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

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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

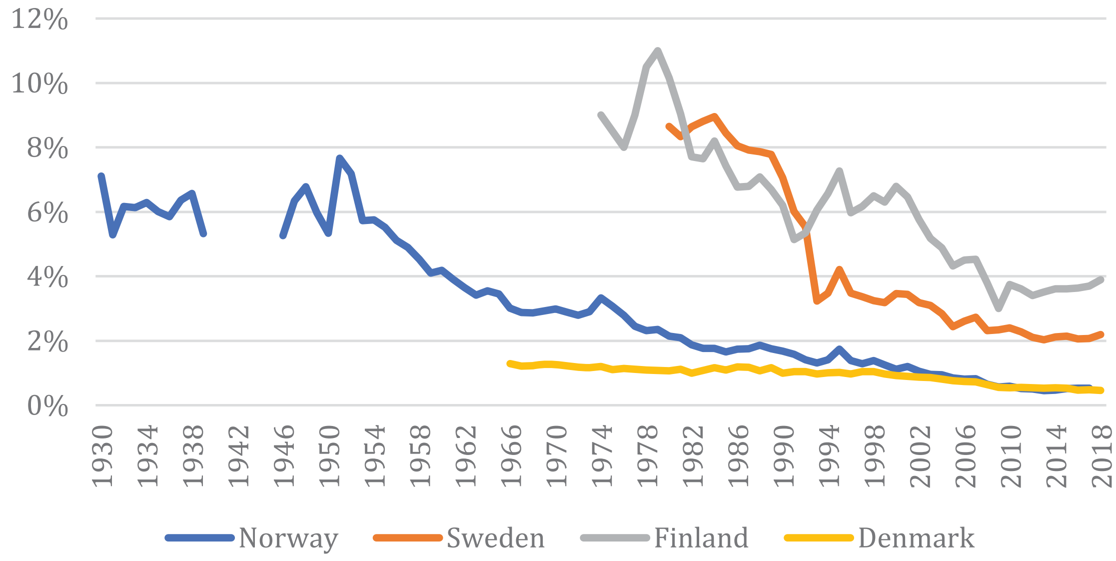

Figure 1. The forest sector's share of the total gross domestic product (GDP) in Norway, Sweden, Finland, and Denmark. Source: (Luke, 2019; SCB, 2020; SSB, 1965; SSB, 2007; SSB, 2020b; SSB, 2020c; Statistics Denmark, 2020a).

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

[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.

