the heat and power market, which have been studied extensively in recent years.

Balmorel is a bottom-up partial equilibrium model for the North European heat and power market (Ravn et al., 2001). The objective is to minimise the cost of energy production and transmission within the combined heat and power sector in Northern Europe. Balmorel has been continuously developed since the first version in 2001 (Wiese et al., 2018). The model itself, along with data, is available from the Balmorel community at Github Repository (2019), and the code, as well as the input, is open source and available to everyone (Open Source Initiative, 2020). A strength of Balmorel compared to other energy sector models is its combination of flexible time resolution, high regional resolution, investment optimizing, and simultaneous optimisation of heat and electricity markets.

The current version of Balmorel covers the district heat and power markets in Norway, Sweden, Finland, Denmark, the Baltic countries, Poland, Germany, Belgium, Netherland, France, and UK. The countries are divided into multiple regions and sub-regions. The regions within the Nordic countries are the same as the NordPool bidding areas (NordPool, 2018), as shown in figure 11. In Balmorel the regions have to balance production, consumption, and transmission of electricity for every time-period studied. Each region is divided into one or more sub-regions that cover the heat market with production and consumption of heat. The time resolution in Balmorel is hours, but it is possible to aggregate hours together such that the modelling time resolution is 1–8760 hours per year. The model optimises all studied hours within a year. A full study may entail optimizing multiple years; it is not necessary to optimise every following year, but the years must be in the correct order.

The objective function of the base model includes cost components such as fuel costs, operation and maintenance costs, reservoir and operation costs for hydropower reservoirs, transmission costs, annuity of investment cost, transmission, electricity and heat storage capacities, and taxes. In addition, many different optional extensions of Balmorel are available: electric vehicle (EV), policy, and water value of hydropower are among those frequently used, but many others exist (Wiese et al., 2018). Balmorel includes the most frequently used energy sources in thermal energy plants, variable renewables, and waste incineration. The most important energy sources are wind, solar, hydro (with pump, reservoir, and run-of-river), coal, natural gas, nuclear, wood chips, pellets, other bioenergy, and different grades of waste. Thermal fuels may be incinerated in heat only, electricity only, or combined heat and power (CHP) plants. The exogenous plant capacities in Balmorel are based on existing capacities; according to expected technical and economic lifetime and political goals the exogenous capacity is reduced as a function of year. To meet the energy demand, Balmorel has an investment module that can invest in the most profitable plant. The model can choose between all the possible raw materials and technologies, but the investment may be restricted by exogenous capacity constraints.

4 Results and discussion

A quick overview of the different studies is shown in table 1 with the main research question, method, and key findings of each. In this chapter the different papers are presented briefly, and the most important findings are discussed in a broader context.

Table 1. Overview of the different papers.

Paper	Main research question	Model	Focus	Methods	Key findings
I	What are the main divers of uncertainty in the Norwegian forest sector?	NTM3 Basis year 2013 Studied years 2013-2025	Uncertainty in market price of forest products and exchange rate.	Estimation of historical market price variation and the effects of similar market variation 8 years into the future using Monte Carlo simulations.	Roundwood has higher price uncertainties than final products, while production level has higher uncertainty than the harvest levels.
II	What are the implications of the Nordic forest sector for various levels of biofuel production?	NFSM Basis year 2013 Studied year 2013	Forest sector effects of 0-11.6 billion litres of Nordic produced biofuel.	Estimation of forest sector effects using exogenous biofuel production levels.	Biofuel production leads to increased pulpwood prices, use of harvest residues, harvest, and import, while production of pulp and paper decreases.
III	Which subsidy scheme is most profitable for increasing biofuel production?	NFSM Basis year 2013 Studied year 2013	Effects of different policies.	nth plant estimation of biofuel production combined with different policies is used for finding the endogenously biofuel production.	Feed-in premium gives the lowest needed subsidy cost for low production level, while quota obligations has lower cost for higher volume.
IV	What is the role of forest biomass in the North European heat and power sector?	Balmorel Studied years 2020-2040	Effects of removing forest biomass out of the energy system.	Estimation of fossil carbon effects of using endogenously defined chips levels in biofuel production instead of heat and power production.	Biomass substitute heat pumps, natural gas, and wind power. Fossil emission reduction is highest when biomass is used for biofuel production.
V	What are the strength and weakness of integration of an energy sector model and a forest sector model?	Balmorel and NFSM Basis year 2018 Studied years 2018-2050	Integration procedure, strength, and weakness of the integration.	Integration of NFSM and Balmorel.	An integrated model gives better representation of electricity costs in the forest sector and biomass prices in Balmorel.

4.1 Market effects of biofuel production

The Nordic forest sector is closely interconnected, and any significant disturbance may cause changes in roundwood availability and roundwood prices. In order to describe those changes in roundwood balance and prices, the research reported in paper II was conducted. In paper II five scenarios were tested with production of 0-11.6 billion litres of biofuel corresponding to 0-40% of the Nordic consumption of liquid fuel in 2017. According to the assumptions in paper II, with a production of 11.6 billion litres around 100 million m^3 of forest biomass will be needed; of this, 25 million m^3 will come from increased domestic harvest, which is equal to 17% of the reference harvest. This led to a 22% increase in pulpwood price, and thus a significant revenue increase for forest owners. The rest of the biomass needed comes from 35 million m^3 of harvest residues, a 15 million m^3 increase in roundwood imports, reduced consumption in the pulp and paper industries, and a slight increase in by-products from sawmills. In total, the roundwood balance in the Nordic countries changes by roughly 120 million m^3 in the 40% scenario. The reason for the 20 million m^3 “extra” available forest resources is the increased pulpwood price; pulpwood consumption in the pulp and paper industry decreases as district heat producers start using more harvest residues. This sums up to a net change of 20 million m^3 more than needed solely for biofuel production.

Nordic forest-based biofuel is not likely to be cost competitive with fossil fuel with the same tax regime in the near future. Policies will be needed to increase competitiveness. In paper III the main focus was on different policies that can be implemented to increase Nordic biofuel production. The policy schemes tested were feed-in premiums, increased fossil fuel tax, investment support, overall and national quota obligations, support of using harvest residues, and tax exemption for biofuels. According to the results, fully covering investment costs and offering full tax reduction are not enough to make biofuel production profitable, but it is highly dependent on the cost assumptions used in the study. The feed-in premium and fossil fuel tax increase induce biofuel production from a subsidy level of 0.61 €/L, while supporting use of harvest residues is more expensive and needs a subsidy of at least 0.86 €/L. The amount of subsidy needed to make biofuel production competitive with fossil fuel is of course dependent on the market price of fossil fuel. The fossil fuel market price tends to vary with changes in the general economy. With a high fossil fuel market price, the need for subsidies will decrease. Instead of policies that promote and increase the profitability of biofuel production, a possibility be that the cost of using fossil fuel increase above the production costs of biofuel. The break-even price for biofuel is estimated to be around 1.3 €/L; this is about three times the reference fossil fuel price used in paper III. A drawback of this study is that the model does not cover the fuel market.

Both papers II and III show that sawnwood producers are almost unaffected by biofuel production. The main reason for this is that an increase in biofuel production increases the market prices for all roundwood categories, both for raw materials (sawlogs) and by-products (dust, chips, bark, and shavings). The market prices increase more for by-products than for sawlogs, but not enough to cover new investment. In total, sawnwood production increases by around 3% with 40% biofuel production. Meanwhile, pulp and paper production decreases by as much as 32% with the same biofuel production, mainly because of increased pulpwood prices.

Harvest level and roundwood price increase steadily as biofuel production increases. Pulpwood is the most likely raw material for biofuel production in papers II and III and hence prices and harvest increase more for pulpwood than for sawlogs. As shown in paper III, the choice of subsidy scheme will not affect the harvest, except for raw material support of harvest residues. For harvest residues support, it should be noted that at a higher level of support, the value of harvest residues may be so high that the support will drive more harvest in order to sell more harvest residues. This will create a large disturbance to the roundwood market and will be a very unintended effect.

NFSM finds the most cost competitive locations for biofuel production, meaning the location where the biofuel production target is fulfilled with the lowest costs. As shown in papers II, III, and V, Sweden is the country that is likely to have the highest biofuel production in all scenarios, followed by Finland. There are many reasons for this, but the most important one is that Sweden and Finland have the largest forest sectors. In the more advanced model in paper V, more of the biofuel production is allocated to Norway and Denmark because these countries use less forest resources for district heat production than Sweden and Finland. This results in less competition between biofuel and bioheat production, which in turn results in higher biofuel production in Norway and Denmark.

4.2 Energy system effects of biofuel and bioenergy

Europe has started to decarbonise its power and heating systems; this will leave biomass as one of the few raw materials for energy production that can be stored at low cost. In the Nordic countries, low grade forest products are the main source of biomass within the energy sector. Balancing demand and production may be more difficult in the future than it is today, implying that forest biomass may become more important for energy production. Paper IV was designed to quantify effects in the energy production sector. The role of biomass in the energy system was studied with a detailed analysis of the GHG impacts of using forest biomass for heat and power production compared to biofuel production under different carbon price scenarios. Nine different carbon price scenarios were evaluated: all had a carbon price of 23 €/tonne CO_2 in 2020, 5–103 €/tonne CO_2 in 2030 and 15–127 €/tonne CO_2 in 2040. The geographical focus in paper IV is Northern Europe (Norway, Sweden, Finland, Denmark, the Baltic countries, Poland, and Germany).

The results from paper IV show that increased carbon prices increase the use of wood chips for heat and power generation from 66 TWh to 216 TWh. Wood chips mainly replace natural gas, wind, and electrical heating, and to some extent coal power. When wood chips are an option, it reduces the need for natural gas by 25–82 TWh (15–60%) in 2030 compared to a scenario without wood chips, highest for high carbon prices, and 45–80 TWh (16–48%) in 2040, wind power up to 63 TWh (13%), and coal with maximum 32 TWh (23%), highest at medium carbon prices. Similarly, wood chips reduce the need for heat storage while slightly increasing the need for electrical storage. Consequently, the use of wood chips reduces the emissions from heat and power generation by 7–19 million tonnes of CO_2. If the same amounts of wood chips were instead used for biofuel production, it would yield approximately 3.8–13 billion litres of biofuel. These amounts are equal to 3.4–11% biofuel blended in the 2016 fuel consumption in the Northern European countries and could reduce the total emissions from road traffic by 11–35 million tonnes of CO_2. For all carbon prices, forest biomass will reduce the fossil carbon emissions the most if used for biofuel production instead of heat and power production, but the cost of reducing carbon emissions through biofuel production is estimated at 389–400 €/tonne CO_2, which is higher than the marginal cost of reducing carbon emissions in other sectors.

4.3 Model integration

Linear partial equilibrium models have the advantage of finding optimal solutions with relatively low computational costs, but since they are partial, they do not cover a larger part the economy. Paper V is meant to cover some of the gaps in Balmorel and NFSM. The goal in paper V was to develop a model that could find the optimal solution for both models at once and to describe the strengths and weaknesses of the model integration. The effects of the integration are described using a scenario with a carbon reduction of up to 73% in 2050 compared to 2017. The results in paper V show that an integrated model estimates electricity prices that are slightly higher than in Balmorel and considerably higher than the 2018 electricity prices used in NFSM. The model estimates higher consumption of forest raw materials used for heat and power production compared to the constant 2018 levels. Since the use of forest resources in heat production also increases the harvests by up to 7% when the models are integrated. As in paper II and III, in paper V we also find increasing raw material prices with increasing biofuel production, but the industrial production is less affected than in papers II and III. A reason for this is that in paper V the optimisation horizon is multiple years (2018–2050), which allows for forest growth, and biofuel investment is made over a 19-year period, which allows the forest industries to slowly adapt to the increasing biofuel production.

The integration procedure shown in paper V increases the complexity of both NFSM and Balmorel, taking both models a step further towards more realistic prediction. The integrated model gives a more realistic picture of the electricity prices the forest sector is facing because it has electricity prices changing with time according to assumptions regarding the transition to a low carbon electricity supply. But how much the variation in electricity price actually impacts the forest sector is uncertain since part of the forest sector is power-intensive industries. We know that the forest sector consumes a lot of electricity, but the exact amount of power consumption at the mill level is uncertain, as is how sensitive the production is to changing power prices.

According to paper IV there is more use of forest biomass for heat production in scenarios with little fossil fuel, and to account for this it is beneficial to have reasonable biomass prices within the energy sector since biomass is far from homogenous and is related to significant transportation costs. This conclusion is heavily strengthened in paper V, and it works both ways since the forest sector will also face increasing demand for raw materials for heat production. If the level of subsidies needed in paper III was estimated using the model in paper V, it would likely increase because biofuel and district heat production will to some extent compete for the same biomass.

4.4 Model uncertainty

The future development of the forest and energy sectors is uncertain. To reduce the uncertainty, models are used to test several obvious and non-obvious assumptions about the future. All studies done in this thesis can be boiled down to a huge amount of assumptions in combination with economic theory. For instance, product price and consumption are related through price elasticity based on economic theory, while we assume that the level of price elasticity used is valid not only for the past but also for the future. In order to quantify some of the uncertainty in the results, two different approaches were used: 1) Monte Carlo simulations (paper I) and 2) sensitivity analysis (papers II–IV).

The main topic of paper I is price uncertainty in global forest products markets and how this uncertainty effects the Norwegian forest sector. Paper I explore historical variation in market prices for the main products in the Norwegian forest sector and analyses them using NTM. The results show that fibreboard historically has had the highest price variation. A shortcoming of the analysis is that the study does not correct for change in product quality. It does, however, account for the change in long-term trends in world market prices, which, for some products, is significant. Even though fibreboard has the highest observed price variation, the study finds that its domestic price variation is lower than that of sawnwood, for instance, but the production level varies most for fibreboard. Sawnwood is found to be most variable when it comes to domestic prices, and not that variable for production levels; the reason for this is the price elasticities used.

In paper II the sensitivity of the main results was tested using nine scenarios: high and low roundwood supply price elasticity; zero and double the amount of biomass usage in district heating; reduced and increased demand for pulp and paper and sawnwood; and, finally, national quota obligations. The results show mainly expected changes. Lower roundwood supply price elasticity caused higher pulpwood prices, while higher roundwood supply price elasticity caused lower pulpwood prices; this had a direct effect on the use of pulpwood in the pulp and paper industry and on the pulpwood harvest. The effects of no bioheat production were less collection of harvest residues and increased imports, while doubling the amount of biomass used in district heating had the opposite effect. Reduced demand for pulp and paper reduced pulpwood prices and the use of harvest residues, while increased demand had the opposite effect. A reduction in the demand for sawnwood resulted in more imports of pulpwood and more consumption in other industries, while an increase reduced pulpwood prices due to more by-products being available.

The robustness of the main conclusion in paper III was evaluated using sensitivity analysis for five sensitivity parameters. The sensitivities tested were conversion efficiency, capital cost, harvest restriction, pulp and paper production, roundwood logging costs, and transportation costs. The production volume for quota obligation was unaffected by the sensitivities, while the production costs were found to be sensitive to conversion efficiency and investment costs. Biofuel producers are less affected by changes in raw material costs than the rest of the forest sector; this means that when biofuel producers get sufficient subsidies and take an investment decision, they have to produce at constant capacity whenever the raw material prices increase or decrease. Overall, conversion efficiency and investment cost are the most sensitive parameters for biofuel production; they are also the most uncertain parameters in all papers. Hence the results from papers II, III, and V should be interpreted in light of the chosen technology and the effects of using the raw material input may be the most important factor to consider, not the amount of biofuel produced.

In paper IV the sensitivity of the main conclusion was tested with a scenario that has endogenous investment in transmission lines. The results show that endogenous transmission line investment increases the use of wood chips by up to 13% compared with known investments and simultaneously increases wind power investments by 22%. The use of wood chips reduces carbon emissions by up to 17 million tonnes of CO_2 (32%) with endogenous transmission line investment; correspondingly, the emissions were reduced by up to 19 million tonnes of CO_2 (28%) with exogenous transmission line investment. This shows that with optimal transmission line investment, more wood chips are used, which results in larger fossil carbon savings.

4.5 Discussion

Even though the results from the different papers explicitly mention biofuel, the implications for the forest sector are the same if we instead look at biochemicals, not restricted to only biofuel. The only assumption we need to the transition from biofuel to the more general biochemical is that the input of the raw materials must be the same. In the studies that only cover the forest sector, we can go even further and say that the effects may also be valid for bioenergy in general. The rationale behind this increased scope is that the consumer market is not modelled explicitly for biochemicals, bioenergy, or biofuel and changing the production between them may change the value of the end-product but not how much the inputs is used. The only exception to this statement is in paper III where we find the endogenous production of biofuel.

As shown in the various papers, it is likely that the traditional forest sector will lose market share and profitability compared to the rest of the world with huge production of Nordic forest-based biofuel. This result omits some other effects that may be valid. For instance, the studies do not take forest-based biofuel production outside the Nordic countries into account, nor do they account for biofuel production as a side stream in existing pulp production. Both factors may change the profitability of biofuel production. Producing biofuel as a side stream may increase the competitiveness of the entire pulp plant, but it is unlikely that production of more than 10 billion m^3/year is possible solely from by-products. Co-production of pulp and biofuel may be realistic, however, especially for new pulp mills. Biofuel production outside the Nordic countries may influence the competition between the Nordic countries and the rest of the world (ROW), since biofuel production in ROW may increase roundwood prices as well as increasing the learning effects that may be in favour for the Nordic biofuel producers as well. It is unlikely that huge amounts of forest-based biofuel will be produced in ROW in the near future as there are many other raw materials on the global market that can be used for biofuel production. However, technology learning between different lignocellulosic raw materials may happen.

None of the studies in this thesis includes sustainability criteria in the forestry sector (except one sensitivity parameter in paper III). Sustainability in the forest sector is a topic that may be more important in the future as the role of the forest carbon sink becomes more important. This may, increasing the price of sustainably harvested roundwood. But only in the most extreme scenarios in papers II and III does the estimated harvest level increase above the FRL levels (163 million m^3/year). This shows that the harvest levels projected in these studies are within the best estimate of sustainable harvest levels, but it is not given that the FRL level would be the best harvest level if reducing the carbon concentration in the atmosphere in the long run is the main goal.

None of the studies conducted in this thesis quantifies the climate impact of using forest resources for biofuel or bioenergy purposes, but in papers IV and V we discuss the reduction in fossil fuel emissions when replacing fossil fuel with forest biomass in heat and power production, and in papers II, III, and V we quantify the effects in the forest sector of the production of a huge amount of forest based biofuel, which will decrease the fossil emissions from road transportation. A transition from documenting fossil carbon reduction to climate impact is not directly possible since other aspects need to be discussed, for instance, time frame, substitutional effects for third party goods, and forestry effects. Forestry effects in particular are important to look at since forests have the ability to take up and store carbon for a long time, although they will at some point die and release the carbon. For this reason, it is the net effect that is interesting when discussing the climate impact of forestry. In most of the scenarios in papers II, III, and V, the growing stock in the Nordic countries increases and the harvest is under the FRL levels. For this reason, it is tempting to conclude that the climate impact of using forest biomass for bioenergy and biofuel is positive in the long run, but the method used and the results do not directly allow us to make such a conclusion. We can only conclude that there are indications of a positive climate impact in the long run.

It is not straightforward to determine which types of policies will be most suitable to promote fossil-fuel-free transportation: some policies seek to increase forest-based biofuel, agriculture-based biofuel, or electric vehicle use, while others make it easier to directly target forest-based biofuel such as quota obligation or feed-in premium; still others may effect both biofuel and electrical vehicles, such as increasing fossil fuel taxes. As shown in papers IV and V, an increase in the use of electric vehicles and bioenergy may have an effect on the energy market, as well as on the forest sector.

In the short run (until 2030 or 2040), it may be important to increase the amount of forest resources to reduce fossil fuel emissions as quickly as possible in multiple sectors. Results in papers II–V show that significant amount of biomass may be available for energy production without huge negative impacts on the forest sectors and forestry. Directing more biomass towards energy production will of course have some distributional effects, for example some pulp and paper producers may struggle to be profitable, but this only follows a long-term trend with declining profits for newsprint, printing, and writing paper. On the other hand, forest owners will profit from increased energy production since they will get paid more for their roundwood and they may sell more harvest residues. But in the longer run (2040 and after) it is more difficult to find positive economic and carbon effects of massive expansion of bioenergy and biofuel since it is likely that zero emissions technologies will become more economically mature, and electrification is taking most of the market share in transportation as well in heat production. Considering this, it is less certain what the best use of forest resources will be. A competition between electricity and biofuel or bioheat may not be the most climate-friendly solution. In the longer run, it may be most climate-friendly and economical to use forest resources to substitute for products that do not have any other renewable options, such as construction elements, chemicals, fuel for long distance aviation and marine transportation, reduction agents, or other products with industrial applications.

4.6 Methodological strength and weakness

As Rørstad et al. (2019) have shown, it is hard to foresee sudden events within the forest sector because the forest sector is heavily impacted by the general economy. This makes it difficult to make projections into the future using forest sector models, since the models assume steady state conditions in rest of the economy. As shown in paper I, projected future forest product prices are highly dependent on the starting values, since the historical prices have varied significantly between years. This creates uncertainty around the reference data on which all other simulated years are based. It is not easy to correct for such uncertainties since it is hard to know if the price variation is a random variation or is part of a long-term trend or trend shift. Furthermore, the models are not suited to endogenously find trend shifts since they are mainly capable of following the existing well-known trends.

A drawback with (almost) all forest sector models is that they tend to overemphasise historical trends when projecting the future; a reason for this is that they tend to extrapolate the historical trends. Since most of the economy tends to increase, it is easy to assume that the consumption of forest products also will increase. Newsprint is an example of this. Newsprint consumption is normally estimated with a positive GDP elasticity, meaning that the consumption of newsprint increases when the economy increases. On the one hand, Buongiorno (2015) estimates the GDP elasticity of newsprint in high-income countries to be 0.39±0.17; when looking at the production, it is hard to visually confirm a positive GDP elasticity. On the other hand, Hurmekoski and Hetemäki (2013) estimate the GDP elasticity to be 0.42 for the period 1980–1999 and -0.24 for 2000–2012. At the same time that the extrapolation of historical trends overestimates some consumption, it may also affect results the other way, with IEA's underestimation of solar power investment (Enkhardt & Beetz, 2018) being a well-known example. This can obviously happen for forest products as well. Underestimation may be most likely for new products that increase almost exponentially: CLT, for instance, is forest product that may be at risk of being underestimated in the forest sector. Overestimation is most likely happen with old products that are being ousted by new innovative products. Hetemäki and Hurmekoski (2016) point out that most partial equilibrium forest sector models do not capture structural changes; this observation is also relevant to the model used in this thesis.

All papers in this thesis optimise the system over a single year with perfect foresight within that year. This approach yields some unlikely effects. For investment, this myopic approach might be unrealistic because in real life, an investor will maximise the lifetime profit of the investment rather than maximizing profit in a single year. For instance, single year optimisation may underestimate the investment of a new pulp mill that produces pulp used in a product that has only a marginal market share today; however because demand for pulp will increase in the future it is smart to invest in the pulp mill today to maximise lifetime profits. The single year optimisation horizon may also overestimate the investment since a biofuel plant will experience a higher demand for liquid fuel today than the last year it will produce biofuel. For other investments, a single year optimizing might be too long of a horizon. This is especially relevant for the energy sector, where real-life production depends to some extent on weather conditions, which are uncertain. This is a particularly important topic when introducing storage, whether it be hydro storage, batteries, or heat storage, or it may underestimate the investment since the models do not need reserves in order to fulfil the demand if there is a sudden drop in wind power production.

4.7 Future research

In the studies, we did not analyse the effects of carbon capture and storage (CCS) or more precisely bioenergy CCS (BECCS). This is an interesting topic that was not a focus of this thesis, but as de Coninck et al. (2018) point out, BECCS may be important in the future, not only because BECCS reduces emissions but also because it offers a promising path to both producing energy and achieving negative emissions. It is likely that BECCS will be taken into consideration when it comes to decarbonizing the energy sector and reducing emissions within the forest industry. BECCS is not suitable for consumption of biofuel but in production may BECCS be possible.

Another topic not addressed in this thesis is the market for transportation fuel. We only modelled biofuel production and assumed that biofuel is chosen if biofuel production is cheaper than the global market price of gasoline and diesel. It would be interesting to investigate the effects of including the fuel market in the model both to better represent the actual willingness to pay for biofuel and to better cover the competition between electricity and liquid fuel.

More effort can be made to describe the underlying variability in the forest sector and to quantify the uncertainty. This may increase our understanding of the main parameters within the forest sector. Additionally, more can be done to fully incorporate all couplings between the forest sector, the energy sector, and the transportation sector. In the future, we might consider including locally produced heat, industrial heat, and fossil fuel production from crude oil to final consumption, as well as increasing the time resolution in NFSM to something closer to the time resolution used in Balmorel.

Finally, more research is needed to determine the optimal use of forest resources. What will reduce the carbon emissions the most: carbon storage in forests or in products? Iordan et al. (2018) have addressed this question using historical data, but it will be interesting to look at effects on the future forest sector in a renewable energy scenario.

5 Conclusion

The goal of this thesis was to analyse the effects of Nordic forest-based biofuel production on the existing forest and energy sectors. Different models were used, both alone and together. The forest sector model NFSM yielded important results, namely showing how the existing forest industry and forestry will adapt to changing economic conditions due to biofuel investment. In the same way, the energy sector model Balmorel provided insight into how the energy sector is dependent on low grade forest biomass in order to produce energy at a low cost and with low fossil emissions.

The results show that forest biomass and the forest sector could contribute significantly to lowering total fossil carbon emissions. Moreover, the forest sector is able to adapt to increasing demand for low quality raw materials for different kinds of energy production, although some parts of the forest sector will struggle with higher pulpwood prices, and consequently reduced production of pulp and paper has to be expected. However, forest owners can expect increased roundwood prices and more easy trading of tops and branches, which will allow them to profit from biofuel production. Biofuel production would increase the price and demand for low quality biomass; sawnwood producers will benefit from this because they increasingly get paid for their by-products while bioheat producers, the traditional consignees for harvest residues and by-products from sawmills, will face competition from biofuel production. Simultaneously, the industrial sector is under pressure to become carbon neutral and higher carbon prices will increase the demand for forest biomass.

Using forest biomass to produce biofuel is expensive compared to using fossil fuel. Therefore, different policies are needed to achieve significant Nordic biofuel production. These policies can either target forest-based biofuel directly or a fossil fuel price increase. None of the scenarios in this thesis found strong enough spin over effects to the forest sector for biofuel production to be profitable without any new policies, and it is unlikely that the increased revenue for forest owners will be higher than the reduced losses for the traditional forest industries.

5 Conclusion

The final paper shows that there may be enough low-price low-quality biomass available in the Nordic countries to produce biofuel, heat, and electricity, but until 2030 this would increase fossil fuel emissions from heat and electricity generation in the Nordic countries. In the energy sector, the use of biomass will substitute natural gas for lower carbon prices, while for higher carbon prices it is more likely that biomass will substitute for heat pumps, electrical boilers, and wind power. This shows that the optimal use of forest biomass may vary along with the total emissions levels in the economy. For low carbon price and short time frame biomass will contribute equally to fossil carbon emissions when used for heat and electricity as well as to produce biofuel. In this case, heat and electricity may be the low-cost solution. For higher carbon prices and a longer time frame biomass will contribute more to reducing fossil carbon emissions when used for biofuel production than for heat and electricity production since the heat and power sector will have low emissions anyway.

The main conclusion in this thesis is that there are enough raw materials of suitable quality for Nordic forest-based biofuel production. However, it is not economically profitable to reach the full production potential without huge subsidies, since most of the traditional actors will face an increase in competition and prices.

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Modelling of uncertainty in the economic development of the Norwegian forest sector

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ABSTRACT

Quantitative forest sector modelling includes many model parameters that are treated as being deterministic in the modelling framework, but are in reality often highly uncertain. Few studies have addressed the impacts of this uncertainty and the main objectives of this article are to quantify major market uncertainties in the Norwegian forest sector and analyse their impacts on the results of a forest sector model study for Norway. The uncertainties are derived from historical time series of the prices and exchange rates for international forest products, and their possible impacts are addressed by applying a Monte Carlo approach. A probabilistic approach in modelling is found to have significant impacts on harvest and forest industry production levels. When uncertainty is included, the relative standard deviation for modelled harvest levels varies from 15% to 45%, while for forest products the standard deviations vary from 30% to 80%. We conclude that the most important uncertainty factor for the Norwegian forest sector is the development of international forest product markets, and improved data on demand should be given high priority in future forest sector modelling development.

Introduction

The forest sector, i.e. forestry and forest industries together, is undergoing a major transition. One of the most prominent changes is the reduced demand for printing paper in industrialized countries as a result of competition with digital media (Bolkesjø et al., 2003; Hetemäki and Hurmekoski, 2016; Latta et al., 2016). In addition, relocation of forest industries to low-cost countries is heavily influencing the economics of the forest sector. Price impacts of these changes are shown in Fig. 1, which also illustrates that the economic development of the forest sector is generally highly uncertain. However, most quantitative forest sector analyses and outlook studies based on forest sector modelling largely ignore this uncertainty by using deterministic approaches (Buongiorno, 1996; Latta et al., 2013; Toppinen and Kuuluvainen, 2010).

Forest sector models used to analyse the economic development of forest products' value chains rely on a large set of model parameters that are either relatively well known or based on expert judgements or statistical estimations with varying precision. Sensitivity analysis is the common approach to explore the importance of uncertainty, and is used in several forest sector studies to explore impacts of risks; for example in analysing impacts of changes in tax levels (Buongiorno et al., 2012), demand profiles for forest products (Moiseyev et al., 2014), or introducing new products such as biofuels (Kallio et al., 2018; Mustapha et al., 2017a; Mustapha et al., 2017b; Sjølie et al., 2015; Trømborg et al., 2013). However, sensitivity studies exploring the impacts of just one or a few parameter values normally exclude synergy effects between different parameters, which may lead to over- or under-estimation of the impacts on the system.

Kallio (2010) is the first study to introduce uncertainty parameters in forest sector modelling and addresses the underlying uncertainty related to the growth rate of the standing timber stock, the stock and price elasticities of wood supply, the world market prices, and transportation costs, using Monte Carlo simulations. She also analysed how different scenarios for energy prices and stochastic price developments for forest products, as well as change in forest conservation policy, affected the model outcome, and concluded that uncertainty in the basic parameters was of less importance than scenario uncertainties.

As described by Chudy et al. (2016), the procedure for investigating uncertainties in the forest sector modelling should preferably involve the following steps: First, determine which parameters are most important to include and make simplifications necessary for their

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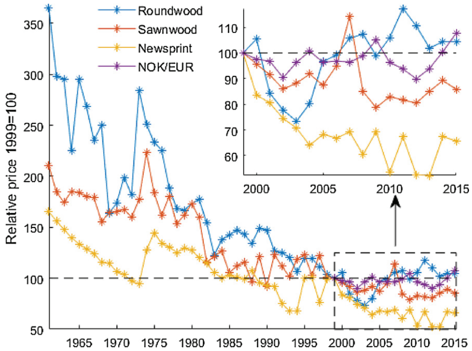

Fig. 1. Historical price development for roundwood, sawnwood and newsprint for the period 1961–2015 and the NOK/EUR exchange rate for the period 1999–2015 (in 2013 prices, adjusted for inflation according to the Norwegian consumer price index).

inclusion in a deterministic model; second, perform sensitivity analyses to identify those parameters which are most important; third, provide probability distributions for these most important parameters based on historical variation; next, apply the probability distributions in Monte Carlo simulations until convergence; and finally, analyse the model results.

A major share of the production in the Norwegian forest industries is exported. A large fraction of the wood consumption in the Norwegian pulp and paper industries has traditionally been imported, whereas Norway now has a significant net export of pulpwood and wood chips. The Norwegian forest sector is thus vulnerable to market developments such as changes in exchange rates and export prices, and consequently, the main objective of this study is to quantify how uncertainties in these parameters might affect the developments in the Norwegian forest sector.

Based on historical data, we quantify the annual fluctuations in the foreign exchange rates (NOK/EUR) and export prices for sawlogs (pine and spruce), pulpwood (pine and spruce), fibreboard, particleboard, sawnwood (pine and spruce), and newsprint. We then apply the forest sector model NTMIII calibrated for Norway (Trømborg and Sjølie, 2011) to quantify how these uncertainties affect the equilibrium prices and quantities of the Norwegian forest sector, and the underlying uncertainties. NTM III is a multi-periodic, spatial, partial equilibrium model. The theoretical basis for the model is that of spatial equilibrium in competitive markets as first solved by Samuelson (1952) for several commodities. NTMIII is based on the principles of the Global Trade Model (GTM) (Kallio et al., 1987), which is the basis for several national models with regional disaggregation, such as the Finnish Forest Sector Model (Ronnila, 1995) and previous versions of the Norwegian Trade Model.

Through Monte Carlo simulations, the impacts of the fluctuations on consumption, production, harvest and prices in Norway were analysed. Similar to Kallio (2010), we include analysis of the time-dependent impacts of the uncertain factors, with the main focus on initial impacts as well as impacts 8 years into the future, which corresponds to the years 2017–2025.

Method

Forest sector model specifications

NTM has been developed in two previous stages by Trømborg and Solberg (1995) and Bolkesjø et al. (2005), before the current and third version named NTMIII (Trømborg and Sjølie, 2011). NTMIII includes a more detailed representation of harvesting residues as well as the bioenergy market compared to previous versions of the model. In this study, the reference year is updated using data described in Mustapha (2016), and Trømborg and Sjølie (2011). The NTM model has previously been used to analyse impacts of forest conservation (Bolkesjø et al., 2005), increased use of bioenergy (Trømborg et al., 2007; Trømborg and Solberg, 2010), transport cost changes (Trømborg et al., 2009), and establishment of wood-based biofuel plants (Trømborg et al., 2013).

The NTMIII is recursive dynamic and largely based on the principles of the Global Trade Model (GTM) (Kallio et al., 1987), with harvest, production, consumption, maintenance, transport and prices solved simultaneously for each period by maximizing, for each period, the sum of consumer and producer surpluses. As shown by Samuelson (1952), this maximizes the economic utility and simulates the economic development of the sector assuming perfect competition. Latta et al. (2013) gives a review of historic developments in forest sector models.

The model consists of four components: (1) consumer demand, (2) timber supply, (3) industrial production, and (4) trade. Timber supply is determined by supply elasticities, changes in growing stock, and price of timber in the industry. The amount of final product produced in the factories is modelled by input-output coefficients of timber and intermediate industrial products, and exogenous input prices like the costs of labour and energy. The production costs and product prices determine the volume of production. The demand for final products is determined by regional consumer demand profiles, demand elasticities, and product prices. Finally, trade between regions for raw materials, intermediate products and final products occurs until the price difference between regions equals the transport cost.

The model is multi-periodic, but the model optimization is static as it gives an equilibrium solution for each future period modelled. The model solution for a particular period is used to update the model input for the subsequent period for the data on market demand, timber supply, prices, and changes in production costs and available technologies. Thereafter, a new equilibrium is computed subject to the new demand and supply conditions, new technologies, and new capacities. As such, the dynamic changes from year to year are modelled using a forward recursive programming approach, meaning that the long-run spatial market equilibrium problem is broken up into a sequence of short-run problems, one for each year. Hence, the modelling is based on the assumption that the decision makers in the economy have imperfect foresight.

In total, the model consists of 21 regions, of which 19 are in Norway, one region covering Sweden and one region representing the rest of the world. The model contains six wood categories (pine, spruce and non-coniferous for both sawlogs and pulpwood), nine intermediate products for use in industry and 12 final products for end consumption. A full description of the data and model will occupy too much space here, but the main principles are given below. The object function is:

$$Max_{q_f^i,h_w^i,y_l^i,e_k^{ij}}\left\{\sum_{if}\varepsilon^i\rho_f q_f^i\left[\left(1-\frac{1}{\tau_f}\right)(1-N_f^i(0,\vartheta_f))+\frac{1}{2q_{f0}^i\tau_f}q_f^i\right]\right.$$
$$\left.-\sum_{iw}\varepsilon^i\int_0^{h_w^i}(\alpha_w^i h_w^{i\beta_w^i})dh_w^i-\sum_{il}\varepsilon^i c_l^i y_l^i-\sum_{il}\varepsilon^i\varphi_l^i y_l^i-\sum_{ijk}\varepsilon^i D_k^{ij}e_k^{ij}\right\} \tag{1}$$

where the indexes i and j refer to regions, k to products (final products, intermediate products and roundwood categories), f to final products, w to roundwood categories, and l to production activities. ε^i represents the currency exchange factor for region i. Term 1 is the inverse demand function. ρ_f is the base price, τ_f is the price elasticity, $N_f^i(0,\vartheta_f)$ is the probability distribution with mean of zero and a relative uncertainty ϑ_f, q_f^i is the new consumption, and q_{f0}^i is the reference consumption of product f in region i. $\alpha_w^i h_w^{i\beta_w^i}$ (term 2) represents the timber supply, with h_w^i as harvest level of roundwood w in region i. β_w^i is the econometrically estimated roundwood supply elasticity and α_w^i is calculated with use of β_w^i and base-year harvest; a further description of α and β is shown in Bolkesjø et al. (2005). $c_l^i y_l^i$ (term 3) and $\varphi_l^i y_l^i$ (term 4) represent the exogenous part of the marginal industrial production costs, with c_l^i as an input cost, φ_l^i as maintenance cost, and y_l^i as the produced quantity of production activity l in region i. $D_k^{ij} e_k^{ij}$ (term 5) represents trade of product k between regions i and j, with D_k^{ij} as the unit transportation cost and e_k^{ij} as the quantity that is exported from region i to region j.

The objective function solution is found subject to the following constraints:

$$q_f^i - \sum_l a_{fl} y_l^i + \sum_j (e_f^{ij} - e_f^{ji}) = 0 \ \forall \ f, i \tag{2}$$

$$-\sum_l a_{wl} y_l^i - h_w^i + \sum_j (e_w^{ij} - e_w^{ji}) = 0 \ \forall \ w, i \tag{3}$$

$$y_z^i \leq K_z^i \ \forall \ i, z \tag{4}$$

$$\sum_{ilr} a_{rl} y_l^i \leq \sum_{if} \left(\phi_f^i q_f^i \right) \tag{5}$$

$$e_k^{ij}, q_f^i, y_l^i, h_w^i \geq 0 \ \forall \ i, j, k, f, l, w \tag{6}$$

where index z represents all production activities related to pulp and paper and r represents recycled paper. a_{fl} and a_{wl} are final product and roundwood inputs, respectively, for production activity l. K_z^i is the capacity for production activity z in region i, and, finally, ϕ_f^i is the predetermined recycling rate for final products f in region i.

Eq. (2) ensures that consumption of final products is equal to the difference between production and trade in each region. Eq. (3) ensures that roundwood harvest is equal to the difference between the use of roundwood in the production and trade for each region. Eq. (4) ensures that the production of pulp and paper does not exceed production capacity, and Eq. (5) ensures that the total use of recycled paper does not exceed a predetermined recycling rate share of the total paper consumption. Finally, export, consumption, production and harvest are non-negative endogenous variables for every product in every region (Eq. (6)). To find the optimal solutions for the object function (1) under constraints (2)–(6), we used the General Algebraic Modelling System (GAMS) (GAMS Development Corporation, 2017), with CONOPT (CONOPT, 2017) as the nonlinear solver.

Estimating uncertainty

The observed historical values and quantities of forest products in the FAOSTAT database (FAOSTAT, 2017) were used for quantification of parameter uncertainties. First, the price time series were adjusted for inflation by using the consumer price index of Norway. Then ordinary least squares regression was applied to identify trends, and the annual differences between the estimated least square trend line and the historical deflated prices were calculated. The standard deviations of these differences were defined as the short-term variations.

Uncertainty regarding foreign exchange rates was calculated in the same way using the exchange rate data from Norges Bank (2017).

Monte Carlo simulations

Monte Carlo simulation is a simple method for addressing uncertainty in large models with many parameters (Metropolis and Ulam, 1949) which is rarely used in forest sector models (Kallio, 2010). The algorithm starts by drawing a random value for every uncertain parameter and running a simulation. Then the process repeats until the result satisfies a predefined convergence criterion. In this study, Monte Carlo simulations are performed by drawing random samples from the assumed probability distribution (Table 1) of world market prices for spruce and pine sawnwood, newsprint, fibreboard, and particleboard, and exchange rate. The heuristic rule used to decide satisfactory convergence was that the mean of variable in question did not change more than 0.1% after 1000 new repetitions were included in the dataset. For each simulation, a sample from the assumed normal distribution was randomly chosen.

Data

The data used in the analysis of historical variations (section 3.1) was collected from the FAOSTAT database (FAOSTAT, 2017) and Norges Bank (2017). The prices for sawnwood, particleboard, fibreboard and newsprint from the FAOSTAT database (FAOSTAT, 2017) were used to calculate the Norwegian product prices for the period 1961–2015, assuming that the Norwegian export values per unit (export values divided by export quantities) reflect the real Norwegian product prices. Data for the exchange rate were obtained from Norges Bank (2017) for the period 1999–2015.

A vital assumption made here is that historical prices of forest products in Norway are representative for the uncertainty in the model. The historical prices were adjusted for variations caused by inflation and linear trends before the uncertainty calculation. Fitting the observed historical annual prices by applying least squares analysis, the linear trends were obtained. When subtracting the linear trend from the historical prices we found the basis for the uncertainty analysis, where the uncertainty is calculated as the year-to-year variation. Uncertainty in exchange rate was similarly calculated from the year-to-year variations, but no trends were identified.

Scenarios

The model analyses quantify the impacts of uncertainty in three scenarios: (i) international forest products prices, (ii) exchange rates for the Norwegian currency (NOK) and (iii) uncertainty related to (i) and (ii) combined. The modelled period is 2017–2025 and like (Kallio, 2010) we consider the accumulation of uncertainty over the modelled period. NTM is executed in deterministic modus for the first five-year period (2013–2016), and then the uncertainties are added in the next nine simulated years (2017–2018). The reason for doing this was to enable the investigation of both uncertainties in parameters that are normally considered given, and the short-run implication of those parameters.

When analysing uncertainty in international forest products prices, we assume that Norwegian forest industries are price takers in the international market since the Norwegian consumption and production of final forest products are very small compared to the total world production (FAOSTAT, 2017). Uncertainty in the world market prices is implemented in our study as a vertical shift in the inverse demand function (term 1 in function (1)). ϑ_f represents the relative uncertainty of final product f. Two scenarios are analysed using this approach: first, only sawnwood world market prices are varied (SAW), followed by a variation in world market prices of fibreboard, particleboard and newsprint (PROD).

In the analysis of exchange rate uncertainties (EXC), the exchange rate is modelled as a scaling factor which scales all prices and costs in the Norwegian regions, similar to the approach used by Kallio et al. (2004). The exchange rate (parameter ε in Eq. (1)) is implemented with the number 1 for the regions outside Norway and a higher or lower number for the Norwegian regions, which represents per cent differences in the Norwegian exchange rate. This implementation ensures that a change in the exchange rate influences trade, demand and production for Norwegian producers and does not directly affect the parameters in the regions outside Norway.

In the last scenario (ALL), uncertainty is implemented for all parameters specified in Table 1. One assumption applied here is that the parameters are uncorrelated in their variation, even though they may be correlated in reality.

Table 1

The historical mean values and standard deviation used in the Monte Carlo simulations. All parameters are assumed to be normally distributed for main forest products and the exchange rate (NOK/EUR). It is assumed that the price of pine and spruce sawnwood has the same standard deviation.

Product	Mean value [NOK/unit]	Std [%]	Probability distributions	Source
Spruce sawnwood	1510	13	Normal	(FAOSTAT, 2017)
Pine sawnwood	1610	13	Normal	(FAOSTAT, 2017)
Newsprint	3250	11	Normal	(FAOSTAT, 2017)
Particleboard	2024	14	Normal	(FAOSTAT, 2017)
Fibreboard	3038	30	Normal	(FAOSTAT, 2017)
Exchange rate	7.8	5.1	Normal	(Norges Bank, 2017)

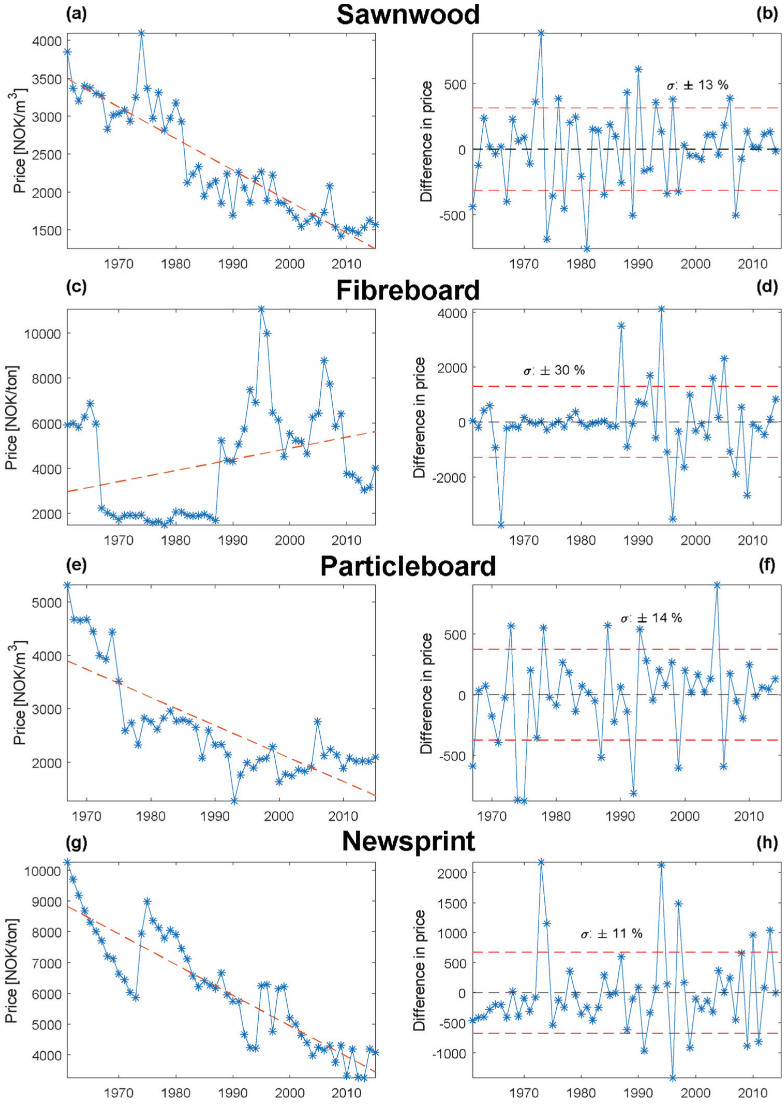

Fig. 2. Historical prices for sawnwood (a, b), fibreboard (c, d), particleboard (e, f) and newsprint (g, h) used in uncertainty analyses. Price (NOK/m^3) is adjusted for inflation to 2013 levels (a, c, e, g). The graphs (a, c, e, g) show the trend line (stippled), and the graphs (b, d, f, h) show the year-to-year difference in price, adjusted for the trend line. One standard deviation from the average year-to-year variation is shown (stippled).

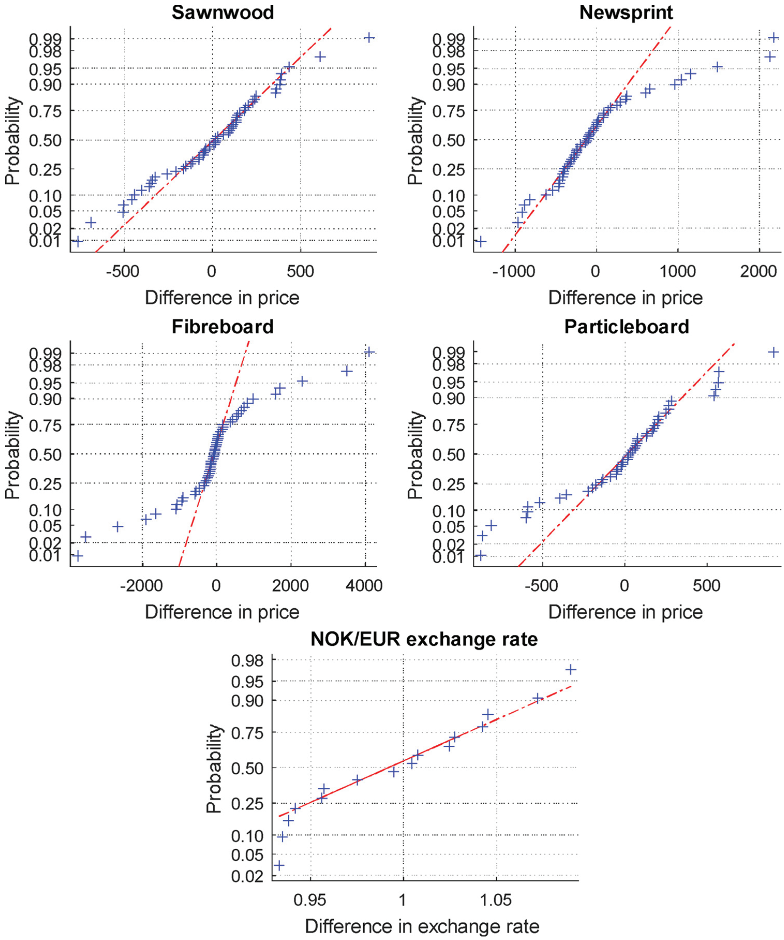

Fig. 3. Normal probability plots for the historical year-to-year variation for sawnwood, newsprint, fibreboard and particleboard price (Fig. 2) and normal probability plots for the change in the NOK/EUR exchange rate are shown. Normal distribution implies that all historical variation (crosses) should intercept the line.

Results

Historical variation and uncertainty calculations

Fig. 2(a, c, e, g) shows historical prices for sawnwood, newsprint, particleboard and fibreboard, corrected to real-term 2013 prices. The prices for sawnwood, newsprint and particleboard have declined substantially since the mid-1960s, while fibreboard prices increased slightly during the 1990s and 2000s. The price changes are either a consequence of real price change or related to changes in the quality of the average product. Fig. 2(b, d, f, h) shows the trend prices (stippled line) in order to visualize the year-to-year variations. The average historical price variation is highest for fibreboard, while sawnwood, particleboard and newsprint display similar average variation.

The assumption of normal distribution is addressed in Fig. 3 showing normal probability plots for the historical year-to-year variation of sawnwood, newsprint, fibreboard and particleboard prices, and normal probability plots for the change in the exchange rate. Variation in sawnwood prices and the exchange rate appear to follow a normal distribution, but the fibreboard and newsprint might have shorter tails. The same is true for particleboard, albeit the trend is observably weaker. Even though the year-to-year variation does not follow a perfect normal distribution, it is assumed to be normally distributed for methodological purposes in this study.

Table 1 shows the average prices in the reference year, the identified standard deviations from Fig. 2 and the exchange rate. The price of fibreboard has the highest standard deviation, whereas the standard deviation of the exchange rate is low. Price variation may be related to the change in the product quality.

Table 2 displays the correlations between the addressed parameters. High correlation in the parameter values implies that correlation needs to be accounted for in the subsequent analysis. However, the historical prices for sawnwood, particleboard, fibreboard and newsprint, and the exchange rate are mostly correlated to a low extent (< 0.50). The highest observed correlation is between newsprint and sawnwood (0.51). This may reflect a causality relationship, but also that both the price of sawnwood and newsprint are linked with the exchange rate and that bi-products from sawmilling represent a vital input into the pulp production used for newsprint production.

Table 2
Correlation matrix of the historical prices for main forest products and the exchange rate (NOK/EUR).

Product	Sawnwood	Fibreboard	Particleboard	Newsprint	Exchange rate
Sawnwood	1.0	0.49	0.15	0.51	0.32
Fibreboard		1.0	0.39	0.20	0.11
Particleboard			1.0	−0.05	0.26
Newsprint				1.0	0.40
Exchange rate					1.0

Model simulation results

Simulation results without variation in the parameters are used as a reference in order to quantify the uncertainty of model results caused by the observed historical variation in the addressed parameters. There are minor deviations between model-simulated prices and historical prices displayed in Table 1, as the 1st year simulated with uncertainties is 2017 whereas the reference model year is 2013 and the small error is related to the calibration of the model. The modelled 2017 prices are, however, within the standard deviation of the observed 2013 prices.

An outline of the total variation in 2017 (1st year) and 2025 (8th year) is shown in Fig. 4, with the mean, median as well as the 5th percentile and 95th percentile resulting from the forest sector model Monte Carlo simulations. Due to the aggregation of uncertainty from the annual sampling, the variability increases from 2017 to 2025. The highest modelled uncertainty in prices is found for sawlogs and sawnwood. According to our findings, the assumed uncertainty related to exchange rates and international forest products markets causes fairly high uncertainty in prices of sawlogs towards 2025 (5–95% interval of -/+ 60% relative to the mean price). Similar magnitudes are found for sawnwood prices, while pulp and paper prices have somewhat lower price uncertainty according to the model simulations. Production and harvest level generally show greater variation than price, presumably due to the implemented elasticities in the model. Production level variation generally exceeds the harvest level variation because of added uncertainty from different products that does not affect the harvest variation directly.

Table 3 displays the median uncertainty of the individual scenarios and shows indirectly the relative contribution of the uncertainty from the exchange rate (EXC), all product prices (PROD) and sawnwood prices (SAW) on the total uncertainty (ALL), respectively. The results show that uncertainty in the exchange rate has a relatively large impact on the modelled price and production variations. Production and sawnwood price uncertainties affect both price and production level to a considerable degree, since both the production of final products and world market sawnwood prices affect the pulpwood prices. As a result

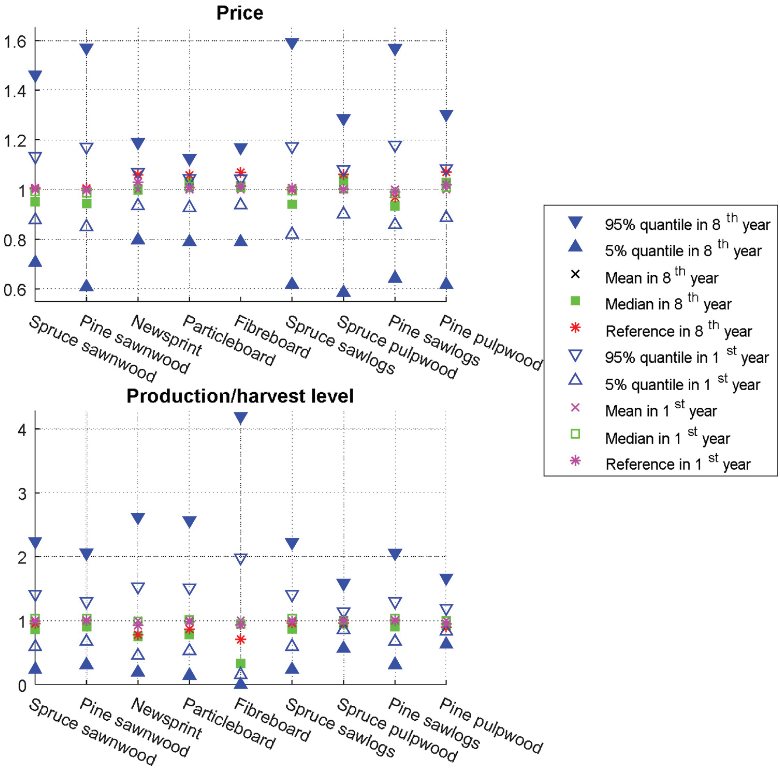

Fig. 4. Modelled mean, median, and 5% and 95% quantiles for prices and production levels for main forest products and roundwood assortments. Uncertainty in world market prices for the main forest products, and the exchange rate parameters (ALL). The y-axis is a ratio axis with the mean as the reference.

Table 3
Calculated median uncertainty for the four scenarios for price, production and harvest, for all products and roundwood, for the main forest products, and for roundwood separately. The median is calculated with use of the representative relative uncertainty for products shown in Fig. 4. (ALL – uncertainty in exchange rate and product prices, EXC – uncertainty in exchange rate, PROD – uncertainty in product prices and SAW – uncertainty in sawnwood prices).