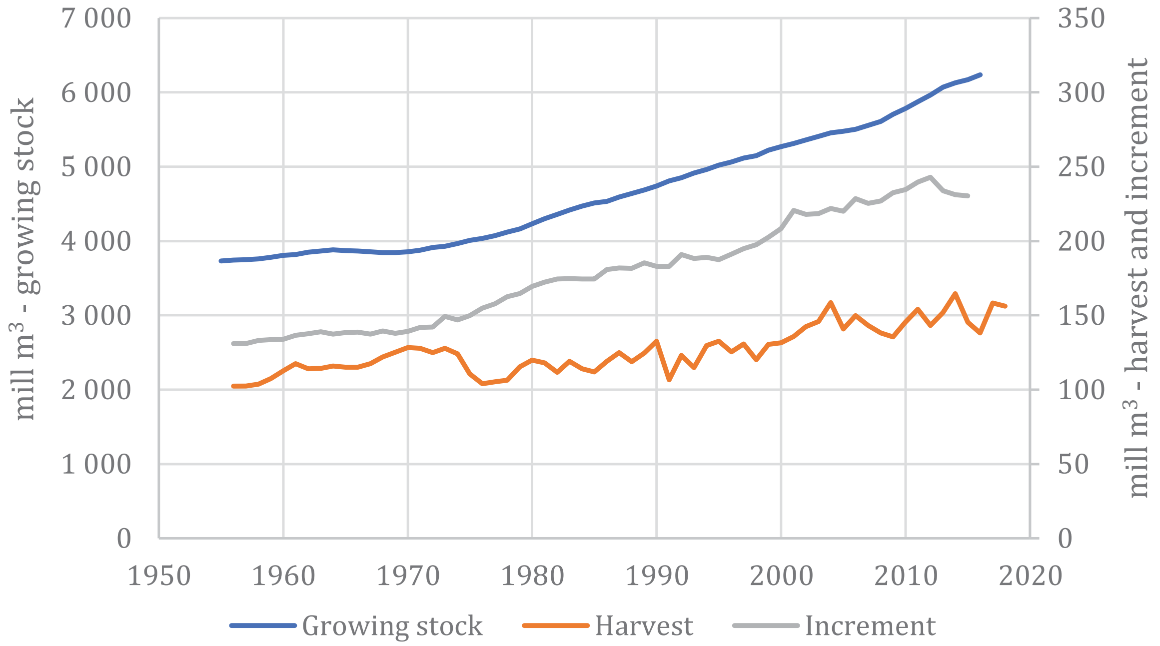

Figure 2. The Nordic (Norway, Sweden, and Finland) growing stock (left axis), yearly harvest (right axis), and increment (right axis). Source: (Luke, 2020a; Luke, 2020b; SLU, 2020a; SLU, 2020b; SLU, 2020c; SSB, 2020e; SSB, 2020f).

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

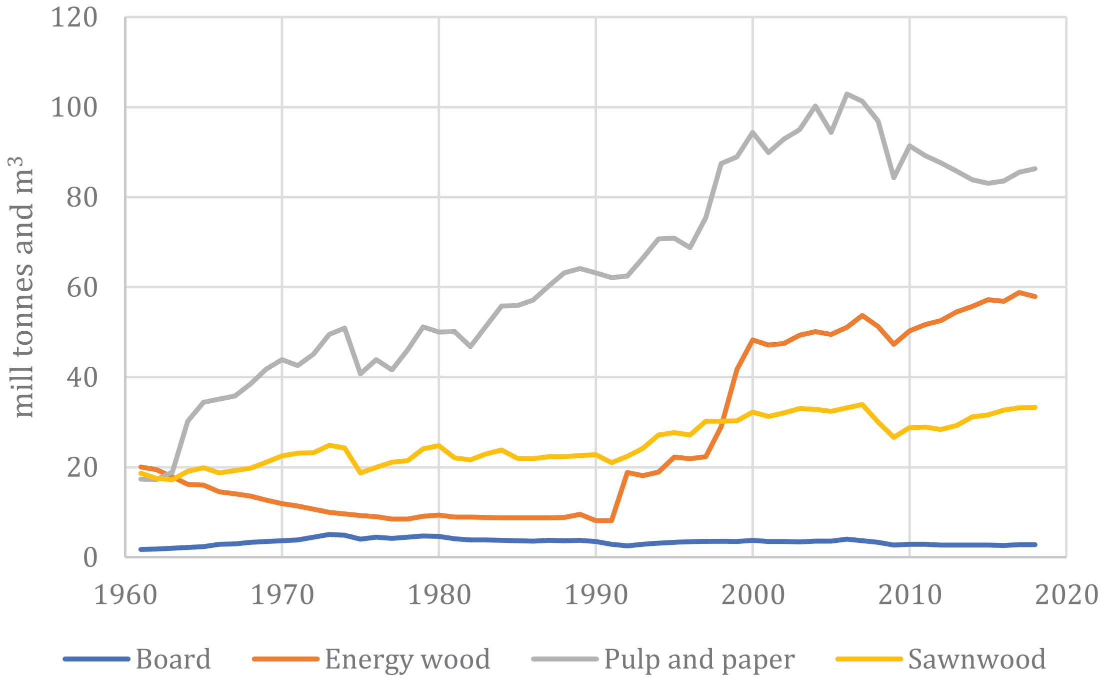

Figure 3. Nordic industrial production of board, pulp and paper, sawnwood, and energy wood. Source: (FAOSTAT, 2019).