Scenario	Final products and roundwood		Final products		Roundwood	
	Price	Production	Price	Production	Price	Harvest
1 st year with uncertainty						
ALL	6.1%	26%	4.1%	30%	7.9%	15%
EXC	3.1%	3.8%	3.1%	3.8%	3.5%	4.7%
PROD	0.5%	5.0%	0.5%	30%	2.0%	3.1%
SAW	5.5%	7.6%	0.8%	1.9%	7.5%	13%
8th year with uncertainty						
ALL	23%	64%	12%	80%	26%	45%
EXC	10%	14%	10%	10%	10%	14%
PROD	3.2%	24%	3.2%	82%	7.4%	14%
SAW	20%	15%	3.1%	6.8%	23%	33%

of being affected by more parameter uncertainties, the production level shows the highest variability. As in Fig. 4, variation increases with compounding uncertainty, being 2–4 times higher in the 8th year compared to the 1st year.

Fig. 5 displays simulated uncertainty intervals from 2017 to 2025 for the different forest products for the ALL scenario. The means approximate the deterministic model solution. As mentioned above, the variation increases annually with annual compounding of parameter uncertainty and as seen from the figure, the uncertainty intervals towards 2025 are large. It should be noted that the model is run without any option to divest in new capacity, and that closures of mills would also likely take place in the low-price scenarios.

Similar to price variation, production variation increases with compounding parameter uncertainty (Fig. 6). The median and mean production levels suggest a declining trend for Norwegian production, but the variability range shows that the future production levels are associated with great uncertainty. The production of all products ceases or is close to zero in the 5% quantiles.

Discussion

Even though the uncertainty in the underlying historical data material is easily available, only a few studies have used uncertainty simulations systematically in full-scale partial equilibrium forest sector models. This paper analyses the uncertainty and potential impact of some of the central parameters in the Norwegian forest sector. Norway has a small and open economy with an internationally oriented forest sector highly dependent on the world market. An important factor in this regard is the exchange rate, which directly influences the competitiveness of Norwegian producers. Over the last 10 years, the NOK/EUR exchange rate has varied widely (Norges Bank, 2017) (Fig. 1). Uncertainties are calculated for the exchange rate as well as for world market prices of spruce and pine sawnwood, particleboard, fibreboard and newsprint. We have analysed the impact on the products mentioned, as well as on sawlogs and pulpwood from spruce and pine, because these roundwood assortments are the most prevalent in Norway.

One of the main assumptions applied in this study is that the year-to-year price variation is normally distributed (Fig. 2). However, the real probability distribution may not be normally distributed. Fig. 3 shows that historical variation for fibreboard and newsprint may not be normally distributed. Therefore, some of the highs and lows in Fig. 2 may stem from increased or decreased shares of high or low-quality products sold in a specific year, or the fact that world market prices follow a more random distribution than assumed in this paper. Moreover, the historical prices are unit export prices, and exact quantities and prices for the products traded within Norway are not available. It is possible to test statistically which distributions explain the various uncertainties best. However, normally distributed prices are a fair simplification, which makes the Monte Carlo simulation more straightforward, although other distributions can be handled as shown in (Kallio, 2010).

We have assumed that no correlation exists between the different parameters included in the uncertainty analysis. This is a simplification, but as most of the product prices have rather low correlation (< 0.50) (Table 2), the assumption does not imply significant errors. Indirect effects may adjust some of the correlation, such as price elasticities and change in timber supply.

The mean and median for the predicted values are not always equal (Fig. 4). This implies that the probability distribution is a skewed normal distribution, which means that some result values are more likely, for example, for production of fibreboard in the uncertainties in the ALL scenario, where the median value is 0.33 of the mean value. It also appears that the deterministic reference value is higher or lower than the average values. Hence, a Monte Carlo approach is necessary to detect the most likely values under the assumed distribution of the input parameters (Table 1).

In this paper, change in world market prices is modelled as a vertical shift in the demand function, which leads to an increased or decreased demand for final products. This method for implementing the change in world market prices leads to observation of almost identical variation in the simulated consumption in product price scenario (PROD) and when both production prices and exchange rates are changed (ALL scenarios), while changes in exchange rates only (EXC) give little uncertainty in consumption. This shows that the uncertainty related to consumption, without the demand shift, is much lower than that related to price, production and harvest.

In the ALL scenario, the production and harvest levels have the highest observed uncertainty (Fig. 4) since production is more exposed to what happens abroad than to changes in domestic prices. These results are consistent with Kallio (2010) and are particularly true for the exchange rate scenario, where producers are exposed to different production costs in Norway than abroad. This trend is strongest after the first year with uncertainties and does not have the same increase rate as production uncertainties. If the prices in Norway fall due to the price elasticities, demand will rise. The total production may therefore increase because of the added Norwegian demand, and this production may come from within Norway or abroad, depending where the lowest marginal cost occurs, as long as the marginal cost does not exceed the marginal revenue.

Kallio (2010) suggests that the exchange rate may radically change the supply and demand balance across regions. This is in line with our findings, which suggest that the exchange rate is the most important uncertainty factor in the first period, as it leads to a direct change in the competitiveness between foreign and domestic producers. For the domestic forest industry, uncertainties in world market price are the most important factor (Table 3). The overall uncertainty is highest in the ALL scenario, as both product prices and the exchange rate are assumed to be uncertain.

The implications of an extreme combination of changing world market prices and exchange rate can be very dramatic (Fig. 5). The prices of sawnwood will in the most extreme scenarios either be close to zero or result in a three-fold price increase. The extreme scenarios are, however, outside of the 10th and 90th quantiles. The values between the quantiles may be plausible, since the values are less extreme than the variation observed over the last 25 years, at least for sawnwood and particleboard. The demand for newsprint has undergone a dramatic change historically with rapidly decreasing prices (Fig. 2). These changes will make it difficult to predict plausible future prices of newsprint. The predicted prices (Fig. 5) for newsprint are marginally decreasing from today's level, and a future drop in newsprint prices is

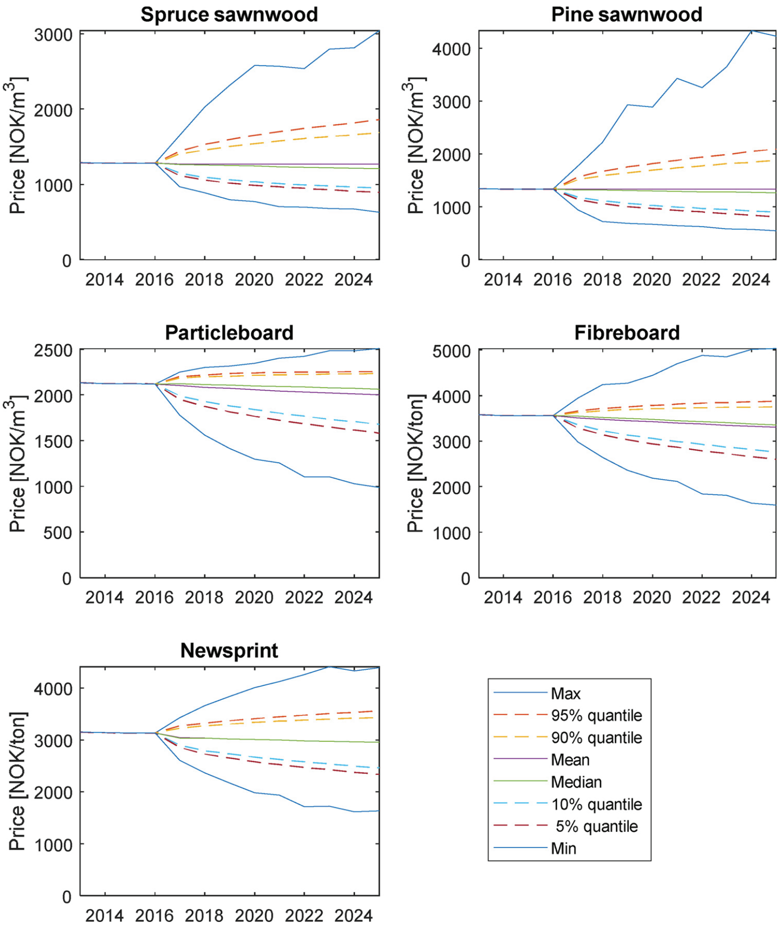

Fig. 5. Modelled mean, median, 5%, 10%, 90%, and 95% quantiles and max/min for prices of main forest products for the ALL scenario.

plausible given results in Fig. 5. However, the predominant driver for the declining newsprint production and prices in the future is the declining demand. The approach applied in this study may not portray the future demand for newsprint accurately.

It is difficult to predict future production levels with the use of NTM, since the model is extremely sensitive with regard to price parameters resulting in changes in production capacities. Maximizing producer and consumer surplus annually is an unrealistic assumption, since in practice investors tend not to be that myopic. Therefore, our projections may well exaggerate the volume of capacity investments in the timeframe applied in this study. The largest changes in prices and quantities may also not be captured since the model is partial and assumes all other prices and quantities fixed. Technological advancements, shifts in trends or, for instance, the proliferation of forest-based biofuel production, which will affect pulpwood prices (Kallio et al., 2018; Mustapha et al., 2017a), may have a significant impact on the future trajectory of the Norwegian forest industries.

This study has modelled only short-term uncertainty impacts on the initial values as well as nine years ahead, with uncertainties related to the Norwegian forest sector based on historical figures. If the model is used for long-term projections, other uncertainties should be taken into consideration, such as long-term trends in prices, the impact of climate change on growing stock, GDP growth, production technology improvements and new emerging products. Other factors related to demand and supply parameters such as elasticities regarding prices, GDP and growing stock are associated with high uncertainty and are strong candidates for inclusion in future forest sector modelling studies.

To incorporate more risk factors, it may be beneficial to include other and more computing-effective techniques than those applied in this study, such as Latin hypercube sampling (McKay, 1992). When using a model, it is always important to have a good understanding of the uncertainties that are related to the model. It should be noted that historical variations are usually good proxies for determining uncertainties within a short time frame, but caution must always be exercised when trying to extrapolate historical uncertainty.

Conclusions

This study has found that the analysed uncertainties in exchange rate and world market prices as derived from historical data have significant impacts on harvests and forest industry production levels in the Norwegian forest sector. The relative standard deviation of modelled harvest levels was 15–45%. The relative standard deviation of modelled industrial productions was 30–80%, with fibreboard production having

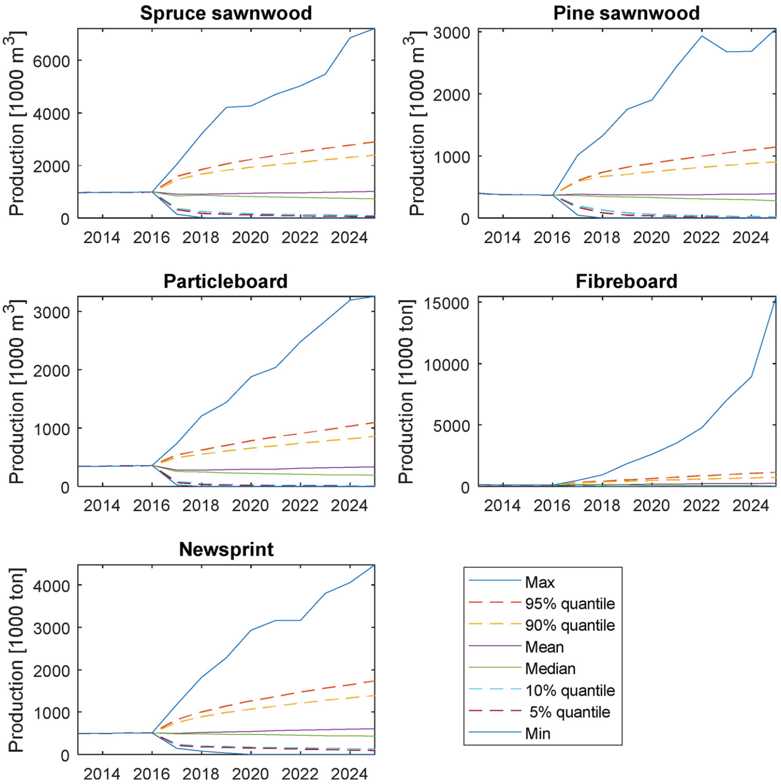

Fig. 6. Modelled mean, median, 5%, 10%, 90%, and 95% quantiles and max/min for production volumes of main forest products for the ALL scenario.

the highest value.

The uncertainty of modelled price, harvest and production level increased with the number of periods modelled. Exchange rates showed a lower gradient of uncertainty increase after the first year compared to the uncertainty caused by variation in world market prices. The uncertainty regarding world market prices is important for the Norwegian forest sector.

The study illustrates that improved modelling of forest products demand should be of high priority in future forest sector modelling development.

Within a short time frame, historical variations usually provide good proxies for determining uncertainties, but caution must always be exercised when trying to extrapolate historical uncertainty. To incorporate more risk factors, it may be beneficial to include other and more computing-effective techniques in the future, such as Latin hypercube sampling.

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Paper II

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Large-scale forest-based biofuel production in the Nordic forest sector: Effects on the economics of forestry and forest industries

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ABSTRACT

Forest-based biofuel is a promising solution to increase the share of renewable and sustainable energy in the transportation sector. Large-scale implementation of biofuel, however, not only affects the energy and transportation sectors, but also the forest sector value chains. This study uses a partial equilibrium forest sector model to quantify how large-scale production of forest-based biofuel would affect forest owners and forest industries in the Nordic countries. In a scenario assuming that forest-based biofuels cover a 0–40% share of the current Nordic road transportation and domestic aviation fuel consumption, the model results show that the sawmill industry increases their profit slightly due to increasing prices for their sawmilling residues. The traditional pulp and paper industries, on the other hand, see a reduced profit by up to 3.0 billion €, corresponding to 8% of their annual turnover, due to the increase in the price of pulpwood. Due to the increasing wood prices, the forest owners benefit significantly from biofuel investments. According to the model, their gross revenue from harvesting increases up to 31% without the need to increase the harvest more than 15%. The overall profit in the traditional forest sector is reduced by 400–600 million €. The decrease in profit is largest when the biofuel production volume covers 20%–30% of the liquid fuels in the Nordic countries. The reduction in overall profit is lower at 40% biofuel implementation, owing to the significant increase in revenue for the forest owner and the fact that the main reduction in pulp and paper industries happens at between 0% and 30% biofuel implementation. The study shows substantial economic spill-over effects from large-scale biofuel implementations to other parts of the forest sector.

1. Introduction

The European Union (EU) has set the target of reaching a 10% share of renewable fuels for transportation by 2020 and, further, that 14% of the energy consumption in the transportation sector will be renewable by 2030 [1,2]. Since the electrification of the transportation sector is a slow process, the EU member states need to produce or import large amounts of biofuel to reach this target. Currently, biofuel is mainly produced from food crops and palm oil, and thus the sustainability of using increased amounts of such feedstock for energy is questionable [3]. Second-generation (i.e., advanced forest-based) biofuels are often regarded as a sustainable alternative [4]. Such biofuels based on sustainably produced raw wood material may be available in large volumes around the world [5], with low indirect land-use implications [6].

Large amounts of biofuel are needed to fulfil the requirement for renewable fuel. One sustainable option is to produce forest-based biofuel. Large-scale implementation of forest-based biofuel production will affect not only the energy and transportation sectors, but also the forest sector, which includes forestry, wood-processing industries, and pulp and paper industries.

The forest sector has long traditions in the Nordic countries, and has undergone significant transitions since year 2000. Decreasing demand for some paper grades, together with the relocation of some forest industries to low-cost countries, have led to the closure of several mills over the last 20 years [7–9]. This in turn has led to a lower demand for pulpwood. Alongside the closure trend in the pulp and paper industries, which is being driven by digitalization, another trend also has started, driven by the increasing focus on GHG-related emissions from the production and use of fossil fuel and cement. Other products may therefore become more important in the future, such as sawnwood and biofuels. These changes may increase the demand for roundwood, byproducts from the forest industry, and harvest residuals.

Although it may be of great importance when developing adequate

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policies for second-generation biofuel production, few studies have investigated the implications of significant forest-based biofuel production in the Nordic countries for the existing forest industries. One exception is a study by Trømborg et al. [10], which investigates how biofuel production may influence the Norwegian forest sector using a national forest sector model that covers Norway. They find that a production level of 500 million litres of biofuel yearly will lead to a small decrease in pulp production, a marginal increase in sawnwood production, and a significant decrease in biomass used to produce heat in Norway. The results are, however, highly sensitive to assumptions regarding international wood prices. Similarly, Kallio et al. [11] vary global demand for wood in bioenergy production, and investigate the influences on the global forest sector using a global partial equilibrium model. They report significantly higher harvest levels and prices for forest chips and pulpwood when increasing biofuel production up to 115 billion litres world-wide, while they find almost no change in the use of sawlogs in the European Economic Area (EEA). Kallio et al. [11] also find that there is a strong competition for feedstock between biofuel and bioheat, since they use the same feedstock. Lundmark et al. [12] investigate the effects of biofuel production implementation on the forest sector's profitability. They use three different models to investigate the implications of 0.5–3 billion litres of biofuel production in Sweden. Lundmark et al. [12] conclude that implementation of biofuel production in Sweden will have only a minor effect on the established forest industry, but the profitability of sales of by-products and harvest residuals will increase with increasing biofuel use.

Kallio et al. [13] study the Finnish chips market and conclude that an increase in sawnwood capacity is needed to make a significant increase in the use of chips and harvest residuals profitable. de Jong et al. [14] find an increase in profit for biofuel and sawnwood producers if they are co-located. These findings are supported by Mustapha et al. [15], who report a modest increase in sawnwood production volume in regions where biofuel is produced. Mustapha et al. [16] report a 12–35% increase in the price of chips in the Nordic countries if a 20% biofuel target is met.

Previous studies either apply models covering a single country or they use broad global models [17]. The national models have a simplistic modelling of international trade, while the global ones have a coarse regional resolution which means that the regional characteristics of raw material supply, production technologies, demand, and transportation costs are ignored. In addition, few (if any) studies provide a holistic overview of the effects on all the major stakeholders in the forest sector value-chain—forest owners, the sawmilling industry, pulp and paper industries, and biofuel producers.

In the present study, we apply a model covering the Nordic countries, which have a highly integrated forest products market [18–20]. This Nordic model includes modelling of sub-national regional markets and trade, which give a better representation of the forest sector than previously used national models. Mustapha et al. [15] used an earlier version of the model to study the optimal allocation of biofuel production in the Nordic region.

In this study, we quantify the economic effects of large-scale production of forest-based biofuel on forestry and forest industries in the Nordic countries—a region with considerable forest resources that may be utilized for biofuel production. We analyse the implications of different forest-based biofuel production levels ranging from 0% to 40% of total Nordic liquid fuel consumed within the transportation sector. The two main research questions in this paper are: a) what are the implications for the Nordic forest sector for different level of biofuel production? And b) which actors in the forest sector will gain or lose market shares with large-scale production of biofuel?

The paper is organized as follows: Chapter 2 describes the forest sector model used, along with the main assumptions regarding biofuel production in the model; Chapter 3 describes the scenarios that are used; Chapter 4 presents the results; Chapter 5 discusses the results; and finally, Chapter 6 provides the study's conclusions.

2. Method

2.1. Nordic forest sector model — NFSM

The Nordic Forest Sector Model (NFSM) is a spatial, partial equilibrium model covering forestry, forest industry, and bioenergy in Norway, Sweden, Finland, and Denmark. The model structure is built on the Norwegian Trade Model (NTM) [21–23], which in turn originates from the Global Trade Model (GTM) [24]. The NFSM has recently been used to identify optimal locations for biofuel production [15] and to estimate *n*th plant total production costs in the Nordic countries [16] as well as the impacts of different conversion effectivities for different technologies [16].

The NFSM maximizes social welfare—i.e., consumer plus producer surplus—for each simulated period. The solution provides market equilibrium prices and quantities for each period, as shown by Samuelson [25]. In the NFSM, roundwood supply, industrial production, consumption of final products, and trade between regions are estimated simultaneously. Roundwood supply is determined in the model by supply elasticities, the demand of roundwood by the industry, and growing stocks. Harvest of logging residues is related to the roundwood supply and the amount of harvest residuals is constrained up to 40% of the energy content in harvested roundwood in each region and period. The simulation of industrial production uses exogenous given input–output coefficients such as labour, energy costs, and feedstock requirements in combination with endogenous raw, intermediate, and final product prices. Consumption of final products is determined by regional demand, endogenous product prices, and price elasticity. Finally, trade between regions occurs until the price differences equal the transportation costs. Transportation cost is calculated with a fixed and variable per-kilometre cost between the assumed consumption, production, and harvest centre in each region. Transportation is chosen from the following options: truck, train, and ship. The model has 29 different products, including 6 types of roundwood supply (spruce, pine, and non-coniferous sawlogs and pulpwood), harvest residuals, 9 types of intermediate products, and 13 final products (3 sawnwood grades, 3 board grades, 4 paper grades, firewood and district heating, and biofuel). Norway, Sweden, and Finland are each modelled with 10 regions, while 1 region covers Denmark and 1 region covers the rest of the world. The latter is included to ensure that import and export to the Nordic countries is possible. The data used in the model are adapted from Mustapha [26]. The most important reference values for this study are shown in Table 1.

A full description of the objective function and constraints of the NFSM is found in Appendix A. The model is solved as a Mixed Integer Linear Programming (MILP) problem, with the CPLEX solver using the General Algebraic Modelling System (GAMS) [27].

2.2. Biofuel production

Different conversion routes can produce biofuel, and the routes have different levels of economic maturation, efficiency, and other technical parameters [28–31]. Biofuel production can have other chemical products as a main or side stream. Products that can be produced simultaneously with biofuel include a large variety of marketable products, such as methanol, ethanol, dimethyl-ether, methane, diesel, gasoline, paraffin, jet fuel, and other tradable biochemical products [32,33]. Since the biomass to biofuel conversion effectivity is highly uncertain, we assume that biofuel production has an overall energy efficiency of 58% independent of feedstock used, which is within the scope of what may be reasonable in the future. As we focus on large production volumes in this study, some technology and raw materials may have different effectivity—however, we assume that 58% is valid as an average. The effectivity and input–outputs for the biofuel production are based on a techno-economic study carried out by Serrano et al. [34], and we have selected the technology route of hydrothermal

Table 1

The reference production, harvest, roundwood prices, and elasticity of roundwood supply [26].

		Norway	Sweden	Finland	Denmark
Production	Sawnwood [million m^3]	2.21	18.6	9.73	0.36
	Boards [million m^3/metric ton]	0.59	0.89	1.20	0.35
	Pulp & paper [million ton]	1.53	22.2	21.5	0.5
	Chips, briquettes, firewood [TWh]	4.79	39.4	40.3	15.3
Harvest	Sawlogs [million m^3]	4.63	34.5	19.5	0.80
	Pulpwood include chips [million m^3]	6.75	41.3	34.2	2.60
	Harvest residuals [TWh]	0	7.55	6.01	0.28
Price delivered gate	Sawlogs [€/m^3]	68	76	74	68
	Pulpwood [€/m^3]	36	48	49	38
Price elasticity of roundwood supply	Sawlogs	0.8	0.6	1.0	0.8
	Pulpwood	1.2	0.8	1.2	1.2

Table 2

Labour, fixed costs, investment costs, and production level for the different plant sizes [input feedstock]. Source: Serrano et al. [34].

	150 MW	300 MW	450 MW	600 MW
Labour input [h/1000 L]	0.57	0.44	0.38	0.42
Fixed costs [€/L/year]	0.56	0.49	0.45	0.42
Investment costs [€/L/year]	0.40	0.34	0.31	0.29
Production [million L/year]	79	157	236	315

Table 3

Costs of labour, electricity, and natural gas used for biofuel production in the Nordic countries [44–48].

	Denmark	Finland	Norway	Sweden
Labour [€/hour]	27	18	39	20
Electricity [€/MWh]	54.5	42.9	39.9	41.3
Natural gas [€/MWh]	36.1	36.1	36.1	36.1

liquefaction (HTL), which allows different raw materials and products. The assumed energy efficiency implies that about 8.6 m^3 solid wood is needed to produce 1 m^3 of biofuel. We further assume that biofuel production has the same effectivity for different raw materials. The model can choose the most economical solution from the following raw materials: spruce, pine, and non-conifer pulpwood; residuals from sawmills; harvest residuals; or a mix of these. The difference between the raw materials is only the energy content, which is adapted from Mustapha [26]. The model can invest in fixed-size production units, of which the sizes—adapted from Serrano et al. [34]—are set to 150, 300, 450, and 600 MW feedstock capacity. This equals 79, 157, 236, and 315 million litres as annual production volumes. Table 2 shows the main assumption for each production unit. The consumption of electrical energy is assumed to be 0.355 kWh/$L_{biofuel}$ and 4.2 kWh/$L_{biofuel}$ of natural gas used as hydrogen source under upgrading, for all production sizes. Table 3 shows the regional costs of labour and electrical power.

The Nordic countries have set ambitious targets for reducing their consumption of fossil fuel. Norway, Finland, and Demark have use mandates to this effect: by 2020, at least 20% of the liquid fuel used in Norway and Finland must come from biofuel [35–37], and the corresponding figure for Denmark is 10% [38]. Sweden has set their target for reducing transportation-related carbon emission at 2.6% for gasoline and 19.3% for diesel in 2018, and they plan to increase this target to 70% within 2030 [39]. For this reason, we assume that the future production of biofuel in the Nordic countries is equal to a certain share (i.e. use mandate) of the diesel, gasoline, and jet fuel consumed in the Nordic countries in 2017, which was about 29.1 billion litres [40–43]. The analysed scenarios of 0%, 10%, 20%, 30%, and 40% of current fuel consumption thus represent 0, 2.9, 5.8, 8.7, and 11.6 billion litres of biofuel produced annually. The amount of biofuel is implemented as quota obligations, and the model finds the most competitive location and plant size for each given production level—i.e., minimizing the costs of reaching the production target.

3. Scenario description

3.1. Baseline scenario

In the base scenario, we mainly use data described in Mustapha [26]. However, we have made some changes to the NFSM, and the changes are described here, as well as in chapter 2 and the Appendix A.

We have doubled the price elasticity of roundwood supply compared to values found in Mustapha [26]. The reason for this is that different studies report different values of elasticity of roundwood supply. For example, Tian et al. [49] found high uncertainties for the level of elasticity of roundwood supply, while Bolkesjø et al. [50] found high price elasticity of roundwood supply. There are thus considerable uncertainties regarding the level of price effects on the roundwood supply in the Nordic countries; as such, this study assumes that the elasticity of roundwood supply may be higher than the level used in the data report for the NFSM [26].

Harvest residuals may be important as raw materials for biofuel production in the future; in Norway, harvest residuals are not currently used, but Finland and Sweden are utilizing some harvest residuals for energy purposes. In all scenarios, we allow the model to use harvest residuals for biofuel and heat production—within the constraint mentioned above.

3.2. Alternative scenarios

In addition to the base case, we analyse the effect of different alternative scenarios regarding techno-economic developments in the forest and bioenergy sectors. These scenarios are divided into five groups. In group A, we analyse the effect of changing the elasticity of roundwood supply: doubling (A3) and halving (A2) the elasticities compared with the base (A1) case. This is done because of the considerable uncertainty regarding the elasticity of roundwood supply and may actually have quite different level than that assumed in A1.

In group B, we test different levels of biomass consumption in district heating. The implications for the forest sector will likely be affected by competition over low-grade biomass usage (i.e., competition with the district heating sector). Biomass used for heating today may be used as raw material for biofuel plants in the future. For this reason, in scenario B1, we assume no use of biomass for district heating. On the other hand, increasing the CO_2 price may increase the utilization of biomass in district heating. For this reason, we double the biomass consumption from today's level in scenario B2.

Since year 2000, the Nordic pulp and paper industries has undergone a transition. For some paper grades, demand has reduced

Table 4
Summary of the different scenarios. All changes are relative to the base scenario (A1).

Scenario name	Description	Changes
A1	Base	
A2	Low timber price supply elasticity	Halving the value of the price elasticity of roundwood supply
A3	High timber price supply elasticity	Doubling the value of the price elasticity of roundwood supply
B1	Low level of biomass use in district heating	No use of biomass in district heating
B2	High level of biomass use in district heating	Doubling the amount of biomass in district heating
C1	Reduced demand for pulp and paper	Reduced demand for pulp and paper by 50% in the Nordic countries
C2	Increased demand for pulp and paper	Increased demand for pulp and paper by 50% in the Nordic countries
D1	Reduced demand for sawnwood	Reduced demand for sawnwood by 50% in the Nordic countries
D2	Increased demand for sawnwood	Increased demand for sawnwood by 50% in the Nordic countries
E1	Each country has their own quota obligation	Each of the Nordic countries produces their own biofuel

dramatically due to increased digitalization, while for other paper grades, demand has increased due to globalization. In group C, we cover both these cases, targeting what happens if the demand for Nordic pulp and paper reduces (C1) and increases (C2) by 50%, respectively.

Reducing GHG emissions from the construction sector may increase the production of sawnwood in the future. We therefore run a scenario with a 50% reduction (D1) and 50% increase (D2) in sawmill capacity.

Finally, in group E, we assume that each country has individual national consumption and production mandates for forest-based biofuel (E1). This means that there will be no trade of biofuels between the Nordic countries in these scenarios.

As mentioned above, all scenarios are run for five levels of biofuel production: 0%, 20%, 30%, and 40% of the total fossil fuel consumption. Table 4 shows a summary of the scenario used in this study.

4. Results

4.1. Base scenario

4.1.1. Changes in biomass supply and biomass prices

The overall harvest level in the Nordic countries is about 145 million m^3 (Table 1), of which 72 million m^3 is used by the pulp and paper industries [26]. Biofuel production corresponding to 40% of the current total fuel use in the Nordic region would require roughly 100 million m^3 of biomass. This represents a substantial increase in demand for wood (Fig. 1). As expected, the wood consumption for biofuel production comes from multiple sources: increased roundwood harvest, increased harvest of harvest residuals, and increased imports from other countries. In addition, increasing wood demand from the biofuel industry causes a significant reduction in wood use in the pulp and paper industries due to increasing wood prices (Fig. 1). Of the 98 million m^3 wood consumption in the 40% scenario, only about 25 million m^3 originates from increased domestic roundwood harvest in the Nordic countries. According to the model results, the average pulpwood price in the Nordic countries increases by 20–25%, while the total harvest increases by 17%. The combined effect of the increase in harvest and price significantly increases revenues for forest owners.

At 40% biofuel production, the increase in available roundwood in the Nordic countries (Fig. 1) is around 120 million m^3, while only 98 million m^3 is consumed for biofuel production (Fig. 2). The reduction in pulp and paper occurs simultaneously with an increase in the use of harvest residuals (Fig. 1). For this reason, the surplus of 20 million m^3 available roundwood from pulp and paper mill closures is higher than the actual need of roundwood for biofuel production. This is because biofuel producers use more harvest residuals than pulp and paper producers, which means that in the Nordic countries, traditional forest industry production becomes less competitive compared with the rest of the world due to increased pulpwood prices.

4.1.2. Economic effects to forest industries

Increased biofuel production affects the economy of sawmilling in

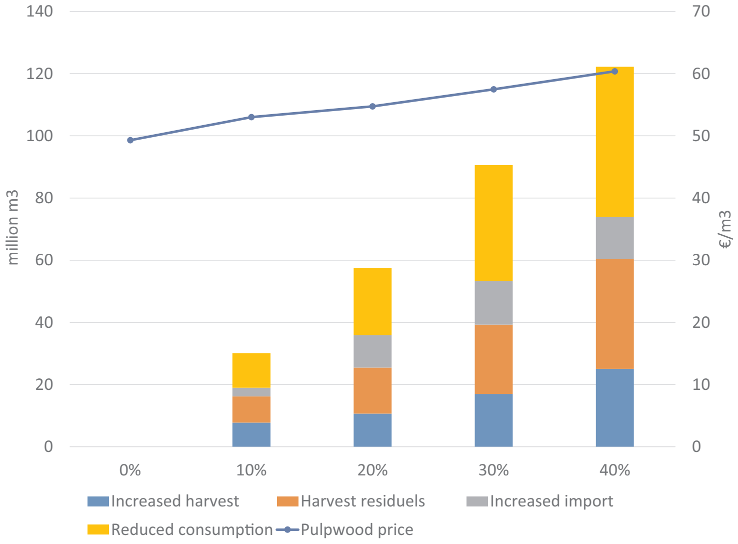

Fig. 1. Modelled sources of wood consumption for biofuel production, values show increase from 0% scenarios for harvest (blue), harvest residual (orange), import (grey), and reduced consumption in other industries (yellow) (left axis) and corresponding pulpwood prices (right axis) in the Nordic countries for the five base scenarios.

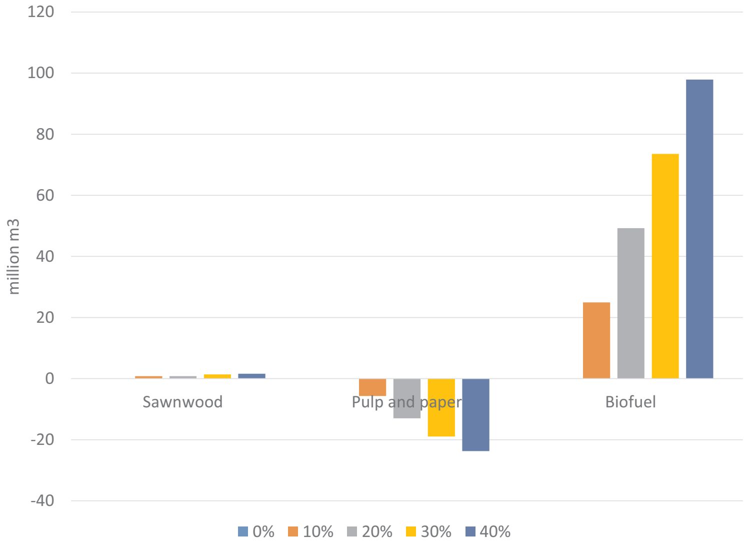

Fig. 2. Modelled change of wood consumption in sawmills, the pulp and paper industries, and biofuel production in the Nordic countries, for the different base scenarios.

Table 5
Modelled purchasing sawlogs costs, sales revenue of sawnwood and by-products, and changes in profit in the Nordic countries for the different base scenarios, in million €.

	0%	10%	20%	30%	40%
Sawlogs purchases	4392	4563	4559	4654	4740
Sawnwood sales	7010	7103	7061	7105	7095
Sales of by-products	1009	1111	1163	1247	1347
Profit	1969	1969	1979	1991	1993

Table 6
Modelled cost of purchasing pulp and wood, sales revenue, and changes in profit for the pulp and paper industries in the Nordic countries for the different base scenarios, in million €.

	0%	10%	20%	30%	40%
Sales revenue	35 852	33 988	31 877	29 707	28 271
Cost of importing pulp and purchasing pulpwood	14 275	13 702	12 964	12 078	11 562
Profit	13 163	12 350	11 507	10 697	10 149

multiple ways. The overall quantified effects on Nordic sawmilling profits are shown in Table 5. Total sawnwood production increases by 2.8% and board production increases by 0.6% when the biofuel share increases from 0% to 40%. This is due to increased revenue from sale of by-products. The pulp and paper industries reduce their production by 32%, due to higher raw materials costs.

The market value of wood by-products from sawmilling increases rapidly with increased production of biofuel (Table 5), whereas the market price for sawnwood decreases only slightly. In total, the sawmill profit increases by 24 million € when the biofuel production increases from 0% and 40%.

In the pulp and paper industries, the profit reduces by 3 billion € in the 40% scenario compared to the 0% scenario, due to a large reduction in sales revenue caused by a reduction in the production level. The reduction in cost is lower than the reduction in production due to the increasing pulpwood prices, while the market prices for pulp and paper only slightly increase (Table 6).

4.1.3. *Biofuel production*

Table 8 shows how the modelled production of biofuel is distributed between countries. Sweden produces the largest amount of biofuel in all scenarios, followed by Finland. Some production is allocated to Norway in all scenarios, while biofuel production is only allocated to Denmark in the scenarios with more than 20% overall biofuel obligation. Norwegian production stabilizes at 10% biofuel production, while production in Finland and Sweden increases almost linearly.

4.2. *Alternative scenarios*

4.2.1. *Changes in biomass supply and biomass prices*

Table 7 shows the changes in harvest levels, use of harvesting residuals, import of sawlogs and pulpwood, reduced consumption of roundwood in other industries, and pulpwood prices for biofuel production from the base scenarios (A1) for each of the scenarios (A2–E1). For the scenario with low elasticity of roundwood supply (A2), we observe (as expected) higher pulpwood prices and lower harvest levels than in the base case. The reduction in harvest is substituted by harvest residuals and a larger reduction in consumption in the rest of the forest industry. High elasticity of roundwood supply (A3) provides lower pulpwood prices and an increase in consumption for other industries and thereby an increased harvest.

Without the use of biomass in the district heating sector (B1), the use of harvest residuals is substantially reduced compared to the base scenario, especially at high biofuel production levels, due to the lower pulpwood prices. Harvest residuals are substituted by increased import. Simultaneously, the harvest and use of roundwood in the other industries increases compared to the base. When doubling the use of biomass in the district heating sector (B2), the use of harvest residuals increases in the 20% and 30% scenario at the expense of import and use of biomass in other industries.

As expected, when reducing the pulp and paper demand (C1), we observe a reduction in pulpwood prices and reduced use of harvest residuals. The new biomass for the 30% and 40% biofuel scenarios comes mainly from increased import. With increased pulp and paper

Table 7

Modelled differences between base case (A1), and the other scenarios for wood consumption for biofuel production. Values represent difference for harvest, harvest residual, import, reduced consumption in other industries (million m^3), and corresponding difference for pulpwood prices (€/m^3) in the Nordic countries for the five different production levels for biofuel. "–" means no change from base.

		Increased harvest	Harvest residuals	Increased import	Reduced consumption	Pulpwood price
0%	A1					–
	A2					–
	A3					−0.2
	B1					−7.6
	B2					4.0
	C1					−1.1
	C2					0.3
	D1					0.5
	D2					−0.6
	E1					–
10%	A1	–	–	–	–	–
	A2	−2.2	0.5	−1.3	2.7	1.4
	A3	0.7	−0.5	1.0	−0.8	−1.9
	B1	3.7	−7.6	3.3	−4.2	−3.9
	B2	−2.6	−0.3	2.6	−0.7	2.8
	C1	−0.5	−0.3	2.6	−1.5	−1.1
	C2	0.1	−0.5	−0.3	0.5	0.4
	D1	−0.7	−0.1	−0.1	0.8	0.5
	D2	−1.4	0.4	0.4	1.0	−1.0
	E1	0.1	−2.3	2.5	4.4	–
20%	A1	–	–	–	–	–
	A2	−2.1	1.4	−4.2	8.1	2.7
	A3	2.8	−3.2	3.4	0.3	−1.9
	B1	6.5	−7.7	2.0	−5.7	−2.4
	B2	0.1	2.4	−4.8	6.4	4.0
	C1	0.3	−2.3	3.5	0.3	−0.8
	C2	0.8	−0.4	0.6	1.5	0.8
	D1	0.2	−1.7	1.3	2.6	1.0
	D2	−0.5	−1.9	2.2	1.8	−0.6
	E1	0.4	–	0.3	5.6	0.1
30%	A1	–	–	–	–	–
	A2	−4.1	2.7	−1.6	4.3	3.3
	A3	3.2	−2.7	1.5	−2.8	−2.8
	B1	4.9	−9.9	5.8	−7.1	−3.4
	B2	0.9	5.5	−7.7	8.4	4.7
	C1	−0.7	−1.6	1.8	0.2	−1.3
	C2	1.0	1.0	−1.7	0.4	1.0
	D1	−0.2	−0.8	−2.0	2.8	0.7
	D2	−1.6	0.9	1.2	0.5	−1.0
	E1	−0.1	2.7	−0.2	0.4	−0.4
40%	A1	–	–	–	–	–
	A2	−5.3	1.7	−0.3	4.6	4.2
	A3	4.4	−2.2	1.4	−3.8	−3.8
	B1	2.9	−11.6	10.3	−9.5	−4.4
	B2	2.0	1.3	−1.2	4.0	5.0
	C1	−1.2	−0.4	3.4	−0.9	−1.9
	C2	1.4	1.2	−0.8	−0.8	1.4
	D1	–	−1.8	2.4	−1.6	0.2
	D2	−1.4	0.4	1.4	0.8	−0.7
	E1	0.7	0.9	1.4	0.1	−0.2

demand (C2), we find increased pulpwood prices and increased harvest levels.

When reducing the sawnwood demand (D1), we find increased pulpwood import and more roundwood consumption in other industries, while increasing the sawnwood demand (D2) leads to reduced pulpwood prices. Finally, forcing each country to produce according to their own biofuel consumption (E1) causes minor effects only to the biomass balance compared to the base.

4.2.2. Changes in biofuel production

Table 8 shows the changed biofuel production from the base (A1) for the different cases. Small changes occur, with the exception of cases where biomass is not used in district heating (B1), where more of the biofuel production is allocated to Finland. In the case of self-production of biofuel (E1), biofuel production in Norway and Denmark increases by 100% and 84%, respectively, compared to the base (A1) 40%. In the same scenario, production in Sweden and Finland reduces by 21% and 33%, respectively. Hence, according to this study, biofuel production in Finland and Sweden is more cost competitive than production in Norway and Denmark.

4.2.3. Harvest level and wood prices

The base scenario increases the pulpwood prices at mill gate from 50 €/m^3 with 0% biofuel to 61 €/m^3 with 40% biofuel. The prices deviate from −15% to 8% with 0% biofuel and from −7% to 8% with 40% biofuel: the highest is for high use of biomass in district heating (B2) and the lowest for low use of biomass in district heating (B1). Sawlogs prices increase from 74 €/m^3 to 78 €/m^3 for the base case (A1). The scenarios can be divided into three groups: group 1 has a high sawnwood demand (D2) that starts at 82 €/m^3 and ends at 84 €/m^3; group 2 has a low sawnwood demand (D1), starting at 68 €/m^3 and ending at 72 €/m^3; and the rest of the cases (group 3) have a maximum deviation of ± 4% from the base case for all biofuel production levels. Generally, the modelled roundwood prices are robust to changes in the scenario parameters. The flexibility in wood supply from different wood sources (roundwood, harvest residuals, by-products, and imports), as well as changes in wood consumption from different wood consumer sectors, reduces the influence from the scenario parameters.

The modelled harvest levels follow the same pattern as prices. Again, we find that the pulpwood harvest is highest for high use of biomass in district heating (B2). For sawlogs, harvest is almost constant across scenarios. The highest sawlogs harvest is with high sawnwood demand (D2), at a constant level of +7% from the base level, while the lowest harvest is with low sawnwood demand (D1), with a harvest that deviates from −7% to −9%. The rest of the cases deviate at a maximum of ± 2% from the base case.

4.2.4. Production levels

The scenarios affect different parts of the forest industry differently. The changes between the base (A1) 0% and the different cases for sawnwood production are shown in Fig. 3. In most cases, the production of sawnwood increases in Sweden, while the production in Finland slightly decreases for the cases with low use of biomass in district heating (B1). This shows that countries with high pulpwood demand also have high production of sawnwood. The largest changes appear for low sawnwood demand (D1) and high sawnwood demand (D2). The board production is almost unchanged across all scenarios and cases.

Since the pulp and paper industries are major consumers of pulpwood, their production reduces with increased biofuel production (Fig. 4), especially in Finland and Sweden. The introduction of biofuel will directly compete with pulp and paper for the pulpwood, resulting in a reduction of pulp and paper production. In the simulations, the model is forced to produce biofuel to fulfil a given consumption or blending requirement. The competitiveness of pulp and paper versus biofuel production, or Nordic biofuel production versus imported biofuels, is not analysed in this study.

4.2.5. Cost, revenue and profit

Increased production of biofuel increases the market price of by-products from sawmills, which increases profits and production. The increased sawnwood production increases the consumption of sawlogs and therefore sawlogs unit prices, as shown in Table 9. The highest sawlogs unit costs are observed when we also increase the demand for sawnwood (D2). Revenues from by-product sales (Table 9) increase when more biomass is demanded in biofuel production. In total, the market price of sawnwood (Table 9) is almost constant when increasing biofuel production—major changes happen only when we increase/decrease the sawnwood demand (D2, D1). Profit for sawmills (Table 9)

Table 8
Modelled production of biofuel in the base scenario (A1) and modelled changes from base for all scenarios and cases, in the different countries, all numbers are in billion litres annually. "–" means no change from base.

Country	Scenario	A1	A2	A3	B1	B2	C1	C2	D1	D2	E1
Norway	0%	0	–	–	–	–	–	–	–	–	–
	10%	0.32	–	–	–	−0.08	–	–	–	–	0.32
	20%	0.32	–	–	–	–	–	–	–	–	0.87
	30%	0.32	0.32	–	–	0.32	–	0.32	0.32	0.24	1.42
	40%	1.18	−0.08	–	−0.55	–	−0.08	–	−0.08	−0.08	1.18
Finland	0%	0	–	–	–	–	–	–	–	–	–
	10%	0.55	0.08	–	0.39	0.08	0.08	–	0.08	0.08	0.08
	20%	1.89	−0.32	0.08	0.32	–	–	− 0.08	–	–	−0.63
	30%	2.60	0.24	0.08	−0.08	0.08	0.39	0.16	0.39	0.32	−0.79
	40%	3.62	−0.16	–	0.39	−0.32	−0.24	–	0.08	−0.24	−1.18
Sweden	0%	0	–	–	–	–	–	–	–	–	–
	10%	2.13	−0.08	–	−0.39	–	−0.08	–	−0.08	−0.08	−1.02
	20%	3.70	−0.32	−0.55	−0.32	−0.63	−0.63	−0.24	−0.63	−0.32	−1.58
	30%	4.65	−0.55	−0.08	0.39	−0.71	−0.39	−0.47	−0.71	−0.55	−1.50
	40%	5.36	0.24	–	0.16	0.32	0.32	–	–	0.32	−1.10
Denmark	0%	0	–	–	–	–	–	–	–	–	–
	10%	0	–	–	–	–	–	–	–	–	0.79
	20%	0	0.63	0.63	–	0.63	0.63	0.32	0.63	0.32	1.50
	30%	1.26	–	–	−0.32	0.32	–	–	–	–	0.95
	40%	1.58	–	–	–	–	–	–	–	–	1.34

increase with the production and the market price of sawnwood. If the sawnwood demand increases by 50% (D2), we find the unit production profit increases by 7% compared to the base scenario.

The raw material costs for pulp, paper, and board industries rise with increasing biofuel production (Table 9). The highest unit costs are in the cases where pulp and paper demand is also increased (C2) and/or there is an increased amount of biomass in district heating (B2) due to increased competition for biomass.

The average unit market price for pulp and paper products rises with increasing biofuel production (Table 9), due to the increased competition for biomass between the pulp and paper industries and biofuel producers, which lowers production in the pulp and paper industries. The unit profit is relatively stable for all cases (Table 9).

5. Discussion

This study demonstrates how biofuel production could influence the Nordic forest sector. One main finding is that the implementation of large-scale wood-based biofuel plants will significantly affect the forest and bioenergy sectors in the Nordic countries. The pulp and paper industries will reduce production volumes and profits, whereas sawmills will tend to increase their profit due to increased demand for their by-

Fig. 3. Modelled change in sawnwood production compared to base (A1) 0%, split by countries, for the different cases and scenarios.

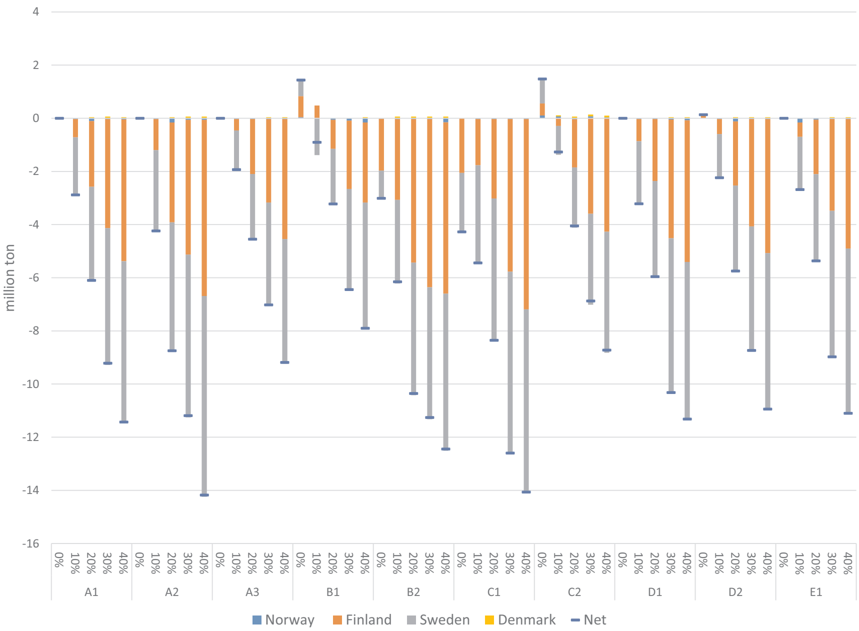

Fig. 4. Modelled change in pulp and paper production compared to base (A1) 0%, for the different cases and scenarios, split by countries.

products. The forest owners will increase their revenue when biofuel production is introduced, as market prices for pulpwood and the use of harvest residuals will increase. The reduction in profit in the pulp and paper industries will be greater than the increase in profit for sawmills and the increase in revenue for forest owners combined. Added together, the net annual profit in the forest sector (excluding biofuels) will thus be reduced by 400–600 million € compared with the 0% biofuel production scenario. The effect is largest in the 20–30% scenarios and lowest in the 40% scenario. The results indicate that the least favourable production volume for the Nordic forest sector is around 20%, i.e., the same as the Norwegian 2020 goal for renewable fuel in transportation [36]. For levels above 30%, the increase in revenue for forest owners will occur faster than the reduction in profit for pulp and paper producers, giving a lower total loss in profit for the sector.

High levels of biofuel production, especially in the 40% case, will lead to a significant increase in demand for forest resources. A level of 40% biofuel will demand a 98 million m^3 pulpwood equivalent, which is two-thirds of the reference harvest in the Nordic countries (144 million m^3). The increased consumption for forest-based raw materials will be mainly sourced from import and harvest residuals, which is in agreement with Lundmark et al. [12]. The sawlogs consumption will be largely unaffected by the production level of biofuel, in line with Mustapha et al. [15] and Lundmark et al. [12]. In the reference year (2013), the Nordic countries harvested 65% of the annual growth; with an increase of 98 million m^3, the utilization of roundwood will be 108% of the growth if we assume no changes in import and no reduction in consumption in other parts of the forest sector. This would not be sustainable; thus, the mass balance in the model is reached by increasing the net roundwood import and reducing the consumption in other industries—mainly in the pulp and paper industries. Forest owners in the Nordic countries and in the rest of the world will benefit from a high penetration of forest-based biofuel in the Nordic countries, while the Nordic pulp and paper industries will meet increased costs and decreased production. This result is supported by Schwarzbauer et al. [51], although they focus on the Austrian forest sector.

Pulpwood prices will increase by 22%, which is consistent with Mustapha et al. [15] but is lower than what was reported by Trømborg et al. [10] for the Norwegian market. The Norwegian roundwood market constitutes about 8% of the total Nordic roundwood markets, hence the significantly higher roundwood prices in Trømborg et al. [10], which were due to the lower available amount of roundwood. In the present study, we use a regionalized model covering all the Nordic countries that is capable of modelling trade across the borders. This gives a more realistic picture of the roundwood market than in a single country model.

Sawmills in the Nordic countries will tend to benefit from forest-based biofuel production through increased production and increased unit profit due to increased by-product prices. However, production of sawnwood will increase only marginally, as is shown in previous studies [10,11]. Simultaneously, the pulp and paper industries will reduce their profitability and production volume, making the implementation of biofuel controversial. Since biofuel production is not competitive with fossil fuel at today's costs, biofuel production must be subsidized. This will be highly controversial, since subsidizing biofuel will lead to reduced profit in other industries.

The results are stable across the different scenarios. In accordance with our expectations, the results tend to give higher pulpwood prices if the demand for forest products increases (B2, C2), while the price and use of harvest residuals decreases if the demand is reduced. Increased demand will not affect the allocation of biofuel production substantially. A reduction in demand (B1, C1) will move some production of biofuel from Sweden to Finland.

Increased production of forest-based biofuel will create a substantial reduction in the need for fossil fuel, but it will also reduce the profitability of pulp and paper producers. Reduced activity in the pulp and paper industries may reduce the forest sector's willingness and opportunity to invest in other types of biorefineries and thus in other green products. Several biorefinery technologies that use by-products from pulp and paper industries as raw materials have shown promising results [52,53]. For those technologies, integration with the existing pulp

Table 9
Modelled unit profit, sales revenue and main products and by-products, and cost of raw materials for sawmills and pulp, paper, and board industries in €/m^3 or €/ton as Nordic average.

		Sawmills				Pulp, paper, and board industries		
Case	Scenario	Profit	Sales revenue	Sales revenue by-products	Cost of sawlogs	Profit	Sales revenue	Cost of raw materials
A1	0%	63.5	226	32.5	142	270	737	293
	10%	62.6	226	35.3	145	270	742	299
	20%	62.9	225	37.0	145	270	749	305
	30%	62.7	224	39.3	147	271	753	306
	40%	62.5	223	42.3	149	272	759	310
A2	0%	61.9	226	32.6	143	271	737	293
	10%	62.2	226	36.3	147	270	746	302
	20%	63.1	226	38.8	148	268	749	306
	30%	62.9	225	41.7	150	269	759	314
	40%	62.2	224	45.5	154	273	767	316
A3	0%	63.1	226	32.4	141	271	737	293
	10%	62.6	226	34.1	143	269	740	298
	20%	62.9	224	35.6	143	271	744	299
	30%	62.9	223	37.2	144	272	745	299
	40%	63.2	222	39.6	144	272	748	301
B1	0%	61.5	229	25.5	140	276	725	276
	10%	61.9	227	30.5	142	270	737	294
	20%	61.7	226	32.4	143	267	740	299
	30%	62.1	225	34.8	145	269	746	303
	40%	62.1	225	36.8	146	271	748	302
B2	0%	62.8	225	35.8	145	270	744	300
	10%	62.8	224	37.8	145	270	750	306
	20%	62.9	224	40.4	147	270	756	310
	30%	62.9	222	43.7	149	275	771	318
	40%	64.6	224	46.6	152	281	781	323
C1	0%	62.1	226	31.8	142	266	726	287
	10%	62.4	226	34.7	145	268	738	296
	20%	63.1	225	36.4	145	272	740	294
	30%	63.9	225	38.4	146	273	747	298
	40%	62.5	223	41.2	148	274	753	303
C2	0%	63.5	226	32.7	142	274	746	297
	10%	62.6	226	35.6	145	272	752	306
	20%	62.9	224	37.5	145	272	757	310
	30%	63.2	224	40.1	148	270	766	319
	40%	63.0	222	43.4	149	273	772	321
D1	0%	59.4	209	32.6	129	270	737	293
	10%	59.6	208	35.5	131	272	743	298
	20%	59.4	206	37.6	131	271	749	304
	30%	59.5	206	39.6	133	268	752	308
	40%	59.7	208	42.1	138	272	759	310
D2	0%	67.7	246	32.0	156	271	736	293
	10%	68.4	246	34.5	158	268	741	300
	20%	68.8	245	36.4	158	271	747	301
	30%	69.2	244	38.6	159	269	748	304
	40%	70.0	243	41.9	160	271	759	312
E1	0%	63.5	226	32.5	142	270	737	293
	10%	62.6	226	35.4	145	268	743	302
	20%	62.6	224	37.2	145	269	748	305
	30%	62.8	224	39.5	147	271	749	303
	40%	63.2	222	42.8	148	274	758	309

and paper industries is essential. This study does not include possible synergy effects of such technologies. However, one assumption is that the pulp and paper industries will be unable to restructure from traditional mills into biorefineries with biofuel as a co-product. Pulp mills that manage this restructuring may not reduce their profit in the same magnitude as that mentioned in this study. We further assume that residuals from the pulp and paper industries (tall oil, kraft lignin, black liquor, etc.) will not be used to fulfil the biofuel mandate. At the moment, only some plants are using residuals from pulping in biofuel production [54]. Molinder et al. [55] estimate the total potential production of crude tall oil to be 600 000 ton/year in Scandinavia, while Backlund et al. [56] estimate a maximum of 5 TWh/year of lignin-based biofuel in Sweden. Together, lignin and tall oil will produce a maximum of 1.26 billion L biofuel in Sweden, which corresponds to 4.3% of the current fuel consumption in the Nordic countries. It is unlikely that the full potential will be reached since both tall oil and lignin have other higher-value applications than biofuel [57]; as such, we assume that the share of tall oil and lignin that would be utilized for biofuel production is limited, and therefore it is not considered in this study.