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

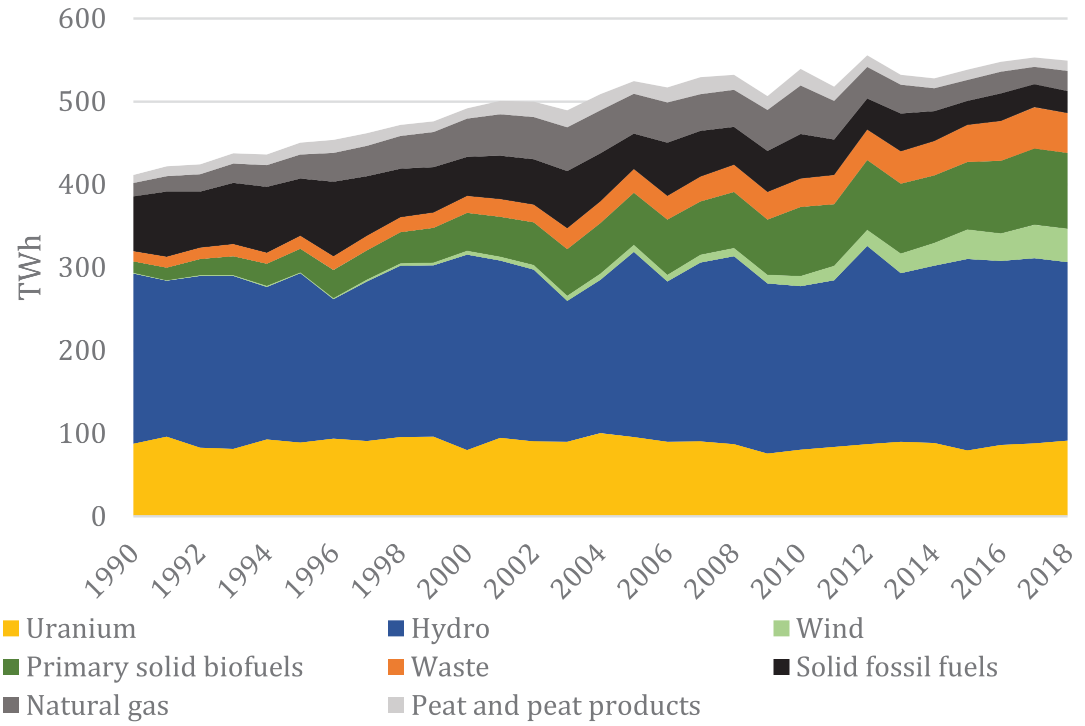

Figure 4. Production of electricity and heat for the main fuel categories in the Nordic countries. Source: (Eurostat, 2020a).

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

[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.