At present, there are no full-scale stand-alone biofuel plants, leading to uncertainties regarding the energy efficiency and choice of raw materials for commercial biofuel plants. Many different technology pathways are under development; however, to analyse the forest sector impacts we have chosen to use a generic technology in this study with an efficiency that may be realistic in the future but is still uncertain. A change in the efficiency within the modelling framework used in this study will only increase/decrease the amount of biomass needed for producing a certain amount of biofuel. The effects of a given amount of biomass consumption will be the same for the forest sector as those shown in this study. A significant strength of the way biofuel production is implemented in the NFSM is that the model can freely choose the location of the production unit and raw materials mix according to what is most economical. The assumption that the production unit has a fixed size is reasonable, since the investors will only consider plants of a certain size. In this study, we assume that biofuel can be consumed without being mixing with fossil fuel. This has led to 100% biofuel consumption in some regions, and 0% in others. This assumption might influence the location of the biofuel plants. As the cost of transporting roundwood exceeds the cost of biofuel transportation, the effect of this assumption will likely be small. In addition, this study assumes a fixed demand for biomass in district heating independent of biofuel production. Some studies have indicated that the integration of biofuel production and heat production has considerable effect on which technology that will be optimal [58]. However, Börjesson Hagberg et al. [58] have shown that biofuel production only has a minor impact on heat production. It can be assumed that flexibility in the heat sector may dampen the price effects, but the potential influences of reduced bioheat and biopower (co-)generation are not considered here. Further development of the model will include better representation of the bioheat sector.

Since the NFSM is a partial equilibrium model, it has the same benefits and limitations as other partial equilibrium models. These include the fact that the model does not cover the raw material supply and cost precisely enough, since the model requires regional aggregation. Because of the aggregation, the NFSM is not able to model forest dynamics at the same detailed levels as forest models. But we are assuming that the NFSM can model the forest dynamics precisely enough for industrial studies. The NFSM models only the main industrial processes and products, because the larger variety in final products, similar products is aggregated to product groups with same market price. This simplification, together with the uncertainty in the techno-economic data for each mill, will make it impossible to determine exact implications for single mills, but on an aggregate level, the NFSM is able to provide robust result. As with every other partial equilibrium model, the NFSM is highly dependent on the input data. The NFSM uses the year 2013 as a reference year, but since the forest sector is under development, those input data may contain small inaccuracies, such as mill closures and investments that has happen from the reference year and until present. For example, in Finland, the harvest has increased by 7.2 million m^3 [59] since the calibration of the model, but such minor inaccuracies are not assumed to significantly affect the results of this study.

This is the first time that the biofuel data used in this study are used in a partial equilibrium model covering the Nordic forest sector. Together with the implementation of discreet production unit, this study yields new insights into the connection between the traditional forest sector and biofuel production.

6. Conclusion

This study shows that large-scale forest based biofuel production will substantially influence the economics of the forest sector. Sawnwood producers will increase their profit because they produce by-products that are suitable for use in biofuel plants, but the overall effects for sawmills are found to be minor. Forest owners, on the other hand, will benefit substantially from biofuel production since demand for chips, pulpwood, and harvest residuals will increase the wood prices. The model's results indicate an increase in roundwood prices up to 11% when assuming 40% biofuel implementation. On the other hand, implementation of biofuel will result in large reductions in the production (−25%) and profitability (−23%) in the pulp and paper industries and lead to mill closures, while harvest levels will increase up to 17% and the use of harvest residuals will increase by 56 TWh from current levels.

The different scenarios show that the total profit for sawnwood, pulp and paper producers, and forest owners will diverges ± 7% from the base case for all scenarios in the Nordic forest sector, which suggests that the model results are quite robust with respect to the implications of the biofuel production.

Forest owners and sawnwood, pulp, and paper producers will reduce their total profit when biofuel production is implemented. The total profit in the Nordic forest sector will be reduced by 400–600 million € or 1.8–2.2% p.a. The greatest reduction in profit will occur with 20–30% biofuel implementation, due to a heavy reduction in the pulp and paper industries. This shows that policy makers should be aware of the reduction in profit for the traditional forest industry when implementing support schemes for biofuel producers. The total biofuel production volume in the Nordic countries will affect how much profit the forest sector loses. For higher volumes of forest-based biofuel, the Nordic pulp and paper industries will reduce their profit by 3 billion € p.a. This may reduce the traditional pulp and paper industries opportunities to research and develop new chemical products based on roundwood that, in the future, may reduce the use of fossil fuel.

Declaration of interest

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

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CRediT authorship contribution statement

Eirik Ogner Jåstad: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Torjus Folsland Bolkesjø:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization, Supervision. **Erik Trømborg:** Conceptualization, Writing - original draft, Writing - review & editing. **Per Kristian Rørstad:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Supervision.

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Appendix A

This appendix describes the objective function and constraints used in the Nordic Forest Sector Model (NFSM). NFSM is a linearized mix integer model with five special ordered sets of type 2 (SOS2) variable [60], one integer variable and six continues variables. The model consists of one objective function, 15 constraints used to handle the linearization, and 10 ordinary constraints. All indexes, variables, and parameters used in the

Table A.1
List of indexes, variables, and parameters used in the appendix.

Indexes	
i, j	Region
k, k_2	All products, i.e., final products, intermediate products, and roundwood categories
f	Final products
w, w_2	Roundwood categories
l	Final and intermediate products
n	Linearization numbering
t	Production activity
ti	Time step
p	Pulp and paper categories
b	Biofuel product
tb	Biofuel production activity
r	Recycled paper grade
FS	Biofuel factory size
Variables used for linearization SOS2 variable	
λ^a	Consumption
λ^b	Harvest
λ^c	Harvest of harvest residuals
λ^e	Input of labour
λ^f	New investments
Integer variable	
δ	Counting number of biofuel production unit
Value steps	
x^a	Consumption
x^b	Harvest
x^c	Harvest of harvest residuals
x^d	Size of biofuel production unit
x^e	Input of labour
x^f	New investments
Variable	
γ	Consumption
φ	Production
θ	Harvest
ω	Interregional trade
ϵ	Harvest residues
Θ	Downgrading
Scalars	
N^a	Number of segments for linearization of consumption
N^b	Number of segments for linearization of harvest
N^c	Number of segments for linearization of harvest residuals
N^d	Number of segments for linearization of biofuel production
N^e	Number of segments for linearization of input of labour
N^f	Number of segments for linearization of new investments
An	Annuity factor
NP	Net present value of an investment
Parameters	
Γ	Reference price
ζ	Reference consumption
τ	Price elasticity
α	Roundwood supply shifts periodically according to changes in growing stock via this parameter
β	Econometrically estimated roundwood supply elasticity
η	Reference roundwood price delivered to gate mill
χ	Reference harvest
S	Growing stock
κ	Growing stock rate
μ	Intercept for harvest residuals
ν	Slope harvest residuals
D	Interregional cost for transportation
I	Investments costs
ι	Exogenous production costs
Λ	Input of products with exogenous costs
a	Input of product

(*continued on next page*)

Table A.1 (*continued*)

R	Recycling rate
Ξ	The technical potential of harvest residuals
ξ	Labour costs for biofuel production
Π	Operation cost for biofuel production
ρ	Investments cost for biofuel production
ψ	Max fraction of pulpwood and sawlogs
υ	Binary parameter counting spruce and pine
Φ	Parameter with costs of new investments
ϖ	Unit labour costs

model are shown in Table A.1.

A.1 The objective function

NFSM is solved by maximising the objective function:

$$\max\left[\sum_{i,f} Rconsume_{i,f} - \sum_{i,w} Charvest_{i,w} - \sum_{i} CharvestResidues_i - \sum_{i,b,tb} Cbiofuel_{i,b,tb} - \sum_{i,l,t} Clabour_{i,l,t} - \sum_{i,j,k} Ctrans_{i,j,k} - \sum_{i,l,t} Cproduction_{i,l,t} - \sum_{i,l,t} CNewInvestments_{i,l,t}\right]$$

where the first-term represents the inverse demand function, i.e., the consumers surplus. Second-term represent the harvest supply function. Third-term represents cost of harvesting harvest residuals. Fourth-term represents the cost of biofuel plants. Fifth-term represents the labour costs. Sixth-term represents the cost of interregional trade. The seventh-term represents the maintenance and other exogenous production costs. While the eighth-term represent the cost of increasing the industrial production capacity.

The values used in the objective function is solved with use of a piecewise linearization [60].

Calculation of sales revenue is shown in Eqs. (A.1)–(A.3). Where $Rconsume_{i,f}$ is defined as the total revenue of final product f in region$i$. In the linearization of the revenue function, two dummy variable are in use: $x^a_{i,f,n}$ and $\lambda^a_{i,f,n}$, where $x^a_{i,f,n}$ is predefined range of possible consumption levels with N^a pieces in range from zero to the double of the reference value and $\lambda^a_{i,f,n}$ is a SOS2 variable. The SOS2 variable is used for ensuring one out of two outcome: (1) if the level of consumption $\gamma_{i,f}$ hit exactly a level in $x^a_{i,f,n}$, then only one number in $\lambda^a_{i,f,n}$, is different from zero (binary case). Or, (2) if the level of consumption $\gamma_{i,f}$ hit somewhere between the levels defined in $x^a_{i,f,n}$, than two neighbouring numbers in $x^a_{i,f,n}$ are different from zero (SOS2 case), with the constraint that they add up to 1 (A.3).

$$Rconsume_{i,f} = \sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} * \left(\left\{\Gamma_{i,f} - \frac{\Gamma_{i,f}}{\tau_f}\right\} * x^a{}_{i,f,n} + \frac{1}{2}\left\{\frac{\Gamma_{i,f}}{\zeta_{i,f} * \tau_f}\right\} * (x^a{}_{i,f,n})^2\right) \;\forall\; i, f \tag{A.1}$$

$$\gamma_{i,f} = \sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} * x^a{}_{i,f,n} \;\forall\; i, f \tag{A.2}$$

$$\sum_{n=1}^{N^a} \lambda^a{}_{i,f,n} = 1 \;\forall\; i, f \tag{A.3}$$

where $\Gamma_{i,f}$ and $\zeta_{i,f}$ are the reference price and reference consumption of final product f in region i, respectively, while τ_f is the price elasticity.

Cost of harvest (A.4)–(A.6), cost of harvesting harvest residuals (A.8)–(A.10), cost of labour (A.13)–(A.15), and cost of installing new capacities (A.16)–(A.18) are linearization in the same way as for sales revenue (A.1)–(A.3).

The cost of harvesting roundwood ($Charvest$) is calculated using SOS2 variable $\lambda^b{}_{i,w,n}$ and range $x^b_{i,w,n}$ with N^b segments. $\beta_{i,w}$ is econometrically estimated roundwood supply elasticity for roundwood category w in region$i$. $\alpha^t_{i,w}$ is estimated with use of Eq. (A.7), for the first year ($ti = 1$)$\alpha^{ti}_{i,w}$ is calculated using reference price $\eta_{i,w}$ and reference harvest$\chi_{i,w}$. For the second year ($ti = 2$) $\alpha^{ti}_{i,w}$ is calculated using reference standing stock $S_{i,w}$ and for the subsequent years ($ti > 2$) $\alpha^{ti}_{i,w}$ is calculated with use of the modelled standing stock $S^{ti}_{i,w}$. The standing stock is growing at a rate $\varkappa_{i,w}$ and reduced by harvesting $\theta_{i,w}$. For more detailed description of α and β are found in [22].

$$Charvest_{i,w} = \sum_{n=1}^{N^b} \lambda^b_{i,w,n} * \left(\frac{\alpha^t_{i,w}}{\beta_{i,w}+1}\right) * (x^b_{i,\;w,n})^{\beta_{i,w}+1} \quad\forall\quad i, w \tag{A.4}$$

$$\theta_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * x^b{}_{i,w,n} \;\forall\; i, w \tag{A.5}$$

$$\sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} = 1 \;\forall\; i, w \tag{A.6}$$

$$\alpha^{ti}_{i,w} = \begin{cases} \dfrac{\eta_{i,w}}{\chi_{i,w}^{\beta_{i,w}}}, & if\ ti = 1 \\ \alpha^{ti-1}_{i,w} / \left(\dfrac{[\{((1+\varkappa_{i,w}) * S^{ti-1}_{i,w}) - \theta^{ti-1}_{i,w}\} + S^{ti-2}_{i,w}]\,/\,2}{S^{ti-2}_{i,w}}\right)^{\beta_{i,w}}, & if\ ti \geqslant 2 \end{cases}, \quad\forall\quad i, w \tag{A.7}$$

Cost of collection harvest residuals ($CharvestResidues$) is estimated with use of $\lambda^c{}_{i,n}$ and range $x^c_{i,n}$ with N^c segments. Where μ_i and ν_i is the intercept and slope of harvesting harvest residuals in region i, while ϵ_i is the amount of collected harvest residuals.

$$CharvestResidues_i = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * \left\{\mu_i * x^c_{i,n} + \frac{1}{2} * \nu_i * (x^c_{i,n})^2\right\} \;\forall\; i \tag{A.8}$$

$$\epsilon_i = \sum_{n=1}^{N^c} \lambda^c{}_{i,n} * x^c{}_{i,n} \quad \forall \quad i \tag{A.9}$$

$$\sum_{n=1}^{N^c} \lambda^c{}_{i,n} = 1 \quad \forall \quad i \tag{A.10}$$

Cost of producing biofuel (*Cbiofuel*) is estimated using the integer variable $\delta_{i,tb,FS}$ where *tb* is the technology used in production of biofuel (b) and FS is the name of the discrete biofuel unit production volume with size $x^d_{i,b,tb,FS}$ and N^d is the total number of factory sizes NFSM can choose between. Each discrete factory size has their own labour costs ($\xi_{i,b,tb,FS}$), operation costs ($\Pi_{b,tb,FS}$), and investment costs ($\rho_{b,tb,FS}$), NP is used to calculate the net present value of the biofuel investment, while $\varphi_{i,b,tb}$is the production level of biofuel.

$$Cbiofuel_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * (\xi_{i,b,tb,FS} + \Pi_{b,tb,FS} + NP * \rho_{b,tb,FS}) \ \forall \ i,\ b,\ tb \tag{A.11}$$

$$\varphi_{i,b,tb} = \sum_{FS=1}^{N^d} \delta_{i,tb,FS} * x^d{}_{i,t,tb,FS} \ \forall \ i,\ b,\ tb \tag{A.12}$$

Cost of labour input (*Clabour*) is estimating using the SOS2 variable $\lambda^e{}_{i,l,t,n}$ and range$x^e_{i,l,t,n}$ with N^e segments. Labour costs ($\varpi_{i,l,t,n}$) is divided in to 4 segments with the first segment represent zero production which lead to zero labour cost, second segments represent 1% of the reference production capacity for product (l), produced with technology (t) in region (i). The third segment represents the reference production, for production between the second and third segment lead to a unit labour cost equal to the reference unit labour costs. Finally, the last segment represent production above the reference value, this will give a linearly increased unit cost from the reference labour cost with 1% increase in unit labour cost when 1% increased production above the reference quantity. $\varphi_{i,l,t}$ is the production of product (l) with production activity (t) in region (i).

$$Clabour_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * \varpi_{i,l,t,n} \quad \forall \quad i,\ l,\ t \tag{A.13}$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * x^e{}_{i,l,t,n} \quad \forall \quad i,\ l,\ t \tag{A.14}$$

$$\sum_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} = 1 \quad \forall \quad i,\ l,\ t \tag{A.15}$$

The costs of new production facility (*CNewInvestments*) is estimated with use of the SOS2 variable $\lambda^f_{i,l,t,n}$ and range $x^f_{i,l,t,n}$ with N^f segments. The range $x^f_{i,l,t,n}$ consists of the reference production capacity for production of l with use of technology t in region i or the new production capacity with the previous period investment. $\Phi_{i,l,t,n}$ is zero for segments (N^f) that represent production less than 120% of reference production for pulp and paper industry and 140% for rest of the model. For production over the threshold, $\Phi_{i,l,t,n}$ is estimated as a unit increase cost. If the production level for two subsequent year is far below the installed capacity will the model, assume that the production unit has been partly or fully closured, it will then have a cost to increase the production level in a following year.

$$CNewInvestments_{i,l,t} = An * \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * \Phi_{i,l,t,n} \ \forall \ i,\ l,\ t \tag{A.16}$$

$$\varphi_{i,l,t} = \sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * x^f{}_{i,l,t,n} \ \forall \ i,\ l,\ t \tag{A.17}$$

$$\sum_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} = 1 \ \forall \ i,\ l,\ t \tag{A.18}$$

In addition to the linearized costs, the objective function include two parts which are calculated directly, this is (1) *Cproduction* (A.19) that represent the annuity (An) of the investment cost (I_l) of product (l) and exogenous given production costs, where ι_i and $\Lambda_{i,t}$ represent the exogenous price and input of exogenous product in region$i$, respectively, produced with use of technology$t$. In addition to (2) *Ctrans* (A.20) that represent the transportation cost of transporting quantity $\omega_{i,j,k}$ with unit costs $D_{i,j,k}$ for product (k) between region i and region$j$.

$$Cproduction_{i,l,t} = [An * I_l + \iota_i * \Lambda_{i,t}] * \varphi_{i,l,t} \quad \forall \quad i,\ l,\ t \tag{A.19}$$

$$Ctrans_{i,j,k} = \omega_{i,j,k} * D_{i,j,k} \quad \forall \quad i,\ j,\ k \tag{A.20}$$

A.2 Constraint

The objective function is solved with following constraints:

$$\theta_{i,k} + \sum_{k_2} \Theta_{i,k,k_2} - \sum_{l,t} \varphi_{i,l,t} * a_{k,l,t} - \gamma_{i,f} + \epsilon_i + \sum_j \omega_{j,i,k} - \sum_j \omega_{i,j,k} = 0 \quad \forall \quad i,\ k \tag{A.21}$$

$$\sum_{k,k_2} \Theta_{i,k,k_2} = 0 \quad \forall \quad i \tag{A.22}$$

$$\theta_{i,w} * \upsilon_{w,w} \le \psi_{i,w} * \sum_{w_2} \upsilon_{w,w_2} * \theta_{i,w_2} \quad \forall \quad i,\ w \tag{A.23}$$

$$\sum_{i,p,t} \varphi_{i,p,t} * a_{r,p,t} \le \sum_{i,p} R_p * \gamma_{i,p} \quad \forall \quad r \tag{A.24}$$

$$\epsilon_i \le \Xi \sum_w \theta_{i,w} \quad \forall \quad i \tag{A.25}$$

$$\varphi_{i,l,t},\ \gamma_{i,f},\ \theta_{i,w},\ \epsilon_i,\ \omega_{i,j,k} \ge 0 \ \forall \ i,\ j,\ f,\ l,\ k,\ w \tag{A.26}$$

where $a_{k,l,t}$ is the input of product k in production of product l with use of technology$t$. $\Theta_{\mathrm{i,k,k_2}}$ is the amount of product k that are downgrading to product k_2 in region i. $\upsilon_{w,w}$ is a binary parameter that relates spruce sawlogs and pulpwood and pine sawlogs and pulpwood. $\psi_{i,w}$ are the max amount of sawlogs and pulpwood allowed in each region i, while R_p is the assumed recycling rate of paper grade p.

Eq. (A.21) ensure that every product and roundwood have to be used as either input in industry, consumption by final consumer, downgraded, or traded with other regions. Eq. (A.22) ensure that the amount of original product is equal the amount of the downgraded product. Eq. (A.23) ensures that harvest of pulpwood and sawlogs not exceed the possible fraction of each of the quality. Eq. (A.24) ensure that the use of recycling paper grade (r) not exceed a predefined recycling rate. Eq. (A.25) ensure that the harvest of harvest residuals not exceed the theoretical limit (Ξ) as a function of harvest, and finally (A.26) ensure that every variable is non-negative. In this study, the total production of bioheat and biopower assumed equal to the reference demand in each regions.

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Paper III

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Modelling effects of policies for increased production of forest-based liquid biofuel in the Nordic countries

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ABSTRACT

The Nordic countries have ambitious plans to reduce the use of fossil fuels. One possible solution is to blend biofuel into the liquid fuel mix. A large share of this biofuel could potentially be produced from forest biomass, which is an easily available resource in the Nordic countries. However, technologies for producing liquid biofuel from forest-based biomass are immature, implying high risk for biofuel investors. This study assesses six different support schemes that may increase the attractiveness of investing in forest-based liquid biofuel production facilities. Furthermore, the study simulates the likely effects of policy schemes on the future production of forest-based liquid biofuels using a partial equilibrium forest sector model. The study applies an n^{th} plant estimate for the costs of various biofuel technologies and analyses investment support, feed-in premiums, quota obligations, increase in fossil fuel taxes, biofuel tax exemptions, and support for using harvest residues. According to the model results, a feed-in premium gives the lowest needed subsidy cost for production levels below 6 billion L (25% market share) of forest-based biofuel, while quota obligation is the cheapest option for production levels above 6 billion L. The necessary subsidy level is in the range of 0.60–0.85 €/L (82–116% of the fossil fuel cost in 2030) for realistic amounts of biofuel production. The pulpwood prices increase up to 24% from the base scenario due to increasing biomass demand.

1. Introduction

The European Union (EU) has set a target to reach 10% renewable energy in the transportation sector by 2020 and 14% by 2030 (European Commission, 2018a; 2018b; Wilson, 2019). In order to increase the renewable share, EU member states may introduce different kinds of policy mechanisms, such as feed-in tariffs, feed-in premiums, quota obligations, tax exemptions, tenders, and investment support (European Commission, 2018c). Neither the EU states nor the other participants in the European Economic Area (EEA), i.e. the EFTA member states Iceland, Liechtenstein, and Norway, have harmonized subsidies across member states. Instead, the European Commission leaves the member states to choose their own subsidy schemes and level of subsidy when it comes to environmental issues, as long as the subsidy conforms to the requirements set by the European Commission (2018c). However, the European Commission (2018c) considers feed-in premiums more appropriate than the other subsidy schemes since feed-in premiums encourage producers to be coupled with the market. The subsidy schemes mentioned above may all be feasible for increasing biofuel production in the Nordic countries, where incentives such as green certificates, tax exemptions, investment support, flexible grid tariffs, feed-in premiums, and feed-in tariffs are widely used in the heat and power sectors (Sandberg et al., 2018).

In the Nordic countries, several plans exist for producing forest-based liquid biofuel, but none have been implemented (Nyström et al., 2019). This may be partly because lack of technological maturity, which makes forest-based biofuel risky to investors. Another aspect is that the policy supporting biofuel consumption does not distinguish between locally produced biofuel and imported first- and second-generation biofuel. Although Norway has a separate target for using advanced biofuel (Lovdata, 2018), it is not directly targeting forest-based biofuel. Moreover, there is a raw material competition between traditional, new forest industry, high value forest products, energy, and biofuel, which makes the availability of low cost raw material suitable for biofuel production uncertain. All this may lead to reduced optimism and interest in biofuel plant investments. More targeted subsidies may be introduced, which may increase production. From a policy point of view, it is essential to find policy schemes that target the problem precisely and effectively, at the lowest cost to society.

The economic potential of investing in forest-based liquid biofuel is not only interesting from a climate mitigation viewpoint, but also for the economic development of the forest and forest industries as several

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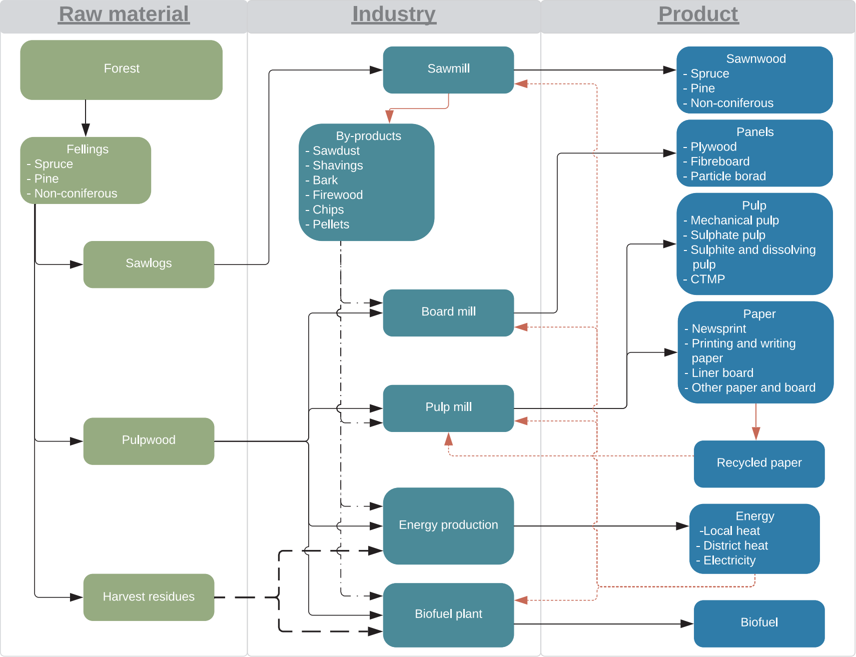

Fig. 1. Flowchart of the mass flow in NFSM, covering the raw materials, the main groups of industrial processes and the main final products.

studies have shown that large-scale biofuel production would heavily affect the Nordic forest sector markets (Jåstad et al., 2019; Kallio et al., 2018; Lundmark et al., 2018; Mustapha et al., 2017b; Trømborg et al., 2013).

Among previous studies analysing biofuel policies, Raymond and Delshad (2016) conclude that normative schemes are more influential than economic schemes for increasing the use of biofuel in the US. According to Khanam et al. (2016), a total biofuel subsidy equal to the ordinary emission taxes of fossil fuel decreases the consumer costs of purchasing biofuel by 7.7% and increases the biofuel consumption by 15%. Similarly, Ribeiro et al. (2017) conclude that the market share of advanced biofuel in the US could increase from today's level (2.01%) up to 27.4% with a 50% petrol tax and a 50% biofuel price subsidy.

Other studies have investigated the necessary level of subsidy that will make biofuel production profitable. For example, Zhao et al. (2016) calculate the breakeven price for a fast pyrolysis process in the US to be 0.74 ± 0.06 €/L. Similarly, Dimitriou et al. (2018) estimate the necessary subsidy for a Fischer-Tropsch biodiesel to become competitive with fossil fuel in Europe to be 12 €/ton of dried wood (0.14 €/$L_{biofuel}$). According to Dimitriou et al. (2018), there is a 14% probability that biofuel production cost would meet the market price of fossil fuel without subsidy by learning effects and optimum design of the plant, but if the tax on biofuel is reduced by 8%, the probability of profitable production increases to 50%.

While most of the abovementioned studies have focused on first-generation biofuel or the US market for biofuel, very few studies have addressed policy instruments for second-generation biofuel based on woody biomass, and, to our knowledge, no previous studies of forest-based biofuel policy impacts have accounted for the competition for biomass from the traditional forest industries. Hence, the main objective of the present paper is to quantify the level of subsidy needed for various policies to increase forest-based liquid biofuel production and thereafter the economic impacts of such an increase on the rest of the forest sector. For this purpose, we use a forest sector modelling approach wherein the interactions between the biofuel and forest industries are properly addressed.

The study quantifies the approximate biofuel subsidy levels needed to reach various biofuel market shares in the Nordic countries in a profitable way (for the producers). It also compares the costs of different types of support and how they affect the rest of the forest sector.

We have organized the paper as follows: Section 2 describes the method and main assumptions we have used; Section 3 describes the results; Section 4 discusses the results; and finally, Section 5 provides the study's conclusion.

2. Method

2.1. NFSM

We use the Nordic forest sector model (NFSM), which is a spatial, partial equilibrium model covering forestry, the forest industry, and the bioenergy sector in Norway, Sweden, Finland, and Denmark. The model structure is built on the Norwegian Trade Model (NTM) (Bolkesjø et al., 2005; Trømborg and Solberg, 1995; Trømborg and Sjølie, 2011) that originates from the Global Trade Model (GTM) (Kallio et al., 1987). NFSM has recently been used to find optimal locations of biofuel production (Mustapha et al., 2017b), to estimate total production costs for biofuel production in the Nordic countries (Mustapha et al., 2017a), and to estimate implication for the Nordic forest sector if large investments in forest-based biofuel are made in the Nordic countries (Jåstad et al., 2019).

NFSM maximizes social welfare (i.e. consumer plus producer surplus) for each simulation period. The solution provides market equilibrium prices and quantities for each period and region as shown by Samuelson (1952). NFSM simultaneously estimates roundwood supply, industrial production, consumption of final products, and trade between regions. The model has 29 different products, including six types of roundwood (spruce, pine, and non-coniferous sawlogs and pulpwood), harvest residues, nine types of intermediate products, and 13 final products (three sawnwood grades, three board grades, four paper grades, local and district heating, and biofuel). Fig. 1 shows a flowchart of the main mass flow in NFSM. Norway, Sweden, and Finland are modelled with ten regions in each country, while Denmark accounts for one region, as does the rest of the world, see appendix B for regionalization details. For further explanation of the model, see appendix A.

The model is solved as a mixed integer linear programming (MILP) problem, with the CPLEX solver using the General Algebraic Modelling System GAMS (GAMS Development Corporation, 2017).

2.2. General model assumptions

In this study, we use data and assumptions from Mustapha (2016). The most important assumptions regarding the Nordic forest sector are shown in Table 1. In this study, we run the Nordic Forest Sector Model (NFSM) in a single-year mode (i.e. the reference year 2013) and we hence assume that all market adjustment, including new investments, as a result of new subsidies occur immediately. The currency in the model is euro and the average exchange rates for the reference year are assumed valid.

2.3. Biofuels – cost and technology assumptions

Biofuel can be produced by different conversion routes with different levels of economic maturity, efficiency, and other technical parameters (Mustapha et al., 2017a). In this study, we assume that the biofuel production unit uses 1.0 MWh of biomass, 0.021 MWh of electricity, and 0.25 MWh of natural gas in order to produce 35 L (0.33 MWh) of gasoline and 25 L (0.25 MWh) of diesel. These assumptions correspond to a biomass carbon efficiency of 58% and a total energy efficiency of 46%, which is in line with Serrano and Sandquist (2017). We also assume the same efficiency for different types of raw materials used for biofuel production in the model: spruce, pine, and non-coniferous pulpwood; residuals from sawmills; harvest residues; and a mix of these materials. The model will choose the cheapest available raw materials for producing biofuel. The model assumes that new investments are in fixed size production units with the following sizes 150, 300, 450, and 600 MW feedstock capacity. Table 2 shows the exogenous production costs for the different production unit sizes. All costs are estimated as yearly costs. We calculate the yearly investment costs – annuity – based on an interest rate of 10% p.a. and a payback time of 25 years. Table 3 shows the main exogenous product prices in NFSM and the total fossil fuel consumption in the Nordic countries.

In 2017, the total Nordic fossil fuel consumption was about 24.3 billion L (SCB, 2018; SSB, 2018; Statistics Denmark, 2018; Tilastokeskus, 2018). We assume a constant fuel demand, i.e. that the total demand does not depend on the fuel price. The model chooses the cheapest option of locally produced biofuel with or without subsidy and fossil fuel at a constant spot price; the model has to fulfil the total demand for liquid fuel. In practice, 100% of the demand is fulfilled with fossil fuel until the production cost of biofuel and subsidy falls below the spot price of fossil fuel. The production cost of biofuel increases with increasing biofuel volumes. We assume equal transportation costs for biofuel and fossil fuel.

2.4. Subsidy schemes analysed

As a way of stimulating biofuel producers, Norway, Finland, and Denmark have introduced quota obligations. In Norway in 2019, 12% of the fuel traded must be biofuel, of which 4.5% (with double counting) has to be so-called advanced biofuel (Lovdata, 2018). Norway will increase the biofuel share to 20% in 2020 (Lovdata, 2018; Ministry of Climate and Environment, 2017). Finland has set the quota obligation at 15% and plans to increase it to 20% in 2020 (Petroleum and Biofuels, 2018). Meanwhile, Denmark has set its quota obligation at 5.75% and plans to increase it to 10% by 2020 (Energistyrelsen, 2018). In 2018, Sweden has implemented obligations to reduce total carbon emissions from liquid fuel with 2.6% for gasoline and 19.3% for diesel compared the fossil alternative. The emission reduction obligations, in line with the renewable energy directive (European Commission, 2018b), correspond to a 23–51% share of biodiesel and a 3.7–5.3% share of bioethanol. The Swedish goal is to reach a 70% reduction by 2030 (Regeringskansliet, 2018). The EU has a goal of using a share of at least 6.8% biofuel in the liquid fuel mix, and a minimum of 3.5% of the liquid fuel mix has to be advanced biofuel (Wilson, 2019).

The assumptions for the subsidy schemes analysed are described in Table 4, and the implementation is shown in Appendix A.3.

2.5. Sensitivity analysis

We test the sensitivity of the results for some of the main parameters regarding biofuel production and the forest sector. These parameters are the following:

1. The conversion efficiency of biofuel production – which is 58% (base) in the base scenario – ranges from 42% (low) to 74% (high). The low and high levels are based on the range found in Serrano and Sandquist (2017).
2. The discounting rate used for calculating the yearly capital costs of a biofuel plant – which is 10% (base) in the base scenario – ranges from 5% (low) to 15% (high).
3. There is a cap on maximum allowed harvest in each country. The cap is set first at the reference harvest level shown in Table 1 (ref.) and then at the forest reference level (FRL). In Norway, the forest reference level for the period 2021–2030 is set to 14.5 million m^3 solid ub. as a yearly average (Klima- og miljødepartementet, 2019), in Finland to 68 million m^3 solid ub. (Jord- och skogsbruksministeriet, 2018), in Sweden to 77 million m^3 solid ub. (Miljödepartementet, 2019), and in Denmark to 3.65 million m^3 solid ub. (Johannsen et al., 2019).
4. The production capacity in pulp and paper production is 46 million tons (base) in the base scenario; this number is increased exogenously with two new chemical pulp mills that both consume 2 million m^3 solid/year[1] (increase).
5. The sensitivity of roundwood logging and transportation costs range from −25% (low) to +25% (high) relative to the base level.

3. Results

3.1. Required price of fossil fuels

For a given level of cost, biofuel investments may be triggered in one of the two following ways: (i) the price of fossil fuels increases above the cost level of biofuels, or (ii) the additional costs of biofuels are compensated for through policy.

We quantify the first mechanism in Fig. 2, which shows how the modelled biofuel production increases with increasing fossil fuel prices without any policy measures in place. According to these assumptions, a fossil fuel price of 1.3 €/L is needed for the first biofuel production units to produce. This is about three times the baseline price (see Table 3). Above this level, each € cent/L increase in the fossil fuel price will lead to about a 225 million L increase in the production of biofuels.

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[1] The plants are located in Värmland in Sweden and in Karelia in Finland.

Table 1
The base production, harvest, roundwood prices, exchange rate local currency/€, and elasticity of roundwood supply adapted from (Mustapha, 2016).

		Norway	Sweden	Finland	Denmark
Production	Sawnwood [million m^3 solid]	2.21	18.6	9.73	0.36
	Fibreboards [million metric tons]	0.17	0	0.07	0.01
	Particle boards and plywood [million m^3 solid]	0.42	0.89	1.13	0.35
	Pulp & paper [million tons]	1.53	22.2	21.5	0.5
	Chips, briquettes, firewood [TWh]	4.79	39.4	40.3	15.3
Harvest	Sawlogs [million m^3 solid ub.]	4.63	34.5	19.5	0.80
	Pulpwood, including chips [million m^3 solid ub.]	6.75	41.3	34.2	2.60
	Harvest residues [TWh]	0	7.55	6.01	0.28
Exchange rate	Local currency/€	7.81	8.62	1.00	7.46
Price delivered at gate	Sawlogs [€/m^3 solid ub.]	68	76	74	68
	Pulpwood [€/m^3 solid ub]	36	48	49	38
Price elasticity of roundwood supply	Sawlogs	0.8	0.6	1.0	0.8
	Pulpwood	1.2	0.8	1.2	1.2

Table 2
Labour [h/1000 l], fixed and investment costs [€/L/year], and production level [million L/year] for the different plant sizes [input feedstock]. Source: Serrano and Sandquist (2017).

Input feedstock	150 MW	300 MW	450 MW	600 MW
Labour input [h/1000 L]	0.57	0.44	0.38	0.34
Fixed costs [€/L/year]	0.56	0.49	0.45	0.42
Investment cost [€/L/year]	0.40	0.34	0.31	0.29
Production [million L/year]	79	157	236	315

Table 3
Assumed prices for inputs and outputs, and observed consumption levels for transportation fuels, for the Nordic countries.

	Norway	Sweden	Finland	Denmark	Source
Electricity [€/MWh]	39.9	41.3	42.9	54.4	Eurostat (2018)
Natural gas [€/MWh]	36.1	36.1	36.1	36.1	Serrano and Sandquist (2017)
Labour [€/h]	39	20	18	27	Eurostat (2017)
Fossil gasoline [€/L] – base year	0.43	0.43	0.43	0.43	Drivkraft Norge (2018a)
Fossil diesel [€/L]- base year	0.44	0.44	0.44	0.44	Drivkraft Norge (2018a)
Fossil fuel price 2030 [€/L] – used in scenarios	0.73	0.73	0.73	0.73	IEA (2017)
VAT [%]	25	25	24	25	Drivkraft Norge (2018b)
Special fuel taxes gasoline [€/L]	0.66	0.64	0.65	0.62	Drivkraft Norge (2018b)
Special fuel taxes diesel [€/L]	0.53	0.42	0.50	0.46	Drivkraft Norge (2018b)
Consumption diesel [million L]	3831	6197	3236	3048	SCB (2018); SSB (2018); Statistics Denmark (2018); Tilastokeskus (2018)
Consumption gasoline [million L]	1089	3400	1834	1673	SCB (2018); SSB (2018); Statistics Denmark (2018); Tilastokeskus (2018)

3.2. Required subsidy level

In the results presented below, the price of fossil fuel is kept constant at 0.73 €/L (corresponding to a crude oil price of $94/barrel), which is in line with the expectations of the IEA's New Policies Scenario for fuel prices by 2030 (IEA, 2017). The support level for the different policy instruments is gradually increased in the model runs. For the investment support alternative, we observe that due to high variable costs, even an investment support level of 100% does not cause any biofuel investments. Similarly, a complete tax exemption from the special fuel taxes is not sufficient to create profitable investments. In other words, investment support and tax exemptions alone are likely not sufficient to trigger biofuel production. Investment subsidies may, however, reduce investors' risk. Lower risk should reduce investors' required rate of return and hence may help make biofuel investments more attractive. This effect is, however, not included in the model.

For the other five subsidy schemes listed in Table 4, the model finds that biofuel investments and production are profitable for support over a specific threshold: feed-in premiums induce production at a subsidy level of 0.62 €/L; fossil fuel tax increases lead to production at 0.61 €/$L_{\text{fossil fuel}}$; harvest residues support results in production starting at 52 €/MWh_{input}, which corresponds to 0.86 €/L; and finally, quota obligations result in biofuel production both overall and in each of the Nordic countries (Fig. 3b).

3.3. Cost of subsidy schemes

The total direct costs of the different subsidy schemes are shown in Fig. 3a, while the unit costs are shown in Fig. 3b. The modelled total cost rises steadily with the amount of biofuel produced due to increasing raw material prices and transport costs. The support needed to reach a certain biofuel quantity is substantially higher for the harvest residues support scheme (cf. Table 4) than for the alternatives. For the four remaining subsidy schemes, there are only minor differences in the total impact on production levels up to about a 30% share of biofuel production. For larger volumes, quota obligations require less support than feed-in premiums and fossil fuel tax increases at high production volumes ($>$ 25%). This is because quota obligations support the difference between producer cost (Fig. 3c) and fossil fuel price. One possible solution for reducing the gap between producer cost and fossil fuel retail prices is to increase the retail price. Meanwhile, feed-in premiums represent a fixed amount of subsidy producers get for producing. Quota obligations increase linearly with production cost, while the costs associated with feed-in premiums and increasing fossil fuel taxes do not increase linearly because of the increasing raw material costs.

Assuming renewable directives figures (European Commission, 2019) for savings from Fischer-Tropsch diesel based on farmed land, a subsidy level of 0.70–1.00 €/L equals a net carbon reduction cost of 256–366 €/ton CO_2. The total cost of reducing 10 million tons CO_2 (around 19% of the current Nordic emissions from transportation (Eurostat, 2019)) is estimated to be 2.7 billion €/year.

The unit production cost of biofuel always increases with increasing biofuel production (Fig. 3c) due to increased chips prices. Production costs are highest for national quota obligations due to higher labour costs and less accessible biomass in Norway and Denmark than in

Table 4
Assumptions regarding subsidy schemes, abbreviation, and modelled range.

Scheme	Abbreviation	Description	Min level	Max level
Feed-in premium	Feed-in	Biofuel producers get a premium when producing biofuel. Simulated as a flat value that is added to the market price.	0 €/L	1.1 €/L
Increase in fossil fuel tax	Fossil inc.	Increase in the fossil fuel tax. Assumed to result in the same increase in fossil fuel retail prices.	0.73 €/$L_{\text{fossil fuel}}$	1.8 €/$L_{\text{fossil fuel}}$
Investment support	Invest	Implemented as a reduction in the capital costs.	0%	100%
Quota obligation for all Nordic countries	Nordic quota	Forest-based biofuel has to cover a minimum share of the total fuel consumption in the Nordic countries.	0%	50%
Quota obligation each country independently	National quota	Forest-based biofuel has to cover a minimum share of the total fuel consumption in each of the Nordic countries.	0%	50%
Raw material support	Raw	Support for using harvest residues as raw material for biofuel production.	0 €/MWh_{input} (0 €/Lbiofuel)	75 €/MWh_{input} (1.25 €/Lbiofuel)
Tax exemption	Tax	Biofuels get tax exemptions for special fuel taxes.	0%	100%

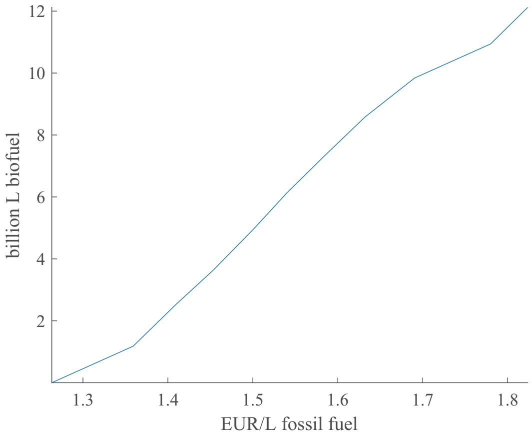

Fig. 2. Modelled biofuel production with increasing diesel and gasoline prices, assuming no policy support and no fossil fuel tax.

Sweden and Finland. The lowest unit costs are observed for harvest residues support due to the low demand for harvest residues in rest of the forest sector.

Harvest residues support has the lowest production costs (Fig. 3c) and highest subsidy costs (Fig. 3b) since the socioeconomic costs for the entire forest sector are highest for harvest residues support. The reason for this effect is that increased utilization of harvest residues, within limits, has few spillover effects on the rest of the forest sector. This means that the socioeconomic cost of harvest residues support is almost equal to the actual costs to the government since the market effects on the rest of the forest sector are relatively small. On the other hand, the other policies will lead to greater market gain and reduced need for governmental support since increased biofuel production will increase the roundwood prices, resulting in increased income for forest owners. The increased income for forest owners is higher than the decrease in production levels for pulp and paper producers; all together this increases the total welfare in the forest sector and reduces the need for governmental support.

3.4. Implications for the forest sector

Wood-based biofuel production implies an increase in demand for wood; hence, policies supporting biofuel will affect forestry and other forest industries. The modelled changes in harvest level and price for sawlogs and pulpwood for increasing subsidy levels are shown in Fig. 4. As expected, increasing subsidy levels, which is similar to increasing biofuel production levels, causes higher harvest levels and wood prices. Apart from the harvest residues support scheme, all subsidy schemes have more or less the same impact on harvest levels and prices. For the harvest residues support scheme, however, prices and harvests remain on the reference level up to a subsidy level of 75 €/MWh_{input} (1.25 €/L). From that point, harvest increases and price decreases rapidly because all easily available harvest residues are collected. From a harvest residues subsidy of 75 €/MWh_{input}, forest owners would harvest more roundwood in order to sell more harvest residues to the biofuel producers, and this additional roundwood would decrease roundwood prices.

For sawmills, the subsidy of biofuels would have two indirect impacts: (i) the sawlogs harvest level would tend to increase since the demand for pulpwood increases pulpwood prices, and (ii) the price received for sawmilling residues such as chips, dust, and bark would increase as these are used for bioenergy purposes. The overall impacts

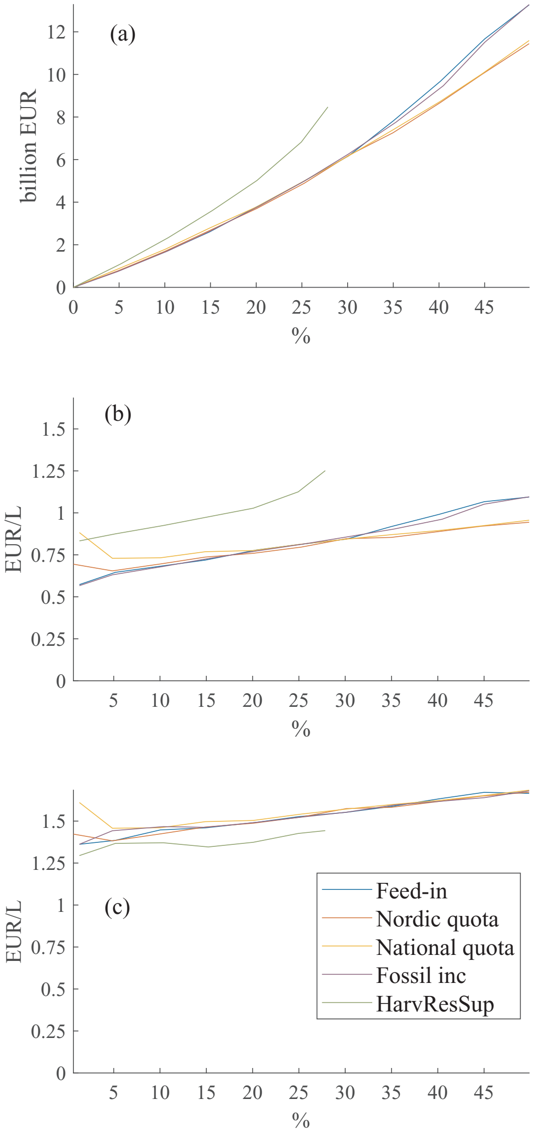

Fig. 3. Modelled total (a) and unit (b) subsidy amount needed for biofuel production, and the unit production cost (c), for the different support schemes, plotted against the volume share of biofuel in the Nordic countries (assuming 2017 consumption of liquid fuel), see Table 4 for scenario explanations.

are hence increasing sawlogs harvest levels and prices, increasing sawnwood production (Fig. 5a), and decreasing sawnwood prices (Fig. 5b).

While the impacts to the sawmill industry are rather modest, a more notable impact is seen for the modelled pulp and paper production (Fig. 5c) due to significantly increasing pulpwood prices. Moreover, pulp and paper prices increase slightly (Fig. 5d). Also, in terms of production and prices, the subsidy for harvest residues deviates from the rest of the case due to less competition for raw materials.

3.5. Regional results

Appendix B (Table B.1) shows modelled biofuel production at a regional level for the national and Nordic quota obligations scenarios at 20% biofuel production. According to these results, the biofuel production will mainly be located in central and southern Sweden and southern Finland. At a regional level, the highest production volume is found in the areas around Oslo (N2), Stockholm (S6), and Helsinki (F10). These areas have low, or no, pulp and paper production and are at the same time close to consumers. It should be noted that most of the production happens in the areas with high activity in the forest sector, e.g. regions in central Sweden and central Finland. When assuming national instead of Nordic quota obligations, the model solution has significantly lower production volumes in Finland, especially in the region around Helsinki, and an equal increase in production in Denmark. The harvest levels increase in all regions when biofuel investments are included. This increase is most significant in F2 and F8.

3.6. Sensitivity analysis results

All nine alternatives (sensitivities) described in chapter 2.5 are tested for feed-in premiums, fossil fuel tax increases, harvest residues support, and Nordic and national quota obligations. In order to make the results comparable, the subsidy level is kept constant within each of the five different policy schemes. The subsidy levels assumed in the sensitivity scenarios are feed-in premiums at 0.783 €/L, fossil fuel tax increases at 0.779 €/$L_{\text{fossil fuel}}$ (total fossil fuel price 1.51 €/$L_{\text{fossil fuel}}$), harvest residues support at 61.6 €/MWh_{input}, Nordic quota obligations at 19.5%, and national quota obligation at 19.9%. These subsidy levels resulted in close to a 20% biofuel share in the base scenarios (Fig. 3).

The biofuel production level (Fig. 6) for the Nordic quota obligation is not sensitive to any of the tested sensitivity parameters; the reason for this is that the quota obligations scheme ensures a constant minimum level of biofuel production. On the other hand, we find significant changes regarding the subsidy cost of using a quota obligations scheme (Fig. 7). The changes in the subsidy cost follow the changes in production cost when the raw material costs change.

The unit subsidy level (Fig. 7) is not sensitive to the tested parameters for feed-in premium and fossil fuel tax increase. The reason for this is that the subsidy is defined based on a unit of biofuel, making it sensitive to production volume (Fig. 6). The unit subsidy for harvest residues support is only sensitive to the conversion efficiency. This follows from the fact that the subsidy is based on the unit input of raw material.

The studied policy schemes almost do not change the production level of biofuel (Fig. 6) or the subsidy cost (Fig. 7) for the sensitivity parameters harvest restriction and increase in pulp and paper production capacities. The reason for this is that these restrictions only introduce a marginal change in the roundwood balance. The strictest harvest restriction lowers the harvest by only 7% (Fig. 8). For the increase in pulp and paper production capacities of total 4 million m^3 solid ub. pulpwood, however, the model will compensate by reducing the production capacities at other plants. The sensitivity of biofuel production and subsidy cost regarding harvest costs is also relatively low; consequently, when the cost of harvest increases by 25%, the market will reduce the demand for roundwood, which will stabilise the price. Biofuel production decreases by a maximum of 6% when the harvest costs increase by 25%, while the pulp and paper production decreases by 12% in the same simulation. This shows that the rest of the forest sector is more affected by change in harvesting costs than biofuel production. This stabilises the raw materials costs for biofuel producers.

The two parameters included in the sensitivity analysis that directly target biofuel production are those with largest changes in production level (Fig. 6) and cost of subsidy (Fig. 7). When changing the interest rate, the largest effect is found for Nordic quota obligations, which has a subsidy cost increase of 15% when the interest rate increases from 10%

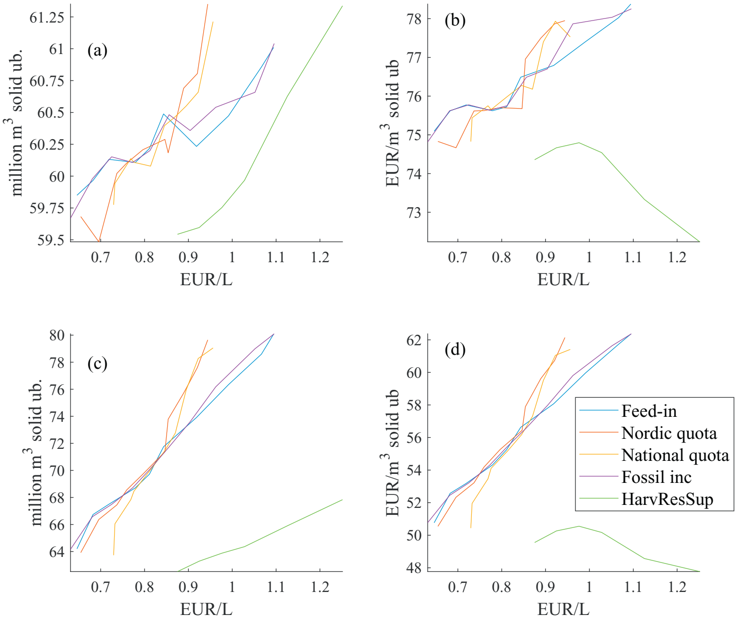

Fig. 4. Modelled sawlogs harvest (a), sawlogs prices (b), pulpwood harvest (c), and pulpwood prices (d) plotted against the unit amount of subsidy in the Nordic countries, see Table 4 for scenario explanations.

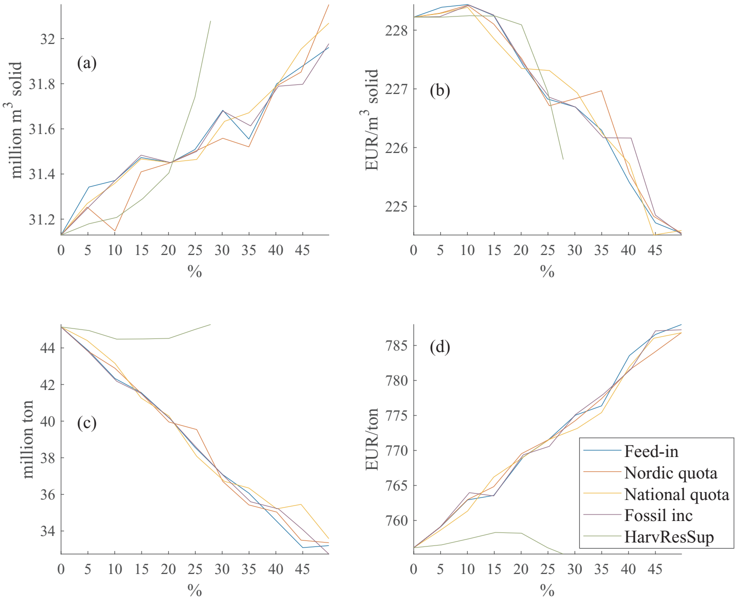

Fig. 5. Modelled sawnwood production (a), sawnwood prices (b), pulp and paper production (c), and pulp and paper prices (d) plotted against the volume share of biofuel in the Nordic countries (assuming 2017 consumption of liquid fuel), see Table 4 for scenario explanations.

to 15%; the production level for feed-in premiums and fossil fuel tax both decrease to 9% blend-in to fossil fuel for the same interest rate. The model is sensitive to conversion efficiency; if the conversion efficiency is reduced from 58% to 42%, the production with feed-in premiums and fossil fuel tax becomes zero, while an increase to 74% efficiency results in an increase in biofuel production to 55% blend-in to fossil fuel.

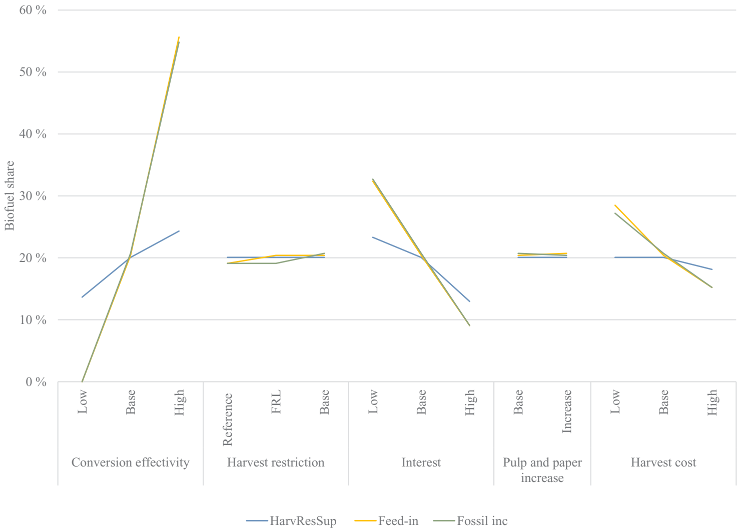

Fig. 6. Modelled fraction of biofuel production (assuming 2017 consumption of liquid fuel) for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in percentage of total liquid fuel consumption. The subsidy schemes for Nordic and national quota obligations are uninfluenced by the different sensitivities regarding biofuel production levels and are omitted in the graphical representation.