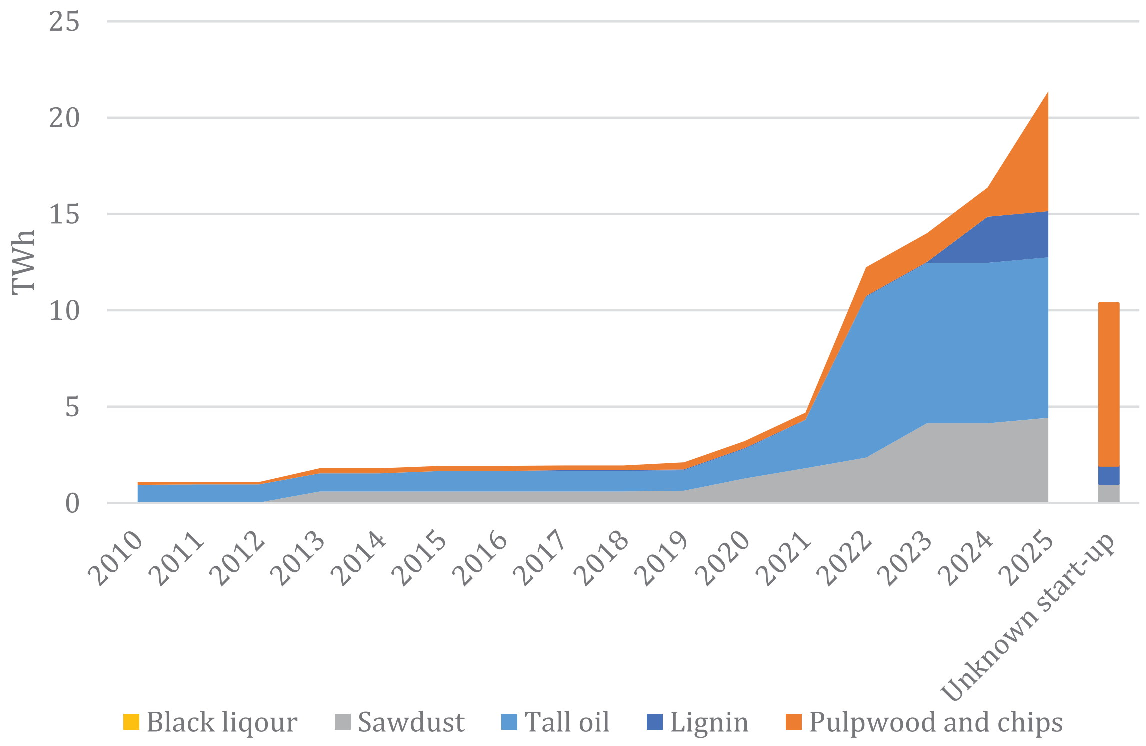

Figure 5. Identified liquid forest-based biofuel production capacity (accumulated) in Norway, Sweden, and Finland for the period 2010-2025 and additional production capacity in projects with unknown start-up date that may be regard as uncertain. Source: (Bioenergi Tidningen, 2019).

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.

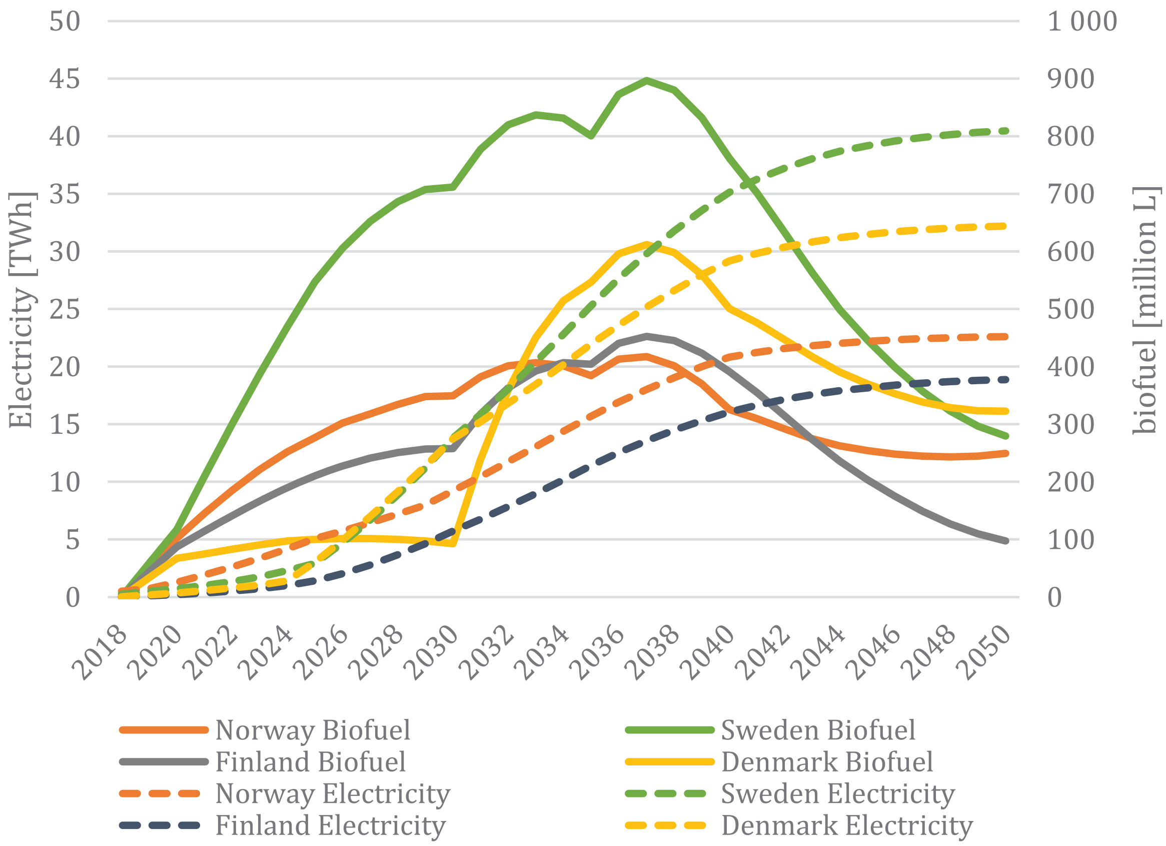

Figure 6. Forecast of second-generation biofuel demand and electricity demand in the transportation sector based on extrapolation of existing policies and trends. The salient points in 2030 and 2035 are the result of the transition from one policy period to another. Source: (Avinor, 2020; Energistyrelsen, 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).