4. Discussion

This study uses a partial equilibrium modelling framework. The results show that the breakeven price for forest-based biofuel produced in the Nordic countries is around 1.3 €/L (price for fossil fuels + subsidy). This level is 75% higher than the breakeven price estimates from Zhao et al. (2016). A major reason for higher costs in the present study, compared to Zhao et al. (2016), is that converting roundwood to fuel is a more challenging process than converting corn stover. Another reason may be that labour and construction costs are higher in the Nordic countries than in the US. Hagos et al. (2017) found that a subsidy of 0.43 €/L is enough to promote biofuel production in inland Norway. This is almost half the subsidy level we found for biofuel production (0.7 €/L). The main reason for this difference is a the assumed willingness to pay a higher price for biofuel than fossil fuel (Lanzini et al., 2016), which was included in Hagos et al. (2017) but was not considered in the present study. Baral and Rabotyagov (2017) reported the willingness to pay for forest-based biofuel to be 6% of the fossil fuel price, while Lim et al. (2017) estimate the willingness to pay a premium for bioethanol may be as high as 15.6% of the gasoline retail price, which will reduce the need for subsidies only slightly.

According to the model results, feed-in premiums and increased fossil fuel taxes have similar effects on the optimal biofuel production level. Feed-in premiums lower production costs, while an increase in the fossil fuel tax increases the alternative fuel price. Although these two policies may influence the market similarly, their distributional

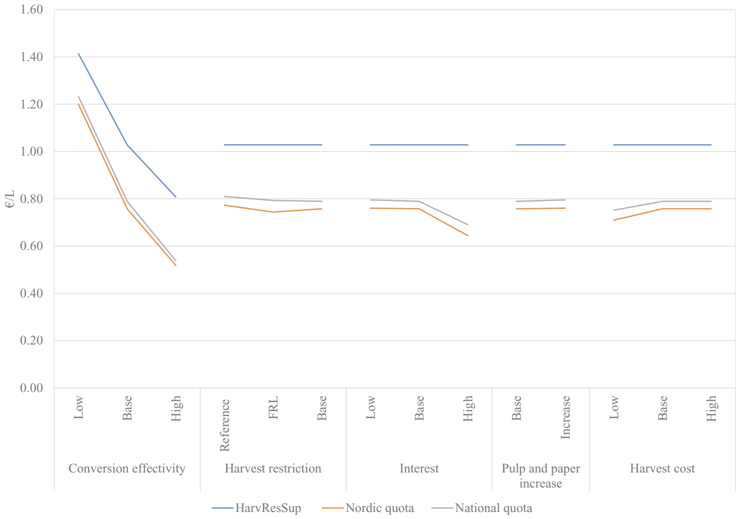

Fig. 7. Modelled unit subsidy cost for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in €/$L_{biofuel}$. The subsidy schemes for feed-in premium and increasing fossil fuel tax are uninfluenced by the different sensitivities regarding subsidy cost and are omitted in the graphical representation.

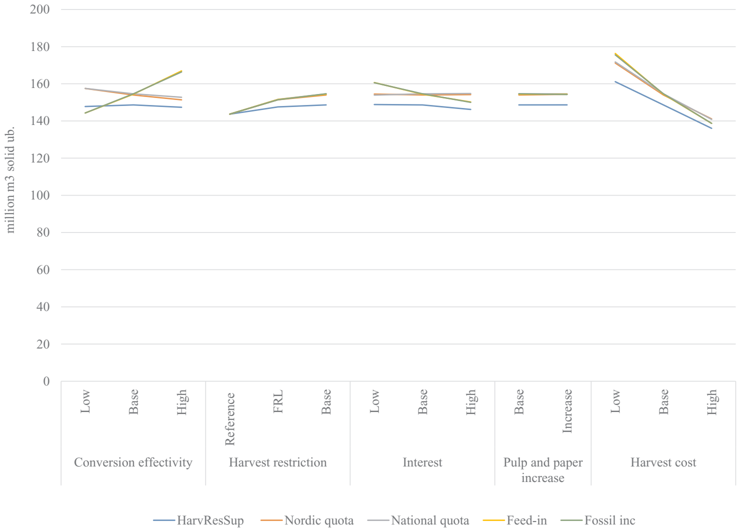

Fig. 8. Modelled harvest level for the different sensitivity parameters (chapter 2.5) and subsidy schemes (Table 4), given in 1000 m^3 solid ub.

effects are different. For feed-in premiums, the government supports the producers directly for each unit of biofuel produced. This means that the costs of the policy are shared among all taxpayers. For increased fossil fuel tax, the fuel consumer pays via increased fuel prices. When interpreting the results, it should be stressed that the model assumes fully rational and informed producers and consumers, and that the economic valuation of the climate benefits of reducing the use fossil fuel or costs of indirect land use are not included in the economic benefits. A possible impact of increasing fuel taxes is a lower total demand for liquid fuel and increased use of fossil fuel substitutes such as electric cars. The model does not cover this effect.

Harvest residues have barely been used to this end for applications other than district heating. In this study, we assume harvest residues can be used as a raw material in biofuel production. Our results show that harvest residues support schemes may increase biofuel competitiveness, but their feasibility depends on the support level. If the support is too low (< 50 €/MWh_{input}, according to this study) no harvest residues will be used for biofuel production, while if the support is too high (exceeds 75 €/MWh_{input}, according to this study), forest owners will increase roundwood harvest to increase their residues supply. This in turn might lead to lower roundwood prices. For lower subsidy levels, it will be possible to utilize harvest residues for biofuel production without interfering with the traditional forest sector. Luke (2019) reports a selling price for logging residues in the Finnish market of 17.7 €/m^3, which means that a subsidy of 60 €/MWh_{input} is 3.4 times higher than the market price. Thus, subsidising harvest residues makes sense if the goal is to support forest owners, but it is not the most effective means of increasing production of forest-based biofuel. It should, however, be noted that the short and long run climate impacts of bioenergy from long rotation crops are widely debated (Cintas et al., 2017; Guest et al., 2013; McKechnie et al., 2011; Norton et al., 2019). The use of harvest residues for energy purposes is regarded favourably in this perspective since the alternative leads to a rather rapid decay of the stored carbon in the tops and branches. Simply put, this will shift the emission from decaying harvest residues to the time of combustion. Support of harvest residues relative to virgin wood fibre in biofuel production may hence be optimal from a climate viewpoint although the cost per litre produced is higher.

The model results show that the needed policy costs for quota obligations, feed-in premiums, and fossil fuel tax increases are at similar levels for the range of 0–30% biofuel implementation. Above 30%, feed-in premiums and fossil fuel tax increases have higher total costs than quota obligations. Both feed-in premiums and fossil fuels taxes should be relatively easy to implement since feed-in premiums are already in use in the power sector and fossil fuel tax already exist, but politically they may be difficult to introduce. However, to reach a renewable share target for transportation, increasing the fossil fuel tax is likely to be more effective than feed-in premiums since higher fossil fuel prices will not only stimulate investments in forest-based biofuel but also increase the use of electric cars and other renewable fuel alternatives. On the other hand, introducing a feed-in premium will make it possible to target forest-based biofuel, which is equal to stimulate the production of forest-based biofuel at the expense of food-based biofuel. This will not be possible with an increase in the fossil fuel tax without further regulations. Feed-in premiums may also support less mature technologies and ultimately boost technology learning since the premium may vary between technologies. Regardless of which type of subsidy is used to increase the implementation of biofuels, a long time horizon is important, as is the predictability of the subsidy.

From a governmental point of view, quota obligations may be the most profitable scheme since they ensure that the production of biofuel continues, even with significant changes in the production cost or alternative fuel cost, but the consumer price may change dramatically. The main drawback with quota obligations is that the produced volume of biofuel will be reduced with reduced liquid fuel demand. Thus, with this approach, biofuel producers will bear the risk of increased use of electric cars. On the other hand, a feed-in premium will ensure a stable production of biofuel even if the use of liquid fuel decreases, as long as the production cost and fossil fuel spot price is almost stable. This shows that over time the different schemes will give rise to different risk takers.

All kinds of subsidy schemes have transaction costs, and these costs vary between different types of subsidies (Coggan et al., 2010; Rørstad et al., 2007). Some subsidy schemes may have rather high transaction costs, while others have low costs. Transactions costs are not part of this study, but they may have a large impact on the economic ranking of the subsidy schemes. For instance, increasing fossil fuel prices may have a lower transaction cost than harvest residues support since the method of increasing fossil fuel prices through taxes is already widely used in the Nordic countries and the marginal cost of increasing the tax from 0.66 €/$L_{\text{fossil fuel}}$ to, for example, 1.3 €/$L_{\text{fossil fuel}}$ is relatively low. For harvest residues support, a new reporting system has to be built up, which has (new) operational costs.

There are other types of subsidy besides the ones shown in this study that may lower producers' risk; one option may be reverse auction. Since NFSM is a deterministic model, it is close to impossible to model reverse auction in a satisfactory manner, but the pattern for reverse auction will probably follow the feed-in premium scheme modelled in this paper. Bittner et al. (2015) estimate that the probability of biofuel producers losing money for reverse action is lower than for capital subsidy and that the probability of loss is > 50% for capital subsidy for shorter contracts. This is in accordance with our study since we do not get any investment under the investment subsidy scheme.

For the most part, the sensitivity analyses in this paper did not lead to significant changes in the production of biofuel or subsidy costs. The exceptions to this are conversion efficiency and interest rate. One conclusion that may be drawn from this it that the results are sensitive to the assumption regarding biofuel production but not sensitive to changes in the forest sector. A reason for this is that the chosen level of sensitivity is largest for the biofuel production parameters, but this also reflects the uncertainties in the model quite well. The assumed biofuel plant in this study is yet to be built. There is hence a high uncertainty regarding the ‘real’ conversion efficiency of a commercial biofuel plant.

The NFSM is a regional model which divides the Nordic countries into a total of 31 regions. Although the regionalization gives a proper representation of the current industrial production and harvest, when we introduce biofuel production with endogenously defined location it becomes more uncertain. Since the model maximizes total welfare, the location of a biofuel plant could be decided by its having only marginally better economic conditions than other locations. Since we use fixed size production unit, a marginal change in the biofuel cost may lead to significant changes in the entire forest sector for a given region. When a biofuel producer decides on a location for a biofuel plant, factors besides the availability of raw materials and synergic effects for the traditional forest sector will also be considered. These may include access to educated labour, local taxes or subsidies, price of land, access to existing infrastructure, possibility of using a side stream from existing industry (including non-forest industry), and many other aspects that are not covered by this model.

The model used in this study is a spatial partial forest-sector model; as is the case with all models, the NFSM is a simplification of the real world. The Nordic forest sector is the only part of the economy covered in the study, which leads to assumptions regarding the different intersections. The most important assumption in this study is the assumption regarding demand for fossil fuel. We have assumed constant demand for liquid fuel in the transportation sector; but the demand for liquid fuel will likely decrease if retail prices increase, which may be the case with implementation of large biofuel subsidies. Dahl (2012) found that the demand for gasoline and diesel in the Nordic countries is quite price inelastic (-0.05 to -0.40); for simplicity, we assume that the fuel demand is constant. In the model, we assume that harvest, production, and consumption happen in the regional centres. For this reason, pulp mills, sawmills, and biofuel plants may be co-located in the modelling framework. The reference year used in the NFSM is 2013, and all results depend on the assumptions regarding the forest sector that year.

5. Conclusion

This study assesses the impacts of various energy policies targeted at increasing wood-based liquid biofuel production in the Nordic countries. According to the model results, the fossil fuel spot price plus unit subsidy has to be above 1.3 €/L for wood-based biofuel production to be profitable. Furthermore, to reach a forest-based biofuel share of 20% of the Nordic liquid fuel consumption, a total subsidy level in the area of 3.9–5.3 billion €/year is needed, assuming a fossil fuel price of 0.73 €/L. This support corresponds to a support level of 0.77–1.0 €/L produced biofuel. Correspondingly, to reach 10% and 40% targets, the costs would be 0.67–0.91 €/L and 0.86–0.98 €/L, respectively. For a forest-based biofuel share in the range of 15–25%, quota obligations, feed-in premiums, and increased fossil fuel taxes will have almost the same economic effectiveness according to the present study.

According to the sensitivity analysis, the results are relatively stable for parameters related to the traditional forest sector and more dependent on the assumption when it comes to biofuel production cost. Harvest residues support tends to be more stable than the other schemes when it comes to the tested sensitivities due to lower consumption of harvest residues in other parts of the forest sector.

The study finds that biofuel production will interfere with and reduce the profits of the traditional forest sector. The different subsidy schemes have, to some extent, different implications for forest owners and forest industries; quota obligations, feed-in premiums, and increased fossil fuel taxes will increase pulpwood prices and hence increase forest owners' revenues, as well as raw material costs in the pulp and paper industry. Support of harvest residues, however, will hardly interfere with the traditional forest sector but will instead increase the use of harvest residues. Increased biofuel subsidies will increase the profitability of biofuel production and are important for changing from fossil fuel to biofuel.

Declaration of Competing Interest

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

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Appendix A. Nordic forest sector model

This appendix describes the objective function and constraints used in the Nordic Forest Sector Model (NFSM). NFSM is a linearized mixed-integer model with five special ordered sets of type 2 (SOS2) variables (Lin et al., 2013), one integer variable, and six continuous variables. The model consists of one objective function, 15 constraints used to handle the linearization and 10 ordinary constraints. All indexes, variables, and parameters used in the model are shown in Table A.1.

Table A.1
List of indexes, variables, and parameters used in the appendix.

Indexes	
i, j	Region
k, k_2	All products, i.e., final products, intermediate products, and roundwood categories
f	Final products
w, w_2	Roundwood categories
l	Final and intermediate products
n	Linearization numbering
t	Production activity
ti	Time step
p	Pulp and paper categories
b	Biofuel product
tb	Biofuel production activity
r	Recycled paper grade
FS	Biofuel factory size
h	Harvest residues
F	Fossil fuel
m	Countries

Variables used for linearization SOS2 variable	
λ^a	Consumption
λ^b	Harvest
λ^c	Harvest of harvest residuals
λ^e	Input of labour
λ^f	New investments

Integer variable	
δ	Counting number of biofuel production unit

Value steps	
x^a	Consumption
x^b	Harvest
x^c	Harvest of harvest residuals
x^d	Size of biofuel production unit
x^e	Input of labour
x^f	New investments

Variable	
γ	Consumption
φ	Production
θ	Harvest
ω	Interregional trade
ϵ	Harvest residues
Θ	Downgrading

Scalars	
N^a	Number of segments for linearization of consumption
N^b	Number of segments for linearization of harvest
N^c	Number of segments for linearization of harvest residuals
N^d	Number of segments for linearization of biofuel production
N^e	Number of segments for linearization of input of labour
N^f	Number of segments for linearization of new investments
An	Annuity factor
NP	Net present value of an investment

Parameters	
Γ	Reference price
ζ	Reference consumption
τ	Price elasticity
α	Roundwood supply shifts periodically according to changes in growing stock via this parameter
β	Econometrically estimated roundwood supply elasticity
η	Reference roundwood price delivered to gate mill
χ	Reference harvest
S	Growing stock

(*continued on next page*)

Table A.1 (*continued*)

Parameters	
κ	Growing stock rate
μ	Intercept for harvest residuals
ν	Slope harvest residuals
D	Interregional cost for transportation
I	Investments costs
ι	Exogenous production costs
Λ	Input of products with exogenous costs
a	Input of product
R	Recycling rate
Ξ	The technical potential of harvest residuals
ξ	Labour costs for biofuel production
Π	Operation cost for biofuel production
ρ	Investments cost for biofuel production
ψ	Max fraction of pulpwood and sawlogs
υ	Binary parameter counting spruce and pine
Φ	Parameter with costs of new investments
ϖ	Unit labour costs
M	Matrix that represents which regions are included in which country

Biofuel subsidy parameters	
σ	Feed-in premium given in €/L
Ω	Subsidy for use of harvest residues €/MWh
Δ	Fraction of investment support
ς	Increase in fossil fuel taxes
Ψ	Level of quota obligations

A.1. The objective function

This Section (A.1) is adapted from Jåstad et al. (2019).

NFSM is solved by maximising the objective function:

$$\max\left[\sum\nolimits_{i,f} Rconsume_{i,f} - \sum\nolimits_{i,w} Charvest_{i,w} - \sum\nolimits_{i} CharvestResidues_{i} - \sum\nolimits_{i,l,t} Clabour_{i,l,t} - \sum\nolimits_{i,j,k} Ctrans_{i,j,k} - \sum\nolimits_{i,l,t} Cproduction_{i,l,t} - \sum\nolimits_{i,l,t} CNewInvestments_{i,l,t} - \sum\nolimits_{i,b,tb} Cbiofuel_{i,b,tb} + BioSubsidy\right]$$

where the first term (*Rconsume*) represents the inverse demand function, i.e., the consumers' surplus. The second term (*Charvest*) represents the harvest supply function. The third term (*CharvestReduidues*) represents the cost of harvesting harvest residuals. The fourth term (*Clabour*) represents the labour costs. The fifth term (*Ctrans*) represents the cost of interregional trade. The sixth term (*Cproduction*) represents the maintenance and other exogenous production costs. The seventh term (*CNewInvestments*) represents the cost of increasing the industrial production capacity. The eighth term (*Cbiofuel*) represents the cost of biofuel plants. Finally, the ninth term (*BioSubsidy*) represents the biofuel subsidy that is directly relevant for the objective function, see section A.3 for detailed description.

The values used in the objective function are solved using piecewise linearization (Lin et al., 2013).

Calculation of sales revenue is shown in equation ($A.\ 1 - A.\ 3$), where $Rconsume_{i,\ f}$ is defined as the total revenue of final product f in region i. In the linearization of the revenue function, two dummy variable are used, $x_{i,\ f,\ n}{}^{a}$and $\lambda_{i,\ f,\ n}{}^{a}$, where $x_{i,\ f,\ n}{}^{a}$is predefined range of possible consumption levels with N^{a} pieces ranging from zero to double the reference value and $\lambda_{i,\ f,\ n}{}^{a}$ is an SOS2 variable. The SOS2 variable is used for ensuring one out of two outcomes: (1) if the level of consumption $\gamma_{i,\ f}$ hits exactly a level in $x_{i,\ f,\ n}{}^{a}$, then only one number in $\lambda_{i,\ f,\ n}{}^{a}$ is different from zero (binary case); or (2) if the level of consumption $\gamma_{i,\ f}$ hits somewhere between the levels defined in $x_{i,\ f,\ n}{}^{a}$, then two neighbouring numbers in $x_{i,\ f,\ n}{}^{a}$ are different from zero (SOS2 case), with the constraint that they add up to 1 ($A.\ 3$).

$$Rconsume_{i,f} = \sum\nolimits_{n=1}^{N^a} \lambda^{a}{}_{i,f,n} * \left(\left\{\Gamma_{i,f} - \frac{\Gamma_{i,f}}{\tau_f}\right\} * x^{a}{}_{i,f,n} + \frac{1}{2}\left\{\frac{\Gamma_{i,f}}{\zeta_{i,f} * \tau_f}\right\} * (x^{a}{}_{i,f,n})^2\right) \quad \forall \quad i, f \tag{A1}$$

$$\gamma_{i,f} = \sum\nolimits_{n=1}^{N^a} \lambda^{a}{}_{i,f,n} * x^{a}{}_{i,f,n} \quad \forall \quad i, f \tag{A2}$$

$$\sum\nolimits_{n=1}^{N^a} \lambda^{a}{}_{i,f,n} = 1 \quad \forall \quad i, f \tag{A3}$$

where $\Gamma_{i,\ f}$ and $\zeta_{i,\ f}$ are the reference price and reference consumption of final product f in region i, respectively, while τ_f is the price elasticity.

Cost of harvest ($A.\ 4 - A.\ 6$), cost of harvesting harvest residuals ($A.\ 8 - A.\ 10$), cost of labour ($A.\ 13 - A.\ 15$), and cost of installing new capacities ($A.\ 16 - A.\ 18$) are linearized in the same way as for sales revenue ($A.\ 1 - A.\ 3$).

The cost of harvesting roundwood (*Charvest*) is calculated using SOS2 variable $\lambda^{b}{}_{i,w,n}$ and range $x_{i,\ w,\ n}{}^{b}$ with N^{b} segments. $\beta_{i,\ w}$ is the econometrically estimated roundwood supply elasticity for roundwood category w in region i. $\alpha_{i,\ w}{}^{t}$ is estimated using the equation ($A.\ 7$). For the first year ($ti = 1$) $\alpha_{i,\ w}{}^{ti}$ is calculated using reference price $\eta_{i,\ w}$ and reference harvest $\chi_{i,\ w}$. For the second year, ($ti = 2$) $\alpha_{i,\ w}{}^{ti}$ is calculated using reference standing stock $S_{i,\ w}$, and for subsequent years, ($ti > 2$) $\alpha_{i,\ w}{}^{ti}$is calculated using the modelled standing stock $S_{i,\ w}{}^{ti}$. The standing stock grows at a rate $\kappa_{i,\ w}$ and is reduced by harvesting $\theta_{i,\ w}$. A more detailed description of α and β can be found in (Bolkesjø et al., 2005).

$$Charvest_{i,w} = \sum\nolimits_{n=1}^{N^b} \lambda^b{}_{i,w,n} * \left(\frac{\alpha_{i,w}^{t}}{\beta_{i,w} + 1}\right) * (x_{i,w,n}^{b})^{\beta_{i,w}+1} \quad \forall \quad i,\, w \tag{A4}$$

$$\theta_{i,w} = \sum_{n=1}^{N^b} \lambda^b{}_{i,w,n} * x^b{}_{i,w,n} \quad \forall \quad i,\, w \tag{A5}$$

$$\sum\nolimits_{n=1}^{N^b} \lambda^b{}_{i,w,n} = 1 \quad \forall \quad i,\, w \tag{A6}$$

$$\alpha_{i,w}^{ti} = \begin{cases} \dfrac{\eta_{i,w}}{\chi_{i,w}{}^{\beta_{i,w}}}, \ if \ ti = 1 \\ \alpha^{ti-1}{}_{i,w} \Big/ \left(\dfrac{[\{((1+\kappa_{i,w}) * S_{i,w}^{ti-1}) - \theta_{i,w}^{ti-1}\} + S_{i,w}^{ti-2}] / 2}{S_{i,w}^{ti-2}}\right)^{\beta_{i,w}}, \ if \ ti \geq 2 \end{cases} \quad \forall \quad i,\, w \tag{A7}$$

Cost of collection harvest residuals (*CharvestResidues*) is estimated using $\lambda^c{}_{i,n}$ and range $x_{i,\,n}{}^c$ with N^c segments, where μ_i and ν_i are the intercept and slope of harvesting harvest residuals in region i and ϵ_i is the amount of collected harvest residuals.

$$CharvestResidues_i = \sum\nolimits_{n=1}^{N^c} \lambda^c{}_{i,n} * \left\{\mu_i * x_{i,n}^c + \frac{1}{2} * \nu_i * (x_{i,n}^c)^2\right\} \quad \forall \quad i \tag{A8}$$

$$\epsilon_i = \sum\nolimits_{n=1}^{N^c} \lambda^c{}_{i,n} * x^c{}_{i,n} \quad \forall \quad i \tag{A9}$$

$$\sum\nolimits_{n=1}^{N^c} \lambda^c{}_{i,n} = 1 \quad \forall \quad i \tag{A10}$$

Cost of producing biofuel (*Cbiofuel*) is estimated using the integer variable $\delta_{i,\,tb,\,FS}$, where *tb* is the technology used in production of biofuel (*b*) and *FS* is the name of the discrete biofuel unit production volume with size $x_{i,\,b,\,tb,\,FS}{}^d$, and N^d is the total number of factory sizes NFSM can choose between. Each discrete factory size has its own labour costs ($\xi_{i,\,b,\,tb,\,FS}$), operation costs ($\Pi_{b,\,tb,\,FS}$), and investment costs ($\rho_{b,\,tb,\,FS}$). *NP* is used to calculate the net present value of the biofuel investment, while $\varphi_{i,\,b,\,tb}$ is the production level of biofuel.

$$Cbiofuel_{i,b,tb} = \sum\nolimits_{FS=1}^{N^d} \delta_{i,tb,FS} * (\xi_{i,b,tb,FS} + \Pi_{b,tb,FS} + NP * \rho_{b,tb,FS}) \quad \forall \quad i,\, b,\, tb \tag{A11}$$

$$\varphi_{i,b,tb} = \sum\nolimits_{FS=1}^{N^d} \delta_{i,tb,FS} * x^d{}_{i,t,tb,FS} \quad \forall \quad i,\, b,\, tb \tag{A12}$$

Cost of labour input (*Clabour*) is estimating using the SOS2 variable $\lambda^e{}_{i,l,t,n}$ and range $x_{i,\,l,\,t,\,n}{}^e$ with N^e segments. Labour costs ($\varpi_{i,\,l,\,t,\,n}$) are divided in to 4 segments with the first segment representing zero production, which leads to zero labour cost. The second segment represents 1% of the reference production capacity for product (*l*) produced with technology (*t*) in region (*i*). The third segment represents the reference production for production between the second and third segment leading to a unit labour cost equal to the reference unit labour costs. Finally, the last segment represents production above the reference value; this will give a linearly increased unit cost from the reference labour cost with a 1% increase in unit labour cost for 1% increased production above the reference quantity. $\varphi_{i,\,l,\,t}$ is the production of product (*l*) with production activity (*t*) in region (*i*).

$$Clabour_{i,l,t} = \sum\nolimits_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * \varpi_{i,l,t,n} \quad \forall \quad i,\, l,\, t \tag{A13}$$

$$\varphi_{i,l,t} = \sum\nolimits_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} * x^e{}_{i,l,t,n} \quad \forall \quad i,\, l,\, t \tag{A14}$$

$$\sum\nolimits_{n=1}^{N^e} \lambda^e{}_{i,l,t,n} = 1 \quad \forall \quad i,\, l,\, t \tag{A15}$$

The cost of a new production facility (*CNewInvestments*) is estimated with use of the SOS2 variable $\lambda_{i,\,l,\,t,\,n}{}^f$ and range $x_{i,\,l,\,t,\,n}{}^f$ with N^f segments. The range $x_{i,\,l,\,t,\,n}{}^f$ consists of the reference production capacity for production of *l* with use of technology *t* in region *i* or the new production capacity with the previous period investment. $\Phi_{i,\,l,\,t,\,n}$ is zero for segments (N^f) that represent production < 120% of reference production for the pulp and paper industry and 140% for the rest of the model. For production over the threshold, $\Phi_{i,\,l,\,t,\,n}$ is estimated as a linear unit increasing cost. If the production level for two subsequent years is far below the installed capacity, the model assumes that the production unit has been partly or fully closed, and there will then be a cost to increase the production level in the following year.

$$CNewInvestments_{i,l,t} = An * \sum\nolimits_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * \Phi_{i,l,t,n} \quad \forall \quad i,\, l,\, t \tag{A16}$$

$$\varphi_{i,l,t} = \sum\nolimits_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} * x^f{}_{i,l,t,n} \quad \forall \quad i,\, l,\, t \tag{A17}$$

$$\sum\nolimits_{n=1}^{N^f} \lambda^f{}_{i,l,t,n} = 1 \quad \forall \quad i,\, l,\, t \tag{A18}$$

In addition to the linearized costs, the objective function includes two parts that are calculated directly: these are (1) *Cproduction* (*A*. 19), which represents the annuity (*An*) of the investment cost (I_l) of product (*l*) and exogenous given production costs, where ι_i and $\Lambda_{i,\,t}$ represent the exogenous price and input of exogenous product in region *i*, respectively, produced with use of technology *t*, and (2) *Ctrans* (*A*. 20), which represents the transportation cost of transporting quantity $\omega_{i,\,j,\,k}$ with unit costs $D_{i,\,j,\,k}$ for product (*k*) between region *i* and region *j*.

$$Cproduction_{i,l,t} = [An * I_l + \iota_i * \Lambda_{i,t}] * \varphi_{i,l,t} \quad \forall \quad i, l, t \tag{A19}$$

$$Ctrans_{i,j,k} = \omega_{i,j,k} * D_{i,j,k} \quad \forall \quad i, j, k \tag{A20}$$

A.2. Constraints

The objective function is solved with following constraints:

$$\theta_{i,k} + \sum\nolimits_{k_2} \Theta_{i,k,k_2} - \sum\nolimits_{l,t} \varphi_{i,l,t} * a_{k,l,t} - \gamma_{i,f} + \epsilon_i + \sum\nolimits_{j} \omega_{j,i,k} - \sum\nolimits_{j} \omega_{i,j,k} = 0 \quad \forall \quad i, k \tag{A21}$$

$$\sum\nolimits_{k,k_2} \Theta_{i,k,k_2} = 0 \quad \forall \quad i \tag{A22}$$

$$\theta_{i,w} * \upsilon_{w,w} \le \psi_{i,w} * \sum\nolimits_{w_2} \upsilon_{w,w_2} * \theta_{i,w_2} \quad \forall \quad i, w \tag{A23}$$

$$\sum\nolimits_{i,p,t} \varphi_{i,p,t} * a_{r,p,t} \le \sum\nolimits_{i,p} R_p * \gamma_{i,p} \quad \forall \quad r \tag{A24}$$

$$\epsilon_i \le \Xi \sum\nolimits_{w} \theta_{i,w} \quad \forall \quad i \tag{A25}$$

$$\varphi_{i,l,t}, \gamma_{i,f}, \theta_{i,w}, \epsilon_i, \omega_{i,j,k} \ge 0 \quad \forall \quad i, j, f, l, k, w \tag{A26}$$

where $a_{k,\ l,\ t}$ is the input of product k in production of product l with use of technology t. $\Theta_{\mathrm{i},\ \mathrm{k},\ \mathrm{k}_2}$ is the amount of product k that is downgraded to product k_2 in region i. $\upsilon_{w,\ w}$ is a binary parameter that relates spruce sawlogs and pulpwood and pine sawlogs and pulpwood. $\psi_{i,\ w}$ is the maximum amount of sawlogs and pulpwood allowed in each region i, while R_p is the assumed recycling rate of paper grade p.

Equation (A. 21) ensures that every product and roundwood have to be used as either input in industry, consumption by final consumer, downgraded, or traded with other regions. Equation (A. 22) ensures that the amount of original product is equal to the amount of the downgraded product. Equation (A. 23) ensures that harvest of pulpwood and sawlogs does not exceed a certain fraction of each possible quality grade. Equation (A. 24) ensures that the use of recycled paper grade (r) does not exceed a predefined recycling rate. Equation (A. 25) ensures that the harvest of harvest residuals does not exceed the theoretical limit (Ξ) as a function of harvest. And finally, (A. 26) ensures that every variable is non-negative. In this study, the total production of bioheat and biopower are assumed equal to the reference demand in each region.

A.3. Biofuel policies

A.3.1. Feed-in premium

When the feed-in premium subsidy is activated, the *BioSubsidy* element in the objective function is as shown in (A. 27), where σ is the unit feed-in premium given in €/unit biofuel and $\varphi_{b,\ tb,\ i}$ is production of biofuel b in region i with use of technology tb. The subsidy σ varies between 0 and 1.1 €/L biofuel produced.

$$BioSubsidy = \sigma \sum_{b,tb,i} \varphi_{b,tb,i} \tag{A27}$$

A.3.2. Increase in fossil fuel tax

For the fossil fuel tax increase policy scheme, the cost consumers are willing to pay for biofuel is $\Gamma_{i,\ b}$ in region i, changed to $\Gamma_{i,\ b} = \Gamma_{i,\ b} + \varsigma$ in function (A. 1), where ς is the unit fossil fuel price increase.

A.3.3. Investment support

In the investment support policy scheme, the investment cost $\rho_{b,\ tb,\ FS}$ for biofuel b produced with technology tb and factory size FS is changed to $\rho_{b,\ tb,\ FS} * (1 - \Delta)$ in function (A. 11), where Δ is the fraction of investment support.

A.3.4. Quota obligation for all Nordic countries and for each country independently

For the quota obligation policy scheme, the constraint (A. 28) is added for Nordic quota obligations and the constraint (A. 29) is added for national quota obligations, where $\zeta_{F,\ i}$ is the reference consumption of fossil fuel F in region i and the quota obligation level is Ψ. $M_{m,\ i}$ is a binary parameter that represents the connection between region i and country m and ensures that the quota obligations level Ψ is fully met in each region.

$$\Psi \sum_{F,i} \zeta_{F,i} \le \sum_{b,tb,i} \varphi_{b,tb,i} \tag{A28}$$

$$\Psi \sum_{F,i} \zeta_{F,i} M_{m,i} \le \sum_{b,tb,i} \varphi_{b,tb,i} M_{m,i} \quad \forall \quad m \tag{A29}$$

A.3.5. Harvest residues support

For harvest residues, the support scheme is the *BioSubsidy* element in the objective function as shown in (A. 30), where $\varphi_{b,\ tb,\ i} a_{b,\ tb,\ h}$ is the input of harvest residues h when producing biofuel b with use of technology tb in region i. The unit input subsidy Ω is defined in €/input harvest residues, in this study is the subsidy in ranges 0–75 €/MWh.

$$BioSubsidy = \Omega \sum_{b,tb,i,h} \varphi_{b,tb,i} a_{b,tb,h} \tag{A30}$$

Appendix B. Regional results

The regional harvest and biofuel production are shown in Table B.1. There some regional differences between the Nordic quota and national quota scenarios. In all regions, the harvest level increases when biofuel is included, and there are only small differences between the two scenarios with biofuel production.

Table B.1
Overview of the different regions in the model and the production of biofuel and total regional harvest for the Nordic quota and national quota scenarios. The policy level is 20% quota obligations for both scenarios. Regional harvest without biofuel production is also included for comparison.

NFSM Regions	Regions	**Biofuel production [million L]**		**Harvest [1000 m^3]**		
		Nordic quota	National quota	Without biofuel	Nordic quota	National quota
N1	Østfold	0	0	769	882	882
N2	Akershus, Oslo	315	315	919	1046	1037
N3	Hedmark	0	79	3930	4577	4526
N4	Oppland	0	0	1254	1456	1444
N5	Buskerud, Vestfold	0	315	1276	1435	1442
N6	Telemark, Aust-Agder	0	0	1066	1176	1173
N7	Vest-Agder, Rogaland	0	0	462	505	501
N8	Hordaland, Sogn og Fjordane	0	0	311	332	335
N9	Møre og Romsdal, Sør-Trøndelag	0	0	560	609	619
N10	Nord-Trøndelag, Nordland, Troms, Finnmark	0	315	836	881	881
S1	Norrbottens län	0	0	3980	4123	4143
S2	Västerbottens län	315	315	6533	6953	6978
S3	Jämtlands län	236	0	5008	5304	5325
S4	Västernorrlands län	0	0	6698	7021	7041
S5	Gävleborgs län, Dalarnas län	315	315	11,313	11,933	11,852
S6	Västmanlands län, Uppsala län, Stockholms län, Södermanlands län	630	315	8173	8375	8376
S7	Örebro län, Värmlands län	315	315	8587	9085	8998
S8	Västra Götalands län	315	0	6381	6892	6884
S9	Kalmar län, Kronobergs län, Gotlands län, Jönköpings län, Östergötlands län	315	315	11,826	12,623	12,622
S10	Hallands län, Skåne län, Blekinge län	236	315	7498	7583	7709
F1	Lappi	0	0	3640	3775	3828
F2	Kainuu, Pohjois-Pohjanmaa	315	315	7913	9284	9277
F3	Keski-Pohjanmaa, Pohjanmaa, Etelä-Pohjanmaa	0	0	4691	4879	4879
F4	Keski-Suomi	0	0	4695	4810	4869
F5	Pohjois-Savo	0	0	5434	5542	5583
F6	Etelä-Karjala, Kymenlaakso, Pohjois-Karjala	0	0	8700	9108	9127
F7	Satakunta, Varsinais-Suomi, Åland	315	315	3969	4216	4226
F8	Päijät-Häme, Pirkanmaa, Kanta-Häme	315	315	8955	10,198	9982
F9	Etelä-Savo	0	79	5505	5829	5766
F10	Uusimaa	945	0	1148	1326	1179
D1	Denmark	0	945	3593	3783	3957
Sum		4880	4880	145,627	155,541	155,444

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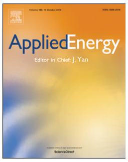

The role of woody biomass for reduction of fossil GHG emissions in the future North European energy sector

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HIGHLIGHTS

- The optimal share of woody biomass for power and heat is estimated to 5–14% in 2040.
- Bioheat will mainly replace coal, natural gas, and wind power in the region to 2040.
- Use of woody biomass may reduce cost of power and heat.
- One TWh woody bio-heat reduce fossil emissions by 10–17 million tonne CO_2 in 2040.
- The substitution effect of biomass declines as the carbon price increases.

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ABSTRACT

In this study, we analyse the use of woody biomass in the heat and power sector in Northern Europe towards 2040 and quantify the fossil GHG-emission reductions from biomass use at different carbon price levels. The applied partial equilibrium energy system model has endogenous capacity investments in relevant heat and power technologies. The results show that use of woody biomass can reduce the direct emissions from the Northern European power and heat sector by 4–27% for carbon prices in the range of 5–103 €/tonne CO_2eq in 2030 compared to a scenario where woody biomass is not available for power and heat generation. The cost of delivering heat and electricity increases with 0.2–0.7% when wood chips are excluded, depending on the carbon price. At a low carbon price, the use of natural gas, wind, and coal power generation increases when biomass is not available for power and heat generation. At higher carbon prices, solar power, wind power, power-to-heat, and natural gas become increasingly competitive, and therefore the use of biomass has a lower impact on emission reductions. Using the same biomass volumes for liquid transport fuel, we find a higher impact on fossil carbon emission reductions but substantially higher costs. The main conclusion from this study is that woody biomass contribution to lowering the fossil emission from heat and power generation in the Northern Europe, and the transition to low carbon energy system will likely be more costly if biomass is excluded from heat and power generation.

1. Introduction

The European Union has set a binding target of 32% renewable energy in the energy mix within 2030, which corresponds to a reduction in GHG emissions of 40% compared to the 1990 level [1]. This reduction requires a significant reduction in emissions from the energy and transportation sector, which accounted for 47% of the union's total GHG emissions in 2017 [2]. In the energy transition needed to reach these targets, multiple fossil-free or emissions-free solutions must grow substantially the coming years and decades. In recent years, wind and solar power have had the largest relative growth in Europe. These variable renewable technologies are expected to continue to increase their market shares in the coming decades, but due to the merit order effect [3], the need for power system balancing [4], and issues related to social acceptance [5], other power and heat technologies will likely also be important in fossil-free energy systems [6].

Bioenergy comprises diverse technologies for generating heat, electricity, and transportation fuel. Used for heating and electricity generation, bioenergy may provide energy security and flexibility in electricity systems with large shares of intermittent renewable energy

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such as wind and solar [7]. In the transport sector, biofuel is one of the few alternatives to fossil fuels for heavy transportation and aviation. Therefore, bioenergy is envisioned as having an important role in fossil free energy systems in the future. For example, the IEA [8] reports that biomass will remain the largest renewable energy source in the Nordic energy system to 2050. Since woody biomass have many other possible applications than heat and power generation, it is highly uncertain how much woody biomass that will be available for power and heat generation in the future. The objective of this study is to analyse the use of woody biomass in the heat and power sector in Northern Europe towards 2040 and quantify the fossil GHG-emission reductions at different carbon price levels.

Welfle et al. [9] conducted several life cycle assessment (LCA) of different biomass grades used for heat generation in UK and found that some conversion pathways reduce the overall GHG emission while other increase the GHG emission. Energy intensive processing step increases the risk of increasing the overall GHG emission. The risk of increasing GHG emission when increasing the use of bioenergy is discussed by Booth [10] and Searchinger et al. [11], while Reid et al. [12] pointed out that bioenergy is important for the transition to low fossil emissions, and that in longer terms bioenergy is beneficial. Gustavsson and Truong [13] points out that biomass within the transportation sector may need as much as 40–50 year before reaching carbon neutrality compared with fossil fuel, and that increasing the use of electricity within transportation is a much faster way to reduce the carbon emissions. On the other hand, there is a rather large literature on forest as carbon sinks and climate change mitigation through forest management [14,15,16,17]. Climate friendly forest management strategies is important in the overall assessment of forests and forest products in climate change mitigation, but in the present study we rather focus on the substitution effects of replacing fossil fuels for biomass.

Other studies have focused on the immediate substitution effects of forest bioenergy on the concentration of GHG-emissions to the atmosphere. Holmgren and Kolar [18] reviewed recent literature and conclude that no studies have found that increased used of bioenergy decrease the carbon emission when solely investigating the substitution effects. This is supported by Rentizelas and Li [19] who studied the effects of imported biomass used for co-firing in a British coal fired power plant, and they found that in order to lower the environmental consequences of electricity production, a low co-firing share is more appropriate than using 100% biomass input. Clancy et al. [20] used a similar approach to study the use of biomass for co-firing in Ireland, and they found that the use of 10 TWh (7.5 times the level in 2016) biomass for co-firing in the heat and electricity sector would contribute to fulfil the Irish climate target in 2030 (total energy consumption in heat and electricity in 2016 was 110 TWh). Finally, Khanna et al. [21] discuss GHG implications of using forest biomass as input in energy production and conclude that the timeframe and how the market reacts are the most determining factors.

Another branch of bioenergy research investigates the system effects of using bioenergy [22,23]. Tsiropoulos et al. [24] and Tsiropoulos et al. [25] used energy sector models for the Netherlands and studied the role of biomass in the energy system. According to these studies, more biomass is used for heating when assuming slow progress of new technologies. When assuming a faster technological progress, they found that more biomass is used for chemicals. Their overall conclusions are that biomass is important for reducing the carbon emissions from the energy sector (heat, power, and transportation). This is in accordance with Zappa et al. [6], who studied the feasibility of 100% renewable energy system in Europe. They pointed out that large-scale mobilisation of Europe's biomass resources is needed in order to be able to fully phase-out fossil fuel. On the other hand, Hagberg et al. [26] found that bioenergy has noteworthy effects on the system cost, but with limited carbon emissions impact due to limited availability. Szarka et al. [27] concluded similarly to Hagberg et al. [26] as they found that most studies project a moderate increase in bioenergy availability towards 2050.

The above literature covers many aspects regarding the role of bioenergy in the future energy system. As shown in Welfle et al. [28] few studies focus on use of wood chips in production of both heat and electricity. And as far as we know, no studies to date have, however, addressed how bioenergy may impact the fossil carbon emission from heat and power generation, with the use of a detailed energy system model that have endogenous investments and cover both heat and power production over multiple regions. It is important to fill this gap, since the carbon impact of woody biomass is highly dependent on what technologies and fuels different bioenergy alternatives displaces. These displacement factors are changing over time as a result of technological development and carbon prices. Sustainable woody biomass is a renewable, albeit limited, resource with many applications. Moreover, forests provide other services besides industrial wood, such as biodiversity and recreational spaces. It is hence important to utilize the woody biomass in ways that have a high impact on fossil fuel emissions while keeping costs low. Against this background, the novelty of the present study is to analyse the cost-optimal use of woody biomass for electricity and heating in the future Northern European energy system and to quantify the extent to which biomass will replace fossil fuels in power and heat generation in the future.

2. Data and methodology

We use a partial equilibrium model (Balmorel) covering the district heat and electricity market in Northern Europe (here represented by Norway, Sweden, Finland, Denmark, the Baltic countries, Poland, and Germany). The model seeks to minimizing cost of producing and delivering heat and electricity, with an hourly time resolution. We focus on the role of using woody biomass for energy production under different carbon price scenarios. To assess the emission impacts of woody biomass, the fossil emissions from the cost-optimal biomass deployment is compared to a case where we assume that no biomass is used for power and heat. Thereafter, we compare the emission impacts from using woody biomass in power and heat with the corresponding effects if the same amounts of biomass were used to replace fossil fuels in the transportation sector.

2.1. The Balmorel model and data

Balmorel is a partial equilibrium model for the North European heat and electricity markets [29]. Balmorel has been continuously developed since the first version in 2001 (see Wiese et al. [30] for a description of the current model). The model itself with data is available at the Balmorel community at Github Repository [31][1]. Below we describe the most important aspects of the model.

The version of Balmorel used in this study optimizes the production of different heat and electricity generation technologies, as well as the transmission of electricity between regions given the assumed exogenously specified demand for heat and electricity while assuming competitive markets. Different primary energy sources are converted into heat and electricity. The most important energy sources included in the model are wind, solar, hydro (with pump, reservoir, and run-of-river), coal, natural gas, nuclear, wood chips, pellets, other bioenergy, and different grades of waste. The primary energy fuel input has exogenously given prices that are equal for all regions in all years, with constant market prices for nuclear at 0.76 €/GJ and wood chips at 7.0 €/GJ. Based on IEA [8], it is assumed that prices will increase for natural gas, from 5.6 €/GJ in 2020 to 9.3 €/GJ in 2040, and for coal,

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[1] The model used in this study is from branch F4R_Final_Model_002 downloaded 21.06.19 (c19cb83b6b4da49951affb8f9f601bea3ccad206), and data is from branch F4R_Final_002 downloaded 21.06.19 (4a0c3434d7c72ca8306c5998fac07a44dbd1e9f4).

Table 1
Technologies data for woody biomass plants for specific technologies (technologies build on known plants), generic, and investment technologies, with plant type, efficiency range, fixed operation costs, operation and maintenance costs, yearly annuity of investment costs, possible investment from year, total number of unique technologies within category and exogenously capacity each modelled year.
Source: [48].

Plant type	Efficiency	Fixed operation costs [k€/MW]	Operating and maintenance costs [€/MWh]	Investment cost - yearly annuity [k €/MW]	Investment from year	Number of unique technologies	Exogenously capacity [MW]		
							2020	2030	2040
Specific technologies									
CHP - Back pressure	89–103%	96.0–97.7	1.11–1.71			12	182	182	114
Generic technologies									
Heat Only	90–120%	39.1	1.26			11	8764	6463	5091
CHP - Back pressure	67–118%	58.8	3.724			17	3258	2264	1294
CHP - Extraction	30%	58.8	3.724			1	92	92	92
Investment technologies									
CHP - Back pressure	114–116%	58.8–274	3.74–6.74	253–459	2020	3			
Electricity only	16–29%	58.8–274	3.74–6.74	253–459	2020	3			
Heat only	117%	37.9	1.26	93.0	2020	1			
CHP - Back pressure	114–116%	49.0–274	3.73–6.74	240–437	2020	3			
Electricity only	16–29%	49.0–274	3.73–6.74	240–437	2020	3			
Heat only	117%	36.8	1.26	88.5	2020	1			

from 2.3 €/GJ in 2020 to 2.7 €/GJ in 2040. Wind, solar, and hydropower have no direct fuel costs. We assumed no upper limit (neither in total amount nor in seasonal levels) on fuel consumption of fossil fuel and biomass, the rationale behind this assumption is that both fossil fuel and biomasses is traded worldwide and may for a shorter period be stored. On the other hand, wind, solar, and hydro has seasonal variations according to historical levels and has upper limits.

The model version of Balmorel used in this study consist of 313 unique technologies, many of the technologies has only marginally differences, example on differences between technologies are: region where the model is available (single region or multiple), year of possible investment, lifetime, exogenously or endogenously capacities, capacity constraints, efficiencies, fuel, variable investment costs, variable costs, fixed costs, and type of plant (heat only, electricity only, CHP with fixed ration between heat and electricity, or CHP with flexible ration between heat and electricity). In addition, variable renewable energy technologies have an exogenously given inflow for every period and region. Table 1 show detailed data for the biomass heat and power technologies used in this study, all other technologies have data with same datelines.

Energy production in Balmorel happens with upper bounds on exogenously or endogenously defined production capacities. Planned capacities, both commission and decommission, are exogenously included in the model, while future investment possibilities are endogenously chosen by the model when market prices cover capital costs and variable production costs. The exogenously installed capacities are show in Fig. 1; the exogenously defined capacities decline over time for all technologies except for hydropower technologies. Decommission of installed capacities follows published phase-out strategies and expected techno-economical lifetimes. It is assumed that the nuclear power plants in Belgium and Germany will be fully decommissioned between 2020 and 2030, which follows known closure plans [32,33].

Due to decommission of existing plants, Balmorel needs to invest in new production units for fulfilling the consumption shown in Table 2. The optimization model estimates investments according to the techno-economically most profitable technology available in order to meet the demand. The final consumption of heat and electricity shown in Table 2 is equal for all scenarios.

The model version used in this study covers supply and demand of district heating and electricity in Norway, Sweden, Finland, Denmark, Estonia, Latvia, Lithuania, Germany, and Poland, and supply and demand of the electricity in Belgium, France, the Netherlands, and the United Kingdom. Each country consists of one or more regions. The model version uses a total of 24 electricity regions, whose borders are similar to the NordPool regions [34], see Fig. 2 for the regional division for the Nordic countries. The transmission capacities are exogenously defined between regions, while within a region, an infinite grid capacity (i.e. a copper plate system) is assumed. A total of 249 heat production, heat consumption, and electricity generation regions are used. Since transmission of district heat need a large network of pipelines and is related to considerable heat losses, we assume that district heat produced within a region cannot be exchanged with neighbouring regions and thus must be consumed in the region in which it is produced.

In this study, we simulate three years – 2020, 2030, and 2040 – with 6 weeks evenly distributed across each year. Within each week we model 72 timesteps – every hour of Mondays, Tuesdays, and Sundays – in total 432 timesteps in each year. We assume perfect foresight within the current year but with no knowledge about the coming years. We further assume only exogenous investment in transmission capacities according to the known investment plans.

A cost-minimizing version of Balmorel is used in this study where the lowest costs are obtained for fulfilling the given energy consumption. The objective function includes cost components such as fuel costs, operation and maintenance costs, reservoir and operation costs for hydro storage, transmission costs, annuity of investment cost of increasing the production, transmission, and electricity and heat storage capacities, and taxes. The most important constraint in Balmorel is the energy balance constraint, which ensures that the sum of energy consumption, production, transmission, losses, and storage of energy is equal to zero for every time step and sub-region.

2.2. Forest biomass and biofuel

The total growing stock in the North European forests is around 12 billion m^3 [35][2]. The annual harvest in the same countries is around 265 million m^3, which corresponds to about 530 TWh [36]. The opportunities to increase the use of forest biomass vary between countries; Sweden harvests more than 90% of annual growth, while Norway and

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[2] 1 million m^3 is approximately equal to 2 TWh lower heating value of primary energy if the roundwood is utilized for energy.

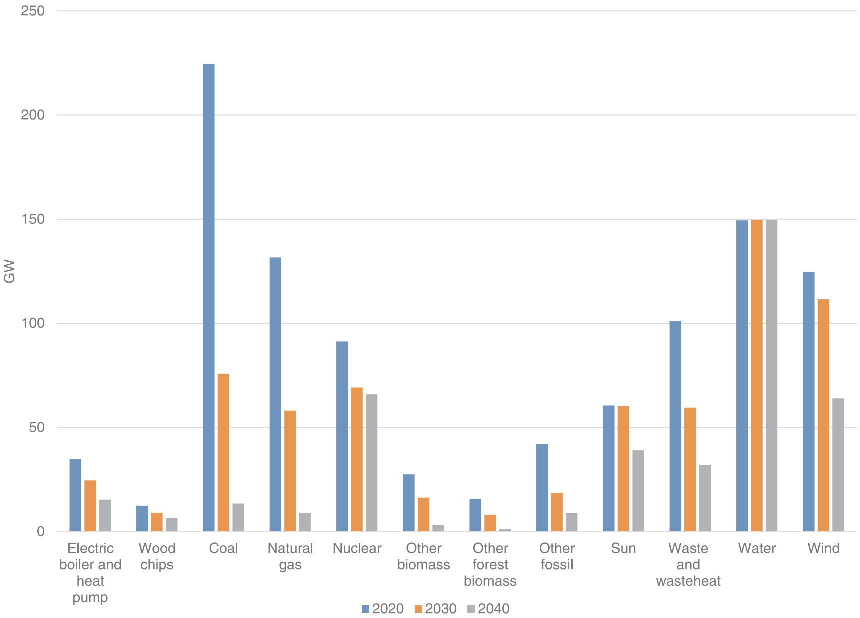

Fig. 1. Exogenous installed electricity and heat generation capacities by fuel/technology (GW), divided by fuel. The exogenous installed capacities in the model decreases following known phase-out plans and expected lifetime.

Table 2
Assumed consumption of heat and electricity (TWh/year), the electricity demand is hold constant for all years and the heat demand increasing for some countries (from-to). Sources: IEA [8] for the Nordic countries, Germany [49] and [50].

	Electricity demand 2020–2040	Heat demand 2020–2040
Germany	530	116
Denmark	32	33
Estonia	7.7	5.0
Finland	82	79–76
Lithuania	6.5	7.7–6.0
Latvia	11	6.0
Poland	144	66–88
Sweden	131	90–85
Norway	121	13–15
Belgium	83	Heat sector not included
France	448	Heat sector not included
Netherlands	111	Heat sector not included
United Kingdom	311	Heat sector not included
Total	2018	415–428

Germany harvest of less than 50% of the reported annual increment. In addition to the harvest, the Northern European countries have a net import of around 11 million m^3 of roundwood each year (Table 3).

When analysing the impacts of using wood chips in biofuel production, we assume a technology similar to hydrothermal liquefaction (HTL), which we assume has the same reduction as Fischer-Torpsch diesel based on managed forests, emitting 5.9 gCO_2/MJ. This is based on the Renewable Energy Directive [37] that states that the fossil GHG savings from forest based biofuel corresponds to 70–95% of the GHG emissions. We assume that 1 TWh biomass will produce 0.58 TWh/58 million L Fischer-Tropsch diesel and reduce the carbon emission from transportation with 0.16 million tonnes CO_2.

In the model, we assume that wood chips cannot be substituted with other types of bioenergy, meaning that changes in the use of wood chips do not affect the use of other kinds of biomass. Wood chips and other biomass materials can be traded between regions. For the alternative use of wood chips for biofuel production, we base our calculation on Serrano and Sandquist [38] with the main assumptions shown in Table 4.

2.3. Scenarios

The use of biomass within the electricity and heating sectors depends largely on the costs of carbon emissions from fossil alternatives, namely EU ETS prices. Chen et al. [39] show that carbon prices are expected to increase, but the long-term carbon price is largely uncertain. In this study, we use carbon prices within the ranges reported by Chen et al. [39] as basis for nine different carbon price scenarios. The carbon price used in all scenarios is 23 €/tonne CO_2eq in 2020, while for 2030 and 2040 the carbon prices vary around the average carbon price found in the literature review. The average carbon price is 37 €/tonne CO_2eq in 2030 and 63 €/tonne CO_2eq in 2040. The impacts of biomass availability (wood chips) are modelled within these carbon price scenarios. In addition to the carbon price scenarios we conduct a sensitivity analysis with endogenously defined transmission line investment.

3. Results

3.1. Fuel and technology mix

In this paper, we focus on forest biomass effects in the energy system in Northern Europe, and for this reason we do not present results for Belgium, the Netherlands, France, and the United Kingdom.

The heat and electricity production from wood chips increases from 90 TWh to 240 TWh when the carbon price increases from 5 to 103 €/tonne CO_2eq. The increase in the use of wood chips occurs mainly in combined heat and power (CHP) plants; their use in heat only plants remains low. In total, around 75% of wood chips are used for heat purposes, and this heat fraction is stable across all carbon price

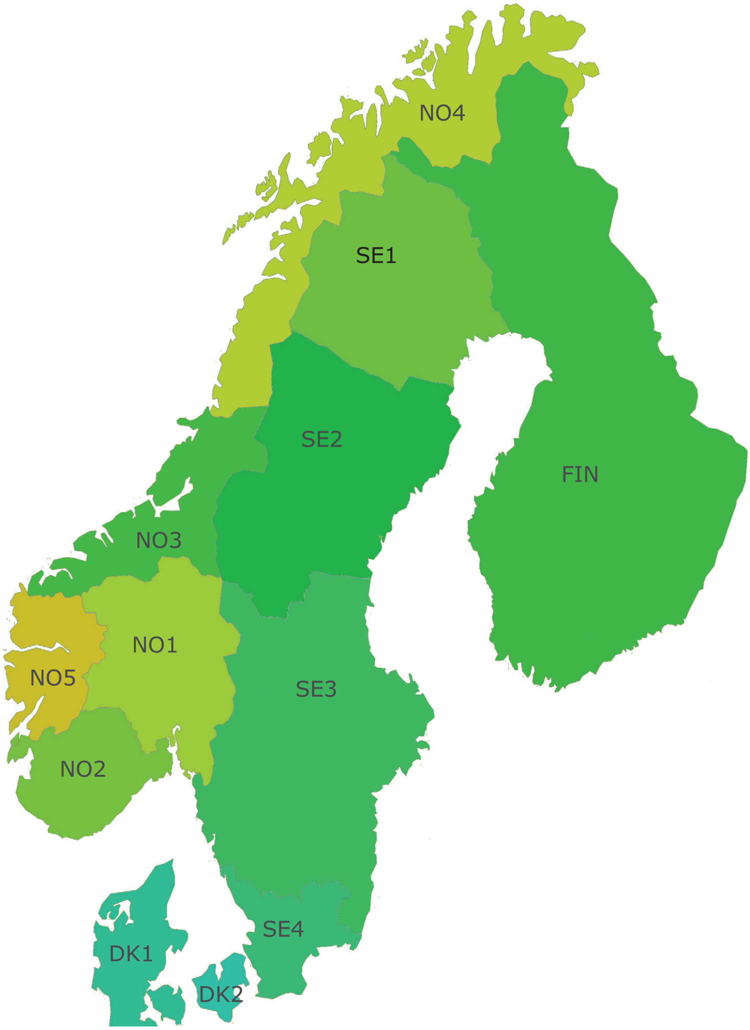

Fig. 2. Regions in the Nordic countries, in addition is Germany divided into 4 regions and Estonia, Latvia, Lithuania, Poland, Belgium, France, the Netherlands, and the United Kingdom dividend into one region each.

Table 3
Total roundwood harvest, harvest of industrial roundwood, domestic use of wood fuel, and net roundwood export in 2016, average annual increment between 2010 and 2015, and growing stocks available for wood supply in 2016 for the different countries.
Source: [35,51].

	Total harvest [mill m^3]	Harvest of industrial roundwood [mill m^3]	Use of wood fuel 2016 [TWh]	Annual increment in forest available for wood supply [mill m^3]	Growing stocks in forest available for wood supply [mill m^3]	Net roundwood export from countries [mill m^3]
Germany	52	43	20	119	3 493	−5.1
Denmark	4	2	4	6	116	0.3
Estonia	10	7	6	12	426	2.6
Latvia	13	11	3	20	616	1.6
Lithuania	7	5	4	11	418	1.1
Poland	42	37	10	62	2 190	0.2
Finland	61	54	14	93	2 099	−5.0
Sweden	75	68	14	79	2 390	−6.4
Norway	12	10	4	26	1 033	3.0
Total	265	227	75	402	11 747	−11

Table 4
Techno-economic data related to biofuel production; the investment cost is based on an annuity factor with 15 years and 10% interest, partly adapted from Serrano and Sandquist [38].

Input per MWh biofuel output		
Biomass	MWh	1.72
Electricity	MWh	0.040
Natural gas	MWh	0.43
Annual capital, maintenance and operating (except biomass, electricity, and natural gas) costs	€	56

scenarios. Wood chips are only used for electricity production in CHP plants. It should be noted that the model only includes district heat and electricity; bioheat in the industrial sector and small-scale heating systems such as local heating systems and wood stoves are not included in the analysis.

Fig. 3 and Fig. 4 show how increased use of wood chips affects electricity and heat production from coal, natural gas, and wind power, as well as heat production from heat pumps and electrical boilers at various carbon price levels. Increased carbon prices reduce the economically optimal deployment of coal, while increasing the use of wood chips and wind power. The use of natural gas increases with increasing carbon prices up to 80 €/tonne CO_2eq in 2030. Thereafter, the natural gas production levels decline slightly. For the 2040 model year, the use of wind power increases until the carbon price exceeds 79 €/tonne CO_2eq, where it becomes almost constant. The reason for this is that the last amount of fossil fuel is needed to balance the energy system; getting rid of the last amount of fossil fuel is difficult with current technologies. In all scenarios is waste and hydro used closed to the theoretically limit and when woody biomass is removed from the simulation, is investment in variable renewable needed in order to covering the reduced use of fossil fuel and woody biomass. The production must cover the demand even in period with low production from solar and wind, this will give investments in expensive storages, or some fossil fuel for use in period with little wind and sun. Woody biomass, on the other hand, contribute to balancing the system, but biomass technologies are, in general, less flexible than natural gas.

Comparison of the model runs with and without wood chips shows that wood chips mainly replace natural gas, in addition to some wind and coal power, as well as heat pumps and electrical boilers in the heating sector. For carbon prices above 60 €/tonne CO_2eq, wood chips substitute the use of natural gas in Germany and Poland, while for carbon prices under 50 €/tonne CO_2eq wood chips substitute mainly natural gas in Finland and Sweden and coal in Germany. This is because Germany and Poland replace coal with natural gas at higher carbon prices in order to minimize costs, while Sweden and Finland mainly replace wood chips with wind power.

The electricity and heat generated from natural gas decrease by 25–82 TWh (15–60%) in 2030 and 45–80 TWh (16–48%) in 2040 when wood chips are included in the fuel mix. Correspondingly, the wind power production decreases by up to 51 TWh (12%) in 2030 and 63 TWh (13%) in 2040 when wood chips are included in the model. The reduction in the use of heat pumps and electrical boilers corresponds to 25–106 TWh (21–43%) in 2030, while the fraction is lower for 2040 (14–119 TWh (10–31%)). The increased use of electricity is flexible but increases the overall electricity consumption and production. Coal is phased out when the carbon price is between 79 €/tonne CO_2eq and 94 €/tonne CO_2eq in 2040, regardless of whether wood chips are used, and the production of heat and electricity from wood chips reduces coal use

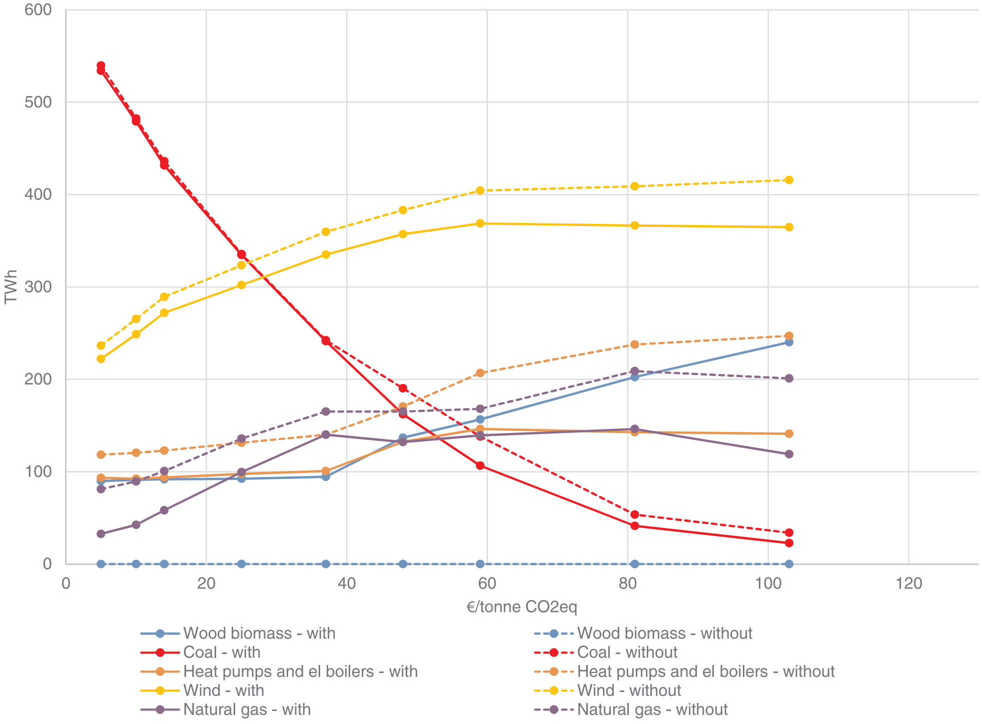

Fig. 3. Modelled production of electricity and heat deliveries in Northern Europe, production mix for different carbon prices, only the main fuel categories are shown. Dotted lines are scenarios without wood chips, while solid lines are with wood chips, for year 2030.

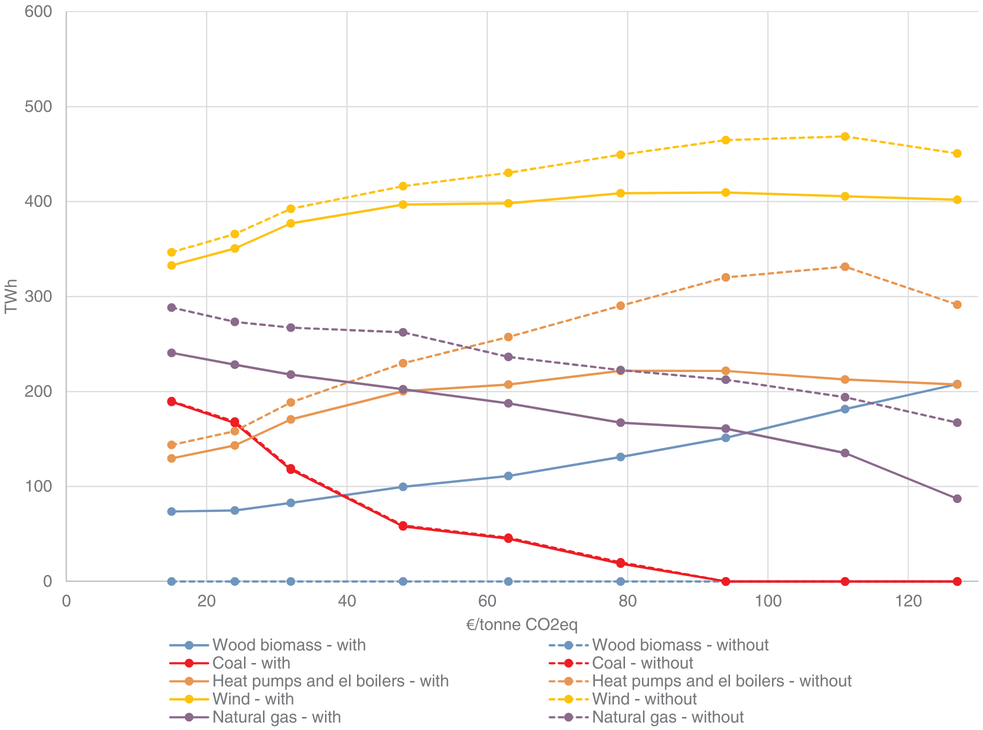

Fig. 4. Modelled production of electricity and heat deliveries in Northern Europe, production mix for different carbon prices, only the main fuel categories are shown. Dotted lines are scenarios without wood chips, while solid lines are with wood chips, for year 2040.

by 32 TWh (23%) in 2030 for a carbon price of 59 €/tonne CO_2eq and is relatively stable for lower carbon prices. The reason for this is that Germany and Poland, which are the largest consumers of coal, are not using wood chips before the carbon price reaches 48 €/tonne CO_2eq.

Biomass combustion may provide valuable system flexibility in the future energy system with high shares of variable renewable energy, since the need for heat storages increases when woody biomass is reduced (Fig. 5), the use of heat storages increase with 3–24% when wood chips are excluded. The use of electric batteries, however, increases slightly in the scenario allowing for wood chips due to reduced fossil CHP capacity and increased use of wind power.

If the carbon prices are higher than 48 €/tonne CO_2eq in 2030, the use of seasonal storage increases by more than 30% when wood chips are excluded due to the increased need for heat storage produced in the summer months relative to the winter months. The interseasonal storages decrease by 7% when chips are included. At lower carbon prices, the impact on interseasonal storages is more limited (1–5%), due to heat production from wood chips that is replaced with higher use of natural gas, which is more flexible.

3.2. Emissions impacts

An important finding from the model runs is that the emission impacts of using wood chips for electricity and heat vary largely with the carbon price assumption (Fig. 6). For 2030, the modelled carbon emissions decrease from 329 million tonne CO_2equivalents at a carbon price of 5 €/tonne to 69 million tonne CO_2eq at a carbon price of 103 €/tonne without the use of chips. In this study, we assume biomass is carbon neutral, and we have not taken emissions related to harvest, transportation, or other types of emission into account. When wood chips are included as an option in the fuel mix, this reduces the emissions from 315 million tonnes CO_2eq to 50 million tonnes CO_2eq. The fossil fuel emission reductions when including wood chips as an option in electricity and heat production decreases by increasing CO_2 prices; this is most significant for carbon prices higher than 37 €/tonne because the optimal use of wood chips is relatively stable within this carbon price span, while wind power and natural gas increasingly outcompete coal-based electricity and heat production. For carbon prices above this level, wood chips become a more competitive alternative to fossil fuels and the optimal use of wood chips (in the 2030 case) more than doubles when the carbon price is increased from 37 €/tonne to 103 €/tonne. Correspondingly, the emissions reduction from fossil fuel combustion varies from 7 to 19 million tonnes CO_2eq when wood chips are included. For the model year 2040, the remaining fossil-based electricity and heat capacity is lower than in 2030, and the optimal use of wood chips increases monotonically with increasing carbon prices from 15 €/tonne to 127 €/tonne. Moreover, the reductions in fossil fuel emissions vary less for different carbon prices than in the 2030 model (minimum of 10 million tonnes CO_2eq and maximum of 17 million tonnes CO_2eq when wood chips are included).

Overall, the economically optimal use of wood chips for electricity and heat varies from 66 TWh to 216 TWh, depending on the model year and carbon price assumption. The reduction of emissions from fossil fuels varies from 7 to 19 million tonnes CO_2eq. If these amounts of wood chips were used for biofuel production, it would yield approximately 3.8–13 billion litres of biofuel. These amounts are equal to 3.4–11% biofuel blend in the 2016 fuel consumption in the Northern European countries (in 2016 the same countries had a 6% blend-in [40]. This amount of biofuel may contribute to reducing the total emissions from road traffic by 11–35 million tonnes CO_2eq.

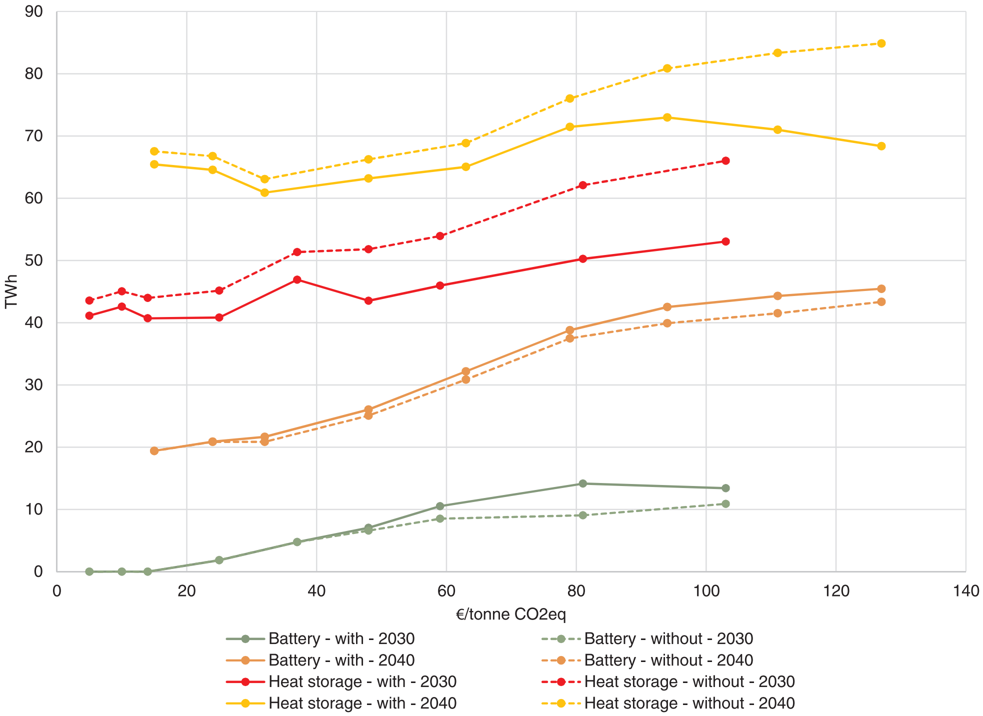

Fig. 5. Modelled energy from batteries and heat storages in Northern Europe, with and without use of wood chips, in 2030 and 2040, for different carbon prices.

Total emissions from using chips for heat and electricity production compared to road traffic is 7.8 million tonnes higher at a carbon price of 37 €/tonne CO_2eq. The difference in emission reductions between heat and electricity production versus biofuel production is relatively low when the carbon price is low (below 14 €/tonne CO_2eq in 2030 and 48 €/tonne CO_2eq in 2040). When assuming a higher carbon price, however, the total carbon reduction for road traffic may be higher than the emissions from heat and electricity production. The reason for this is that for higher carbon prices, wood chips will replace wind to a larger extent as the use of fossil fuels for heat and power production decreases. Fig. 6 shows that while the use of wood chips in heat and electricity production can reduce emissions substantially at constant carbon prices, the reduction is higher if the same amount of wood chips is used for biofuel production, especially at high carbon prices.

3.3. System costs and energy prices

The system cost (i.e. the total cost of producing and delivering energy), corrected for emission taxes (Fig. 7), increases when the carbon price increases and when wood chips are excluded. The system cost increase when not allowing wood chips for electricity and heat varies between 0.2% and 0.7%, depending on the carbon price assumption. The largest system cost differences are seen for carbon prices below 37 €/tonne CO_2eq, according to the model results. For higher carbon prices, the high wind power shares create a need for storage technologies, which to some extent reduces the system value of wood chips. The lowest system cost increase happens with carbon prices above 80 €/tonne CO_2eq. The total system value of wood chips is up to 172 €/tonne CO_2eq, when the carbon price is 37 €/tonne CO_2eq in 2030.

The production cost for wood-based biofuel production is estimated to be around 1.1 €/L, with use of the cost data shown in Table 4 and the heat and power prices shown in Fig. 7. This corresponds to a carbon reduction cost of 389–400 €/tonne CO_2eq, assuming 95% emission reduction comparing fossil fuel. It is thus much more cost efficient to use wood chips to reduce emissions in the heat and electricity sectors since the assumed carbon price is in range 5–103 €/tonne CO_2eq.

As expected, higher carbon prices cause higher power and heat prices. The modelled heat prices (the marginal cost of the last produced unit heat) increase more than the power prices (the marginal cost of the last produced unit electricity) when wood chips are excluded from the fuel mix. About 75% of the wood chips are used for heat production and the heat market is also smaller than the electricity market in total volume, hence the larger price impact in the heat market is not surprising. It should be noted that the heat price shown in Fig. 7 is the weighted average for all regions. In some regions, like Sweden and Finland, the heat price impact is substantially higher than the effects shown in Fig. 7 due to the extensive current use of wood chips for heating. Finland and Sweden have the largest heat price increase when wood chips are excluded, a maximum of 42% and 28% respectively. The reason for this is that those countries use up to 40% and 36% wood chips respectively within the heating sector in the base year. Wood chips cover up to 40% of the produced heat in Denmark, 59% in Germany, and 46% in Latvia, but have respectively only a 19%, 25%, and 3% increase in heat price. This is because Denmark, Germany, and Latvia have low utilization of wood chips in the base year and they must invest in order to use wood chips. When wood chips are excluded, the model simply invests in other technologies with only marginally higher investment costs. Meanwhile, Sweden and Finland use more wood chips in the base year and do not need to invest in wood chips technologies to the same extent as in Germany. When wood chips are excluded, Sweden and Finland invest in other technologies to fulfil the demand. In countries with marginal use of wood chips, such as Poland, almost no changes in heat prices are

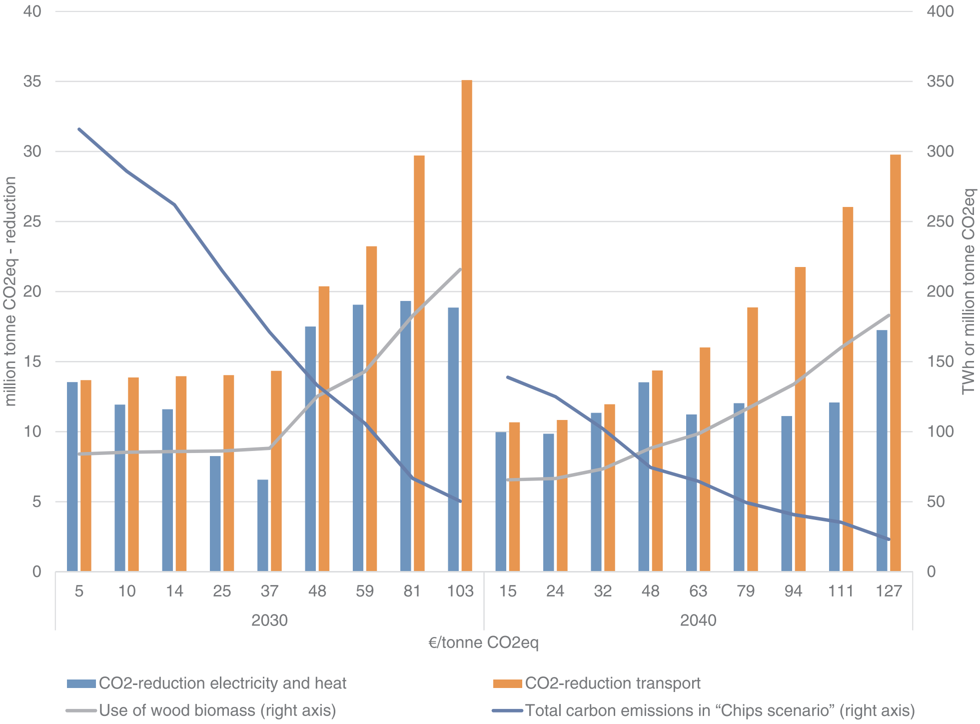

Fig. 6. Modelled use of wood chips (right axis), CO_2 reduction from electricity and heat production (left axis), total emissions when wood chips are included (right axis) from heat and electricity production, and theoretical CO_2 reduction if all wood chips that was used in the model were used for biofuel production (left axis) in Northern Europe in 2030 and 2040 for different carbon prices [€/tonne CO_2eq].

observed.

3.4. Endogenous transmission line investment

In the scenario with only planned transmission line investment, is it assumed that the transmission capacity will increase only according to a predetermined plan. In this section, we look at the effects of the use of wood chips on the energy system when endogenous investments in transmission lines are allowed in the model in addition to planned and implemented investments.

Fig. 8 shows the investment in international cross-border transmission that is added to planned investments when endogenous investment is possible. As shown, the total transmission capacity is 32–123 GW higher than with only planned transmission line investments (Fig. 8). The transmission capacity increases by an additional 4 GW when wood chips are removed from the system. The increase is highest when the carbon price is high because increased use of wind power (up to 138 TWh more production than with planned transmission line investment), which corresponds to increased need for balancing.

When we allow endogenous investments in transmission lines, the use of wind power increases by up to 22% and the use of wood chips increases by 13% compared to only planned transmission line investments. Correspondingly, the use of coal decreases by 13%, heat pump and electrical boilers decreases by 16%, and natural gas decreases by 34%. When comparing the results with and without use of wood chips in endogenous transmission line investment, the use of wind power, heat pumps, and electrical boilers increases even more than in the planned transmission line investment scenario, while the use of natural gas increases less. Use of heat storages increases by 16% when we remove wood chips; this follows the increased use of wind power.

The wood chips–driven reduction in carbon emission is highest for endogenous transmission line investments when the carbon price is under 59 €/tonne CO_2eq in 2030 and under 32 €/tonne CO_2eq in 2040 (Fig. 9), and slightly lower than the scenario with only planned transmission line investment for higher carbon prices. The reason for this is that the total emissions for endogenous transmission capacity scenarios decrease more rapidly for low carbon prices than in the scenario with only planned transmission line investment, while for higher carbon prices, the scenario with only planned transmission line investment decreases fastest because increased transmission capacity helps to balance the system with more wind power.

4. Discussion

This study takes a somewhat different approach than most other studies addressing bioenergy in the energy transition. A main novelty of the present study is that it compares model emissions with cost-optimal deployment against an alternative without use of woody biomass. The model uses endogenously investments in generation capacity, and the temporal resolution of the model are at an hourly level. Through this approach, we are able to assess both the competitiveness of bioenergy in future energy systems and the avoided emissions from fossil fuels.

Unlike a few recent studies [41,42,43,44] that discussion long and short time climate impact, this study does not compare the climate impacts of using bioenergy versus use of fossil alternatives. Instead, the present study provides insights regarding the substitution effects of using bioenergy. Also, the results illustrate that when less biomass is

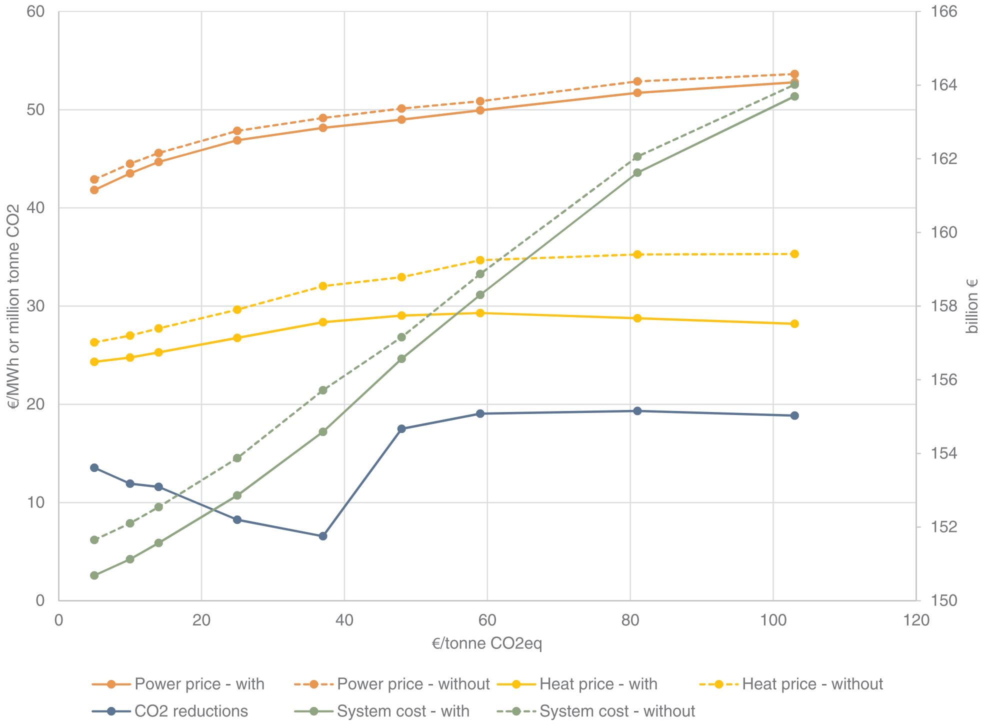

Fig. 7. Modelled weighted power and heat prices (€/MWh), system cost corrected for emission taxes (billion €), and carbon reduction if wood chips re used for heat and electricity production (million tonne) in Northern Europe, for scenarios with and without use of wood chips, in 2030, plotted against the carbon price (€/tonne CO_2eq).

used for energy, more land is needed for wind power or other renewable energy production.

According to the model results, GHG emissions reduction may be in the range of 4–27% in 2030 and 7–43% in 2040 if wood chips are used for heat and power generation. In order to have the same emissions reduction without using wood chips, we need to increase the carbon prices by 1–6 €/tonnes CO_2eq in 2030 and 3–18 €/tonnes CO_2eq in 2040, highest for high carbon prices, due to higher marginal costs of reducing the emission. These results suggest that wood chips effectively reduce fossil emissions as well as system cost for a given renewable share. The use of wood chips also reduces the carbon prices needed to reach a certain renewable share.

As expected, we find larger emission reductions if biomass is used for biofuel, replacing fossil transportation fuels, than if the same amount of biomass is used for heat generation. This is contrary to McKechnie et al. [44], who compared biofuel to heat and power generation in a system using only coal. From a system viewpoint, this is not very realistic since a biomass plant will also compete with other technologies, i.e. wind and natural gas power, and indirectly change the total carbon effects. This is because a new heat or electricity plant using forest biomass will compete with all other heat and electricity plants in the market, and thus create system effects.

We find that the use of biomass gives valuable flexibility to the heat sector since the demand for heat storages and the use of electricity for heat decreasing when we allow woody biomass to produce heat. This do not necessarily mean that biomass itself gives the necessary flexibility, but biomass will enable other technologies to provide the hourly flexibility that otherwise would be used in less economical rational periods.

In the short term, biomass may mainly replace fossil fuel. At some point in time, however, it must compete with zero-emissions technologies. When this happens, biomass may be more suited for use in other sectors than power and heating, i.e. with higher replacement factors. The use of biomass is highest for high carbon prices, but the real market effect of high carbon prices may be different because if the carbon price is high, industries outside the energy sector may start to utilize charcoal in order to replace fossil coal as a reducing agent or use biomass for chemicals. This may lead to increased competition for energy quality biomass and may increase the price of biomass used for energy production.

The carbon prices assumed in this study span from 5 to 103 €/tonne CO_2eq for 2030 and 15–127 €/tonne CO_2eq in 2040. This span covers the lowest observed level historically to more than five times the average 2019 level [45]. For the highest carbon prices in 2040, the modelled reduction in carbon emission is 91% of the 2020 level. Such a dramatic reduction in emissions may be more difficult to achieve than the model projects. Heard et al. [46] and Brown et al. [47] discuss the weaknesses, strengths, and feasibility of modelling energy systems with such low carbon emissions (or equally a high carbon price). They found that it may be possible to reach a 100% renewable system, but the models that are developed and calibrated with today's use of fossil fuels may not be accurate in terms of the system cost or the choice of technologies. Most of the scenarios used in this study give a reduction in carbon emissions in the range of 35–75% in 2030; this should be a valid range for the assumptions applied in the model.

If the raw material is harvest residues, the GHG reduction may be larger than if roundwood is used for heat and power generation. The reason for this is that harvest residues decay relatively fast and emit the same amount of CO_2 when left in the forest. This view is supported by

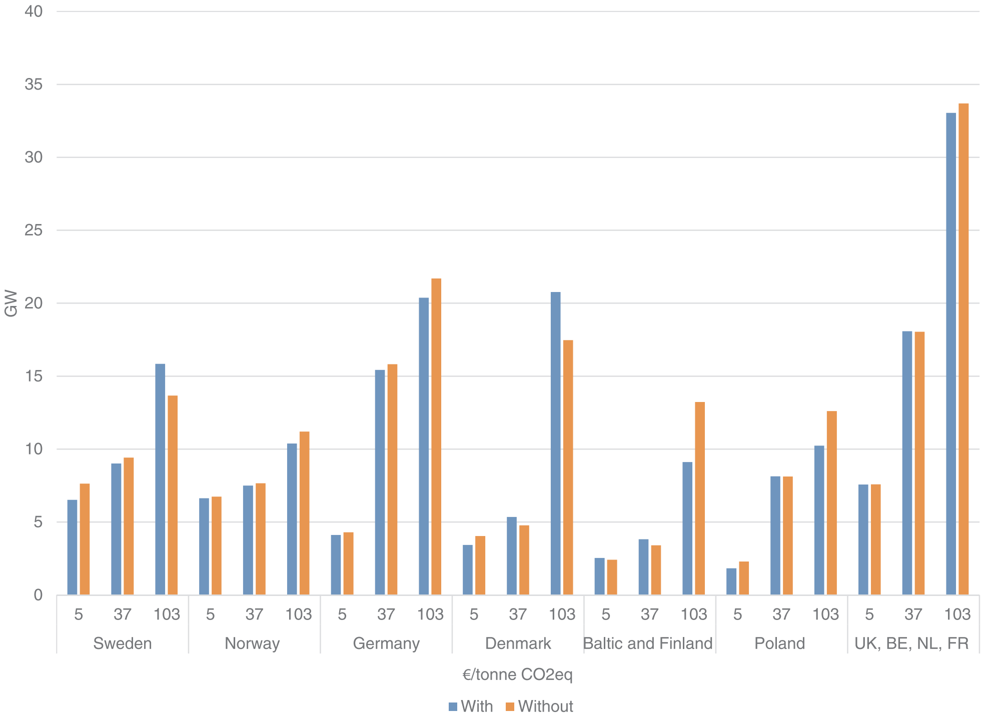

Fig. 8. Investment that exceeds the known planned investment in international cross-border transmission lines in the endogenous transmission investment scenarios in Northern Europe, with and without use of wood chips for selected carbon prices, in 2030.

Gustavsson et al. [42], who studied the climate effects of using forest residues for electricity, heat, and transportation and found the most significant climate benefits occur when harvest residues are used for electricity and heat production, particularly when substituting coal. Finally, it should be mentioned that this study does not include carbon capture and storages (CCS). Introduction of CCS at plants running on fossil fuel may reduce the total emissions from heat and electricity while also increasing the production costs from these technologies. CCS at biomass plants (BECCS) can result in negative carbon emissions when producing heat and electricity, thus increasing the importance of using biomass for energy production. Carbon negative solutions are not possible when biomass is used for biofuels.

As is the cases with all models, Balmorel has both strengths and weaknesses. Endogenous investments are an advantage since the model find the best allocation between technologies when it comes to costs and give the user a clear understanding of which investment that will be most beneficial. At the same time, the model may overestimate or underestimate the investment since an investment decision is often founded on more aspects than only the economics. From this follows that the real-world results may be more sensitive to the investments costs than applied in this study. Balmorel assume perfect foresight, which give the model an opportunity to be too optimistic when it comes to allocate production during a year, since the model do not have any stochastics or uncertainties within a year. This is special relevant for energy storages, such as water, heat storages, and batteries. When the model gets the opportunity to perfectly allocate the resources during a year it may underestimate the need for reserves and following underestimate the investment, in order to have production capacities in backup for periods with low production from wind and solar. The model has hourly resolution, which give the model a strength of finding the correct energy price in situations where the variable renewable production is high or low.

5. Conclusion

This paper addresses the role of wood chips in the future North European energy system with high shares of renewable energy. The novelty of this study is that we address how bioenergy may impact the fossil carbon emissions from heat and power generation. This is important to know since the carbon impact of woody biomass is highly dependent on what technologies and fuels different bioenergy alternatives replaces. Based on detailed modelling of the power and heat systems, we conclude that using woody biomass for heat and electricity production would primarily contribute to reducing natural gas power generation towards 2040. In addition, we find that biomass has a substantially role in providing heat and electricity for all studied carbon prices. When excluding wood chips as an energy source for heat and electricity production the total system costs increase by 0.2–0.7% and the average heat prices increase by 8–20% in 2030. The impacts on the heat price are low in some countries and substantial in others, such as Sweden and Finland.

Increased use of woody biomass would, to some extent, replace wind power, coal power, and electricity used in district heating systems. As such, we can conclude that using wood chips for power and heat reduces emissions from fossil fuels, but the model results show that the magnitude of emissions reductions depends on the assumed carbon price and technology mix in the heat and power sectors. The substitution effects of woody biomass decline with increasing carbon price and is lower in 2040 than in 2030. The latter is due to an in general lower amount of fossil fuel in energy system in 2040. For the Northern

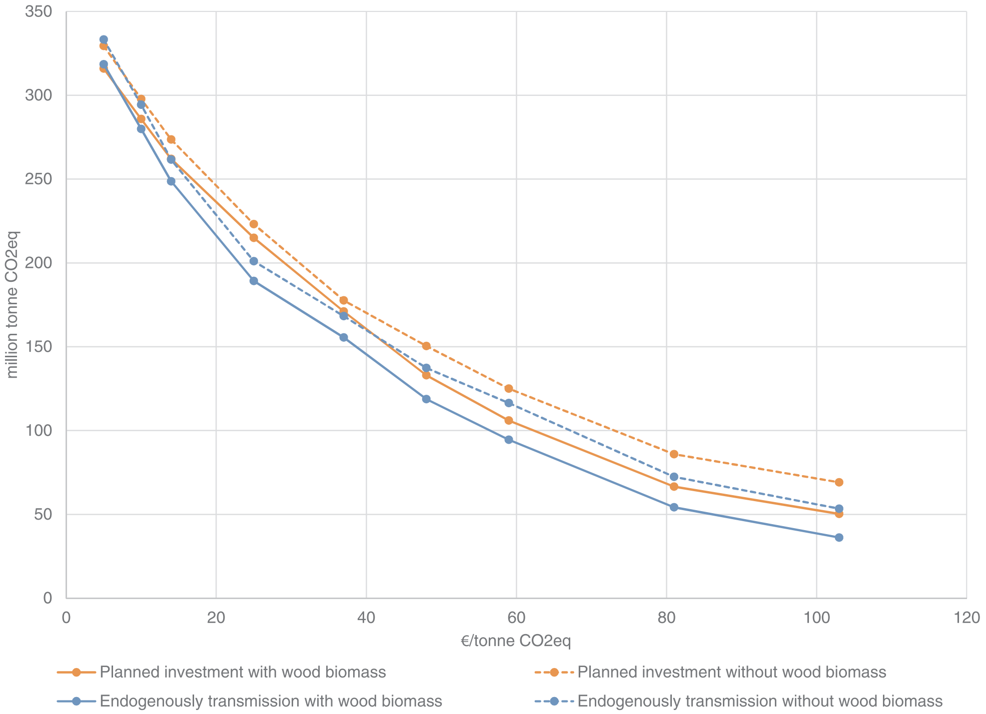

Fig. 9. Modelled total carbon emissions from the energy system if wood chips are included in the system in Northern Europe for the scenario with only planned transmission line investment, with and without wood chips, and endogenous transmission investment, with and without wood chips.

European energy system (Poland, Germany, and the Nordic and Baltic countries) the optimal use of wood chips reduces the fossil carbon emissions by 7–19 million tonnes CO_2eq in 2030 (4–27% emission reduction). In 2040, the corresponding reductions are in the range 10–17 million tonnes CO_2eq (7–43% emission reductions). If wood chips are not included as a fuel option in the model simulations, the use of heat storage capacity increases up to 24% more than when biomass is included.

If wood chips normally used for heat and electricity production were instead used for biofuel production replacing fossil transportation fuels, the fossil emissions from road traffic would be reduced by 14–35 million tonnes CO_2eq. This will give a net carbon reduction of 0–16 million tonnes CO_2eq compared when wood chips are used for heat and electricity production. However, the cost of reducing emissions this way may be as high as 400 €/tonne CO_2eq.

The results illustrate and quantify the trade-offs when assessing the use of wood-based biomass for power and heat versus for transportation fuels; the emissions impacts are higher when using biomass for transportation fuels, but the costs per tonne of fossil emissions reductions will likely be substantially higher than the cost of the biomass in power and heating.

6. Data availability

The dataset and model used in this study can be found at https://github.com/balmorelcommunity at the F4R_Final_Model_002 and F4R_Final_002 branch, version used is from 21.06.19.

CRediT authorship contribution statement

Eirik Ogner Jåstad: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Torjus Folsland Bolkesjø:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing - original draft, Writing - review & editing. **Erik Trømborg:** Conceptualization, Supervision, Validation, Writing - original draft, Writing - review & editing. **Per Kristian Rørstad:** Conceptualization, Supervision, Validation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

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

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Paper V

Integration of forest and energy sector models – new insights in the bioenergy markets

Eirik Ogner Jåstad; Torjus Folsland Bolkesjø; Erik Trømborg; Per Kristian Rørstad

The forest and energy sectors rapidly transitioning to low levels of GHG emission. To fully understand the implications of this transition, it is important to analyse the interactions between these sectors. We herein present a coupled/integrated modelling approach that integrates the Nordic Forest Sector Model (NFSM) and the energy sector model Balmorel. Both models include endogenous investment and market prices obtained by market equilibrium. The new model is used to investigate forest and energy sector impacts of a low carbon scenario in the Nordic countries. The results show a steady increase in use of forest resources for heat and power generation from 47 TWh in 2020 to 117 TWh in 2050, and prices increase when the models are integrated. The study indicates that the integration procedure provides more realistic biomass prices and levels compared with standalone models.

- Bioenergy production increases toward 2050
- An integrated model predicts more use of harvest residues after 2025
- 3x the amount of bioheat only increases the harvest by 1.6%
- Forest sector models underestimates the biomass usage in district heat production
- It is important to include sensitive biomass supply in energy sector model

Keyword: energy system models; forest sector model; model integration; partial equilibrium

1 Introduction

About 33% of the primary energy use in the Nordic countries comes from renewable sources (UNFCCC, 2020). The Paris Agreement may result in increased utilization of wind and solar power, but it will be difficult to complete the transition away from fossil fuel without extensive use of biomass in the heating, industrial, and transportation sectors.

Since biomass has many alternative uses, the supply of biomass for energy is price sensitive. Although this sensitivity is generally accepted (Carneiro & Ferreira, 2012), few previous energy system analyses have addressed this topic. One exception is Oliver and Khanna (2017), who used a model covering electricity from agricultural bioenergy with endogenous raw material prices. They found that biomass could provide 20% of the electricity needed in the US within 2030. Models covering biomass markets, like forest sector models, on the other hand, simplify the energy market in their partial approach. For example, Latta et al. (2013) use a forest sector model and point out the dynamic relationship that exists between the forest and electricity production from biomass, but they do not have endogenously determined input of biomass in electricity production. Another method used to cover the relationship between energy and forest sector is to include different supply curves for biomass, as do Hoogwijk et al. (2009), who estimate production costs of electricity based on different supply curves for biomass. They found that the production costs may vary between 40 and 100 USD_{2000}/MWh. A drawback of this study is that it does not include realistic market prices for electricity. Nguyen and Gustavsson (2020) study co-generation of district heat, electricity, and biofuel production for varying heat demand. They found that the cost-optimum generation mix for each energy type varies according to district heat demand with co-generation being most profitable with high district heat production.

Integration of specialized models may be a way to improve modelling of biomass prices and volumes. Model integration is common in some field such as environmental studies (Belete et al., 2017). Belete et al. (2017) present a review of existing literature on model integration and present a roadmap for the integration process. Different models are integrated when an author believes it will increase our knowledge of the system under investigation. Energy system models have previously been integrated with macroeconomic models (Messner & Schrattenholzer, 2000), general equilibrium models and climate models (Labriet et al., 2015), LCA models (Kypreos et al., 2008), and health impact model (Korkmaz et al., 2020), which all has increased our understanding of the relationship between different sectors. Historically, these integrated models have mainly been used to study different detailed demands or GHG emissions effects. Welfle et al. (2020) reviewed recent studies of bioenergy modelling and found that it is relatively common to use energy sector models or raw materials models to predict the role of bioenergy, but that it is more rare to combine different models within the field of bioenergy. Welfle et al. (2020) conclude that the use of multiple models may lead to robust results, and that few studies have combined bioenergy with forestry and the forest industry. Forest sector models (i.e. forestry and forest industry) usually estimate raw materials used for heat production (Bolkesjø et al., 2006; Trømborg & Solberg, 2010), and newer models usually also include material supply for forest-based biofuels (Kallio et al., 2018; Mustapha, 2016; Trømborg et al., 2013), although bioheat demand is usually determined exogenously or follows a predefined price path.

Forest sector models have previously been linked to forest management models (Härkönen et al., 2019), as well as to bioheat models. For example, Karlsson and Wolf (2008) integrated an hourly bioheat demand model into a traditional forest sector model. They studied the integration of a chemical pulp mills, sawmills, biofuel plants, and district heating systems and concluded that an integrated model gives better representation of the sector than a stand-alone system does. Mustapha et al. (2019) present a hard-linking approach that combines an energy sector model and a forest sector model. They found that a 40% biofuel share in the Nordic countries resulted in a 50% reduction in heat and power produced from forest biomass, concluding that energy models that use constant exogenously determined biomass prices may overestimate the use of biomass in the future energy system. One drawback of the procedure applied by Mustapha et al. (2019) is that the two models were optimized independently of each other and only two parameters were coupled.

Both energy sector models and forest sector models are partial models, meaning that all prices other than those of the goods being studied are assumed to be constant. In the future it is likely that electricity prices will vary more than they have historically while energy production from forest biomass will increase. In the traditional way of modelling the energy and forest sectors, forest biomass costs in the energy sector model, and electricity costs and demand for biomass for heating purposes be assumed to be constant. Consequently, the partial approach will be inaccurate when more biomass is used for heating since the energy sector will increasingly impact the forest sector, and vice versa.

To increase our understanding of how electricity and heat production interact with forest resources, we first present a framework for endogenous estimation of biomass prices in an energy sector model with hourly resolution and endogenous investments. We describe how the model works and how it can be used to increase our understanding of the heating, electricity, and forest sectors in a carbon-neutral scenario. Thereafter, we compare the result from the integrated model with similar model runs for the two separate models and discuss whether the integrated model may provide new insights to decision makers. In the scenarios, we describe a path towards large fossil carbon emissions reductions in the industrial sector, transportation, and energy production: the chosen scenario has a reduction in carbon emissions of 73% compared to 2017, without including the effects of CCS or LULUCF emissions/uptake.

2 Data and methods

2.1 NFSM

The Nordic Forest Sector Model (NFSM) is a partial equilibrium model covering forestry, forest industry, and forest-based bioenergy in the Nordic countries (Norway, Sweden, Finland, Denmark, and trade with third countries). Similar models have been used since Kallio et al. (1987) introduced the Global Trade Model (GTM) in 1987. NFSM originates from the Norwegian Trade Model (NTM) (see Trømborg and Solberg (1995), Bolkesjø et al. (2005), and Trømborg and Sjølie (2011)), which itself was based on GTM. NFSM is previous developed and used in several studies (Jåstad et al., 2019; Mustapha et al., 2017a; Mustapha et al., 2017b). In this chapter we present a brief description of NFSM. For a more complete description of the model see Jåstad et al. (2020).

The aim of NFSM is to maximize consumer plus producer surplus (i.e. welfare) for each time step; the model is usually optimized each subsequent year in a recursive manner. NFSM provides market equilibrium prices and quantities for each region and time step and estimates roundwood supply, industrial production, consumption of end products, and trade between regions. The model includes growth and stock changes in forestry; using the previous period change in roundwood stock, the model calculates the shift in the timber supply curve for the following year. In total, the model includes seven different forest products: sawlogs and pulpwood from spruce, pine, and non-coniferous trees and harvest residues. A constraint ensures that the ratio of harvested sawlogs and pulpwood in a region follows historical and theoretical distributions, and that the amount of harvest residues does not exceed a theoretical limit for each region. The model has a total of 15 final products, including three types of sawnwood, cross laminated timber (CLT), three board grades, four paper grades, charcoal, biofuel, local produced heat, and district heat. CLT can be produced from spruce, pine, and non-coniferous sawnwood. The distribution of the three different types of sawnwood used as raw material for CLT can vary between years and regions, but at least half of the regional production must be from spruce sawnwood. We assume that 1.42 m^3 solid of sawnwood is needed to produce 1 m^3 solid of CLT. Paper can be produced from four grades of pulp: mechanical pulp, chemothermomechanical pulp, chemical pulp, and sulphite and dissolving pulp. Charcoal can be produced from all forest products (raw materials and by-products) in the model with an efficiency of 56% (Wang et al., 2015), but due to raw material costs, it would most likely be produced from sawdust, bark, and harvest residues. Charcoal producers may use different raw materials in different years without making new investments.

Biofuel producers may choose between pulpwood, sawdust, harvest residues, tall oil, and black liquor in their production. The assumed efficiencies for biofuel production and input of electricity, heat, and hydrogen are shown in table 1. The production costs for biofuel are calculated with the use of scale factors, learning rate, and base capacity, as shown in table 2. Scale factors and learning rate are how much the costs are reduced if the production amount is doubled; scale factor is used for a single plant, while learning rate is for accumulated total installed capacity. It is assumed that the learning rate only appears for the given raw material and learning only happens within the Nordic countries. When a biofuel plant first is established, it has to produce at the same capacity with the same raw material for the remainder of the modelled years and the capacity of a constructed plant cannot be increased or decreased.

Table 1. Input data for biofuel production for the different allowed raw materials. Source: (Carvalho et al., 2018; Cashman et al., 2016; Serrano & Sandquist, 2017).

Raw material	Energy efficiencies	Electricity input [MWh/MWh$_{biofuel}$]	Heat input [MWh/MWh$_{biofuel}$]	Hydrogen [MWh/MWh$_{biofuel}$]
Chips	58%	0.05	0	0.60
Dust	58%	0.05	0	0.60
Harvest residues	42%	0.05	0	0.60
Black liquor	60%	0.56	0.65	0
Tall oil	82%	0	-0.01	0

Table 2. Base capacity for the biofuel plant, and base cost data, as well as the scale factors and learning rate. Source: (IRENA, 2016; Serrano & Sandquist, 2017).

Raw material	Base size [MWh$_{biofuel}$]	Base operation and management cost [mill €/year]	Base labour cost [h/year]	Base investment cost [mill €]	Scale factor operation and management cost	Scale factor investment cost	Scale labour costs	Learning rate
Chips	367 920	31.97	44 473	287	0.795	0.755	0.645	0.92
Dust	367 920	31.97	44 473	287	0.795	0.755	0.645	0.92
Harvest residues	367 920	31.97	44 473	287	0.795	0.755	0.645	0.92
Black liquor	257 544	31.97	35 579	27	0.795	0.755	0.645	0.92
Tall oil	257 544	31.97	35 579	16	0.795	0.755	0.645	0.92

Table 3. Base year harvest, industrial production, and unit electricity production in the Nordic countries. Source: (Borregaard, 2020; Energi Företagen, 2020; Energimyndigheten, 2020a; Energimyndigheten, 2020b; Energistyrelsen, 2020a; Energistyrelsen, 2020b; FAOSTAT, 2019; Finnish Energy, 2020; Finnish Forest Industries, 2020; Landbruksdirektoratet, 2020; Luke, 2018a; Luke, 2018b; Luke, 2020a; Luke, 2020b; Luke, 2020c; Mustapha, 2016; Nord-Larsen et al., 2018; Norsk Fjernvarme, 2020; Norsk industri, 2020; Pöyry, 2016; Skogs Industrierna, 2020a; Skogs Industrierna, 2020b; Skogstyrelsen, 2019; SSB, 2020c; Statistics Denmark, 2019; Treindustrien, 2020) and own estimate.

	Unit	Norway	Sweden	Finland	Denmark	Average unit electricity consumption [MWh/unit]
Harvest						
Spruce sawlogs	mill m^3 solid ub.	4.6	22.6	13.3	0.7	
Spruce pulpwood	mill m^3 solid ub.	4.1	17.6	10.4	1.7	
Pine sawlogs	mill m^3 solid ub.	1.5	13.8	10.7	0.2	
Pine pulpwood	mill m^3 solid ub.	1.6	10.7	16.8	0.5	
Non-conifers	mill m^3 solid ub.	1.8	12.0	12.4	2.6	
Harvest residues	mill m^3 solid		3.2	3.0	0.1	
Energy production						
Local heat	TWh	3.9	12	9	10	
District heat	TWh	1.5	15	18	11	
Industrial heat	TWh	2.3	69	46	1.1	
Pulp production						
Sulphite and dissolving pulp	mill tonne	0.15	0.36			1.77
Sulphate	mill tonne		8.29	7.76		0.87
CTMP	mill tonne	0.14	1.29	0.69		0.59
Mechanical pulp	mill tonne	0.12	2.22	2.61		2.25
Production of energy carriers						
Chips	mill m^3 solid	2.2	13	8.2	2.1	
Firewood	mill m^3 solid	2.3	5.1	5.0	2.3	
Pellets	1000 tonne	55	1994	385	136	0.12
Sawnwood production						
CLT	1000 m^3 solid	60	145	140		0.07
Non-coniferous sawlogs	1000 m^3 solid	1.4	108	303	89	0.07
Pine sawlogs	mill m^3 solid	0.63	8.3	5.6	0.09	0.07
Spruce sawlogs	mill m^3 solid	1.9	13	6.4	0.30	0.07
Paper production						
Newsprint	mill tonne	0.5	1.1	0.5		1.04
Linerboard	mill tonne		2.9	1.4	0.02	0.49
Other paper and paperboard	mill tonne	0.2	4.0	4.4	0.3	0.72
Printing and writing paper	mill tonne	0.5	3.0	5.0	0.1	0.81
Board production						
Particle board	1000 m^3	405	550	100	346	0.21
Plywood	1000 m^3		120	1030	80	0.15
Fibreboard	1000 tonne	172		24	2.5	0.71

NFSM models both endogenous investments and decommissioning based on the demand for intermediate and final products. The model finds the optimal yearly production level to be between 0% to 120% of the reference production for pulp and paper and 0% to 140% for sawnwood technologies without investing in new production units. If it is economically sensible to increase production, an investment decision will be taken. The investment is assumed to be fully constructed the first year and producing 100% of the new production capacity already that year. If the model uses less than 70% of the installed capacity, we assume than that half of the unused capacity is decommissioned.

The present model uses 2018 as the reference year and the reference data is shown in table 3. The data were collected mainly from the same sources as in the previous updates described in Mustapha (2016).

NFSM is written in GAMS as a linear mixed-integer programming model (MIP); shown below are the original functional shapes, which are nonlinear for consumption, harvest, and biofuel production. The nonlinear part of the model is implemented as a stepwise linearization, reasons of readability we only show the non-linear version of the model; for a detailed description of the linearized model see Jåstad et al. (2020).

The objective function is shown below and all symbols are briefly explained in table 6:

$$\begin{aligned}
\max \Bigg[& \sum_{i,f} \left[\left\{ \Gamma_{i,f} * \left(1 - \frac{1}{\tau_{i,f}}\right) \right\} \gamma_{i,f,y} - \frac{1}{2} \left\{ \frac{\Gamma_{i,f}}{\zeta_{i,f,y} \tau_{i,f}} \right\} \gamma_{i,f,y}^2 \right] - \sum_{i,w} \frac{\alpha_{i,w,y}}{\beta_{i,w} + 1} \theta_{i,w,y}^{\beta_{i,w}+1} \\
& - \sum_{i} \mu_i \varepsilon_{i,y} + \frac{1}{2} \upsilon_i \varepsilon_{i,y}^2 - \sum_{i,t,k,k2} \left(\iota_{i,k2} \Lambda_{k,t,k_2} + An_i * IC_k \right) \varphi_{i,k,t,y} \\
& - \sum_{i,j,k} D_{i,j,k} \omega_{i,j,k,y} \\
& - \sum_{i,tb,kb} \Bigg\{ LB_{i,tb,kb} \left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}} \right)^{SL_{tb}} + VC_{tb,kb} \left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}} \right)^{SV_{tb}} \\
& + An_{i,kb} VI_{tb,kb} \left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}} \right)^{SI_{tb}} \Bigg\} \Bigg] \quad (N.1)
\end{aligned}$$

where the first term describes consumer surplus where γ is the yearly consumption, ζ is the reference consumption of final products f in the basis year, in region i, and year y, ζ is updated each year with the assumed GDP increase and the GDP elasticities for each final product, and Γ is the reference price and τ is the price elasticity of product f in region i. The second term describes the timber supply, where θ is harvest of roundwood category w in region i, β is the econometrically estimated roundwood supply elasticity, and α is shift in roundwood supply, which changes periodically according to changes in growing stock; the first year is α estimated as

$$\alpha_{i,w,1} = \frac{\Gamma_{\mathrm{i,w}}}{\chi_{i,w}^{\beta_{i,w}}}\ \forall\, y = 1 \tag{N.2}$$

where Γ is the reference timber price at mill gate and χ is the reference harvest, for each subsequent year, α is updated according to

$$\alpha_{i,w,2} = \frac{\alpha_{i,w,1}}{\left\{\frac{(1+\kappa_{i,w})\phi_{i,w,1} + \chi_{i,w} - \theta_{i,w}}{2\phi_{i,w.y-1}}\right\}^{\beta_{i,w}}}\ \forall\, y = 2 \tag{N.3}$$

$$\alpha_{i,w,y+1} = \frac{\alpha_{i,w,y}}{\left\{\frac{(1+\kappa_{i,w})\phi_{i,w,y} + \phi_{i,w,y-1} - \theta_{i,w}}{2\phi_{i,w.y-1}}\right\}^{\beta_{i,w}}}\ \forall\, y > 2 \tag{N.4}$$

This equation shifts the timber supply according to the net change in growing stock for the previous period, where κ is the annual growing stock rate, ϕ is the growing stock in year y, and θ is the harvest in the previous year. The third term describes the costs of harvesting and collecting harvest residues, where ε is the amount of harvest residues collected from region i, the intercept (μ) and slope (υ) of the marginal costs are estimated based on historical and theoretical costs of collecting harvest residues. The fourth term describes the variable production costs with exogenously defined price, where φ is the production of product k using technology t in region i, and ι is the exogenous input price of input k_2, and Λ is the used amount of k_2 in production of product k, An is the annuity of the investment, and IC is the investment costs. The fifth term describes the transportation costs from region i to region j, where $D\ is$ unit transportation cost of product k and ω is the amount of goods transported. The sixth term describes the biofuel production costs, where LB is the labour cost for producing (φ) biofuel grade kb, using technology tb in region i, ξ is the reference size for biofuel plants, VC is the variable costs and VI is the investment cost; SL, SV, and SI are the scale factors of labour cost, variable costs, and investment cost, respectively.