[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.

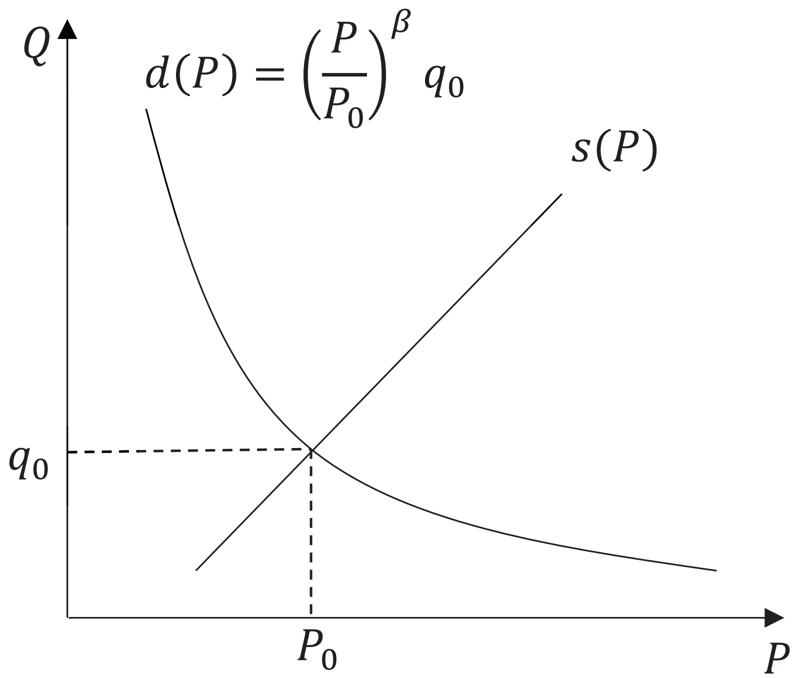

Figure 7. Connection between supply, demand, and price of a good.

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

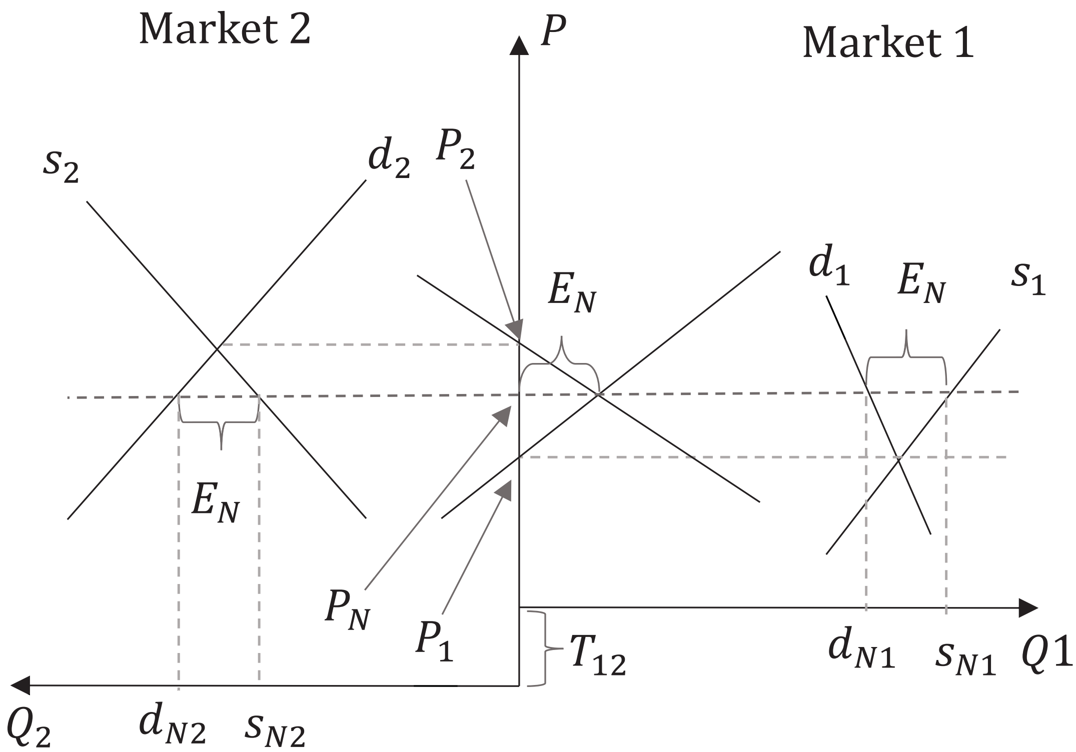

Figure 8. Outline of how the market reacts when an exporting region (market 1) and an importing region (market 2) are connected. Market 2 is shown as the inverse of market 1.

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}

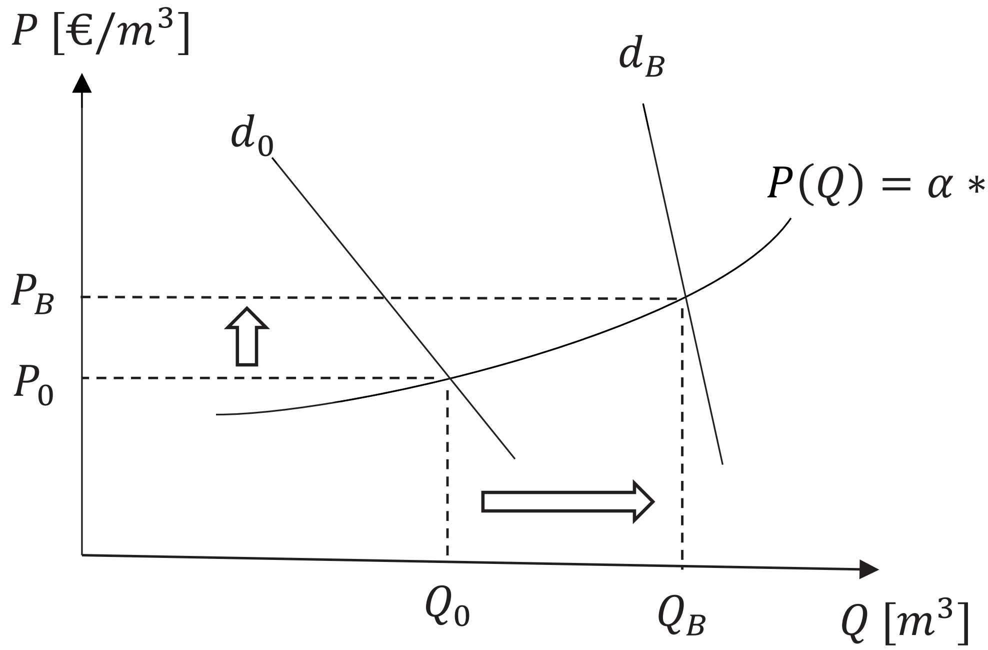

Figure 9. Change in pulpwood supply and marginal price when a biofuel plant is located in the region.