The main equation in NFSM is the material balance equation:

$$\varphi_{i,k,y} + \sum_{k2} \Theta_{\mathrm{i,k,k_2},y} + \sum_{t} \theta_{i,k,t,y} + \varepsilon_{i,y} + \sum_{j} \omega_{i,j,k,y} = \gamma_{i,k,y} + \sum_{k2} \Theta_{\mathrm{i,k_2,k},y} + \sum_{j} \omega_{j,i,k,y} + \sum_{k_2,t} \theta_{i,k,t,y} \Lambda_{\mathrm{k,t,k_2}} \;\forall\, i,k,y \;(N.5)$$

The first term describes harvest (φ) of roundwood category k in region i. The second term describes downgrading (Θ) from category k to k_2, while the seventh term describes gains from downgrading. The third term describes production (θ) of product k, with the use of technology t in region i. The fourth term describes the collection of harvest residues (ε) in region i. The fifth term describes export (ω), and the eighth term import (ω), of product k in region i. The sixth term describes consumption (γ) of product k. The ninth term describes input (Λ) in industrial processing of product k_2 in the production (θ) of product k.

2.2 Balmorel

Balmorel is a partial equilibrium model covering the Northern European heat and power markets. The first version of Balmorel was described in 2001 by Ravn et al. (2001); since then, the model has been developed continuously (Wiese et al., 2018). The core model is available from the Balmorel community at Github Repository (2019), where the background data is also available. The model is open access and published under an ISC license (Open Source Initiative, 2020). In this chapter, we briefly describe the Balmorel core model and the part of the model that is interesting for the integration procedure; for a more complete description of the model see Ravn et al. (2001) and Wiese et al. (2018).

The model's aim is to optimize heat and electricity generation with a given exogenous demand profile. To fulfil the heat and electricity demand, the model finds the optimal allocation of generation technologies, energy storages, and electricity transmission between neighbouring regions under different constraints. The model can distribute the production of heat and electricity from existing technologies or invest in new technologies. The model covers a large variety of raw materials: the most important energy sources are fossil fuels such as coal, lignite, fuel oil, peat, natural gas, and other gases; variable renewable, including wind, solar, and run of river hydro, biomass as straw, chips, pellets, wood waste, biooil, and biogas; and other energy sources such as uranium, municipal waste, waste heat, hydro storages (reservoir and pump), and electricity used for heat generation. In Balmorel the unit input price of fossil fuels, biomass, and uranium is constant and exogenously determined for a given year and region regardless of how much fuel is used; maximum consumption limits exist for some fuel. Wind, solar, and hydropower have no direct exogenous fuel costs, but there are indirect costs through investment cost, fixed and variable maintenance costs, and constraints on the amount of energy available ensure that variable renewable energy stays within reasonable amounts.

Balmorel includes both exogenously and endogenously defined production capacities: the former (both commission and decommission) follow known plans (table 5), while the latter increase when the market condition covers the capital cost and variable production cost. All production facilities are decommissioned exogenously when they reach their techno-economic lifetime, and investment in new production units is needed to fulfil demand; this is valid for all technologies except hydropower. Hydropower is assumed to have reached its technical potential and no construction or decommission is allowed, but the model can endogenously choose how much of the installed capacity will be used. All technologies included in the model are represented with a defined efficiency, amount of pollution, operation and management costs, investment costs, technical lifetime and interest rate, the year when the technology first became mature, and, for CHP plants, the fraction of heat and electricity produced.

The model covers district heat and electricity generation and consumption in Northern Europe (Belgium, Germany, Denmark, Estonia, Finland, France, Lithuania, Latvia, Netherlands, Norway, Poland, Sweden, and United Kingdom). Table 4 shows the electricity and heat consumption, except for the electricity consumption in the forest sector. Each country consists of one or more regions (figure 1); the model allows for transmission of electricity between regions, which mainly follow the NordPool regions (NordPool, 2018). We assume only exogenous investment in transmission capacities based on known investment plans. The model does not allow heat to be transmitted to neighbouring regions; thus, all heat produced must be consumed within the region where it is produced.

The temporal resolution in Balmorel is flexible and easy to adjust; the user can choose to model 1–8760 periods (hours) each year. It is possible to model each subsequent year, but since the computable cost of the model is relatively high, users often choose to only optimize every five or ten years. In this study we assume perfect foresight within the current year but no knowledge about the coming years. The data assumption in the Balmorel model is mainly from the (IEA, 2016), and data related to renewable production is mainly based on weather profiles from 2012.

Table 4. Heat and electricity demand in 2020, except for forest industries for all countries in the model.

	Electricity	Heat
Denmark	32	33.2
Finland	60	79.2
Germany	394	115.6
Netherland	110	18.5
Norway	117	12.7
Sweden	109	89.7
UK	311	17.7
Estonia	6	5.0
Latvia	5	6.0
Lithuania	8	7.7
Poland	105	66.4
Belgium	83	7.1
France	448	24.6

Table 5. Exogenously installed capacities in Balmorel for all countries [GW].

	2020	2025	2030	2035	2040	2045	2050
Coal and lignite	206	146	72	31	1	1	0
Electric heating	5	4	2	1	1	0	0
Hydro	217	217	217	217	217	217	217
Natural gas	193	160	111	78	39	20	9
Nuclear	97	80	79	70	67	43	23
Other biomass (straw, biooil, biogas)	20	16	11	6	2	1	1
Other fossil	49	36	23	17	10	7	3
Sun	74	74	74	72	63	33	10
Waste	110	113	65	54	34	28	19
Wind	132	132	114	90	51	5	0
Wood chips – rest of the model	15	13	7	5	3	3	3
Wood pellets – rest of the model	4	4	4	1	0	0	0
Wood pellets – Nordic countries	2.7	2.4	1.5	1.2	0.92	0.76	0.48
Wood chips – Nordic countries	7.8	7.1	5.5	4.4	3.3	2.3	1.0

The most important factor for the transition to lower carbon emissions in the model is the use of a carbon price. In this study we assume an increase in carbon price from

23 €/tonne CO2 in 2020 to 37 €/tonne CO2 in 2030, 63 €/tonne CO2 in 2040, and 82 €/tonne CO2 in 2050; in addition, we prohibit fossil energy production from 2040 in the Nordic countries (Norway, Sweden, Finland, and Denmark).

Below, we briefly describe the main equation that is directly affected by the integration with NFSM: the objective function, heat balance, and power balance.

The objective function in Balmorel covers costs related to the generation, transmission, storage, and consumption of heat and electricity, including taxes and investments. The objective function is minimized each year (Y) to fulfil the demand at the lowest possible cost. The objective function for the core model is shown below (all symbols explained in table 6):

$$\begin{aligned}\min \Bigg[\sum_{A,F,G} 3.6 \frac{\text{GJ}}{\text{MWh}} * FP_{Y,A,F} * VF_{A,G,Y} + \sum_{A,G,S,T} OM_{A,G} * (VE_{A,G,S,T,Y} + VH_{A,G,S,T,Y}) \\ + \sum_{A,G} (VG_{Y,A,G,Y} + EG_{Y,A,G,Y}) FC_{A,G} + \sum_{A,GH,S,T} HP_{A,S} * VE_{A,GH,S,T,Y} \\ + \sum_{AI,AE,S,T} VX_{AE,AI,S,T,Y} * XC_{AE,AI} + \sum_{A,G} VG_{Y,A,G,Y} * IC_{A,G}\, An_{A,G} \\ + \sum_{AI,AE} VC_{Y,AI,AE,Y} * IX_{Y,AI,AE} * An_{A} \\ + \sum_{A,G} 3.6 \frac{\text{GJ}}{\text{MWh}} * EL_{G} * EC_{Y,A} * VF_{A,G,Y} \ + \ addons \Bigg] \ \forall\, Y \ (B.1)\end{aligned}$$

The first term describes the fuel cost (FP) of producing heat and electricity in region A, with generation technology G that consumes fuel F, where VF is the amount of fuel consumption. The second term describes variable operation and maintenance costs (OM); VE and VH are the amount of electricity and heat respectively produced in week S and hour T. The third term describes the fixed operation (FC) cost of having endogenous (VG) and exogenous (EG) generation capacity installed. The fourth term describes the costs related to electricity production from hydro reservoirs (HP) for week S. The fifth term describes the transmission cost (XC) and amount that is transmitted (VX) from exporting region AE to importing region AI. The sixth term describes the annuity (An) of the investment cost (IC) of investing (VG) in generation technology G in region R. The seventh term describes the annuity (An) of the investment cost (IX) of investing (VC) in transmission lines from exporting region AE to importing region AI. The eighth term describes the costs related to emissions, where EL is the amount of CO_2, SO_2, and NO_x emitted per consumed unit of fuel F, and EC is the emissions costs. The ninth term is available for different user-defined add-ons to the core model.

The two main equations in Balmorel balance production and consumption of heat and electricity. The heat balancing production and consumption for each time step and region are calculated as follows:

$$\sum_{G} VH_{A,G,S,T,Y} - \sum_{GSH} VS_{A,GSH,S,T,Y} = \frac{DH_A * HT_{A,S,T}}{1 - DL_A} + \ addons \ \forall \ A,S,T \qquad (B.2)$$

The first term describes heat production (VH) in region A, using technology G, in week S, and hour T. The second term describes heat going into a heat storage (VS), both short and long-time storages with technology GSH; heat will then be delivered from the storages at a later time step. The third term describes hourly heat demand, where DH is the yearly demand and HT is the demand profile in region A, in week S and hour T, corrected for the transmission losses DL. The fourth term is available for different user-defined add-ons to the core model.

The electricity balance production, transmission, and consumption of electricity for each time step and region are calculated as follows:

$$\sum_{G} VE_{A,G,S,T,Y} - \sum_{GB} \frac{VH_{A,GB,S,T,Y}}{EF_{GB}} + \sum_{A_1} \frac{VX_{A_1,A,S,T,Y}}{1 - DL_{A_1,A}} - \sum_{A_1} VX_{A,A_1,S,T,Y} - \sum_{GSE} VS_{A,GSE,S,T,Y}$$
$$= \frac{DE_A * ET_{A,S,T}}{1 - DL_A} + \ addons_{A,S,T} \ \forall \ A,S,T \ (B.3)$$

The first term describes production of electricity (VE) in region A, with use of technology G, in week S, and hour T. The second term describes the electricity that is consumed in heat pumps and electrical boilers, where VH is the produced heat and EF is the efficiency of the heat pump and the electrical boilers with technology GB. The third term describes imported electricity (VX) from region A_1 to region A, corrected for distribution losses. The fourth term describes exported electricity (VX)

from region A to region A_1. The fifth term describes electricity that is stored (VS), both short and long-term storage, with technology GSE. The sixth term describes hourly electricity demand, where DE is the yearly demand and ET is the demand profile in region A, in week S and hour T, corrected for transmission losses. The seventh term is available for different user-defined add-ons to the core model.

2.3 Integration procedure

Both Balmorel and NFSM are written in the General Algebraic Modelling System (GAMS) (GAMS Development Corporation, 2017), and both are solved using the CPLEX solver (IBM, 2020). Since both models have the same modelling environment, it is not necessary to perform new typing of the core models and all new coding is only related to connecting the two models.

Balmorel has a modelling structure that allows for easy extension of the code without changing the core model. This functionality is called add-ons and is described in Wiese et al. (2018). Since the Balmorel model is still undergoing rapid development, we find it most appropriate to integrate the models through the add-on framework; only minor changes are necessary in the core model of Balmorel. When doing the integration through the add-on structure, we are ensuring that both models can easily be extended independently while keeping the possibility of solving them together without further adjustment. In this chapter, we focus on the linking procedure between the two models, and the procedure used when optimizing the models. The two main connections between the forest sector and the energy sector are the forest sector's consumption of electricity and the given electricity price, and the use of forest biomass as raw material for energy production affecting the biomass balance in the forest sector.

2.3.1 Time resolution

Balmorel and NFSM have different time resolutions: NFSM is optimized each year with one time step, while in Balmorel the user can choose between 1 and 8760 time steps for each year. In the integrated model preserves the difference in time resolution. Only information on yearly level is interchanged endogenously between the models. Balmorel sends average yearly electricity price and yearly forest fuel consumption to NFSM, while NFSM sends yearly forest fuel prices and yearly electricity consumption to Balmorel. The yearly electricity consumption is divided equally on all modelled time steps in Balmorel, which is equal to a constant electricity demand from the forest sector within a year.

Both models have the possibility to optimize each year between 2018 and 2050, but the models differ on how common it is to run all subsequent years. NFSM normally models every year chronologically, since changes in growing stock and regional roundwood cost are heavily dependent on the harvest levels the previous year, which is especially important for stocks that are growing or being reduced at a high rate. If we instead use a multi-year optimization it will give prices that are either too high or low and lead to unrealistic growing stock levels. On the other hand, Balmorel has no costs or stocks that are dependent on the previous year. For this reason, it is possible to only optimize some freely chosen years in Balmorel. To obtain the benefits from both models, we introduce a method for switching between modelling with NFSM alone and with both models at once. We do this by 1) optimizing NFSM in 2018 and 2019, 2) optimizing NFSM and Balmorel in 2020, 3) updating the fuel levels and electricity costs in NFSM, 4) optimizing NFSM for the years 2021-2024, and finally 5) running both models again for 2025. After, steps 3-5 are repeated for every five years until 2050.

2.3.2 Geographical resolution

Balmorel has 24 regions that follow the NordPool regions in the Nordic countries, i.e. five regions in Norway, four in Sweden, two in Denmark and one in Finland. For the countries outside the Nordic countries, Balmorel has one region each for Lithuania, Latvia, Estonia, Poland, United Kingdom, Netherland, Belgium, and France and four regions for Germany. NFSM has 31 regions that cover all of the Nordic countries (figure 1) and one region that covers rest of the world (ROW). In the integration procedure, we assume that the NFSM ROW region follows the weighted average costs in Germany, Lithuania, Latvia, Estonia, and Poland. Each of the NFSM regions is placed

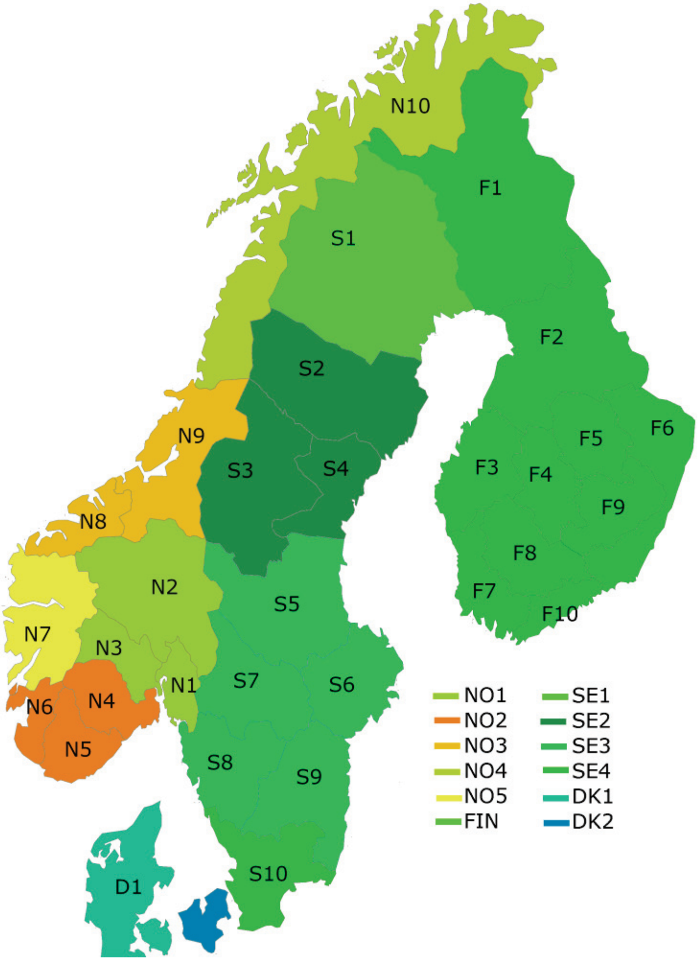

Figure 1. Regions in NFSM (name) and Balmorel (colour) and where they are connected. The NFSM region 'rest of world' and Balmorel regions outside the Nordic countries are not shown.

inside one of the Balmorel regions as shown in figure 1, except NFSM region D1, which is divided equally between Balmorel regions DK1 and DK2. When allocating fuel consumption from Balmorel to the NFSM regions, we disaggregate the consumption according to the reference distribution.

2.3.3 *Electricity demand and supply*

Electricity consumption in NFSM is assumed to be allocated equally over a year. This may be a feasible assumption for pulp and paper mills since they normally do not ramp their production (Helin et al., 2017), but less so for sawmills, which tend to have higher activity during the daytime.

In the years that NFSM is solved alone, the unit electricity cost is assumed constant, and for years with endogenous unit electricity costs are decided by the model with use of the equation $(I.1)$. Each time the full model is solved, the regional unit electricity prices in NFSM are updated using the average yearly electricity prices found in the full model. For subsequent years, the new electricity cost is applied until the next time the full model is solved. This ensures that the forest sector faces changes in electricity costs.

The electricity consumption in the forest sector is added to the electricity balance $(B.3)$ in the seventh term

$$addons_{A,S,T} = \sum_{i,k,t,e} \frac{\Psi_{\mathrm{A,i}} \Lambda_{k,t,e} \varphi_{i,k,t,y}}{\sum_{A_1} \Psi_{\mathrm{A_1,i}} * 8760 \frac{\mathrm{h}}{\mathrm{y}}} \qquad (I.1)$$

where the numerator explains the consumption of electricity in each of the Balmorel regions, and Ψ is a binary parameter that controls which Balmorel region A is connected with NFSM region i; φ is the production of product k with use of technology t; Λ is input of electricity (e) in production. The denominator changes the production from an aggregated year to hourly resolution. In total, equation $(I.1)$ will give a constant MW/region or $\mathrm{MW}_{\mathrm{time\ step}}$/region.

2.3.4 Heat demand and supply

The main integration part is the fuel consumption in heat and power production. To ensure equal amounts of consumed fuel in both models a new equation is introduced. This equation gives the same results as inserting the demand directly into the balance equation $(N.5)$, but this way we have an option to use different names for the same raw materials in the two models, which allows for more categories in the forest sector than are necessary in the energy model:

$$\sum_{q,t,u} \varphi_{i,t,q,y} \Lambda_{q,t,u} \Omega_u = \sum_{A,G} \Psi_{\mathrm{A,i}} VF_{A,G,y} \varpi_{i,A} \ \forall\, i \qquad (I.2)$$

where u represents the different grades of input available for heat and electricity production, which in NFSM are sawdust, bark, shavings, chips, pellets, and harvest residues. The base unit in NFSM is m^3 for sawdust, bark, shavings, chips, and harvest residues and tonne for pellets. Balmorel has only chips and pellets as possible fuel inputs, since we assume that the chips in Balmorel are equal to sawdust, bark, shavings, chips, and harvest residues in NFSM, and the calculated unit in both models is MWh. In this study we assume the energy content (Ω) is 2.18 MWh/m^3 solid for sawdust, shavings, and chips, 1.74 MWh/m^3 solid for bark, 2.68 MWh/m^3 solid for harvest residues, and 5 MWh/tonne for pellets (Belbo & Gjølsjø, 2008). The left side of the equation $(I.2)$ covers input in heat (q) production (φ) with use of heat technology t in NFSM region i, and Λ is the input of raw material u in production. Where on the right side Ψ is a binary variable that takes care of the connection between Balmorel region A and NFSM region i, VF is the fuel consumption of chips and pellets in technology G, and finally, ϖ distributes the fuel consumption to the NFSM regions that are inside a Balmorel region. The left side describes the raw material consumption for heat production in NFSM, and this factor is only used for bookkeeping. The right side calculates the fuel consumption in Balmorel and distributes it to the NFSM regions.

For the years that NFSM is solved alone, the raw material usage in heat and electricity production is kept constant, at the same level as the left side of equation $(I.2)$ the previous year that the full model was solved.

The integrated model covers input in bioheat plants in all regions within the Nordic countries; this mean that the NFSM region ROW and Balmorel regions outside the Nordic countries are handled differently. The only connection between the two models in ROW is that the average fuel costs in the most recent year NFSM is solved alone are used as basis for the woody biomass consumption in the regions outside the Nordic countries in Balmorel. NFSM does not interact with changes in fuel consumption in Balmorel for the regions outside the Nordic countries. The reason for this procedure is that the forest sector in the ROW region is not covered in detail in the forest sector model for the countries outside the Nordic countries; if ROW was modelled similarly to the Nordic countries it may produce some unintended effects.

To ensure the correct distribution between the different forest fuels in years that both models are optimized, a constraint has been added to ensure that this fraction is equal to the most recent year that NFSM was solved alone. This is implemented as

$$\sum_{t,q} \varphi_{q,t,i,y}\Lambda_{q,\mathrm{t},\mathrm{u}}\Omega_{u} = \varsigma_{i,u}\sum_{t,u_2} \varphi_{q,t,i,y}\Lambda_{q,\mathrm{t},\mathrm{u}_2}\Omega_{u_2}\ \forall\ i,u \qquad (I.3)$$

where φ is production of bioenergy using technology t and region i, the input Λ of energy carrier u with energy content Ω has to be equal to the fraction ς from the last year NFSM was solved alone multiplied by the total use of the energy carrier in bioenergy production.

2.3.5 Objective function

The two models have different ways of interpreting objective functions: NFSM is a welfare-maximizing model, while Balmorel a cost minimizing model. As mentioned above, we implement as few changes to Balmorel as possible; for this reason, we do not implement any changes to the Balmorel objective function except to add an element to the ninth term in equation $(B.1)$. And since the models have somewhat different ways of finding the optimal solution, is it not possible to simply add the two objective functions together. Instead we use the fact that maximizing a positive function is the same as minimizing a negative function; for that reason, we set the add-on element in equation $(B.1)$ to

$$addon = -1{,}000{,}000 * \max[\dots] \qquad (I.4)$$

Where $[\dots]$ is equal to equation $(N.1)$, and the factor of one million ensures converting from the base unit in the NFSM objective function (million €) to the base unit in Balmorel (€). The objective value in NFSM is around 42% of the objective value in Balmorel; this gives Balmorel 70% contribution to the total objective value, while NFSM gets the remaining 30%. This ensures that both models find an optimal solution simultaneously.

2.4 Assumptions for modelled scenarios

To find the advantages and disadvantages of the integrated modelling approach, we develop a scenario for the Norwegian forest and energy sector where the assumptions are used as input to model runs in NFSM and Balmorel, as well as in the integrated model.

Figure 2 shows assumptions regarding the demand for various energy commodities and services for the main scenario. The investments in electric vehicles follow known plans and goals (Miljødirektoratet, 2020; Svenskt Näringsliv, 2020; Tilastokeskus, 2020b). The demand for liquid fuel and electricity is estimated using estimated investments in electrical vehicles; for example, Norwegian policy states that all new private vehicles have to be electric from 2025 (Miljødirektoratet, 2020). Total number of vehicles (electric and liquid fuel), yearly driving distances, probability of scrapping, and energy demand are all based on historical figures for the Nordic countries (Miljødirektoratet, 2020; SSB, 2020a; SSB, 2020b; Statistics Denmark, 2020; Tilastokeskus, 2020a; Transport Analys, 2020).

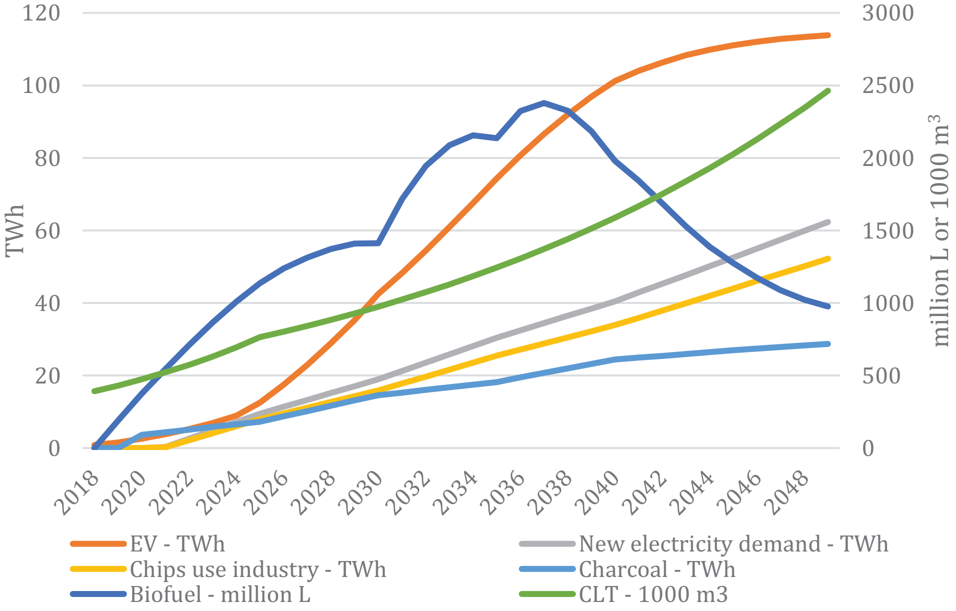

Figure 2. Exogenously determined development of demand used in this study, electricity consumption in electric vehicles (EV) and new electricity demand in industrial processes, chips and charcoal use for industrial processes (left axis), biofuel demand for road transport (right axis), and demand for CLT in construction (right axis).

For non-road transportation, it is assumed that the energy output is constant regardless of whether the uses electricity or liquid fuel. It is assumed that railway transportation is fully electrified within 2025, while the electricity demand from short distance marine increases by 0.3 TWh each year between 2020 and 2025 (Statnett, 2019); and from 2025 it is assumed that all domestic ferries are electric and the potential for shore supply is fulfilled. For domestic aviation, a constant liquid fuel demand is assumed until 2030, and from 2040 the liquid demand decreases to 20% of the 2018 values, while 80% of the energy demand is fulfilled with electricity (Avinor, 2020).

The Norwegian blend-in obligations for biofuel state that 20% of the liquid fuel sold for road transportation in 2020 should be biofuel, and of this at least 1.75% should be advanced biofuel (Lovdata, 2018). The share of advanced biofuel is assumed to increase to 10% in 2030 (Miljødirektoratet, 2020). We assume that the entire advanced biofuel share is fulfilled with Nordic forest-based biofuel. In 2030, we assume that the blend-in obligation will increase to 20% and further increase to 100% in 2050. We assume the same blend-in mandate for all types of liquid fuel. The Swedish biofuel policy is not a blend-in obligation, but a GHG reduction goal: the goal is 40% reduction for all liquid fuel for transportation in 2030 (Regeringskansliet, 2018). We assume that Nordic forest-based biofuel reduces the GHG emissions by 95% (Lovdata, 2018) compared to fossil fuel. With the same assumptions for the forest-based biofuel share in the total biofuel mix as in Norway, we get 1.2% forest-based biofuel in 2020, 10.5% in 2030. 20% in 2035, and 100% in 2050. It is assumed that the Finnish and Danish transportation sectors follow the same assumptions as Sweden, but 2018 and 2019 values follow historical investments.

We assume that all the fossil fuel used for energy generation (173 TWh), both in electricity and heat generation and in industrial processes, is replaced with 80 TWh electricity toward 2050 (Statnett (2019); the rest of the energy demand is assumed to be covered by 67 TWh of chips and 3.6 million tonnes of charcoal.

The Nordic consumption of cross laminated timber (CLT) in 2018 is estimated to be 392,000 m^3 solid (Danske bank, 2019; Eurostat, 2020; SSB, 2019); we assume that the consumption of CLT will increase by 10% yearly in the period 2018–2025 and 5%

thereafter. This will give a Nordic demand of 2.6 million m^3 solid CLT in 2050. The introduction of CLT may reduce the demand for cement and steel in the building sector by up to 1.23 tonnes cement and 0.14 tonne steel per m^3 solid CLT (Gustavsson et al., 2017). In a Nordic context, this is equivalent to an emissions reduction of 0.66 tonne CO_2 per m^3 solid CLT (UNFCCC, 2020).

3 Results

In this chapter, we first describe the main changes in results when the models are integrated versus run separately before analysing the system effects and implications of the integration.

3.1 Power prices

In NFSM, the electricity prices are given exogenously for each region and the prices for electricity delivered at mills are held constant for all years. The electricity prices vary between regions: the average electricity price is 38 €/MWh in Norway and Sweden, 37 €/MWh in Finland, 42 €/MWh in Denmark, and 43 €/MWh in ROW. Balmorel has endogenously determined electricity prices in each region based on the production costs and demand for each period. The estimated average electricity prices in Finland, Sweden, and Norway are shown in figure 3. For the Balmorel model, the electricity prices will increase from 2030 to 2045 due to increasing investment and costs related to high carbon prices. The main reason for the increased electricity price in years 2040 and 2045 is an increase in investment in electricity storage, which in turn is forced into the system due to increased carbon prices. In 2050, all the necessary investments are made and the cost of investing in electricity storage is not shown directly at the marginal production costs.

In the integrated model, electricity prices are 55% higher than in NFSM; the highest increase in electricity prices is found in Sweden, where the price is 60% higher in 2045 compared to the NFSM price. This shows that endogenous electricity prices have a heavy price impact on electricity costs for the forest industries. On the other hand, prices in the integrated model are only 1-3% higher than in Balmorel, because the electricity consumption in the forest industry is modelled without any flexibility or variation over a year. This increases the power demand at all hours, including hours with a shortage of variable power production, which results in the need for more expensive production facilities and, hence, higher electricity prices.

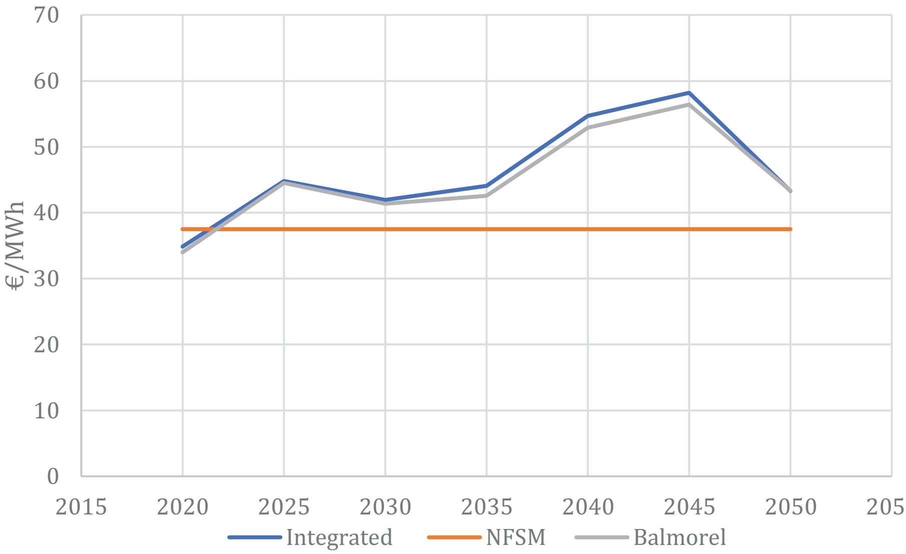

Figure 3. Modelled average electricity prices in Finland, Norway, and Sweden for NFSM, Balmorel (144 time steps), and the integrated model.

3.2 Raw material consumption in bioheat production

Both Balmorel and NFSM have constant exogenously defined district heat demand, but the time resolution is very different in the two models. The district heat demand in Balmorel is modelled at a hourly level, while NFSM has an annual time resolution. NFSM estimates the optimal allocation between the different forest-based raw materials available for energy production. Due to a higher share of harvest residues, the energy input increases slightly from 2020 to 2050 (figure 4) since harvest residues normally have a higher water content than wood chips.

Balmorel finds the optimal allocation of raw material consumption for all available raw materials in the model, including electrical heating. Balmorel estimates a peak in forest resource use of 146 TWh in 2025, and the amount drops to 104 TWh in 2050 (figure 4), mainly due to increased use of heat pumps and electrical boilers. The difference between Balmorel and the integrated model in 2025 comes from the different wood chips prices, which encourage more use of natural gas instead of investment in new chips units. Balmorel has a less detailed representation of the forest recourses than NFSM. For this reason, in the integrated model, we split the

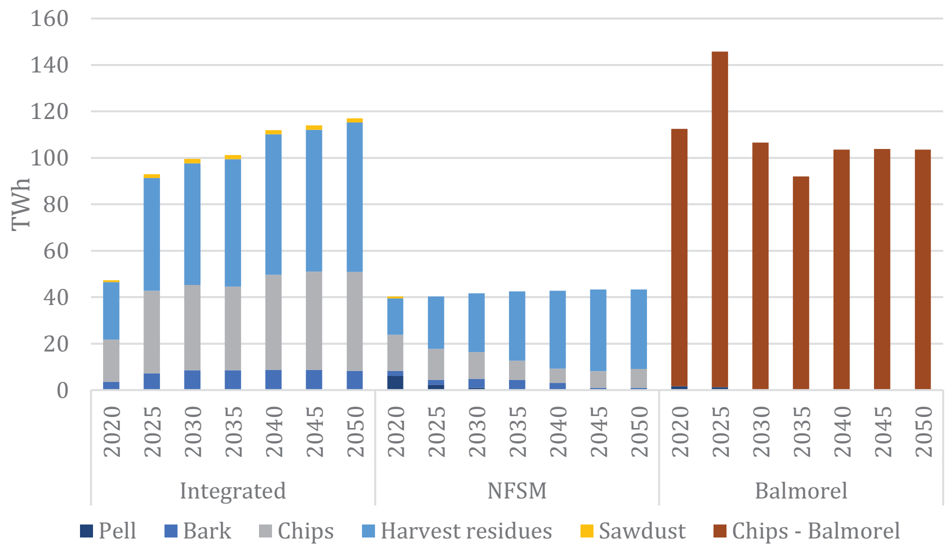

Figure 4. Modelled fuel consumption for district heat production in NFSM, Balmorel (144 time step), and the integrated model, for Norway, Sweden, and Finland. Note that "chips-Balmorel" includes bark, chips, harvest residues, and sawdust.

wood chips category in Balmorel into four different grades of forest raw materials: bark, chips, sawdust, and harvest residues. Results from the integrated model show increasing consumption of forest raw material, from 47 TWh in 2020 to 117 TWh in 2050, most dominated by harvest residuals, bark, and chips.

The exogenous chips price in Balmorel increases from 22 €/MWh in 2020 to 39 €/MWh in 2050, while the modelled chips price in NFSM increases from 23 €/MWh in 2020 to 30 €/MWh in 2030 to thereafter remain almost stable for rest of the modelled period. Thus, the chips price in Balmorel is estimated to be lower in the first years and then to be higher in later years compared to the integrated model (figure 5). NFSM estimate a chips price that is relatively similar to the model result from the integrated model. The reason for the insignificant difference between the integrated model and NFSM is that most of the biofuel investments are equal in both models and the use of chips within the heating sector is similar. The pellets price is lower in Balmorel than in the integrated model and NFSM for all years except 2050, where all models have the same pellets price. The reason for the similarity in pellets price between NFSM and the integrated model from 2035 is that neither model has significant changes in pellets use after 2035.

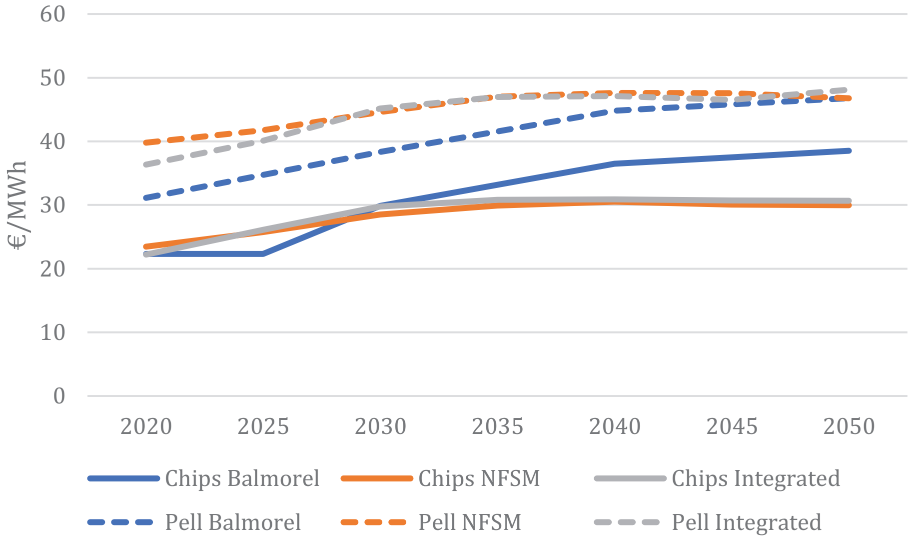

Figure 5. Modelled average chips and pellets prices in Norway, Sweden, and Finland for NFSM, Balmorel (144 time steps), and the integrated model.

3.3 Forest sector

In this section, we describe forest sector effects in Norway, Sweden, and Finland, which are the main forest regions in NFSM. The integration procedure also affects Denmark and the ROW region, but because the Danish forest sector is relatively limited and the ROW region has many specific assumptions, these results are not shown here.

In 2018, the total harvest in Norway, Sweden, and Finland was 153 million m^3 solid ub. where 66 million m^3 solid ub. was spruce and pine sawlogs and 61 million m^3 solid ub. was spruce and pine pulpwood. The remaining (26 million m^3 solid ub.) was different grades of non-coniferous roundwood. NFSM shows an increase in total harvest of 16%, from 153 million m^3 solid ub. in 2018 to 178 million m^3 solid ub. in 2050. When the models are integrated, the harvest increases by an additional 2.9 million m^3 solid ub. in 2050 (figure 6). The main reason for the additional increase in harvest is the increased use of forest resources for energy production. The harvest of sawlogs is relatively similar (-0.8–0.4 million m^3 solid ub. or -1.2–0.5%) in both models, since electricity accounts for a small share of the total cost at sawmills

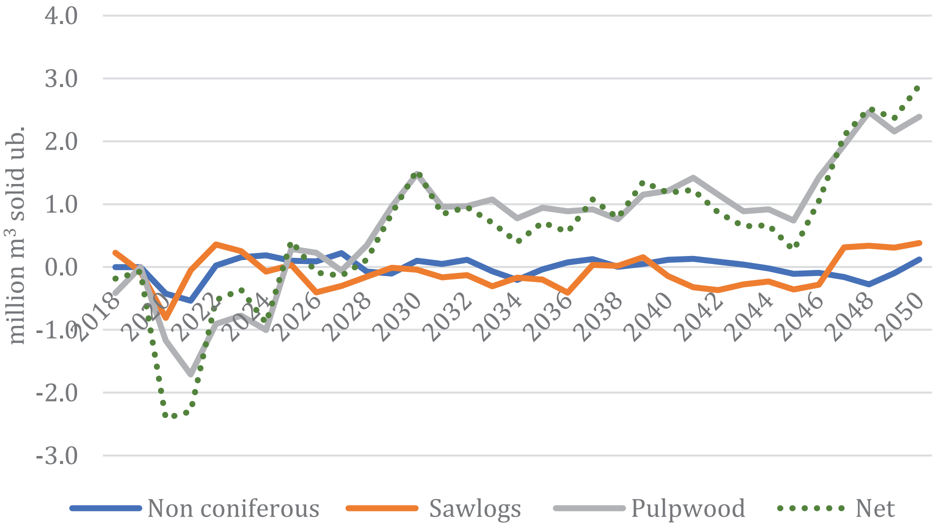

Figure 6. Modelled difference in roundwood harvest levels between the integrated model and NFSM in Norway, Sweden, and Finland; positive number is higher harvest in the integrated model, while negative number is lower harvest in the integrated model.

compared to pulp and paper mills and sawmills get a net increased income from selling by-products which partly compensates for the increased electricity costs. NFSM and the integrated model give similar results for harvest of non-coniferous roundwood. In total, the yearly variation in harvest level is between -1.5% and +1.6% of the NFSM harvest. The difference between the two models is highest in the year that both models are optimized; the main reason for this is the change in raw materials used for heat production (figure 7). If we include collection of harvest residues, the total outtake from the forest increases by up to +7%. The total harvest, including harvest residues, is stable between 2020 and 2024 due to a decreased use of forest raw materials for heat production in the integrated model compared to NFSM, along with a slight increase in industrial heat. The changes in roundwood harvest (figure 6) are lower than the increased input of forest raw material in heat production due to slightly less pulp and paper production in the Nordic countries in the integrated model.

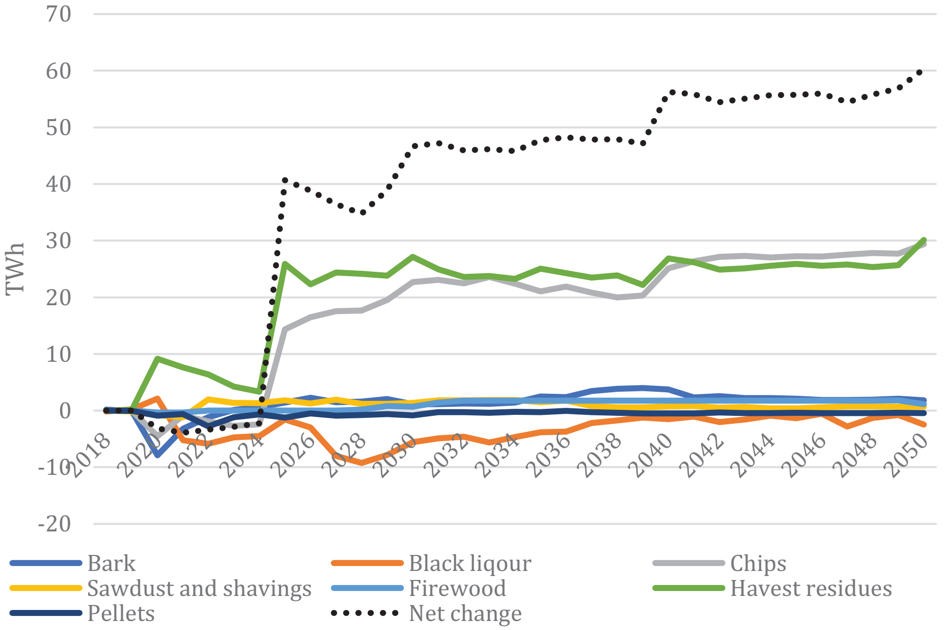

Figure 7. Modelled difference in raw material input in district heat, industrial heat, and locally produced heat between the integrated model and NFSM in Norway, Sweden, and Finland; positive number is greater input in the integrated model, while negative number is lower input in the integrated model.

The use of forest biomass in the production of industrial heat increases in a relatively similar fashion in the integrated model and in NFSM since the assumed demand for industrial heat in industrial production follows the same pattern in both models. We find an increased use of forest resources in district heat generation (figure 4). Figure 7 shows the difference between the two models in terms of the amount of raw materials used for heat production. The total consumption of forest raw materials changes each time both models are optimized (2020, 2025, 2030, 2035, 2040, 2045, and 2050) since the model finds a new optimal level of forest heat production. The same years also show a peak in the total changes due to the integration procedure whereas the Balmorel model has different efficiency coeffects for the different plants and NFSM has one efficiency parameter for each fuel. The small peaks in figure 7 are mainly explained by the shift between the use of bark to the use of sawdust in the production of charcoal, trade with the ROW region, and less collection of harvest residues. The peaks do not give significant short time changes in the raw material

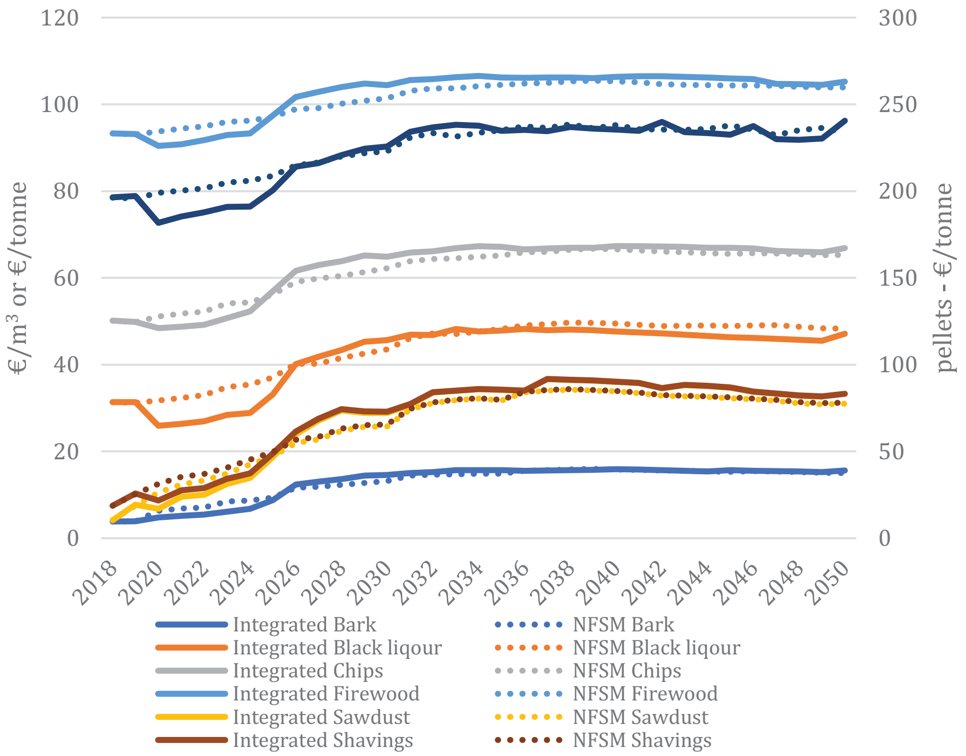

Figure 8. Modelled unit market price for secondary forest products and by-products for the integrated model (solid line) and NFSM (dotted line) in Norway, Finland, and Sweden; pellets price is shown on right axis.

prices (figure 8). The increase between 2024 and 2025 is due to the increased use of forest biomass for district heat production between 2020 and 2025.

The main differences between the integrated model and NFSM for raw material consumption in heat production are found in harvest residues, chips, and black liquor, while the changes are minor for sawdust and shavings, firewood, and pellets. The reason for this is that for the first years, sawdust and shavings are mainly used for drying at sawmills and board production, while in later years dust is also used for biofuel production; both products have few other fields of application except energy production, which remains stable between the two models. We do not find any significant changes in fuelwood consumption between the two models, since firewood is only used for local heat production, which is assumed constant in both models.

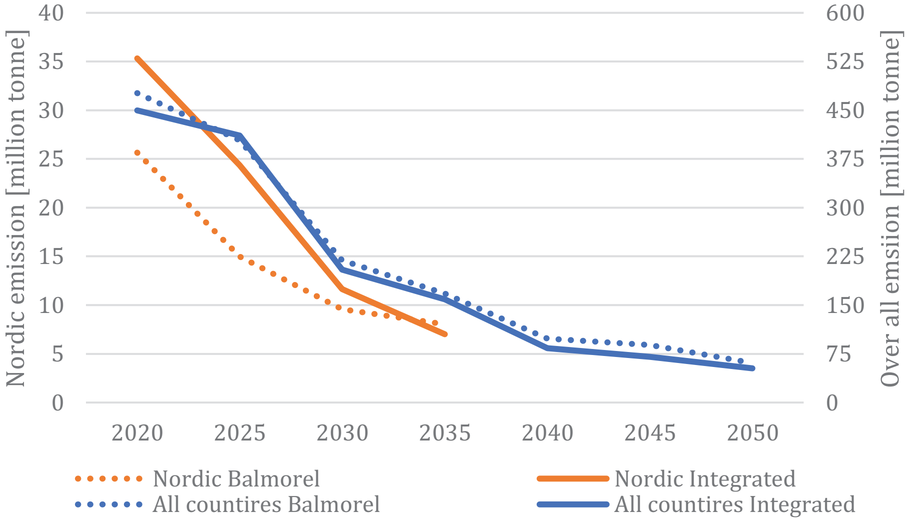

Figure 9. Modelled emissions in the Nordic countries (Norway, Finland, and Sweden) (left axis) and all modelled countries (right axis), for the integrated model and Balmorel alone.

The production of non-energy forest products is relatively constant across the two models and across the years since the integration does not lead to significant changes in demand and supply of roundwood. The greatest change is found for paper production after 2040 where the production is reduced by 3–8%; the main reason for this is the increased price of market pulp driven by increased electricity prices.

The market price for secondary forest products increases over time; this is due to the large production of biofuel, up to 2.3 billion L from 2036, and is the same in the integrated and stand-alone models. All secondary forest products have lower prices in the integrated model in the years 2020 to 2025 (figure 8) because of a slightly lower demand for forest resources for heat production (figure 7).

3.4 Energy sector

The modelled climate gas emissions from fossil fuels decrease from 2020 to 2050 due to increasing carbon prices (figure 9). For Norway, Sweden, and Finland, the modelled emissions are 62% higher in the integrated model than in Balmorel for 2025. The main reason for this is the higher chips price in the integrated model, which implies that fossil fuels are more competitive (figure 5). The Nordic countries do not emit

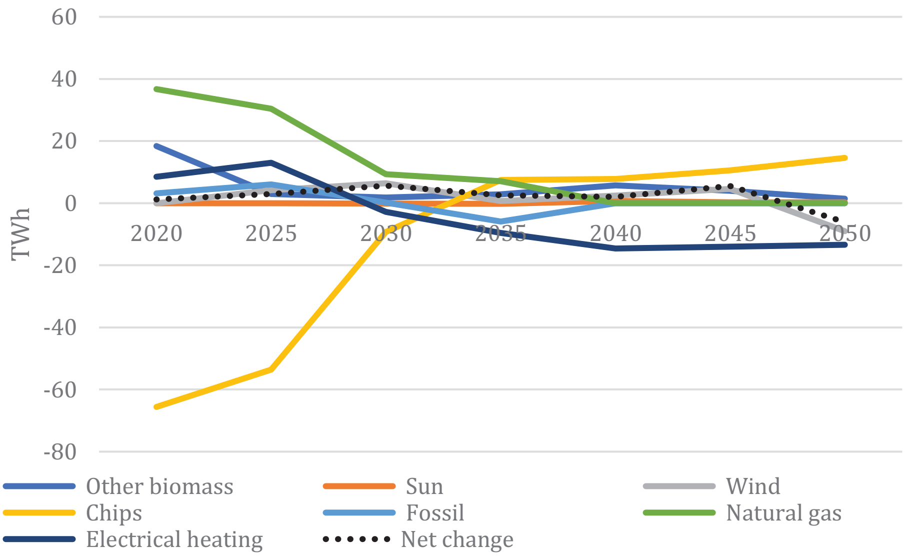

Figure 10. Modelled change in production of heat and electricity between the integrated model and Balmorel in Norway, Sweden, and Finland, divided by main fuel group; positive number is greater production of heat and electricity in the integrated model, while negative number is lower production of heat and electricity in the integrated model.

carbon from power and heat generation after 2035. For the countries outside the Nordic countries, we find a reduction in carbon emissions of up to 20% when the model is integrated, with the largest reduction in 2045. The reason for this is that the chips price is up to 42% lower in the regions outside the Nordic countries in the integrated model than in the Balmorel model.

For the period 2020–2030 the modelled generation of electricity and heat from chips is lower when the models are integrated than when Balmorel is optimized alone. After 2030 more chips are used in the integrated model than in Balmorel. As shown in figure 10, the change in chips consumption mainly affects the use of natural gas for the period 2020–2035 and electrical heating after 2030. Around 78% of the difference in the produced energy from chips is allocated as heat. This fraction is almost equal in periods with reduced production and periods with increased production; the reason for this is that most of the CHP plants that use chips for fuel have a constant distribution between heat and power.

The modelled electricity prices in Balmorel and the integrated model show similar yearly changes, but the prices in the integrated model vary between -1% and 3%

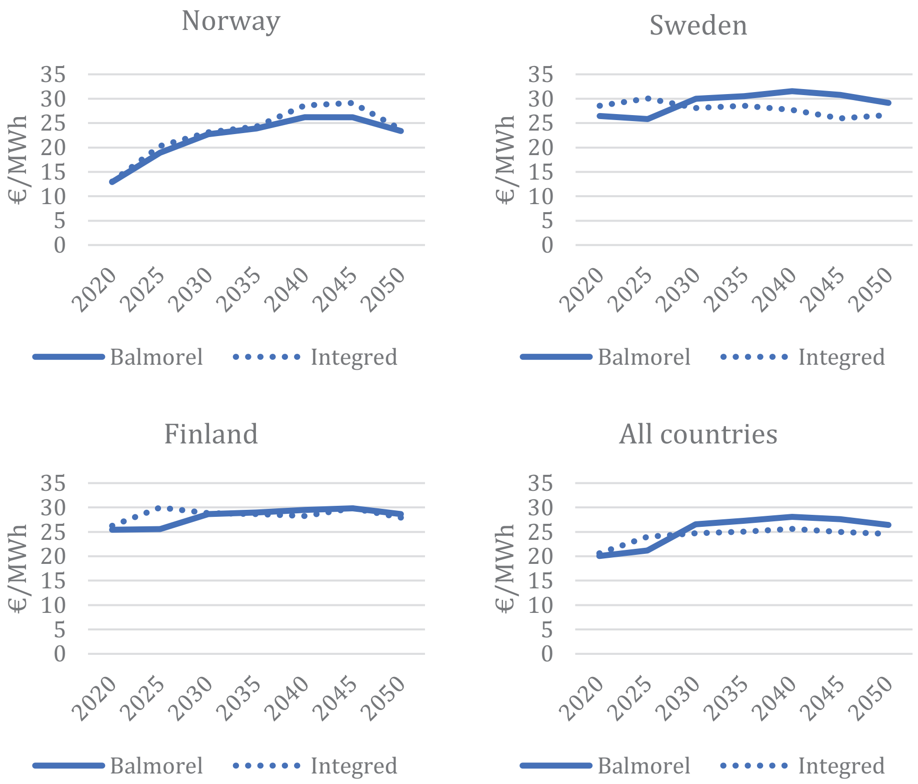

Figure 11. Modelled heat prices in Balmorel and the integrated model, for the Nordic countries, Finland, Norway, Sweden, and an average for all modelled countries.

more than in Balmorel, except in 2050 where the electricity prices decrease by 6%. The highest increase happens in Finland, which also has the highest electricity consumption in the forest sector.

The heat prices are relatively stable for the integrated model and stand-alone Balmorel but tend to increase in Balmorel and decline in the integrated model. The reason for this is that the integrated model has a more stable chips price which gives a more stable heat production cost in the Nordic counties; chips account for 20–63% of the heat production in the integrated model. In the integrated model, we also find a small increase in the price of heat for 2040 and 2045 in Norway (figure 11); the reason for this is that 2040 is the first year that the Nordic energy sector will become carbon neutral, which trigger more investment and use of electrical boilers at industrial sites in western Norway.