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

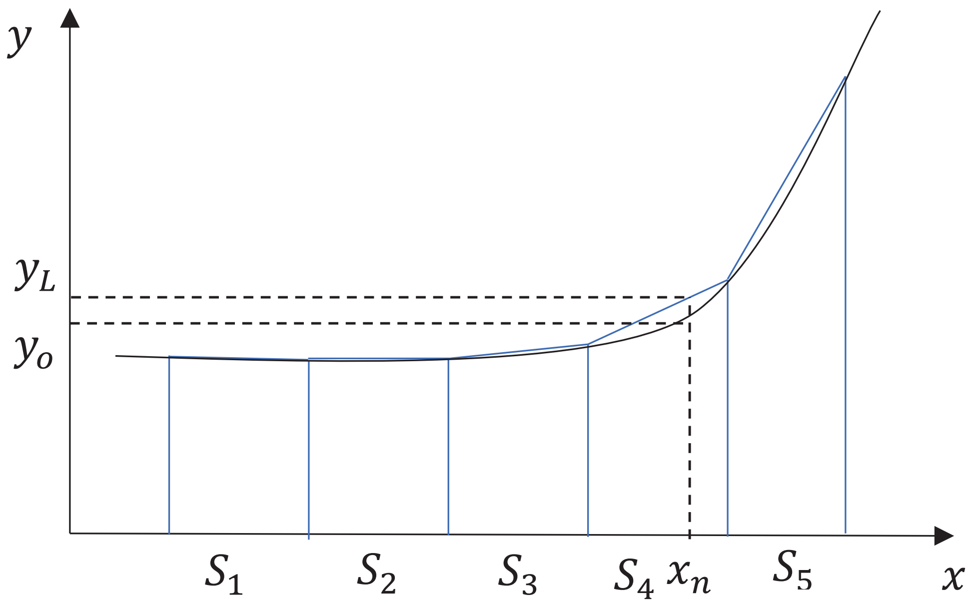

Figure 10. Schematic representation of a linearization.

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).

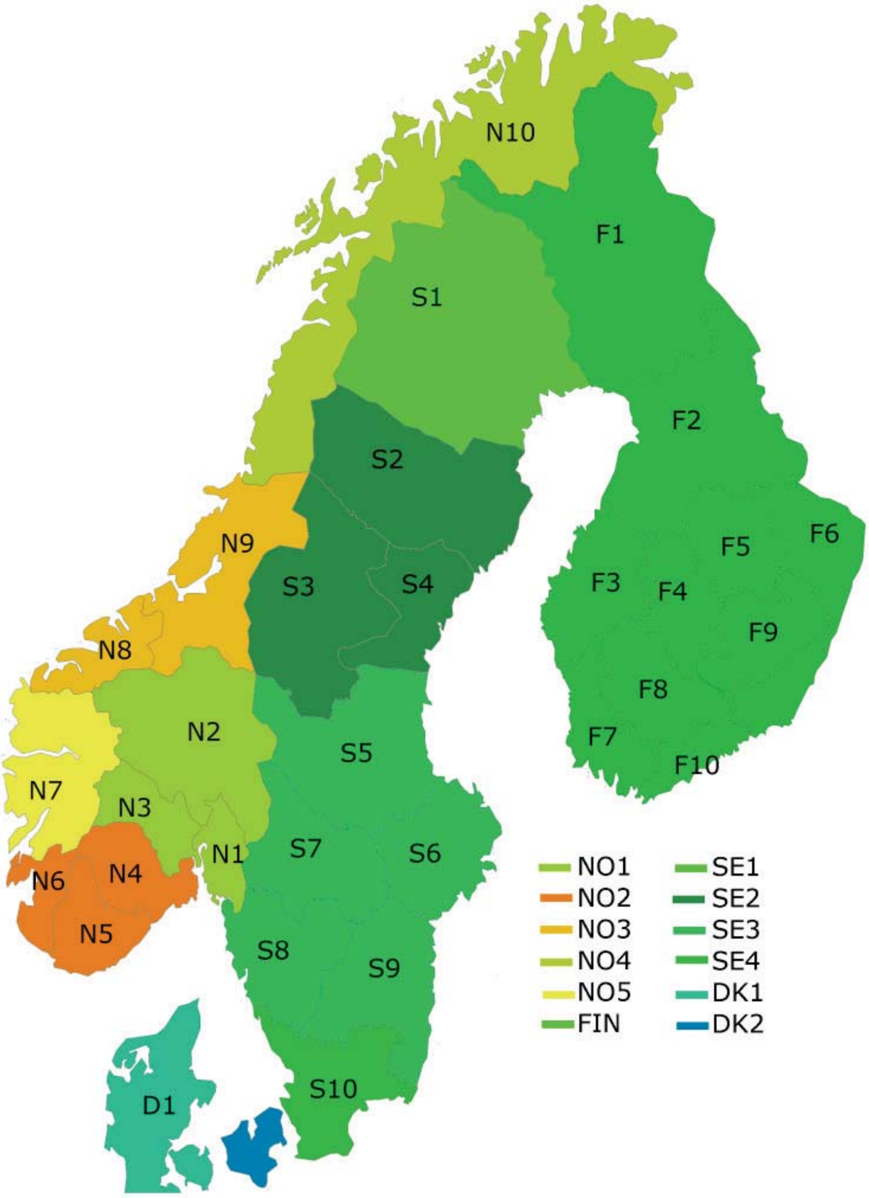

Figure 11. The regionalisation within the Nordic countries as presented in paper V. Colours represent the approximative Balmorel regions, while the border lines show the NFSM regions.