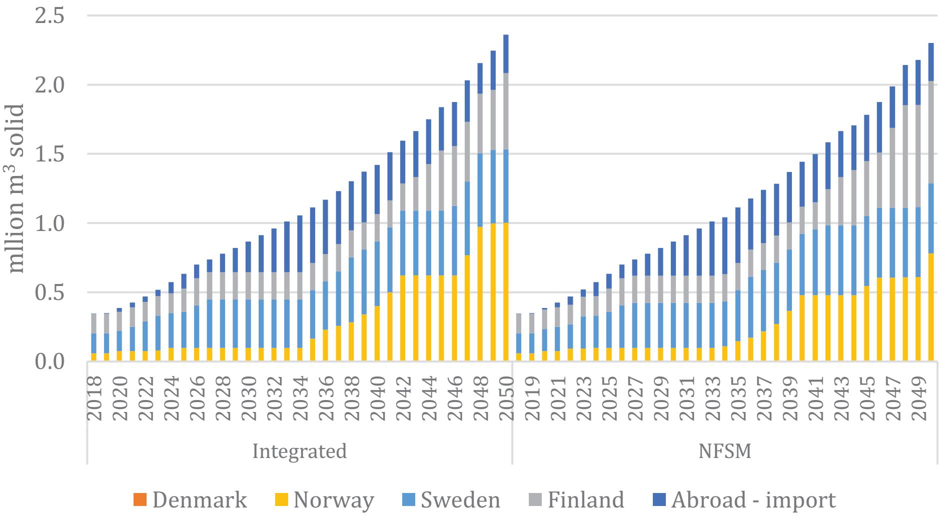

Figure 12. Country specific production of CLT and net import from rest of the world, for the integrated model and NFSM.

3.5 Charcoal, cross laminated timber (CLT), and biofuel production

The consumption of industrial charcoal in Sweden and Norway is assumed to be 0.7 million tonne charcoal in 2050 in both countries, and Finland and Denmark are assumed to consume 1.1 million tonnes each. Most of the demanded charcoal in 2050 will be imported from ROW in both the integrated and the NFSM model, but in the integrated model a bigger fraction of the total consumption is imported than in NFSM. The reason for this is that in NFSM there is less competition for low grade biomass due to higher bioheat production. Bioheat and charcoal production will compete about the same resources and it costs less to transport charcoal to the Nordic countries than to transport raw materials. It should be noted that we do not include electricity consumption in charcoal production in this study.

As shown in figure 2, the Nordic countries may consume up to 2.4 million m^3 solid in 2050, with most of the CLT being produced within the Nordic countries (figure 12). In the integrated model, Norway will have a bigger share of the total production after 2035 than in NFSM, and the reason for this is a slight reduction in sawnwood prices in Norway, which again are the result of a smaller increase in electricity prices in the Norwegian sawmills compared to Sweden and Finland. We assume that at least half

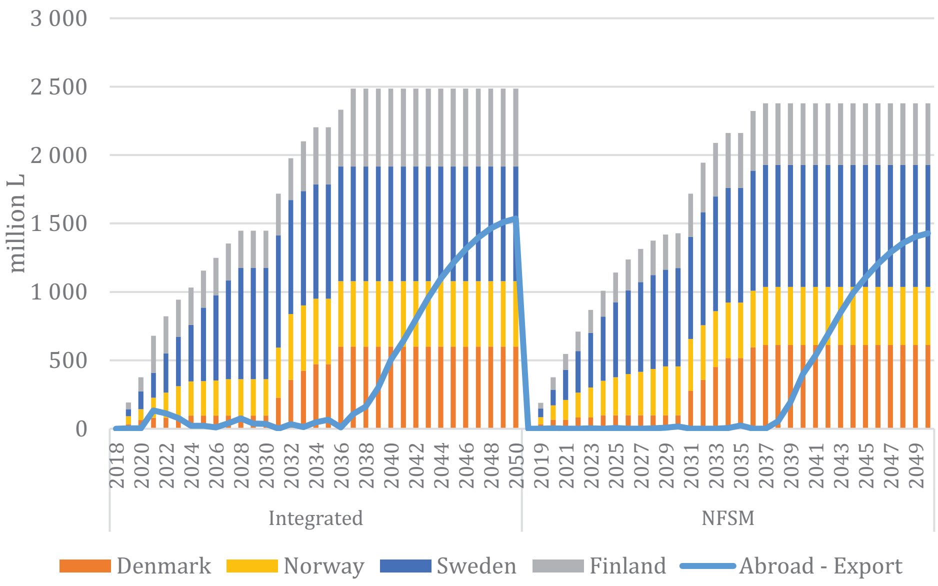

Figure 13. Country-specific production of biofuel and export to rest of the world for the integrated model and NFSM.

of the CLT production must be from spruce sawlogs; this is a binding constraint for all countries and years. The reason for this is that pine sawlogs have a lower estimated market price than spruce sawlogs.

It is assumed that the Nordic biofuel demand will peak in 2037 (figure 2), which the Nordic biofuel demand will start to decline. Since a biofuel plant is assumed to have a longer lifetime than the modelled period, the Nordic countries will start to export forest-based biofuel to ROW after 2037. In the period 2020–2025, when the demand for forest biomass in heat production declines in the integrated model, it will be beneficial to invest in more biofuel plants than in Nordic consumption, which will result in export of biofuel to ROW (figure 13). This shows that declining low-grade forest resources can be caught by other industries, and lock-in is a potential risk with such short-term declines.

4 Discussion

This paper shows that the integration of two models may improve the representation of the overall use of forest resources in the Nordic countries. The process of integrating an energy system model and a forest sector model provides increased understanding of the interactions between the forest and energy sectors in the future Nordic energy system. The integrated model is particularly suited to investigating scenarios that go beyond one of the sectors, as shown in this study, which combines electrification of industrial processes with increased use of biomass.

Some of the main advantages of the integration procedure is that the integrated model covers exogenously predefined changes in the forest sector and the energy sector without any user interference. In the traditional way of solving those two models separately, the users will always try to implement the most realistic exogenously input costs possible, such as the electricity price in NFSM and the chips price in Balmorel. In many studies, such values are only dealt with as one of many sensitivity parameters that are tested, but the main scenarios are often left unaffected by changes in exogenous parameters, even though they may be affected by the assumption that is tested in the model. For instance, when conducting a simulation of a scenario that has a large amount of new biomass in a district heating network, the traditional modelling solution will only have constant biomass prices or at best a biomass price curve, but when the biomass consumption increases the market may react to the changes in consumption and price differently than expected.

The most significant difference between Balmorel and NFSM is the time resolution. In forest sector analyses, it is not beneficial to increase the time resolution, since forests have a long-term cyclic nature with growth mainly in the summer period and harvest all year around, while forest industrial products, unlike electricity and heat, can be stored for a shorter period without significant costs or losses. The pulp and paper industries normally produce pulp and paper without breaks, except for some shorter maintenance periods, and it can be assumed that pulp and paper mills do not optimize their production based on short-term variation in the electricity price; but according to Helin et al. (2017) there may be a significant potential for demand response at mechanical pulp mills. For sawmills, it can be beneficial to increase the resolution of the model to a include daytime, night-time, and weekends, since they do not have as high start and stop costs as pulp and paper mills, but it is unlikely that the sawmills optimize their production according to electricity costs alone, since only a marginal fraction of the total costs is related to electricity. But for bigger sawmills that sell surplus heat, there may be a connection to the heat market. Finally, bioenergy production in the integrated model is modelled with hourly resolution, while raw material usage is modelled with a yearly resolution. Dividing output and input this way ensures that the bioenergy producers are connected to both markets. Nevertheless, it is sensible to use an hourly resolution for the electricity and heat markets since short-term variation in electricity generation and demand is an essential part of the energy market.

The borders between the regions in Balmorel and in NFSM do not fully overlap in Norway since the NFSM regions follow the county borders while the Balmorel regions follow bottlenecks in the grid. In the other modelled countries, the borders are almost identical in the two models. The slight mismatch between the regions is assumed not to impact the solution of the model since forest resources are mainly used in heat-only and CHP plants, both of which have to be connected to a district heat network in order to be profitable. Norway has district heat networks only in the biggest cities and all main cities are within the correct region in both Balmorel and NFSM. Regionalization may introduce minor errors for power consumption within the forest sector since some of the sawmills may be placed in neighbouring Balmorel regions, but all of the pulp and paper mills are in the correct regions in both models.

Solving only NFSM for some years and both models for others reduces the calculating time and memory use, but, as shown in the results section, it may introduce some unrealistic events. The procedure may create some inaccuracies, mainly in the use of secondary forest products; however, it is assumed that those minor changes do not introduce errors that are more significant than the general uncertainties in the model since the changes mainly cause change in regional usage and between the secondary energy production. This has a real life parallel in bioheat plants designed for low quality feedstock that change their input during a season, and especially between years; this may give the plants the possibility to decide between different forest product based on the market price. In a model framework, this may result in larger deviation between years, since NFSM only optimizes over one year. This gives the bioheat plant the opportunity to be more flexible than in the real world, because the model assumes perfect foresight within that year and therefore does not have the problem of storing the raw materials. In reality, the lack of storage space for raw materials, changing heat demand, and varying availability of raw materials over a year will to a large extent deicide which fuel a bioheat plant will use.

The consumption levels of locally produced heat from wood stoves are assumed to be independent of the district heat and electricity markets. This is a simplification since consumers that use wood stoves may change to electrical heating or connect to a district heat network in the long term. However, Nesbakken (1999) reports that short-term cross price elasticity between wood stove heating and electricity prices is relatively low, while the long-term elasticity is probably higher. The main contribution to yearly and seasonal variations in district heat, electricity for heating, and wood stove use is the outdoor temperature, which will affect all sectors at the same time. For this reason, it is likely that firewood consumption and electrical heating will be more connected in the future, which means that local heat production should be included in the integration procedure in the future.

We find that when using the integrated model, bioheat production is lower than was the case with Balmorel for some years and higher for others. This is in contradiction to Mustapha et al. (2019), who stated that studies using fixed biomass prices overestimate the bioenergy production. We find that when the model can use low-grade forest resources for bioenergy production, the amount of bioenergy produced may increase due to the lower price of the raw materials. This shows that when a model can be flexible in terms of the way biomass is used, the total produced bioenergy will increase and we will get better use of the raw materials.

We have assumed no co-generation between charcoal, biofuel production, or bioheat production; this is a simplification since some biofuel technologies have a side stream that can be turned into charcoal or sold as district heat. As shown by Nguyen and Gustavsson (2020), surplus heat from co-generation is only likely to be profitable for bigger biofuel plants connected to bigger district heat networks. This show that while the effects of these simplifications may be assumed to be low overall, they may nevertheless be interesting to investigate in a later study.

For future use of the model, it will be more efficient to update and calibrate each model separately because integration makes the models more complex and increases the solving time. The fact that both models use the same modelling environment reduces the risk of adding new errors to the models when combining them; it also makes it easier to run and compare results from each of the models.

Some of the differences between the integrated model and Balmorel/NFSM may be solved without the integration procedure. It is possible, for instance, to change the electricity price in NFSM and the chips price in Balmorel, but without knowing the results from the other model, it is difficult to use realistic numbers when doing simulations towards 2050. If the model is used without knowledge about the other model, we will make a lot of assumptions regarding the sector indirectly and therefore we do not know the feasibility of those assumptions. For this reason, we recommend using the procedure shown in this paper when doing long-terms projections about the forest and energy sectors.

5 Conclusion

This study describes how the energy sector model Balmorel and the Nordic forest sector model (NFSM) can be integrated and used to increase our understanding of the bioenergy market and the role of bioenergy in the future Nordic energy system. The main implication of the integration procedure for the forest industry was found to be an increase in the electricity price of up to 55% compared to NFSM; for comparison, the price increase was only 1-3% for the energy sector. Results from the integrated model deviated from results from the stand-alone models in several ways. For example, the heat production from biomass in NFSM tends to be significantly underestimated compared to the integrated model; this shows the importance of using an energy model when discussing the role of heat production in the forest sector. Meanwhile, for energy production from forest biomass, we find that the integrated model has less variation between years, which is more likely than the variating levels estimated in Balmorel.

For the integrated models, we find that harvest residues increase in value as a raw material for heat production. Subsequently, the use of harvest residues increases by 7% in 2050 in the integrated model compared to NFSM; the use of harvest residues also increases over time from 25 TWh in 2020 to 65 TWh in 2050, while roundwood harvest increases by 1.6% when the model is integrated. This study shows the importance of including a price sensitive biomass supply in the energy sector to better understand the role of forest biomass in a low carbon energy system.

Although the solving time and complexity increase when we integrate the models, we recommend including endogenous biomass prices in energy sector models and endogenous power prices in the forest sector model.

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A. Appendix

Table 6 shows the sets, variables, and parameters that are used in the model description in this chapter.

Table 6. Table of sets, variables, and parameters used in chapter 2, with a symbol, brief description, unit, and source model.

Symbol	Description	Unit	Model
	Set		
i, j	Regions		NFSM
f	Final products		NFSM
k, k_2	All products, i.e., final products, intermediate products, and roundwood categories		NFSM
y	Year		NFSM
w	Roundwood category		NFSM
t	Technology		NFSM
tb	Biofuel technology		NFSM
kb	Biofuel		NFSM
e	Electricity		NFSM
u, u_2	Raw material used for energy production		NFSM
q	Heat production		NFSM
Y	Current year		Balmorel
A, A_1	Regions		Balmorel
AI	Import to region		Balmorel
AE	Export from region		Balmorel
G	Technologies		Balmorel
GH	Hydropower with reservoir technologies		Balmorel
GSH	Storage technology heat		Balmorel
GSE	Storage technology electricity		Balmorel
GB	Heat pumps and electrical boilers technologies		Balmorel
F	Fuels		Balmorel
S	Week		Balmorel
T	Hour		Balmorel
	Variable		
γ	Consumption	Tonne, m^3, MWh	NFSM
θ	Harvest	m^3	NFSM
ε	Harvest residues	m^3	NFSM
φ	Production	Tonne, m^3, MWh	NFSM
ω	Trade	Tonne, m^3, MWh	NFSM
Θ	Downgrading of roundwood category	m^3	NFSM
VF	Fuel consumption	MWh	Balmorel
VE	Electricity produced	MW	Balmorel
VH	Heat produced	MW	Balmorel
VG	Endogenously capacity	MW	Balmorel
VX	Transmission	MW	Balmorel
VC	Endogenously defined transmission capacity	MW	Balmorel
VS	Loading of energy storage	MW	Balmorel
	Parameters		
ζ	Reference consumption	Tonne, m^3, MWh	NFSM
Γ	Reference price	€/unit	NFSM
τ	Price elasticity		NFSM
β	Econometrically estimated roundwood supply elasticity		NFSM
α	Roundwood supply shifts periodically according to changes in growing stock via this parameter	€	NFSM
χ	Reference harvests	m^3	NFSM
ϕ	Growing stock	m^3	NFSM
κ	Growing stock rate	%	NFSM

Table 6. Continue.

Symbol	Description	Unit	Model
μ	Harvest residues intercept	€/m^3	NFSM
υ	Harvest residues slope	€/(m^3)^2	NFSM
ι	Exogenous input price	€/unit	NFSM
Λ	Input of product	Unit/unit	NFSM
D	Transportation costs	€/unit	NFSM
LB	Labour costs biofuel	€/MWh	NFSM
VC	Variable costs	€/MWh	NFSM
IC	Investment costs	€/MWh	NFSM
ξ	Base production size for biofuel plant	MWh	NFSM
SL	Scale factor labour costs		NFSM
SV	Scale factor variable costs		NFSM
SI	Scale factor investment costs		NFSM
Ψ	Controlling the regions in NFSM and Balmorel		Integration
Ω	Energy content in energy products	MWh/unit	Integration
ϖ	Historical allocation of heat production between NFSM regions in a Balmorel region	%	Integration
ς	Fraction of raw material input previous year	%	Integration
FP	Unit fuel price	€/GJ	Balmorel
OM	Variable operation and maintenance costs	€/MWh	Balmorel
EG	Exogenously capacity	MW	Balmorel
FC	Fixed operation costs	€/MW	Balmorel
HP	Hydro storages costs	€/MWh	Balmorel
XC	Transmission costs	€/MWh	Balmorel
IC	Investment costs	€/MW	Balmorel, NFSM
An	Annuity		NFSM
IX	Investment cost in transmission lines	€/MW	Balmorel
EL	Emission per consumed unit	kg/GJ	Balmorel
EC	Emission costs	€/kg	Balmorel
DH	Demand heat	MWh	Balmorel
HT	Heat demand profile	%	Balmorel
DL	Distribution losses	%	Balmorel
EF	Fuel efficiency	%	Balmorel
DE	Demand electricity	MWh	Balmorel
ET	Electricity demand profile	%	Balmorel

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Appendix

Appendix

This appendix shows the main input data and assumption used in in the Nordic forest sector model (NFSM) for the model version used in paper V. The input data reflect the Nordic forest sector in the reference year 2018 and was collected in autumn 2019. In cases where 2018 data was not available, the newest available data was used instead (i.e. from 2016 or 2017). The data collection builds on the previous collections by Trømborg and Sjølie (2011) and Mustapha (2016), and many of the same sources are used. In cases where new data not was found or the data had other resolution than needed, was data adapted from Trømborg and Sjølie (2011) or Mustapha (2016).

1 Regions and products

The focus in NFSM is the Nordic forest sector (i.e. forestry and forest industry in the Nordic countries). Nordic forest products and roundwood is traded interregional and in order to represent the Nordic forest sector is the Nordic countries divided in to 32 regions as shown in table 1. The regional centre is used for estimating transportation cost between regions. It is assumed that all harvest, production, and trade happen in the regional centre.

NFSM hold 37 different roundwood categories, intermediate product, and final product. Table 2 show the product categories with abbreviation, unit, and industrial production and harvest in the reference year for the Nordic countries and rest of the world (ROW). It is important to notice that the ROW region do not cover a specific area, but instead is the reference production estimated to be the net European (EU-28) production plus the net import to the Nordic countries. This is done in order to balance consumption, harvest, production, and trade within the Nordic countries and simultaneously keep the Nordic countries role as a price taking region.

The base currency in NFSM is euro, since national statistics mostly uses national currencies is the average exchange rate in 2018 used. It is assumed that the exchange rate is kept constant for all modelled year. The exchange rate is 1.18 USD/€, 7.45 DKK/€, 10.25 SEK/€, and 9.60 NOK/€ (Norges Bank, 2020).

Appendix

Table 1. Regions in NFSM and regional centre used for estimation of transportation costs.

	Regions	Administrative districts	Regional centre
Norway	N1	East Viken (Østfold, Akershus), Oslo	Oslo
	N2	Innlandet	Elverum
	N3	West Viken (Buskerud)	Drammen
	N4	Vestfold og Telemark	Skien
	N5	Agder	Kristiansand
	N6	Rogaland	Stavanger
	N7	Vestland	Bergen
	N8	Møre og Romsdal	Sunndalsøra
	N9	Trøndelag	Trondheim
	N10	Nordland, Troms og Finnmark	Bodø
Sweden	S1	Norrbotten	Piteå
	S2	Västerbotten	Umeå
	S3	Jämtland	Östersund
	S4	Västernorrland	Kramfors
	S5	Gävleborg, Dalarna	Borlänge
	S6	Uppsala, Stockholm, Södermanland, Västmanland	Stockholm
	S7	Värmland, Örebro	Karlstad
	S8	Västra Götaland	Trollhättan
	S9	Östergötland, Jönköping, Kalmar, Gotland	Nässjö
	S10	Halland, Kronoberg, Blekinge, Skåne	Hässleholm
Finland	F1	Lappi	Rovaniemi
	F2	Pohjois-Pohjanmaa, Kainuu	Oulu
	F3	Kaski-Pojhanmaa, Etelä-Pohjanmaa, Pohjanmaa	Vaasa
	F4	Keski-Suomi	Jyväskylä
	F5	Pohjois-Savo	Kuopio
	F6	Pohjois-Karjala, Etelä-Karjala, Kymenlaakso	Joensuu
	F7	Varsinais-Suomi, Satakunta, Ahvenanmaa	Turku
	F8	Päijät-Hame, Kanta-Häme, Pirkanmaa	Hämeenlinna
	F9	Etelä-Savo	Mikkeli
	F10	Uisimaa	Helsinki
Denmark	D1	Denmark	Odense
ROW	A1	ROW	Riga

Table 2. All products in the model with abbreviation, base unit, and base year harvest and production, given in 1000 unit.

Category	Product	Abbreviation	Base unit	Nordic countries	ROW
Raw forest categories	Harvest residues	FOFU	m³ solid	6 260	
	Non-coniferous pulpwood	NonConPulp	m³ solid ub.	27 474	83 955
	Non-coniferous sawlogs	NonConSaw	m³ solid ub.	1 386	50 339
	Pine pulpwood	PinePulp	m³ solid ub.	29 641	144 013
	Pine sawlogs	PineSaw	m³ solid ub.	26 212	133 225
	Spruce pulpwood	SprucePulp	m³ solid ub.	33 811	155 039
	Spruce sawlogs	SpruceSaw	m³ solid ub.	41 223	209 519
Intermediate forest products	Bark	Bark	m³ solid	24 306	116 009
	Charcoal	CharCoal	Tonne		
	Chips	Chips	m³ solid	42 454	456 727
	Sawdust	Dust	m³ solid	9 455	58 668
	Firewood	Firew	m³ solid	14 717	172 591
	Pellets	Pell	Tonne	2 570	15 505
	Shavings	Shav	m³ solid	2 687	14 788
Intermediate industrial products	Black liquor	Black_liq	Tonne	31 809	85 244
	Recycled paper	Rcyc	Tonne	17 838	94 807
	Tall oil	TallOil	Tonne	633	1 266
Bioenergy products	Local heat	BioSpace	MWh	35 217	279 615
	District heat	BioWater	MWh	45 502	102 618
	Synthetic diesel	Diesel	MWh		
	Synthetic gasoline	Gasoline	MWh		
	Industrial heat	InduWater	MWh	119 162	382 341
Pulp	Sulphite and dissolving pulp	BORR	Tonne	512	1 486
	Chemical pulp	CHEM	Tonne	16 053	47 673
	Chemi-thermomechanical pulp	CTMP	Tonne	2 124	1 038
	Mechanical pulp	MECH	Tonne	4 952	9 753
Paper	Linerboard	LINR	Tonne	4 275	27 420
	Newsprint	NEWS	Tonne	2 114	6 068
	Other paper and paper board	OPBO	Tonne	8 878	48 935
	Printing and writing paper	PRWR	Tonne	8 585	45 532
Board	Fibreboard	FIBR	Tonne	199	20 500
	Particleboard	PART	m³ solid	1 401	43 532
	Plywood	PlyW	m³ solid	1 230	10 297
Sawn products	Cross laminated timber	CLT	m³ solid	345	815
	Non-coniferous sawnwood	NSAW	m³ solid	501	15 458
	Pine sawnwood	PSAW	m³ solid	14 551	52 996
	Spruce sawnwood	SSAW	m³ solid	21 226	79 421

2 Roundwood supply

Price and harvest

Table 3 show the reference harvest excluding bark in the Nordic countries. The harvest data for Norway is the harvest of industrial roundwood (Landbruksdirektoratet, 2020) plus the estimated firewood harvest (SSB, 2020i). Harvest of firewood is assumed to be pulpwood. The Swedish harvest statistic do not provide detailed harvest data on both the species level and regional level, for this reason is data for entire Sweden used (Skogstyrelsen, 2020) and is disaggregated as in Mustapha (2016). While, the Finnish harvest data is accounted for 15% bark.

A constraint ensure that the distribution between harvest of sawlogs and pulpwood follow reasonable levels (table 4). The distribution is based on the regional harvest and rounded up to nearest 5% the lowest possible upper limit is chosen to be 60%. For all regions with significant harvest is the historical distribution close to half sawlogs and half pulpwood, the only exemption is in the northern regions where the harvest is dominated by energy wood, in those regions is a higher share of pulpwood allowed.

Table 5 show volume-weighted prices for roundwood and harvest residues. Prices of harvest residues is only provided for Norway and Finland. Reference timber prices are found as roadside prices, while NFSM uses roundwood prices at industrial site. For this reason, the estimated interregional transportation cost is added to the roundwood prices as part of the calibration procedure. The transportation cost inside a region is estimated to be the price increase that is closest to zero and still give the correct harvest in each region in the reference year.

Table 3. Reference harvest in 1000 m³ solid under bark. Source: (Landbruksdirektoratet, 2020; Luke, 2020d; Luke, 2020e; Skogstyrelsen, 2020; SSB, 2020i; Statistics Denmark, 2020).

	SpruceSaw	SprucePulp	PineSaw	PinePulp	NonConSaw	NonConPulp	FOFU
N1	775	656	198	190	0.0	155	2
N2	1 826	1 524	685	607	0.1	354	0
N3	382	322	213	216	0.6	118	0
N4	426	404	181	176	0.8	204	0
N5	321	191	183	163	0.8	157	0
N6	46	45	7.2	23	0.0	58	0
N7	233	205	9.3	54	0.0	179	0
N8	157	116	12	29	0.0	94	0
N9	383	478	29	64	0.2	146	0
N10	55	145	13	51	0.1	363	0
S1	743	579	1 123	875	13	792	85
S2	1 234	962	1 866	1 454	22	1 316	142
S3	1 618	1 261	1 013	789	10	615	110
S4	2 168	1 689	1 357	1 057	14	824	147
S5	3 325	2 591	2 394	1 865	21	1 236	339
S6	2 116	1 649	1 747	1 361	13	768	296
S7	2 392	1 864	1 974	1 539	15	868	334
S8	2 234	1 741	573	447	23	1 329	430
S9	4 181	3 258	1 073	836	42	2 488	805
S10	2 600	2 026	667	520	26	1 547	501
F1	150	376	1 006	2 027	0.0	545	97
F2	682	967	1 794	3 774	7.7	1 789	241
F3	862	800	1 026	1 707	16	985	250
F4	1 484	1 022	948	1 442	121	1 079	320
F5	1 718	1 230	711	1 152	149	1 322	241
F6	2 026	1 701	1 704	2 714	190	1 700	273
F7	1 063	855	840	1 054	50	760	479
F8	2 817	1 787	1 081	1 317	197	1 450	580
F9	1 848	1 062	1 288	1 181	229	1 195	338
F10	628	576	267	410	68	586	187
D1	729	1 731	230	546	157	2 453	62
A1	209 519	155 039	133 225	144 013	50 339	83 955	0

Appendix

Table 4. Maximum allowed harvest of spruce and pine sawlogs and pulpwood. Based on historical distribution, own estimate, and theoretical amounts. Source: (Landbruksdirektoratet, 2020; Luke, 2020d; Luke, 2020e; Skogstyrelsen, 2020; SSB, 2020i; Statistics Denmark, 2020).

	Max spruce sawlogs	Max spruce pulpwood	Max pine sawlogs	Max pine pulpwood
N1	60 %	60 %	60 %	60 %
N2	60 %	60 %	60 %	60 %
N3	60 %	60 %	60 %	60 %
N4	60 %	60 %	60 %	60 %
N5	65 %	65 %	60 %	60 %
N6	60 %	60 %	80 %	80 %
N7	60 %	60 %	90 %	90 %
N8	60 %	60 %	70 %	70 %
N9	60 %	60 %	70 %	70 %
N10	75 %	75 %	81 %	81 %
S1	60 %	60 %	60 %	60 %
S2	60 %	60 %	60 %	60 %
S3	60 %	60 %	60 %	60 %
S4	60 %	60 %	60 %	60 %
S5	60 %	60 %	60 %	60 %
S6	60 %	60 %	60 %	60 %
S7	60 %	60 %	60 %	60 %
S8	60 %	60 %	60 %	60 %
S9	60 %	60 %	60 %	60 %
S10	60 %	60 %	60 %	60 %
F1	75 %	75 %	70 %	70 %
F2	60 %	60 %	70 %	70 %
F3	60 %	60 %	65 %	65 %
F4	60 %	60 %	65 %	65 %
F5	60 %	60 %	65 %	65 %
F6	60 %	60 %	65 %	65 %
F7	60 %	60 %	60 %	60 %
F8	65 %	65 %	60 %	60 %
F9	65 %	65 %	60 %	60 %
F10	60 %	60 %	65 %	65 %
D1	70 %	70 %	70 %	70 %
A1	100 %	100 %	100 %	100 %

Table 5. Volume-weighted roundwood prices delivered industrial site given in €/m³ solid ub. The prices are observed timber prices delivered roadside plus estimated transportation costs. Source: (FAOSTAT, 2019; Luke, 2020f; Luke, 2020g; Skogstyrelsen, 2019; SSB, 2020g).

	SpruceSaw	SprucePulp	PineSaw	PinePulp	NonConSaw	NonConPulp	FOFU
N1	79	48	73	41	105	32	74
N2	77	39	69	39	112	32	
N3	68	32	61	41	114	26	
N4	74	34	63	39	119	30	
N5	67	39	64	39	131	28	
N6	59	35	65	38	112	38	
N7	70	31	70	47	111	30	
N8	59	33	56	29	109	18	
N9	68	37	59	31	121	28	
N10	69	56	52	39	116	35	
S1	80	53	86	69	46	54	
S2	78	47	71	55	24	42	
S3	50	49	47	52	38	33	
S4	54	60	60	68	37	41	
S5	63	53	64	55	45	40	
S6	74	43	56	47	37	32	
S7	68	42	58	30	38	30	
S8	77	37	67	21	46	23	
S9	90	35	79	33	52	21	
S10	92	42	82	40	50	27	
F1	92	74	66	39	111	60	0
F2	83	62	84	47	110	45	13
F3	78	72	76	65	111	63	14
F4	70	55	68	65	129	61	17
F5	73	63	70	55	119	46	14
F6	88	68	84	68	117	58	16
F7	85	56	86	66	120	66	15
F8	73	53	79	49	123	48	17
F9	79	59	72	57	133	49	14
F10	78	66	76	61	120	59	15
D1	122	39	54	66	189	108	
A1	127	44	59	71	194	113	

Growing stock and growth

Table 6 and table 7 show the growing stock and the estimated yearly growth given as a percentage of the growing stock. Norway, Sweden, and Denmark provide statistic on standing stocks on species level, but not on categories, for this reason it is assumed that half of the reference standing stocks is pulpwood and rest is sawlogs. For Finland and Sweden is the harvest accounted for 15% bark. The growing rate for Finland and Sweden is based on Mustapha (2016), growth in Norway is based on the yearly average for 2014-2018 (SSB, 2020b), and for Denmark is the growth based on average yearly growth for conifers and non-conifers (Einfeldt, 2020).

Table 6. Growing stock given in million m^3 solid ub. Source: (Einfeldt, 2020; Luke, 2020c; SLU, 2020; SSB, 2020a).

	SpruceSaw	SprucePulp	PineSaw	PinePulp	NonConSaw	NonConPulp
N1	26.09	26.09	14.85	14.85	7.63	7.63
N2	66.95	66.95	40.77	40.77	18.34	18.34
N3	18.35	18.35	13.91	13.91	6.86	6.86
N4	23.24	23.24	16.04	16.04	12.43	12.43
N5	13.62	13.62	22.41	22.41	11.12	11.12
N6	2.80	2.80	4.98	4.98	4.52	4.52
N7	12.49	12.49	13.00	13.00	14.17	14.17
N8	5.46	5.46	5.37	5.37	7.27	7.27
N9	31.42	31.42	8.77	8.77	10.75	10.75
N10	11.02	11.02	5.79	5.79	28.20	28.20
S1	49.30	49.30	97.37	97.37	30.47	30.47
S2	60.78	60.78	75.35	75.35	27.37	27.37
S3	73.99	73.99	58.86	58.86	24.27	24.27
S4	46.20	46.20	37.87	37.87	20.10	20.10
S5	69.96	69.96	111.31	111.31	28.26	28.26
S6	47.05	47.05	49.34	49.34	29.11	29.11
S7	70.98	70.98	52.57	52.57	21.97	21.97
S8	58.10	58.10	29.37	29.37	23.55	23.55
S9	93.03	93.03	79.05	79.05	38.97	38.97
S10	35.57	35.57	10.88	10.88	31.20	31.20
F1	13.14	37.18	36.20	133.65	0.14	33.40
F2	24.36	47.75	53.23	169.60	1.81	55.11
F3	21.00	25.86	37.45	76.75	2.04	28.48
F4	31.58	29.59	30.32	50.60	4.07	27.00
F5	33.01	36.38	21.96	41.90	3.56	31.30
F6	41.75	41.47	53.89	81.92	5.88	44.45
F7	23.69	27.39	26.59	50.81	4.26	23.28
F8	56.30	52.86	31.22	44.87	8.30	38.25
F9	30.29	26.72	34.28	38.90	4.99	27.70
F10	13.64	16.05	8.34	17.04	4.17	15.48
D1	21.01	21.01	6.62	6.62	38.42	38.42
A1	10 634	10 779	12 752	20 384	14 765	39 392

Table 7. Estimated yearly growth given in percentage of the growing stock the current year. Source: (Einfeldt, 2020; Mustapha, 2016; SSB, 2020b; SSB, 2020h).

	SpruceSaw	SprucePulp	PineSaw	PinePulp	NonConSaw	NonConPulp
N1	3.7 %	3.7 %	3.3 %	3.3 %	4.9 %	4.9 %
N2	4.3 %	4.3 %	3.5 %	3.5 %	4.2 %	4.2 %
N3	4.3 %	4.3 %	3.6 %	3.6 %	4.4 %	4.4 %
N4	3.7 %	3.7 %	2.4 %	2.4 %	4.0 %	4.0 %
N5	4.8 %	4.8 %	3.1 %	3.1 %	5.0 %	5.0 %
N6	4.5 %	4.5 %	2.6 %	2.6 %	4.5 %	4.5 %
N7	6.9 %	6.9 %	3.0 %	3.0 %	3.6 %	3.6 %
N8	6.6 %	6.6 %	2.7 %	2.7 %	3.3 %	3.3 %
N9	4.8 %	4.8 %	2.4 %	2.4 %	3.8 %	3.8 %
N10	3.9 %	3.9 %	2.6 %	2.6 %	3.3 %	3.3 %
S1	2.7 %	2.7 %	3.2 %	3.2 %	3.7 %	3.7 %
S2	3.5 %	3.5 %	3.5 %	3.5 %	3.7 %	3.7 %
S3	3.5 %	3.5 %	3.7 %	3.7 %	3.7 %	3.7 %
S4	4.0 %	4.0 %	3.7 %	3.7 %	4.7 %	4.7 %
S5	4.5 %	4.5 %	3.8 %	3.8 %	4.4 %	4.4 %
S6	4.7 %	4.7 %	2.9 %	2.9 %	3.5 %	3.5 %
S7	4.5 %	4.5 %	3.6 %	3.6 %	3.9 %	3.9 %
S8	4.5 %	4.5 %	2.6 %	2.6 %	4.1 %	4.1 %
S9	5.0 %	5.0 %	3.2 %	3.2 %	2.7 %	2.7 %
S10	5.2 %	5.2 %	2.6 %	2.6 %	3.7 %	3.7 %
F1	3.1 %	3.1 %	3.3 %	3.3 %	3.9 %	3.9 %
F2	4.2 %	4.2 %	4.3 %	4.3 %	4.8 %	4.8 %
F3	4.7 %	4.7 %	4.3 %	4.3 %	5.4 %	5.4 %
F4	4.8 %	4.8 %	4.3 %	4.3 %	5.7 %	5.7 %
F5	5.1 %	5.1 %	4.4 %	4.4 %	6.1 %	6.1 %
F6	4.9 %	4.9 %	4.3 %	4.3 %	5.5 %	5.5 %
F7	4.5 %	4.5 %	4.0 %	4.0 %	5.1 %	5.1 %
F8	4.8 %	4.8 %	4.0 %	4.0 %	5.3 %	5.3 %
F9	5.4 %	5.4 %	4.2 %	4.2 %	5.7 %	5.7 %
F10	4.4 %	4.4 %	3.3 %	3.3 %	4.6 %	4.6 %
D1	5.8 %	5.8 %	5.8 %	5.8 %	4.8 %	4.8 %
A1	2.8 %	2.8 %	2.8 %	2.8 %	2.8 %	2.8 %

Harvest residues

Table 8 show the marginal cost intercept and slope for harvest and transport of harvest residues. The upper amount of harvest residues that is available for harvesting in one region is assumed to be 40% of the harvested level by volume. The total cost of collection harvest residues in each region is given with the formula

$$Total\ cost = \ Intercept * quantity + \frac{1}{2} Slope * quantity^2$$

Table 8. Marginal cost intercept and slope for harvest residues, adapted from Mustapha (2016).

	Cost intercept [€]	Cost slope [€/m³]		Cost intercept [€]	Cost slope [€/m³]		Cost intercept [€]	Cost slope [€/m³]
N1	56.3	0.035	S1	42.9	0.040	F1	48.2	0.025
N2	56.3	0.038	S2	42.9	0.045	F2	48.2	0.026
N3	56.3	0.011	S3	42.9	0.026	F3	48.2	0.030
N4	56.3	0.031	S4	42.9	0.026	F4	48.2	0.032
N5	56.3	0.029	S5	42.9	0.026	F5	48.2	0.033
N6	56.3	0.066	S6	42.9	0.014	F6	48.2	0.035
N7	56.3	0.193	S7	42.9	0.014	F7	48.2	0.040
N8	56.3	0.376	S8	42.9	0.014	F8	48.2	0.039
N9	56.3	0.153	S9	42.9	0.016	F9	48.2	0.037
N10	56.3	0.101	S10	42.9	0.016	F10	48.2	0.042
D1	59.0	0.024	A1	59.0	0.024			

Price elasticity of roundwood

There is large variation in estimates of the price elasticity of roundwood, for example, Tian et al. (2017) found high uncertainties for level of elasticity of roundwood supply, while Bolkesjø et al. (2010) found high price elasticity of roundwood supply. There are thus considerable uncertainties regarding the level of price effects on the roundwood supply in the Nordic countries; as such, it is assumed that the elasticity of roundwood supply may be higher than the level used in the previous data report for the NFSM (Mustapha, 2016). For this reasons, we have doubled the price elasticity of roundwood supply compared to values found in Mustapha (2016). This follows the assumption in Jåstad et al. (2019) (Paper II). Table 9 show the used price elasticity of roundwood supply.

Table 9. Price elasticity of roundwood supply.

	Sawlogs	Pulpwood
N1-N6	0.8	1.2
N7-N8	0.6	0.8
N9-N10	0.8	1.0
S1-S10	0.6	0.8
F1-F10	1.0	1.2
D1	0.8	1.2
A1	1.0	1.2

Downgrading

In cases where the model has problem with fulfil the mass balance, may the model choose to downgrade some forest products. The model may downgrade sawlogs to pulpwood, pulpwood to shavings, and shavings to dust. In order to downgrade needs the unit price of the original product and the end product be exactly equal.

3 Forest industry

The reference production in each region and technologies is shown table 11, table 13, table 15, table 17, table 19, table 20, and table 23. The reference production is based on capacities provided by Mustapha (2016), but is updated to 2018. The input/output coefficients for the different technologies is shown in table 12, table 14, table 16, table 18, table 21, table 22, and table 24. The technologies is primary based on Mustapha (2016).

Labour costs (“La” column) is adapted from Mustapha (2016) in cases where new technologies has been added to the model is the median labour costs for the same product in the same country used. The shown labour costs is the marginal labour input at reference production, the marginal costs is modelled to be constant for production capacities within range 0-100%, and levels above increases the marginal cost with 1%-point for each 1%-point increase in production.

The all other costs/income (“MO” column) show for all costs and income that is not covered by the other parameters. The “MO” is only a calibration parameter and the level is chosen in order to get correct production and prices in each region. Values that is in absolute term fare from zero is interpreted as one or more input/output coefficients is not correct for that specific technology.

Appendix

All technologies that use pulpwood, sawlogs, or chips as input is assumed to have 15% bark as a by-product. For most cases is the same amount of bark used for industrial heat production at the same location (chapter 4). Further is industrial heat and electricity inputs for the different products based on Pöyry (2016), except for sulphite and dissolving pulp that is based on Borregaard (2020) and for particleboard that is based on a median particleboard technology data from Mustapha (2016). The figures in table 10 is used for all technologies except for pulp and paper technologies in Sweden where heat and electricity input is provided on mill level by Skogs Industrierna (2020).

The production levels in ROW (A1) is chosen to be approximate equal to the total European production provided from FAOSTAT (2019). While the input/output coefficients are based on the median values of the Nordic technologies. Both the reference production and technologies may have been changed during the calibration of the model.

Table 10. Industrial heat and electricity input for the different technologies shown in table 12, table 14, table 16, table 18, table 21, table 22, and table 24. Source: (Borregaard, 2020; Mustapha, 2016; Pöyry, 2016).

	Industrial heat [MWh/unit]	Electricity [MWh/unit]
BORR	5.86	2.75
CHEM	2.48	0.97
CTMP	1.00	0.45
FIBR	1.50	0.50
LINR	1.31	0.66
MECH		2.14
NEWS	1.31	0.57
OPBO	1.58	0.73
PART	0.64	0.16
PlyW – spruce and pine	0.56	0.12
PlyW – non-conifers	0.69	0.23
PRWR	1.31	0.70
SSAW, PSAW, NSAW	0.31	0.075

Sawnwood production

Sawmill capacity is aggregated in groups according capacity size; large, medium, and small sawmill. The regional location of sawmills at different sizes is kept equal to Mustapha (2016), but the capacities is updated in order to reflect the actual sawlogs harvest at national level (table 3) minus the net export (table 36). The input/output coefficients for sawmill is based on Norwegian statistics (Treindustrien, 2020).

Cross laminated timber (CLT) is a new product in the Nordic countries, and CLT will likely get increased interest in the Nordic countries in the coming years. To have a flexible production of CLT, may CLT be produced from spruce, pine, and non-coniferous sawnwood. A mill may change the distribution between spruce, pine, and non-coniferous sawnwood between years, but at least half of the production must be from spruce.

Table 11. Sawnwood and CLT production in the reference year for different technologies and regions, unit 1000 m^3. Source: (Danske bank, 2019; FAOSTAT, 2019; Mustapha, 2016).

Prod	Tech	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
CLT	FCLT		70	70							
PSAW	FL		998		173	480	1 495	511	867	278	
SSAW	FL	546	385	273	142	355	1 624	723	1 364	273	
PSAW	FM	111	397		56	69		56			
SSAW	FM		86		68	136		355			
NSAW	FS		0.5	1.9	84	23	35	0.5	61	97	0.5
PSAW	FS			67							
SSAW	FS								116		
Prod	Tech	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
CLT	NCLT			60							
PSAW	NL		146		36	52		1.7			2.3
SSAW	NL		302		84	117					
PSAW	NM	82						0.3			0.4
SSAW	NM	77	287							140	22
NSAW	NS	0.0	0.1	0.3	0.4	0.4				0.1	
PSAW	NS	0.0	137	88	39	23	3.0	1.9	5.1	12	2.6
SSAW	NS	239	155	156	90	14	19	95	64	16	
Prod	Tech	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
CLT	SCLT		30					100			15
PSAW	SL	535			559	1 235	534	518		268	790
SSAW	SL		548	350	525	519	1 155	952	292	828	257
PSAW	SM	122	682		146	540	359			492	
SSAW	SM				303	179		182		1 860	1 256
NSAW	SS					19				90	
PSAW	SS	303	156	145	116	277	61		48	336	49
SSAW	SS	57	334	205	64	786	175	361	224	759	439

Prod	Tech	A1	Prod	Tech	D1
CLT	ACLT	815	NSAW	DS	89
NSAW	AS	15 458	PSAW	DS	93
PSAW	AS	52 996	SSAW	DS	295
SSAW	AS	79 421			

Appendix

Table 12. Input and output coefficients for sawnwood and CLT technologies, SS=SpruceSaw [m³/m³], PP=PineSaw [m³/m³], NS=NonConSaw [m³/m³], SP=SprucePulp [m³/m³], PP=PinePulp [m³/m³], NP=NonConPulp [m³/m³], Ch=Chips [m³/m³], Du=Dust [m³/m³], Ba=Bark [m³/m³], Sh=Shav [m³/m³], EL=Electricity input [MWh/m³], IW=InduWater [MWh/m³], Sa=Sawnwood input [m³/m³], MO=Calibration cost [€/m³], La=Labour input [h/m³]. Source: (Mustapha, 2016; Pöyry, 2016; Treindustrien, 2020).

Prod	Tech	SS	PS	NS	SP	PP	NP	Ch	Du	Ba	Sh	EL	IW	Sa	MO	La
								Danish technologies								
CLT	DCLT							-0.29	-0.14			0.08		1.43	802	0.31
NSAW	DS			1.85			-0.28		-0.26	-0.28	-0.07	0.08	0.31		37	1.08
PSAW	DS		1.85			-0.28			-0.26	-0.28	-0.07	0.08	0.31		-80	1.08
SSAW	DS	1.85			-0.28				-0.26	-0.28	-0.07	0.08	0.31		-73	1.08
								Finnish technologies								
CLT	FCLT							-0.29	-0.14			0.08		1.43	806	0.31
PSAW	FL		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-84	0.4
SSAW	FL	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.31		-79	0.4
PSAW	FM		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-90	0.57
SSAW	FM	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.31		-84	0.57
NSAW	FS			1.85			-0.52		-0.26	-0.28	-0.07	0.08	0.31		66	0.42
PSAW	FS		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-40	0.42
SSAW	FS	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.31		-80	0.42
								Norwegian technologies								
CLT	NCLT							-0.29	-0.14			0.08		1.43	780	0.31
PSAW	NL		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.35		-60	0.46
SSAW	NL	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.35		-65	0.46
PSAW	NM		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.35		-50	0.31
SSAW	NM	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.35		-54	0.31
NSAW	NS			1.85			-0.52		-0.26	-0.28	-0.07	0.08	0.35		116	0.42
PSAW	NS		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.35		-60	0.42
SSAW	NS	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.35		-60	0.42
								Swedish technologies								
CLT	SCLT							-0.29	-0.14			0.08		1.43	822	0.31
PSAW	SL		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-85	0.4
SSAW	SL	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.31		-75	0.4
PSAW	SM		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-90	0.57
SSAW	SM	1.85			-0.52				-0.26	-0.28	-0.07	0.08	0.31		-83	0.57
NSAW	SS			1.85			-0.52		-0.26	-0.28	-0.07	0.08	0.31		100	0.66
PSAW	SS		1.85			-0.52			-0.26	-0.28	-0.07	0.08	0.31		-100	0.66
SSAW	SS	1.85							-0.26	-0.28	-0.07	0.08	0.31		-83	0.66
								ROW technologies								
CLT	ACLT							-0.29	-0.14			0.08		1.43	729	0.31
NSAW	AS			2.50			-1.05		-0.35	-0.38	-0.10				50	1.71
PSAW	AS		2.50			-1.05			-0.35	-0.38	-0.10				15	0.8
SSAW	AS	2.50			-1.05				-0.35	-0.38	-0.10				-95	0.8

Board production

Board production in Denmark, Finland, and Sweden is located in the same regions as in Mustapha (2016), but the total national production is adjusted according to FAOSTAT (2019). The Norwegian board production is based on mill specific data (Forestia, 2020; Hunton, 2020; Huntonit, 2020; Norsk industri, 2020). The technology data is adapted from Mustapha (2016).

Table 13. Board production in reference year for different technologies and regions, unit 1000 m^3 for particleboard and plywood and 1000 tonne for fibreboard. Source: (FAOSTAT, 2019; Forestia, 2020; Hunton, 2020; Huntonit, 2020; Mustapha, 2016; Norsk industri, 2020).

Product	Tech	F4	F6	F8	F9
FIBR	FB1			24	
PART	FB2			100	
PlyW	FB3	65			65
PlyW	FB4		55		
PlyW	FB6	120			100
PlyW	FB7			70	
PlyW	FB8			75	
PlyW	FB9				480
		N2	N3	N5	N10
FIBR	NB1		85		
FIBR	NB2		40		
FIBR	NB3			47	
PART	NB4	350			
PART	NB5				55
		S3	S7	S8	S9
PART	SB1				483
PART	SB2	37			
PART	SB3		30		
PlyW	SB4			120	
		A1			D1
FIBR	AB1	20 500	FIBR	DB1	3
PART	AB2	43 532	PART	DB2	346
PlyW	AB3	10 297	PlyW	DB3	80

Table 14. Input and output coefficients for board technologies, SS=SpruceSaw [m^3/unit], NS=NonConSaw [m3/unit], SP=SprucePulp [m3/unit], PP=PinePulp [m3/unit], NP=NonConPulp [m3/unit], Ch=Chips [m3/unit], Du=Dust [m3/unit], Ba=Bark [m3/unit], Sh=Shav [m3/unit], EL=Electricity input [MWh/unit], IW=InduWater [MWh/unit], MO=Calibration cost [€/unit], La=Labour input [h/unit]. Source: (Mustapha, 2016; Pöyry, 2016).

Product	Tech	SS	NS	SP	PP	NP	Ch	Du	Ba	Sh	EL	IW	MO	La
Danish technologies														
FIBR	DB1			0.34	0.89	0.08			-0.29		0.50	1.5	-131	4.9
PART	DB2			0.33		0.01		0.21	-0.09	0.06	0.16	0.64	-67	1.4
PlyW	DB3			2.21					-0.33		0.12	0.56	102	2.0
Finnish technologies														
FIBR	FB1			0.87				0.40	-0.19		0.50	1.50	50	2.0
PART	FB2			0.35				0.45	-0.15	0.20	0.16	0.64	-26	2.4
PlyW	FB3	2.21							-0.33		0.12	0.56	72	2.0
PlyW	FB4		2.21						-0.33		0.23	0.69	0	1.7
PlyW	FB6		2.21						-0.33		0.23	0.69	-18	2.4
PlyW	FB7	2.21							-0.33		0.12	0.56	69	2.1
PlyW	FB8		2.21						-0.33		0.23	0.69	-18	2.2
PlyW	FB9	2.21							-0.33		0.12	0.56	105	1.3
Norwegian technologies														
FIBR	NB1			0.52			1	0.92	-0.37		0.52	0.65	-20	2.4
FIBR	NB2						0.88	0.88	-0.26		0.52	0.65	-20	2.4
FIBR	NB3						0.87		-0.13		1.32	0.65	-302	7.4
PART	NB4			0.20				0.88	-0.16		0.15	0.28	90	0.4
PART	NB5			0.46			0.02	0.16	-0.10		1.38	0.28	-89	2.4
Swedish technologies														
PART	SB1			0.27		0.30		0.50			0.16	0.64	90	0.2
PART	SB2			0.48		0.06	0.06	0.33			0.16	0.64	-46	1.8
PART	SB3			0.47		0.47	0.02	0.02			0.16	0.64	60	0.5
PlyW	SB4			1.86							0.12	0.56	180	1.9
ROW technologies														
FIBR	AB1			0.87				0.40	-0.19		0.50	1.50	39	5.0
PART	AB2			0.35				0.45	-0.15	0.20	0.16	0.64	-7	1.7
PlyW	AB3	1.11	1.11						-0.33		0.12	0.56	96	2.6

Pulp and paper production

The Finnish pulp and paper production is located in the same regions as in Mustapha (2016), but the total national production is adjusted to be equal FAOSTAT (2019). The Swedish pulp and paper production is estimated based on detailed mill data provided by Skogs Industrierna (2020). While the Norwegian pulp and paper production is based on mill specific data (Borregaard, 2020; Glomma papp, 2020; Hellefoss Paper As, 2020; MMK Follacell AS, 2020; Nordic Paper, 2020; Norsk industri, 2020; Norske Skog, 2020; Ranheim paper and board, 2020; Rygene, 2020; Vafos Pulp AS, 2020; Vajda papir, 2020). The technologies is based on Mustapha (2016), except for industrial heat and electricity that is based on Pöyry (2016), while for Swedish technologies is Skogs Industrierna (2020) used.

Table 15. Pulp and paper production in Norway, Denmark, and ROW for the reference year for different technologies and regions, unit 1000 tonne. Source: (Borregaard, 2020; FAOSTAT, 2019; Glomma papp, 2020; Hellefoss Paper As, 2020; MMK Follacell AS, 2020; Mustapha, 2016; Nordic Paper, 2020; Norsk industri, 2020; Norske Skog, 2020; Ranheim paper and board, 2020; Rygene, 2020; Vafos Pulp AS, 2020; Vajda papir, 2020).

Product	Tech	N1	N3	N4	N5	N9	N10
BORR	NP1	153					
CTMP	NP2					140	
MECH	NP3				40		
MECH	NP4			80			
NEWS	NP5					488	
OPBO	NP6	42					
OPBO	NP7		37				
OPBO	NP8						40
OPBO	NP9					92	
PRWR	NP10	485					
PRWR	NP11		50				

Product	Tech	A1	Product	Tech	D1
BORR	AP1	1 486	LINR	DP1	22
CHEM	AP2	47 673	MECH	DP2	4.8
CTMP	AP3	1 038	OPBO	DP3	313
LINR	AP4	27 420	PRWR	DP4	68
MECH	AP5	9 753			
NEWS	AP6	6 068			
OPBO	AP7	48 935			
PRWR	AP8	45 532			

Table 16. Input and output coefficients for pulp and paper technologies in Norway, Denmark. and ROW, SP=SprucePulp [m3/tonne], PP=PinePulp [m3/tonne], NP=NonConPulp [m3/tonne], Ch=Chips [m^3/tonne], Ba=Bark [m3/tonne], CH=CHEM [tonne/tonne], BO=BORR [tonne/tonne], CT=CTMP [tonne/tonne], ME=MECH [tonne/tonne], RY=Rcyc [tonne/tonne], EL=Electricity input [MWh/tonne], IW=InduWater [MWh/tonne], BL=Black_liq [tonne/tonne], TO=TallOil [tonne/tonne], MO=Calibration cost [€/tonne], La=Labour input [h/tonne]. Source: (Mustapha, 2016; Pöyry, 2016).

Prod	Tech	SP	PP	NP	Ch	Ba	CH	BO	CT	ME	RY	EL	IW	BL	TO	MO	La
							Norwegian technologies										
BORR	NP1	6.54				-0.98						2.94	2.55			323	3.49
CTMP	NP2				2.49	-0.37						1.52	0.44	-1.75	-0.04	104	1.11
MECH	NP3				5.00	-0.75						1.64				-80	1.02
MECH	NP4	2.10				-0.32						1.00				110	1.11
NEWS	NP5	1.30			0.44	-0.26						2.40	0.57			-249	1.62
OPBO	NP6		0.95			-0.14						0.62	0.69			456	1.00
OPBO	NP7						0.92					0.81	0.69			-531	7.63
OPBO	NP8						0.77					3.50	0.69			-394	4.59
OPBO	NP9										1.36	0.15	0.06			244	1.86
PRWR	NP10	1.30				-0.20						2.73	0.57			84	1.82
PRWR	NP11	1.75				-0.26	0.17					2.02	0.57			-78	2.65
							Danish technologies										
LINR	DP1	0.35				-0.05	0.10				0.27	0.66	1.31			102	0.54
MECH	DP2	1.29	0.60	0.70		-0.39						2.14				-5	1.07
OPBO	DP3	0.10				-0.05	0.30		0.01		0.27	0.73	1.58			34	3.76
PRWR	DP4			1.35		-0.20	0.02	0.03		0.10		0.70	1.31			211	1.47
							ROW technologies										
BORR	AP1				5.00	-0.75						2.75	5.86			880	1.98
CHEM	AP2				4.08	-0.61						0.97	2.48	-1.75	-0.03	540	0.81
CTMP	AP3				2.60	-0.39						0.45	1.00	-1.75	-0.03	340	0.51
LINR	AP4	0.80				-0.12	0.57				0.15	0.66	1.31			-238	0.79
MECH	AP5				2.50	-0.38						2.14				140	1.04
NEWS	AP6									0.67	0.15	0.57	1.31			-214	0.86
OPBO	AP7				0.77	-0.12	0.28	0.03	0.01	0.09	0.15	0.73	1.58			119	3.26
PRWR	AP8				0.50	-0.08	0.53		0.02	0.04		0.70	1.31			-30	1.42

Appendix

Table 17. Pulp and paper production in Finland for the reference year for different technologies and regions, unit 1000 tonne. Source: (FAOSTAT, 2019; Mustapha, 2016).