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

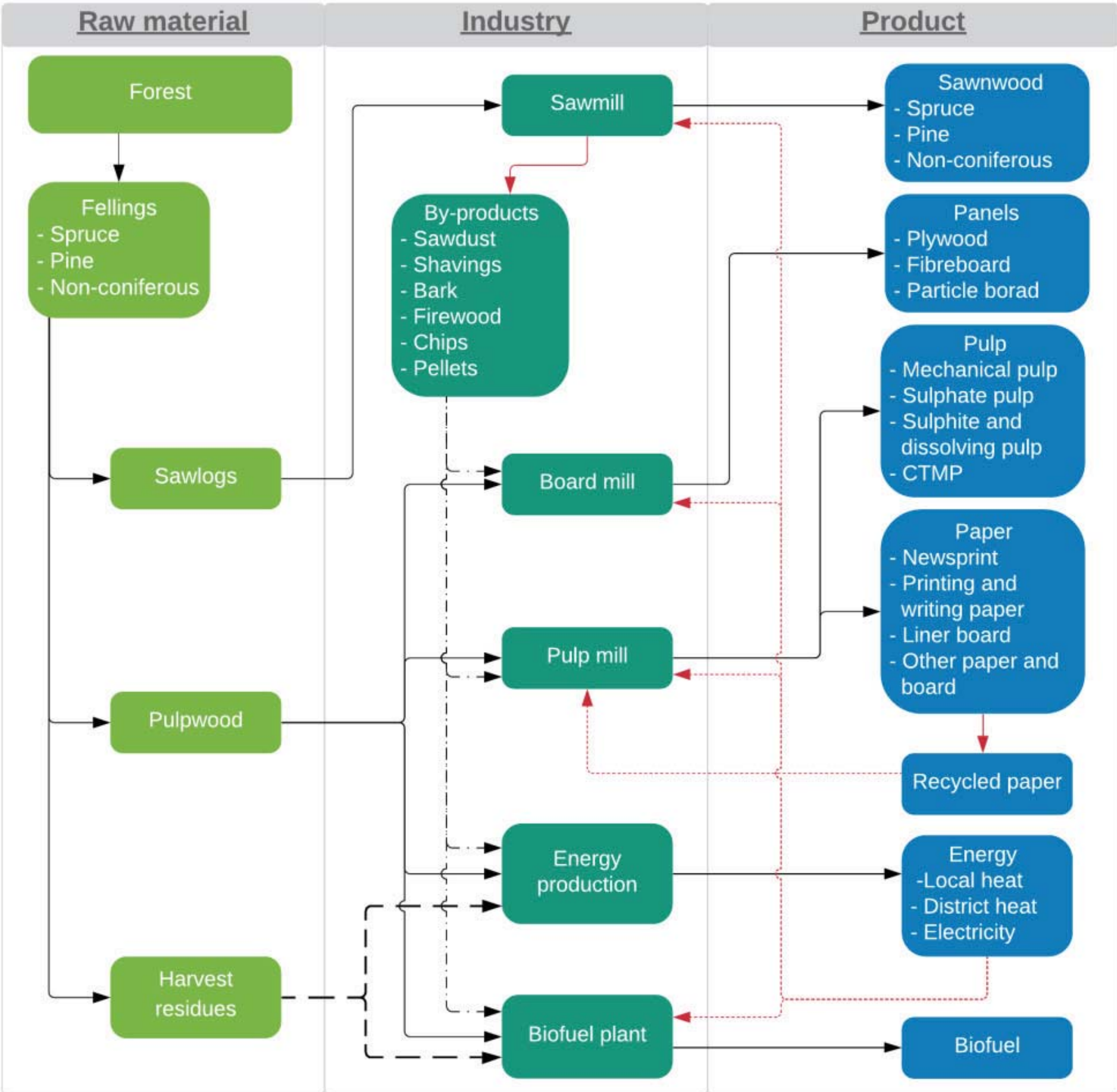

Figure 12. Schematic representation of the forest sector models as presented in paper III.

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.	n^{th} 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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