Product	Tech	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
CHEM	FP1	40	36	79	129		352	64			
CHEM	FP2						690				
CHEM	FP3							650			
CHEM	FP4				1 300						
CHEM	FP5						980				
CHEM	FP6		360								
CHEM	FP7						370				
CHEM	FP8						740				
CHEM	FP9						770				
CHEM	FP10			800							
CHEM	FP11	400									
CTMP	FP12						270				
CTMP	FP13						170				
CTMP	FP14			250							
LINR	FP15								105		
LINR	FP16						300				
LINR	FP17					275					
LINR	FP18								315		
LINR	FP19					390					
MECH	FP20	314				73	146				107
MECH	FP21	590									
MECH	FP22										330
MECH	FP23						450				
MECH	FP24					225					
MECH	FP25	375									
NEWS	FP26						514				
OPBO	FP27										
OPBO	FP28			200							
OPBO	FP29								100		
OPBO	FP30							100			
OPBO	FP31						400				
OPBO	FP32						180				
OPBO	FP33	375									
OPBO	FP34								205		
OPBO	FP35				240						
OPBO	FP36								122		
OPBO	FP37										75
OPBO	FP38						100				
OPBO	FP39					100					
OPBO	FP40								122		
OPBO	FP41						1 095				
OPBO	FP42						290				
OPBO	FP43						220				
OPBO	FP44							125			
OPBO	FP45										22
OPBO	FP46								285		
PRWR	FP47										835
PRWR	FP48		1 325								
PRWR	FP49				1 800						
PRWR	FP50						1 070				

Table 18. Input and output coefficients for pulp and paper technologies in Finland, SP=SprucePulp [m^3/tonne], PP=PinePulp [m^3/tonne], NP=NonConPulp [m^3/tonne], Ch=Chips [m^3/tonne], Ba=Bark [m^3 /tonne], CH=CHEM [tonne/tonne], ME=MECH [tonne/tonne], RY=Rcyc [tonne/tonne], EL=Electricity [MWh/tonne], IW=InduWater [MWh/tonne], BL=Black_liq [tonne/tonne], TO=TallOil [tonne/tonne], MO=Calibration cost [€/tonne], La=Labour input [h/tonne]. Source: (Mustapha, 2016; Pöyry, 2016).

Prod	Tech	SP	PP	NP	Ch	Ba	CH	ME	RY	EL	IW	BL	TO	MO	La
CHEM	FP1				4.25	-0.64				0.97	2.48	-1.75	-0.04	365	0.35
CHEM	FP2	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	362	0.19
CHEM	FP3	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	414	0.18
CHEM	FP4	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	365	0.32
CHEM	FP5	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	338	0.43
CHEM	FP6		4.54		0.09	-0.69				0.97	2.48	-1.75	-0.04	364	0.77
CHEM	FP7	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	309	0.77
CHEM	FP8	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	352	0.23
CHEM	FP9	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	354	0.33
CHEM	FP10	0.55	2.12	1.49	0.09	-0.64				0.97	2.48	-1.75	-0.03	349	0.38
CHEM	FP11	0.74	2.65	2.45	1.15	-1.05				0.97	2.48	-1.75	-0.03	249	0.20
CTMP	FP12	2.68				-0.40				0.45	1.00	-1.75	-0.04	203	0.17
CTMP	FP13	2.68				-0.40				0.45	1.00	-1.75	-0.04	155	0.77
CTMP	FP14	2.68				-0.40				0.45	1.00	-1.75	-0.04	208	0.27
LINR	FP15	0.80				-0.12	0.57		0.15	0.66	1.31			-324	0.83
LINR	FP16	0.80				-0.12	0.57		0.15	0.66	1.31			-374	1.00
LINR	FP17	0.80				-0.12	0.57		0.15	0.66	1.31			-344	0.73
LINR	FP18	0.80				-0.12	0.57		0.15	0.66	1.31			-324	0.81
LINR	FP19	0.80				-0.12	0.57		0.15	0.66	1.31			-344	0.70
MECH	FP20	0.34		1.50	0.62	-0.37				2.14				85	0.70
MECH	FP21	1.50		0.34	0.62	-0.37				2.14				71	0.29
MECH	FP22	1.50		0.34	0.62	-0.37				2.14				120	0.56
MECH	FP23	1.50		0.34	0.62	-0.37				2.14				91	0.77
MECH	FP24	1.50		0.34	0.62	-0.37				2.14				111	0.77
MECH	FP25	1.50		0.34	0.62	-0.37				2.14				61	0.77
NEWS	FP26							0.67	0.15	0.57	1.31			-301	0.81
OPBO	FP27						0.20	0.52	0.15	0.73	1.58			177	1.20
OPBO	FP28						0.57		0.15	0.73	1.58			43	0.50
OPBO	FP29						0.57		0.15	0.73	1.58			23	0.55
OPBO	FP30						0.57		0.15	0.73	1.58			-27	2.00
OPBO	FP31						0.57		0.15	0.73	1.58			-27	1.32
OPBO	FP32						0.57		0.15	0.73	1.58			-27	1.32
OPBO	FP33						0.57		0.15	0.73	1.58			33	0.27
OPBO	FP34						0.57		0.15	0.73	1.58			23	0.98
OPBO	FP35						0.57	1.19	0.15	0.73	1.58			-467	0.83
OPBO	FP36						0.57		0.15	0.73	1.58			-97	4.10
OPBO	FP37						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP38						0.57		0.15	0.73	1.58			-27	1.60
OPBO	FP39						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP40						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP41						0.57		0.15	0.73	1.58			43	0.43
OPBO	FP42						0.57		0.15	0.73	1.58			3	1.55
OPBO	FP43						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP44						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP45						0.57		0.15	0.73	1.58			23	0.81
OPBO	FP46						0.57		0.15	0.73	1.58			-27	1.23
PRWR	FP47						0.18	0.41		0.70	1.31			104	0.56
PRWR	FP48						0.18	0.41		0.70	1.31			74	0.81
PRWR	FP49						0.18	0.41		0.70	1.31			74	0.63
PRWR	FP50						0.18	0.41		0.70	1.31			74	0.78
BORR	FPN1	3.77	0.99	0.66	0.42	-0.88				2.27	4.32			700	0.27
CHEM	FPN2	0.74	2.65	2.45	1.15	-1.05				0.97	2.48	-1.75	-0.03	250	0.20
CHEM	FPN3	0.74	2.65	2.45	1.15	-1.05				0.97	2.48	-1.75	-0.03	250	0.20

Appendix

Table 19. Pulp production in Sweden for the reference year for different technologies and regions, unit 1000 tonne. Source: (Skogs Industrierna, 2020).

Product	Tech	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
BORR	SP1							36			
BORR	SP2										324
CHEM	SP3	315									
CHEM	SP4					653					
CHEM	SP5									378	
CHEM	SP6				656						
CHEM	SP7							226			
CHEM	SP8								69		
CHEM	SP9							266			
CHEM	SP10					229					
CHEM	SP11							370			
CHEM	SP12	267									
CHEM	SP13		280								
CHEM	SP14				396						
CHEM	SP15	556									
CHEM	SP16							181			
CHEM	SP17									757	
CHEM	SP18										247
CHEM	SP19										586
CHEM	SP20							403			
CHEM	SP21	243									
CHEM	SP22										178
CHEM	SP23		60								
CHEM	SP24				224						
CHEM	SP25					188					
CHEM	SP26							308			
CHEM	SP27								15		
CHEM	SP28									242	
CTMP	SP29							111			
CTMP	SP30									72	
CTMP	SP31							264			
CTMP	SP32							102			
CTMP	SP33				99						
CTMP	SP34					180					
CTMP	SP35							283			
CTMP	SP36									183	
MECH	SP37									491	
MECH	SP38						538				
MECH	SP39							71			
MECH	SP40				487						
MECH	SP41										249
MECH	SP42					381					

Table 20. Paper production in Sweden for the reference year for different technologies and regions, unit 1000 tonne. Source: (Skogs Industrierna, 2020).

Product	Tech	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
LINR	SP43	383									
LINR	SP44		454								
LINR	SP45	699									
LINR	SP46							142			
LINR	SP47	767									
LINR	SP48		322								
LINR	SP49							101			
NEWS	SP50									522	
NEWS	SP51								154		
NEWS	SP52										437
OPBO	SP53	154									
OPBO	SP54					719					
OPBO	SP55									344	
OPBO	SP56									169	
OPBO	SP57								72		
OPBO	SP58								29		
OPBO	SP59									28	
OPBO	SP60								51		
OPBO	SP61							471			
OPBO	SP62							31			
OPBO	SP63							43			
OPBO	SP64									15	
OPBO	SP65								68		
OPBO	SP66					374					
OPBO	SP67							778			
OPBO	SP68							17			
OPBO	SP69									54	
OPBO	SP70										12
OPBO	SP71							569			
PRWR	SP72					230					
PRWR	SP73						566				
PRWR	SP74				724						
PRWR	SP75				511						
PRWR	SP76					514					
PRWR	SP77										407

Appendix

Table 21. Input and output coefficients for pulp technologies in Sweden, SP=SprucePulp [m^3/tonne], PP=PinePulp [m^3/tonne], NP=NonConPulp [m^3/tonne], Ch=Chips [m^3/tonne], Ba=Bark [m^3/tonne], EL=Electricity input [MWh/tonne], IW=InduWater [MWh/tonne], BL=Black_liq [tonne/tonne], TO=TallOil [tonne/tonne], MO=Calibration cost [€/tonne], La=Labour input [h/tonne]. Source: (Mustapha, 2016; Skogs Industrierna, 2020).

Prod	Tech	SP	PP	NP	Ch	Ba	EL	IW	BL	TO	MO	La
BORR	SP1	2.31	1.85	1.06	0.48	-0.85	2.75	5.86			570	0.27
BORR	SP2	2.46	1.13	0.93	0.79	-0.80	1.12	4.55			696	0.82
CHEM	SP3	1.38	1.59	0.70	0.39	-0.61	0.73	5.54	-1.75	-0.04	190	0.82
CHEM	SP4	1.35	1.43	0.73	0.47	-0.60	0.74	2.90	-1.75	-0.04	347	0.60
CHEM	SP5	1.79	0.82	0.67	0.58	-0.58	0.75	4.05	-1.75	-0.04	271	0.81
CHEM	SP6	1.38	1.59	0.70	0.39	-0.61	0.75	4.65	-1.75	-0.04	248	0.60
CHEM	SP7	1.68	1.35	0.77	0.34	-0.62	0.67	4.72	-1.75	-0.04	224	0.82
CHEM	SP8	1.68	1.35	0.77	0.34	-0.62	0.91	4.92	-1.75	-0.04	265	0.15
CHEM	SP9	1.68	1.35	0.77	0.34	-0.62	0.72	2.52	-1.75	-0.04	312	0.84
CHEM	SP10	1.35	1.43	0.73	0.47	-0.60	0.78	7.17	-1.75	-0.04	151	0.84
CHEM	SP11	1.68	1.35	0.77	0.34	-0.62	0.92	2.92	-1.75	-0.04	305	0.85
CHEM	SP12	1.38	1.59	0.70	0.39	-0.61	0.65	3.66	-1.75	-0.04	242	0.85
CHEM	SP13	1.38	1.59	0.70	0.39	-0.61	0.57	2.50	-1.75	-0.04	336	0.85
CHEM	SP14	1.38	1.59	0.70	0.39	-0.61	1.13	6.83	-1.75	-0.04	130	0.74
CHEM	SP15	1.38	1.59	0.70	0.39	-0.61	0.57	2.86	-1.75	-0.04	295	0.66
CHEM	SP16	1.68	1.35	0.77	0.34	-0.62	0.65	6.58	-1.75	-0.04	155	0.81
CHEM	SP17	1.79	0.82	0.67	0.58	-0.58	0.73	7.13	-1.75	-0.04	152	0.56
CHEM	SP18	1.79	0.82	0.67	0.58	-0.58	1.28	10.5	-1.75	-0.04	-35	0.77
CHEM	SP19	1.79	0.82	0.67	0.58	-0.58	0.67	7.08	-1.75	-0.04	134	0.74
CHEM	SP20	1.68	1.35	0.77	0.34	-0.62	0.72	3.99	-1.75	-0.04	267	0.75
CHEM	SP21	1.38	1.59	0.70	0.39	-0.61	0.65	4.02	-1.75	-0.04	237	0.72
CHEM	SP22	2.01	0.92	0.76	0.65	-0.65	1.02	7.36	-1.75	-0.04	70	0.72
CHEM	SP23	1.38	1.59	0.70	0.39	-0.61	0.57	2.50	-1.75	-0.04	354	0.72
CHEM	SP24	1.38	1.59	0.70	0.39	-0.61	0.94	5.74	-1.75	-0.04	186	0.72
CHEM	SP25	1.35	1.43	0.73	0.47	-0.60	0.76	5.03	-1.75	-0.04	239	0.72
CHEM	SP26	1.79	1.43	0.82	0.37	-0.66	1.07	4.93	-1.75	-0.04	186	0.72
CHEM	SP27	1.68	1.35	0.77	0.34	-0.62	0.91	4.92	-1.75	-0.04	243	0.72
CHEM	SP28	1.79	0.82	0.67	0.58	-0.58	0.74	5.59	-1.75	-0.04	212	0.72
CTMP	SP29	0.90	0.84	0.44	0.23	-0.36	0.61	1.14	-1.75	-0.04	227	0.30
CTMP	SP30	0.90	0.84	0.44	0.23	-0.36	0.07	0.31	-1.75	-0.04	297	0.30
CTMP	SP31	0.90	0.84	0.44	0.23	-0.36	0.14	0.68	-1.75	-0.04	265	0.30
CTMP	SP32	0.99	0.79	0.45	0.20	-0.36	1.31	0.72	-1.75	-0.04	212	0.24
CTMP	SP33	0.82	0.94	0.41	0.23	-0.36	0.52	2.75	-1.75	-0.04	151	0.31
CTMP	SP34	0.80	0.85	0.43	0.28	-0.35	0.68	0.84	-1.75	-0.04	241	0.32
CTMP	SP35	0.99	0.79	0.45	0.20	-0.36	0.30	0.82	-1.75	-0.04	244	0.29
CTMP	SP36	1.05	0.49	0.40	0.34	-0.34	1.25	0.68	-1.75	-0.04	234	0.33
MECH	SP37	0.98	0.45	0.37	0.32	-0.32	2.40				48	0.72
MECH	SP38	0.74	0.79	0.40	0.26	-0.33	2.38				110	0.36
MECH	SP39	0.92	0.74	0.42	0.19	-0.34	2.91				-151	2.42
MECH	SP40	0.76	0.88	0.39	0.22	-0.34	2.32				85	0.33
MECH	SP41	0.98	0.45	0.37	0.32	-0.32	2.35				39	0.68
MECH	SP42	0.74	0.79	0.40	0.26	-0.33	2.64				84	0.38

Table 22. Input and output coefficients for paper technologies in Sweden, SP=SprucePulp [m³/tonne], Ba=Bark [m³/tonne], CH=CHEM [tonne/tonne], BO=BORR [tonne/tonne], CT=CTMP [tonne/tonne], ME=MECH [tonne/tonne], RY=RCYC [tonne/tonne], EL=Electricity input [MWh/tonne], IW=InduWater [MWh/tonne], MO=Calibration cost [€/tonne], La=Labour input [h/tonne]. Source: (Mustapha, 2016; Skogs Industrierna, 2020).

Prod	Tech	SP	Ba	CH	BO	CT	ME	RY	EL	IW	MO	La
LINR	SP43	0.40	-0.06	0.70					0.45	1.94	-436	0.43
LINR	SP44			0.62				0.18	0.39	1.32	-324	0.35
LINR	SP45			0.80				0.07	0.39	1.52	-474	0.23
LINR	SP46	0.40	-0.06	1.04		0.61			0.46	2.50	-1018	0.85
LINR	SP47	0.20	-0.03	0.75				0.04	0.42	1.73	-455	0.47
LINR	SP48			0.62				0.18	0.39	1.32	-324	0.47
LINR	SP49	0.40	-0.06	1.04		0.61			0.46	2.50	-998	0.47
NEWS	SP50					0.94	0.80	0.10	0.64	0.84	-784	0.23
NEWS	SP51	0.40	-0.06				0.70		0.89	1.35	-304	0.48
NEWS	SP52					0.57	0.47	0.18	0.63	1.15	-504	0.18
OPBO	SP53			0.80					0.55	3.52	-249	1.18
OPBO	SP54			0.91					0.55	1.85	-241	0.75
OPBO	SP55			0.81		0.14			0.57	2.57	-282	1.17
OPBO	SP56							0.41	0.72	0.22	422	1.94
OPBO	SP57							0.32	1.46	1.93	274	3.45
OPBO	SP58			0.93					0.93	2.30	-436	6.12
OPBO	SP59			0.93					1.12	2.18	-473	7.44
OPBO	SP60			0.94					0.68	3.13	-426	4.47
OPBO	SP61			0.56					0.54	1.60	30	1.03
OPBO	SP62			0.55	1.32				0.73	1.58	-1938	5.92
OPBO	SP63			0.93					1.26	2.97	-448	5.16
OPBO	SP64							0.27	1.93	3.15	76	7.31
OPBO	SP65							0.30	1.25	1.55	302	2.84
OPBO	SP66					0.44			1.10	1.33	228	1.10
OPBO	SP67			0.48		0.33			0.69	1.86	-80	0.62
OPBO	SP68			0.93					0.73	1.58	-408	6.50
OPBO	SP69			0.93					1.19	0.78	-396	6.63
OPBO	SP70			0.93					1.07	2.31	-372	4.17
OPBO	SP71			0.61		0.36			0.55	2.54	-221	0.98
PRWR	SP72			0.26	0.17		0.32		0.69	1.24	-196	1.49
PRWR	SP73			0.95			0.89		0.78		-645	0.68
PRWR	SP74			0.67					0.76	1.02	-138	0.62
PRWR	SP75			0.63			0.75		0.54	2.45	-440	0.80
PRWR	SP76						0.74		0.86	0.94	112	0.92
PRWR	SP77				0.74				0.28	1.01	-621	0.94

Other products

Production of chips (table 23) is estimated to be the amount that is demanded within industrial processes minus the net trade (table 36) disaggregated to the region where it is demanded.

Pellets and firewood production in Denmark and Sweden is estimated to be the difference between the use of pellets/firewood (table 31, table 32) and the net export (table 36). Swedish firewood capacities are disaggregated following the regional pulpwood harvest, while pellets capacities follow sawmill allocation. Allocation between spruce, pine, and non-conifers firewood production in Norway follow observed firewood harvest (SSB, 2020i), and is disaggregated on the demand for space heating (table 30). While pellets production is estimated based on the difference between the use of pellets (table 29-table 32) and the net export (table 36), disaggregated on the demand for pellets. The Finnish firewood harvest follow Finnish harvest of energy wood (Luke, 2020i), while pellets production follow Luke (2020j) disaggregated equal as in Mustapha (2016). In all countries is the distribution between the different raw material in pellets production a result of the calibration procedure.

It is assumed that 1 m^3 solid for pulpwood, chips, firewood, and dust is equal, i.e. no loses in transforming between the energy categories. Similar, persistence of the energy is assumed in the raw material for pellets production. The heat and electricity demand for pellets production is adapted from European Pellet Council (2020).

There is almost no charcoal production in the Nordic countries (FAOSTAT, 2019), for this reason is there no reference production in table 23, but charcoal technologies is included in table 24. The charcoal production is based on a dummy input that convert primary and secondary forest products to energy units for than being used within charcoal production. In this way will the charcoal production be very flexible in the choice of raw material. The energy efficiencies for charcoal production is assumed to be 56% (Wang et al., 2015).

Table 23. Production of energy products in reference year for different technologies and regions, unit 1000 tonne for pellets and 1000 m³ for chips, firewood, and dust. Source: (FAOSTAT, 2019; Luke, 2020i; Luke, 2020j; Mustapha, 2016).

Product	Tech	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Chips	FP3	283	244	141	109	255	842	559	768	141	
Chips	FP4	58	723	35	119	285	775	294	450	144	
Chips	FP5		3.5	12	543	147	225	3.5	394	632	3.5
Firew	FP6	34	67	88	58	53	100	146	207	60	119
Firew	FP7	78	219	184	80	57	145	202	170	87	101
Firew	FP8	162	299	221	225	252	346	299	441	229	256
Pell	FP9	3.1	4.6	4.1	1.4	10	7.2	0.1	5.1	1.0	
Pell	FP10	19	53	10	15	30	89	47	68	18	0

Product	Tech	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Chips	NP3	287	666	141	176	83	20	90	51	209	63
Chips	NP4	27	86	31	25	23	3.3	7.7	4.0	9.1	7.2
Chips	NP5	16	36	12	21	16	5.8	18	9.4	15	37
Firew	NP6	61	63	27	50	27	23	36	24	41	40
Firew	NP7	61	63	27	50	27	23	36	24	41	40
Firew	NP8	235	246	103	194	106	89	139	92	159	154
Pell	NP9		12	5.3	5.5	0.2			1.0	2.1	1.2
Pell	NP10		12	5.3	5.5	0.2			1.0	2.1	1.2

Product	Tech	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Chips	SP3	30	457	288	463	769	690	775	267	1 787	1 012
Chips	SP4	498	434	75	426	1 064	495	268	25	568	435
Chips	SP5					372				1 788	
Firew	SP7	5.9	10	7.7	10	30	30	34	35	65	40
Firew	SP8	4.6	7.6	5.9	7.9	23	23	26	27	50	31
Firew	SP9	104	173	134	179	531	518	586	604	1 130	703
Pell	SP10		81	286	107	167		113		178	113
Pell	SP11	46	78	32	78	161	103	91	25	210	126

Product	Tech	A1	Product	Tech	D1
Chips	AP2	1 592	Chips	DP3	948
Chips	AP3	5 967	Chips	DP4	402
Chips	AP4	153 975	Chips	DP5	711
Chips	AP5	139 691	Firew	DP6	403
Dust	AP6	6 795	Firew	DP7	127
Firew	AP7	86 295	Firew	DP8	1 772
Firew	AP8	43 148	Pell	DP9	112
Firew	AP9	43 148	Pell	DP10	24
Pell	AP10	1 673			
Pell	AP11	13 833			

Appendix

Table 24. Input and output coefficients for energy technologies, SP=SprucePulp [m³/unit], PP=PinePulp [m³/unit], NP=NonConPulp [m³/unit], Ch=Chips [m³/unit], Du=Dust [m³/unit], Ba=Bark [m³/unit], Sh=Shav [m³/unit], FO=FOFU [m³/unit], EL=Electricity input [MWh/unit], IW=InduWater [MWh/unit], CC=CharCoal [tonne/unit], MO=Calibration cost [€/unit], La=Labour input [h/unit]. Source: (European Pellet Council, 2020; Mustapha, 2016; Wang et al., 2015).

Product	Tech	SP	PP	NP	Ch	Du	Ba	Sh	FO	EL	IW	CC	MO	La
Danish technologies														
CharCoal	DP1											14.6	516	0.00
Chips	DP2								1				-3.2	0.15
Chips	DP3	1											-2	0.15
Chips	DP4		1										-20	0.15
Chips	DP5			1									-30	0.15
Firew	DP6	1											11.2	0.80
Firew	DP7		1										-12	0.80
Firew	DP8			1									-32	0.80
Pell	DP9				2.29		-0.34			0.12	0.61		23	0.28
Pell	DP10					2.29	-0.34			0.12	0.61		108	0.28
Finnish technologies														
CharCoal	FP1											14.6	584	0.00
Chips	FP2								1				1.2	0.15
Chips	FP3	1											-20.5	0.15
Chips	FP4		1										-24.5	0.15
Chips	FP5			1									-20	0.15
Firew	FP6	1											-24.1	0.80
Firew	FP7		1										-26	0.80
Firew	FP8			1									-23.2	0.80
Pell	FP9				2.29					0.12	0.61		-4.42	0.28
Pell	FP10					2.29				0.12	0.61		91.6	0.28
Norwegian technologies														
CharCoal	NP1											14.6	556	0.00
Chips	NP2								1				-27.9	0.15
Chips	NP3	1											-23.2	0.15
Chips	NP4		1										-22	0.15
Chips	NP5			1									-28	0.15
Firew	NP6	1											-31.3	0.80
Firew	NP7		1										-28.6	0.80
Firew	NP8			1									-36	0.80
Pell	NP9				2.29		-0.34			0.12	0.61		12.98	0.28
Pell	NP10					2.29	-0.34			0.12	0.61		100	0.28
Swedish technologies														
CharCoal	SP2											14.6	574	0.00
Chips	SP3	1											-16	0.15
Chips	SP4		1										-26	0.15
Chips	SP5			1									-24	0.15
Chips	SP6								1				-33.8	0.15
Firew	SP7	1											-12	0.80
Firew	SP8		1										-22	0.80
Firew	SP9			1									-21.6	0.80
Pell	SP10				2.29					0.12	0.61		16.4	0.28
Pell	SP11					2.29				0.12	0.61		100	0.28

Table 24. Continue.

Product	Tech	SP	PP	NP	Ch	Du	Ba	Sh	FO	EL	IW	CC	MO	La
							ROW technologies							
CharCoal	AP1											14.6	504	0.00
Chips	AP2								1				-60	0.20
Chips	AP3			1									-6	0.20
Chips	AP4		1										-15.3	0.20
Chips	AP5	1											-11	0.20
Dust	AP6							1					-4	0.00
Firew	AP7			1									-21.8	1.04
Firew	AP8		1										-30.1	1.04
Firew	AP9	1											-26.1	1.04
Pell	AP10				2.29					0.12	0.61		31.4	0.36
Pell	AP11					2.29				0.12	0.61		84.9	0.36
							Charcoal input technologies							
CC	CP1						0.57							
CC	CP2				0.46									
CC	CP3					0.46								
CC	CP4								0.37					
CC	CP5			0.38										
CC	CP6		0.43											
CC	CP7	0.49												

Paper recycling

The maximum amount of recycled paper allowed in production of pulp and paper is adapted from Mustapha (2016) and is 91% of the consumed newsprint, 72% of the consumed printing and writing paper, and 74% of all other paper grades.

Investments and maintenance costs

Table 25 show the investment and maintenance cost, it is assumed that the maintenance costs are 10% of the investment costs. The investment cost of CLT is assumed equal to sawmill cost, and investment cost for pellets, chips, firewood, and charcoal is only included in order to restrict yearly ramping of the production capacity.

Table 25. Investment and maintenance cost, adapted from Mustapha (2016).

	Unit	Investment costs	Maintenance costs
SSAW, PSAW, NSAW, CLT	€/m³	375	37.5
PART, PlyW	€/m³	1249	124.9
FIBR	€/tonne	1249	124.9
MECH	€/tonne	524	52.4
CHEM, CTMP, BORR	€/tonne	1249	124.9
NEWS, PRWR, LINR	€/tonne	1436	143.6
OPBO	€/tonne	1249	124.9
Pell	€/tonne	375	37.5
Chips, Firew, CharCoal	€/m³	100	10

Exogenously investments

In addition to the existing capacities is exogenously investment and closure included (table 26), more project may be planed that will be part of further work with the model.

Table 26. New capacity and closures that is exogenously defined in the model. Unit: m³ for CLT and tonne for pulp and paper categories. Source: (Byggeindustrien, 2017; Danske bank, 2019).

Product	technology	Region	Investment year	New capacity/ capacity closure
MECH	FP23	F6	2019	-450 000
CHEM	FP8	F6	2019	30 000
BORR	FPN1	F6	2019	430 000
CHEM	FPN2	F2	2020	400 000
CHEM	FPN3	F5	2021	1 200 000
OPBO	SP69	S10	2019	30 000
OPBO	SP71	S7	2019	550 000
CLT	SCLT	S5	2020	100 000
CLT	SCLT	S10	2022	100 000
CLT	NCLT	N2	2020	10 000
CLT	ACLT	A1	2020	150 000

4 Bioenergy

Table 27 show the energy content in the different raw materials used for energy production. The energy content in roundwood is based on Belbo and Gjølsjø (2008), where non-conifers is assumed equal to birch. The energy content in chips, shavings, and dust is assumed equal to the average value for spruce and pine pulpwood; bark is estimated as an average of the energy content in spruce and pine bark; firewood is based on the average energy content in spruce, pine, and birch pulpwood; and harvest residues is based on the average energy content in spruce and pine stubs, tops, and branches.

Table 27. Energy content in raw materials available for heat production, figures is lower heating value. Source: (Belbo & Gjølsjø, 2008; Fraunhofer, 2016; IEA Bioenergy, 2007; Miljødirektoratet, 2019).

	MWh/m^3	MWh/tonne
SpruceSaw, SprucePulp	2.06	
PineSaw, PinePulp	2.30	
NonConSaw, NonConPulp	2.61	
Chips, Shav, Dust	2.18	
Bark	1.74	
Firew	2.32	
FOFU	2.68	
Pell		5.00
Black_liq		3.41
CharCoal		8.19
TallOil		11.28

Table 28 show the energy efficiency for heat production. The efficiency is based on Energistyrelsen (2020b). The average values for each category is used as a basis, and during the calibration of the model was the efficiencies is adjusted to better match the actual raw material consumption from Energistyrelsen (2020a), Energi Företagen (2020), Norsk Fjernvarme (2020), SSB (2020d), and Luke (2020h). For this reason, is the efficiencies different in the different countries.

Table 28. Energy efficiency for local produced heat, district heat, and industrial heat. Source: (Energistyrelsen, 2020b).

		Norway	Denmark	Finland	Sweden
BioSpace	Firew	70 %	80 %	70 %	70 %
	Chips	82 %	82 %	82 %	82 %
	Pell	82 %	82 %	82 %	82 %
BioWater, InduWater	Dust	89 %	68 %	68 %	68 %
	Pell	100 %	59 %	59 %	59 %
	FOFU	89 %	59 %	59 %	59 %
	Chips	89 %	70 %	68 %	68 %
	Bark	89 %	59 %	59 %	59 %
	Shav	89 %	70 %	68 %	68 %
	Black_liq	77 %	77 %	77 %	77 %

The production of industrial heat (table 29-table 32) is equal to the estimated industrial demand for heat in each region. While the choose of raw material in each region is chosen to be the needed level to fulfil the mass balance.

Space heating in Finland is based on the household consumption of wood products (Luke, 2020b), corrected for 15% bark, and the district heat production is from Luke (2020h) also corrected for 15% bark. Space heating in Norway is based on the sum of fuelwood consumption in household (SSB, 2020e) and cabins (SSB, 2020f), while the district heat production is from Norsk Fjernvarme (2020). The Swedish space heat production is based on the use of energy for heating from biomass (Energimyndigheten, 2019a; Energimyndigheten, 2019b; Energimyndigheten, 2019c), while the district heat production is estimated from Energi Företagen (2020). Finally, the Danish space heating is based on the use of forest raw material in the consumer market (Energistyrelsen, 2020a) and the district heat production is based on the consumption of raw materials within CHP plants and heat only plants (Energistyrelsen, 2020a).

Table 29. Estimated production of heat from different raw materials in Finland, unit GWh. Source: (Luke, 2020b; Luke, 2020h).

Heat category	Raw material	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
BioSpace	Chips	15	102	195	46	71	76	143	350	24	46
	Firew	436	932	786	578	576	942	1031	1303	599	759
	Pell	14	52	42	7	3	17	10	24	52	7
BioWater	Bark	7	97	190	52	40	762	283	66	211	0
	Chips	336	646	772	386	280	575	704	878	288	28
	Dust	13	235	141	11	245	99	96	23	55	0
	FOFU	46	161	512	507	328	347	758	734	220	26
	Pell	10	30	23	20	20	15	105	98	13	188
InduWater	Bark	752	548	436	905	478	2 075	451	738	84	158
	Black_liq	1712	1541	4397	5563	0	16905	2782	0	0	0
	Chips	25	0	5	29	0	19	0	24	52	549
	Dust	132	213	10	199	6	279	183	177	25	21
	Fossil	0	906	0	0	808	0	0	1747	149	462
	Shav	13	73	25	118	65	158	48	108	260	53

Table 30. Estimated production of heat from different raw materials in Norway, unit GWh. Source: (Norsk Fjernvarme, 2020; SSB, 2020d; SSB, 2020e; SSB, 2020f).

Heat category	Raw material	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
BioSpace	Firew	609	637	267	503	274	230	361	238	413	399
BioWater	Chips	357	326	20	213	0	0	0	12	58	66
	Dust	0	0	0	0	15	0	0	0	0	0
	FOFU	4	0	0	0	0	0	0	0	0	0
	Pell	269	33	26	2	29	0	0	0	56	0
InduWater	Bark	526	398	169	90	88	8	34	24	337	18
	Chips	247	27	21	1	3	0	0	0	42	32
	Shav	62	48	38	4	13	0	1	2	26	4

Table 31. Estimated production of heat from different raw materials in Sweden, unit GWh. Source: (Energi Företagen, 2020; Energimyndigheten, 2019a; Energimyndigheten, 2019b; Energimyndigheten, 2019c).

Heat category	Raw material	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
BioSpace	Chips	22	66	32	34	141	209	73	176	269	225
	Firew	121	468	242	238	939	1 381	541	1 203	1 813	1 521
	Pell	54	122	54	62	284	450	126	340	531	441
BioWater	Bark	8	140	53	129	191	177	57	187	326	75
	Black_liq	0	0	0	4	5	197	0	0	0	4
	Chips	169	172	282	246	806	731	645	754	1 182	942
	Dust	45	135	73	66	149	153	0	55	221	80
	FOFU	3	33	12	16	117	1 284	45	691	955	433
	Pell	73	194	31	206	145	1 289	134	416	237	380
InduWater	Bark	1 051	432	89	1 224	1 305	473	1 739	135	1 661	1 317
	Black_liq	5 692	1 400	0	5 666	5 151	0	10 366	345	6 724	4 163
	Chips	1 000	7	21	925	125	125	31	154	800	3 683
	Dust	604	126	2	627	487	0	419	78	690	704
	Fossil	336	404	319	857	949	163	620	552	1 315	860
	Pell	300	63	1	312	242	0	0	39	343	350
	Shav	321	67	1	333	259	0	0	41	367	374

Table 32. Estimated production of heat from different raw materials in Denmark and ROW, unit GWh. Source: (Energistyrelsen, 2020a).

Heat category	Raw material	D1	A1
BioSpace	Chips	367	0
	Firew	5 578	279 615
	Pell	3 924	0
BioWater	Bark	0	39 543
	Black_liq	0	49 327
	Chips	4 377	654
	FOFU	152	0
	Pell	6 531	13 094
InduWater	Bark	240	147 331
	Black_liq	0	183 785
	Chips	59	2 438
	Fossil	800	0
	Pell	0	48 787
	Shav	11	0

5 Exogenous costs

The unit electricity, labour, recycled paper, and fossil fuel prices are exogenously defined in the model and is not changed during the optimizing procedure (table 33). The electricity costs is based on electricity prices for 2020 carried out in paper IV (Jåstad et al., 2020) and is equal to the yearly average spot prices for each spot area, electricity taxes is included in the other cost of the production ("MO" column in table 12, table 14, table 16, table 18, table 21, table 22, and table 24). The labour costs is the average costs for wages and salaries in the industrial sector (except constructing) for 2018 (Eurostat, 2020b), for ROW (A1) is the average costs based on EU28. The cost for recycling paper is adapted from Mustapha (2016). Finally, the assumed fossil energy costs is based on the estimated natural gas spot price from IEA (2016) for 2020.

Table 33. Electricity costs, labour costs, price of recycling paper, and fossil fuel costs. Source: (Eurostat, 2020b; IEA, 2016; Jåstad et al., 2020; Mustapha, 2016).

	Electricity [€/MWh]	Labour [€/h]	Rcyc [€/tonne]	Fossil energy [€/MWh]
N1-N4	38.8	45	123	20.3
N5-N6	39.7			
N7	37.9			
N8-N9	37.0			
N10	35.3			
S1	35.4	27	123	20.3
S2-S4	36.4			
S5-S9	38.3			
S10	39.0			
F1-F10	36.8	29	144	20.3
D1	41.7	40	137	20.3
A1	42.7	21	1	20.3

6 Forest products demand

Consumption and prices

Table 34 and table 35 show the reference prices and consumption for 2018. For countries and products that has net export (table 36) is the reference price based on the unit export value, while for countries and products with net import is the reference price based on the unit importing value, for the ROW region is the average EU values used. The reference price for tall oil and black liquor are estimated to each account for around 1% of a chemical pulp mills revenue. While the CLT price in Norway is based on SSB (2019) and Eurostat (2020a) for Sweden, Finland, Denmark, and ROW.

The reference consumption is estimated from the country-based mass balance, which mean that the production minus the net trade must equal the consumption. The country consumption is disaggregated to regional levels based on the regional population (SCB, 2020b; SSB, 2020c; Tilastokeskus, 2020).

Table 34. Reference base year prices in €/unit. Source: (Eurostat, 2020a; FAOSTAT, 2019; SSB, 2019).

	Norway	Sweden	Finland	Denmark	ROW
FIBR	720	443	323	278	367
LINR	553	554	592	424	526
NEWS	423	528	493	400	477
NSAW	794	682	559	648	333
OPBO	978	873	839	726	843
PART	351	262	294	144	228
PlyW	554	645	542	354	576
PRWR	475	729	654	708	753
PSAW	275	260	211	154	173
SSAW	275	260	211	154	173
TallOil	178	167	130	149	157
Black_liq	4	4	3	3	4
CharCoal	502	520	530	462	450
CLT	656	687	570	526	500

Table 35. Reference consumption estimated based on country specific mass balance and regional populations in 1000 units. BS: BioSpace, BW: BioWater, TO: TallOil.

	SSAW	PSAW	NSAW	PART	FIBR	PlyW	NEWS	PRWR	LINR	OPBO	BS	BW	TO	CLT
N1	543	285	7.1	127	83	31	47	71	4.3	75	609	631	0.0	29
N2	131	69	1.7	31	20	7.4	11	17	1.0	18	637	359	0.0	7.1
N3	96	50	1.2	22	15	5.4	8.3	13	0.8	13	267	46	0.0	5.2
N4	144	75	1.9	34	22	8.1	12	19	1.1	20	503	215	0.0	7.7
N5	103	54	1.3	24	16	5.8	9.0	14	0.8	14	274	44	0.0	5.6
N6	161	85	2.1	38	25	9.1	14	21	1.3	22	230	0.0	0.0	8.7
N7	215	113	2.8	50	33	12	19	28	1.7	30	361	0.0	0.0	12
N8	91	48	1.2	21	14	5.1	7.9	12	0.7	13	238	12	0.0	4.9
N9	156	82	2.0	37	24	8.8	14	21	1.2	22	413	114	5.6	8.4
N10	165	86	2.1	38	25	9.3	14	22	1.3	23	399	66	0.0	8.9
S1	151	67	3.2	33	5.2	8.7	9.4	15	4.6	24	196	298	55	3.7
S2	162	72	3.5	36	5.6	9.4	10	16	4.9	26	656	674	14	3.9
S3	78	35	1.7	17	2.7	4.5	4.9	7.8	2.4	12	328	452	0.0	1.9
S4	148	65	3.2	32	5.1	8.6	9.3	15	4.5	24	334	666	55	3.6
S5	345	152	7.3	76	12	20	22	34	10	55	1365	1414	50	8.4
S6	1964	868	42	432	68	114	123	195	60	312	2039	3832	0.0	48
S7	350	155	7.5	77	12	20	22	35	11	56	740	881	101	8.5
S8	1023	452	22	225	35	59	64	101	31	163	1719	2103	3.3	25
S9	794	351	17	175	27	46	50	79	24	126	2613	2922	65	19
S10	1107	489	24	243	38	64	69	110	34	176	2187	1915	40	27
F1	85	35	10	6.5	2.4	2.0	7.4	9.0	27	12	465	1162	12	3.7
F2	230	96	27	18	6.4	5.6	20	24	73	33	1086	1170	16	10
F3	209	87	25	16	5.8	5.0	18	22	66	30	1022	3660	34	9.1
F4	131	54	16	10	3.7	3.2	11	14	41	19	631	1238	39	5.7
F5	117	49	14	9.0	3.3	2.8	10	12	37	17	651	914	0.0	5.1
F6	222	92	26	17	6.2	5.4	19	23	70	32	1035	4049	124	10
F7	345	144	41	27	10	8.3	30	36	109	50	1184	2780	20	15
F8	420	175	50	32	12	10	36	44	133	60	1677	1798	0.0	18
F9	70	29	8.3	5.4	2.0	1.7	6.1	7.4	22	10	675	786	0.0	3.0
F10	785	327	93	60	22	19	68	83	248	113	811	242	0.0	34
D1	1 337	422	123	610	233	354	100	598	275	1 227	9870	11 061	0.0	32
A1	87943	61556	15372	42356	19906	10654	7315	52398	30392	54987	279615	102618	1266	768

Import and export

Table 36 show net export to and from the different countries. For Norway is the net export adapted from SSB (2019), for all categories except for paper products that is from FAOSTAT (2019). Net export from Finland is adapted from Luke (2020a). The Swedish export of industrial products is from SCB (2020a) and forest products from SCB (2020c), while for Denmark is FAOSTAT (2019) used. The net export to ROW is sum of the net export from the Nordic countries. It is assumed no net trade of black liquor, tall oil, and shavings in the reference year, but the model can export if economical rational. Export/import statistics of bark was only obtained for Norway and harvest residue for Denmark. The trade of CLT is based on FAOSTAT (2019) and SSB (2019), and charcoal based on FAOSTAT (2019).

Table 36. Net export from the Nordic countries, given in m^3 or tonne. Source: (FAOSTAT, 2019; Luke, 2020a; SCB, 2020a; SCB, 2020c; SSB, 2019).

	Norway	Sweden	Finland	Denmark	ROW
SpruceSaw	1 129 650	-739 975	-160 000	181 987	-411 661
PineSaw	360 263	-1 522 629	370 000	57 392	734 974
NonConSaw	3 126	-548	-307 000	-7 140	311 562
SprucePulp	221 252	-434 135	-496 500	122 945	586 439
PinePulp	1 246 481	-3 223 508	-602 500	38 772	2 540 755
NonConPulp	128 411	-2 826 333	-5 119 000	-111 634	7 928 556
Pell	-28 420	-225 679	-44 000	-3 115 000	3 413 099
Chips	550 874	-3 316 066	-3 013 000	-696 991	6 475 183
Dust	678 164	-349 282	-251 000		-77 882
Bark	304 741				-304 741
Firew	-116 411	-70 214	103 000	-696 991	780 616
CHEM	-68 817	2 569 894	3 700 000	-92 328	-6 108 749
BORR	138 008	286 937	134 000	-1	-558 944
CTMP	-1 059	118 572	271 000	-1 104	-387 409
MECH	96 584	34 018	1 000	-5 499	-126 103
FOFU				-34 000	34 000
Rcyc	433 017	-270 963	-43 000	536 118	-655 172
FIBR	-103 031	-210 746	-49 000	-230 630	593 407
LINR	-14 363	2 681 607	558 000	-253 224	-2 972 020
NEWS	330 833	729 935	287 000	-100 116	-1 247 652
NSAW	-22 014	-22 168	-8 000	-34 129	86 311
OPBO	-38 282	3 024 227	6 634 000	-914 330	-8 705 615
PART	-16 682	-795 165	-101 000	-264 027	1 176 874
PlyW	-101 923	-234 333	967 000	-273 762	-356 983
PRWR	298 163	2 344 675	5 317 000	-530 482	-7 429 356
PSAW	-358 337	5 458 684	4 370 500	-328 368	-9 142 480
SSAW	28 793	6 384 706	3 732 000	-1 041 232	-9 104 267
CharCoal	-35 584	-26 804	-2 756	-8 461	73 605
CLT	-37 177	-3 917	25 907	-31 771	46 958

Elasticities and GDP growth

The yearly GDP growth in the Nordic countries is assumed to be 1.8% for 2018-2021, 2.0% for 2022-2030, and 1.6% for 2031-2050, and for ROW is the GDP growth 3.5% for 2018-2021, 3.1% for 2022-2030, and 2.5% for 2031-2050. The GDP growth is together with the GDP elasticity used for shifting the demand function for the next modelled period. Table 37 show the price and GDP elasticity used in the model, the elasticities is adapted from Buongiorno (2015). It is assumed that the price elasticity for CLT is equal to sawnwood, and a slightly higher GDP elasticity. While consumption of printing and writing paper (PRWR) and newsprint (NEWS) is assumed to not increase between year. Finally, tall oil and charcoal is assumed to be use in industrial processes not covered by the model and hence is the consumption assumed to be elastic.

Table 37. Price and GDP elasticity for the various end products. Source: (Buongiorno, 2015).

	Price elasticity	GDP elasticity
SSAW	-0.17	0.24
PSAW	-0.17	0.24
NSAW	-0.17	0.24
CLT	-0.17	0.34
FIBR	-0.54	0.92
PlyW	-0.61	0.72
PART	-0.51	0.59
NEWS	-0.04	0
PRWR	-0.53	0
LINR	-0.45	0.4
OPBO	-0.45	0.4
TallOil	-10	
CharCoal	-10	

7 Transportation costs

Table 39 and table 40 show the estimated transportation distances at land sea between the regional centres (table 1). Table 38 show the cost parameters that is used for calculating the transportation costs. The cost parameter is adapted from Mustapha (2016) for forest sector products, while transportation costs for liquids is from Cazzola et al. (2013). The cost of loading roundwood on a truck is already calculated in the roundwood prices (table 5) for this reason we do not have any start cost for truck transportation. Transportation costs to and from ROW region is subjected to modification in order to have correct trade flow in the reference year. The option with the lowest transportation cost between region is selected. The cheapest transportation option for sawnwood and board products is truck for distances under 98 km, train for distances between 98-152 km and ship for distances above 152 km. Pulp and paper products is transported with boat between all region located at sea. While, roundwood is transported with truck for distances under 185 km, train for distances between 185-330 km, and ship for distances above 330 km.

Table 38. Parameters used for calculation transportation costs. Source: (Cazzola et al., 2013; Mustapha, 2016).

	Unit	Truck Intercept [€/unit]	Truck Slope [€/unit/km]	Train Intercept [€/unit]	Train Slope [€/unit/km]	Boat Intercept [€/unit]	Boat Slope [€/unit/km]
Sawnwood and board	m^3	1.3	0.08	6.2	0.03	10	0.005
Pulp and paper	Tonne	1.3	0.08	6.2	0.03	1	0.1
Roundwood and chips	m^3	0	0.08	7.4	0.04	14	0.02
Liquid	Litre	0.1	0.001	0.1	0.001	0.1	0.001

Table 39. Transportation distances between the regional centres for transportation with truck and train, given in km.

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	S1	S2	S3	S4	S5	S6
N1	0	141	44	137	322	559	463	447	499	1203	1093	880	599	711	371	526
N2	141	0	182	275	460	697	502	356	433	1137	1134	921	641	752	412	549
N3	44	182	0	93	282	519	436	491	543	1247	1062	850	534	681	392	604
N4	137	275	93	0	185	422	400	584	633	1337	988	775	460	607	318	553
N5	322	460	282	185	0	237	442	769	822	1526	1411	1198	920	1029	648	770
N6	559	697	519	422	237	0	211	741	1059	1763	1648	1435	1157	1266	885	1007
N7	463	502	436	400	442	211	0	534	443	1147	1395	1234	887	1114	823	993
N8	447	356	491	584	769	741	534	0	166	870	1121	973	612	797	582	789
N9	499	433	543	633	822	1059	443	166	0	704	955	807	446	631	583	791
N10	1203	1137	1247	1337	1526	1763	1147	870	704	0	487	590	720	743	1100	1176
S1	1093	1134	1062	988	1411	1648	1395	1121	955	487	0	184	510	377	758	822
S2	880	921	850	775	1198	1435	1234	973	807	590	184	0	296	127	508	572
S3	599	641	534	460	920	1157	887	612	446	720	510	296	0	127	198	387
S4	711	752	681	607	1029	1266	1114	797	631	743	377	127	127	0	284	348
S5	371	412	392	318	648	885	823	582	583	1100	758	508	198	284	0	150
S6	526	549	604	553	770	1007	993	789	791	1176	822	572	387	348	150	0
S7	220	243	283	241	459	696	682	667	588	1302	994	744	355	496	115	223
S8	250	263	370	349	442	679	682	697	704	1417	1103	853	515	629	317	332
S9	440	453	560	529	632	869	902	887	884	1492	1137	844	587	620	309	260
S10	552	535	703	656	714	951	984	999	982	1784	1332	1039	739	858	505	456
F1	1390	1430	1311	1235	1706	1943	1736	1412	1246	759	297	508	818	701	1082	1146
F2	1399	1439	1320	1244	1715	1952	1745	1421	1255	768	306	517	827	623	1092	1155
F3	1718	1758	1639	1563	2034	2271	2064	1740	1574	1087	623	835	1144	1028	1409	1468
F4	1738	1778	1659	1583	2054	2291	2084	1760	1594	1107	643	855	1165	1048	1375	1493
F5	1684	1724	1605	1529	2000	2237	2030	1706	1540	1054	591	802	1112	995	1376	1440
F6	1793	1833	1714	1638	2109	2346	2139	1815	1649	1162	700	911	1221	1104	1485	1549
F7	2022	2062	1943	1867	2338	2575	2368	2044	1878	1392	952	1163	1473	1356	1737	1801
F8	1926	1966	1847	1771	2242	2479	2272	1948	1782	1295	833	1044	1354	1237	1618	1682
F9	1844	1884	1765	1689	2160	2397	2190	1866	1700	1213	751	962	1272	1155	1536	1600
F10	2005	2045	1926	1850	2321	2558	2351	2027	1861	1374	912	1123	1433	1316	1697	1761
D1	759	896	777	894	1081	1318	1217	1206	1235	1827	1656	1444	1360	1270	860	809

	S7	S8	S9	S10	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	D1
N1	220	250	440	552	1390	1399	1718	1738	1684	1793	2022	1926	1844	2005	759
N2	243	263	453	535	1430	1439	1758	1778	1724	1833	2062	1966	1884	2045	896
N3	283	370	560	703	1311	1320	1639	1659	1605	1714	1943	1847	1765	1926	777
N4	241	349	529	656	1235	1244	1563	1583	1529	1638	1867	1771	1689	1850	894
N5	459	442	632	714	1706	1715	2034	2054	2000	2109	2338	2242	2160	2321	1081
N6	696	679	869	951	1943	1952	2271	2291	2237	2346	2575	2479	2397	2558	1318
N7	682	682	902	984	1736	1745	2064	2084	2030	2139	2368	2272	2190	2351	1217
N8	667	697	887	999	1412	1421	1740	1760	1706	1815	2044	1948	1866	2027	1206
N9	588	704	884	982	1246	1255	1574	1594	1540	1649	1878	1782	1700	1861	1235
N10	1302	1417	1492	1784	759	768	1087	1107	1054	1162	1392	1295	1213	1374	1827
S1	994	1103	1137	1332	297	306	623	643	591	700	952	833	751	912	1656
S2	744	853	844	1039	508	517	835	855	802	911	1163	1044	962	1123	1444
S3	355	515	587	739	818	827	1144	1165	1112	1221	1473	1354	1272	1433	1360
S4	496	629	620	858	701	623	1028	1048	995	1104	1356	1237	1155	1316	1270
S5	115	317	309	505	1082	1092	1409	1375	1376	1485	1737	1618	1536	1697	860
S6	223	332	260	456	1146	1155	1468	1493	1440	1549	1801	1682	1600	1761	809
S7	0	106	213	363	1316	1325	1642	1663	1610	1719	1971	1852	1770	1931	713
S8	106	0	91	216	1427	1436	1752	1774	1721	1830	2082	1963	1881	2042	543
S9	213	91	0	112	1461	1470	1788	1808	1755	1864	2116	1997	1915	2076	511
S10	363	216	112	0	1656	1665	1983	2003	1950	2059	2311	2192	2110	2271	295
F1	1316	1427	1461	1656	0	205	523	543	490	549	851	731	650	810	1951
F2	1325	1436	1470	1665	205	0	319	339	286	394	624	527	445	606	1957
F3	1642	1752	1788	1983	523	319	0	270	376	491	334	321	389	421	2278
F4	1663	1774	1808	2003	543	339	270	0	147	246	308	188	116	268	2298
F5	1610	1721	1755	1950	490	286	376	147	0	136	454	335	162	391	2241
F6	1719	1830	1864	2059	549	394	491	246	136	0	572	410	208	436	2352
F7	1971	2082	2116	2311	851	624	334	308	454	572	0	142	365	168	2603
F8	1852	1963	1997	2192	731	527	321	188	335	410	142	0	202	102	2444
F9	1770	1881	1915	2110	650	445	389	116	162	208	365	202	0	229	2406
F10	1931	2042	2076	2271	810	606	421	268	391	436	168	102	229	0	2565
D1	713	543	511	295	1951	1957	2278	2298	2241	2352	2603	2444	2406	2565	0

Appendix

Table 40. Transportation distances between the regional centres for sea transportation, regions not located at the sea is not shown, given in km.

	N1	N3	N4	N5	N6	N7	N8	N9	N10	S1	S2	S4
N1	0	44	162	291	513	697	1133	1007	1607	2032	1768	1743
N3	44	0	148	267	489	667	1103	977	1577	2002	1738	1713
N4	162	148	0	172	394	566	1002	833	1476	1942	1678	1653
N5	291	267	172	0	222	422	858	737	1332	1986	1722	1697
N6	513	489	394	222	0	184	620	557	1271	2208	1944	1919
N7	697	667	566	422	184	0	592	373	1087	2421	2178	2017
N8	1133	1103	1002	858	620	592	0	231	627	2857	2614	2453
N9	1007	977	833	737	557	373	231	0	505	2850	2632	2516
N10	1607	1577	1476	1332	1271	1087	627	505	0	3331	3088	2927
S1	2032	2002	1942	1986	2208	2421	2857	2850	3331	0	278	432
S2	1768	1738	1678	1722	1944	2178	2614	2632	3088	278	0	230
S4	1743	1713	1653	1697	1919	2017	2453	2516	2927	432	230	0
S5	1482	1459	1402	1422	1644	1837	2273	2276	2747	587	487	269
S6	1292	1262	1202	1246	1468	1837	2273	2051	2747	900	660	582
S8	280	250	190	234	456	643	1079	1090	1553	1832	1630	1514
S9	863	848	806	800	1022	1198	1634	1645	2108	1076	882	732
S10	513	500	457	452	674	850	1286	1306	1760	1458	1269	1124
F1	2035	1985	1932	1941	2163	2341	2777	2795	3251	144	433	506
F2	2005	1971	1924	1964	2186	2385	2821	2820	3295	193	359	505
F3	1722	1688	1641	1681	1903	2102	2538	2537	3012	287	104	232
F7	1401	1367	1320	1360	1582	1781	2217	2216	2691	611	411	365
F10	1527	1493	1446	1486	1708	1907	2343	2342	2817	950	746	653
D1	511	519	457	450	672	850	1286	1304	1760	1717	1526	1354
A1	1587	1508	1559	1545	1767	1995	2431	2469	2905	1072	952	952

	S5	S6	S8	S9	S10	F1	F2	F3	F7	F10	D1	A1
N1	1482	1292	280	863	513	2035	2005	1722	1401	1527	511	1587
N3	1459	1262	250	848	500	1985	1971	1688	1367	1493	519	1508
N4	1402	1202	190	806	457	1932	1924	1641	1320	1446	457	1559
N5	1422	1246	234	800	452	1941	1964	1681	1360	1486	450	1545
N6	1644	1468	456	1022	674	2163	2186	1903	1582	1708	672	1767
N7	1837	1837	643	1198	850	2341	2385	2102	1781	1907	850	1995
N8	2273	2273	1079	1634	1286	2777	2821	2538	2217	2343	1286	2431
N9	2276	2051	1090	1645	1306	2795	2820	2537	2216	2342	1304	2469
N10	2747	2747	1553	2108	1760	3251	3295	3012	2691	2817	1760	2905
S1	587	900	1832	1076	1458	144	193	287	611	950	1717	1072
S2	487	660	1630	882	1269	433	359	104	411	746	1526	952
S4	269	582	1514	732	1124	506	505	232	365	653	1354	952
S5	0	276	1345	622	1000	652	682	504	279	500	1261	737
S6	276	0	1110	311	846	796	997	637	335	394	1048	661
S8	1345	1110	0	600	238	1750	1925	1610	1297	1381	289	1287
S9	622	311	600	0	418	1139	1170	869	559	654	620	689
S10	1000	846	238	418	0	1532	1552	1239	961	883	341	950
F1	652	796	1750	1139	1532	0	93	356	698	883	1787	1289
F2	682	997	1925	1170	1552	93	0	325	762	826	1824	1209
F3	504	637	1610	869	1239	356	325	0	485	745	1483	856
F7	279	335	1297	559	961	698	762	485	0	452	1198	509
F10	500	394	1381	654	883	883	826	745	452	0	1274	498
D1	1261	1048	289	620	341	1787	1824	1483	1198	1274	0	1037
A1	737	661	1287	689	950	1289	1209	856	509	498	1037	0

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