

## Article

# The Future Role of Forest-Based Biofuels: Industrial Impacts in the Nordic Countries

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**Abstract:** This study applies a partial equilibrium forest sector model to analyse the impacts of biofuel deployment for road transport in the Nordic countries, when alternative use of the biomass resources and transport sector electrification are considered. We foresee a strong electrification of the transport sector, resulting in a demand for biofuels of approximately 2.5 billion L in 2035 and 1 billion L in 2050 in a 100% fossil-free base scenario. The simultaneous increase in demand from pulping industries and biofuel will cause an overall increase in wood use, of which the biofuels share will constitute approximately 20–25%. The utilization of harvest residues will increase more than 300% compared to the current level, since biofuel production will reallocate some of the current raw material used in district heating. Biofuel consumption in road transport will likely reduce after 2040 due to increasing electrification, but it is plausible that the declining domestic demand will be replaced by increasing demand from international biofuel markets in aviation and shipping. The main uncertainties in the scenarios are the future costs and profitability of forest-based biofuel technologies and the public acceptance of the close to 100 TWh of new renewable electricity production needed for the electrification of Nordic road transport.

**Keywords:** biofuel; forest sector model; partial equilibrium; harvest residues



**Citation:** Ogner Jåstad, E.; Folsland Bolkesjø, T.; Rørstad, P.K.; Midttun, A.; Sandquist, J.; Trømborg, E. The Future Role of Forest-Based Biofuels: Industrial Impacts in the Nordic Countries. *Energies* **2021**, *14*, 2073. <https://doi.org/10.3390/en14082073>

Academic Editor: Idiano D'Adamo

Received: 1 March 2021

Accepted: 30 March 2021

Published: 8 April 2021

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## 1. Introduction

Greenhouse gas (GHG) emissions from transport have increased in the EU since 1990, in line with economic growth and trends in transport demand. Improvements in the efficiency of combustion engines have helped to limit the overall increase, but reducing the demand for transport services and developing fossil-free alternatives in the transport sector is acknowledged as a main challenge in the decarbonization of energy systems. The EU's Renewable Energy Directive (RED II) [1] has set a renewable energy target for the transport sector of a minimum of 14% in final energy consumption by 2030. The carbon-neutral targets entail ambitious renewable energy targets for the transport sector toward 2050. Eurostat [2] has estimated the share of renewables to be 8% in 2018. Even as 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 [2]. These figures show that the Nordic countries are ahead of the rest of Europe when it comes to emissions reduction in the transportation sector.

As noted by Davis, et al. [3], there are particular challenges related to volumetric and/or gravimetric densities of all renewable transportation fuel alternatives—apart from hydrocarbon from biomass and e-fuels. The market for pure electric cars is still small in most countries [4] and biofuel is therefore an important short-run mitigation strategy

in the transport sector. The energy density of renewable fuel technology is especially challenging in aviation. The electrification of short- and medium-distance aviation is likely to reduce emissions in a 20-year time horizon, and hydrogen and e-fuels may play a role at a later stage. Research conducted by McKinsey & Company [5] indicates that hydrogen-propelled short-range aircrafts will not be introduced before 2035. In addition, in the recent scenarios of BloombergNEF [6], hydrogen in aviation is also absent toward 2050. Aviation represents about 2.5% of the global GHG emissions, but when radiation effects are included, the climate effects are about 3.5% [7]. Emissions from aviation are higher in industrial countries. As an example, direct emission from domestic aviation Norway constituted 2.1% of the total national emissions in 2017, but 5% if emissions from total sales of jet fuels in Norway are included [8].

In a fossil-free future energy system, biofuels from sustainable biomass resources are among the relevant alternatives to fossil fuels in parts of the transportation sector in the foreseeable future. The total Nordic consumption of bioethanol was 3.3 TWh (0.56 million m<sup>3</sup>) in 2018, while the consumption of biodiesel was 23.7 TWh (2.6 million m<sup>3</sup>) [9]; this is around 13% of the total energy consumed in the road transportation sector that year. For comparison, the total global production of biofuel was around 1540 TWh (154 million m<sup>3</sup>) in 2018 [10]. This means that the Nordic countries consume around 2% of the world's annual production of biofuel. Most of the biofuel used comes from agricultural crops [11], but it is technically feasible to use forest biomass instead of other biomasses. As has been described in many previous studies [12–20], several different conversion routes from forest resources to liquid biofuel exist—some of which are more mature than others. 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. Further, some technologies produce biofuel intermediates that need to be upgraded before they can be used as fuel.

There are ongoing policy and scientific discussions about the GHG impacts of biofuel, as well as the trade-offs between climate mitigation and biodiversity conservation related to forest management. The EU will now measure the climate impact of forest management using the 'forest reference level' (FRL) concept (Regulation 2018/841) [21] within the land use, land-use change and forestry (LULUCF) sector. The recast of RED, to be enacted by member states by June 2021, strengthens the EU sustainability criteria for bioenergy. RED II includes minimum GHG emission-saving thresholds for biofuels, and biomass in heat and power and minimum efficiency criteria for bioelectricity-only installations (as noted by Camia, et al. [22] in the Joint Research Centre's 'Science for Policy Report'). The use of wood biomass for energy production in the EU, the general principle of prioritizing residues and the circular use of wood remain key for maximizing the positive climate impact of wood-based bioenergy. The EU taxonomy for sustainable economic activities (Regulation (EU) 2020/852) [23] set conditions that must be met in order to qualify as environmentally sustainable. As such, the conditions of the taxonomy are not mandatory, but it is likely that demand for products that are branded environmentally sustainable will be preferred in the markets. The proposed detailed criteria for forestry in the draft delegated act may be demanding and seem costly for the small-scale forestry typical for the Nordic countries. In the short term, it will likely not restrict timber supply in the Nordics, but there are large uncertainties pertaining to the detailed regulations.

Wood biomass plays an important role in the Nordic countries because of the large resource base and long history of wood processing industries, and forest resources represent the main potential for increased biofuel production in these countries. Previous studies, e.g., Mustapha, et al. [24], have shown that a future biofuel share in the Nordic countries of 40% (road transportation volume) would reduce bioheat use by 50%. A similar result is found in Bryngemark [25], which found a negative connection between the use of forest biomass in the heat and power sector and biofuel production. At the same time, Bryngemark [25] found that board production is vulnerable to a high amount of biofuel production due to increased raw material competition. This is similar to findings by Trømborg, et al. [26],

who reported a potential for both increased bioheat generation and large-scale forest-based biofuel production, but also that increased biofuel production reduces bioheat generation. This somewhat contrasts Kallio, et al. [27], which address the economic potential and impacts of forest biofuel production using the forest sector model EFI-GTM from the European Forest Institute. The authors found that different policies will have a significant impact on the competition of forest products between power, heat, and biofuel production, and further, that the European forest sector will only be marginally affected by the increased wood consumption within energy production.

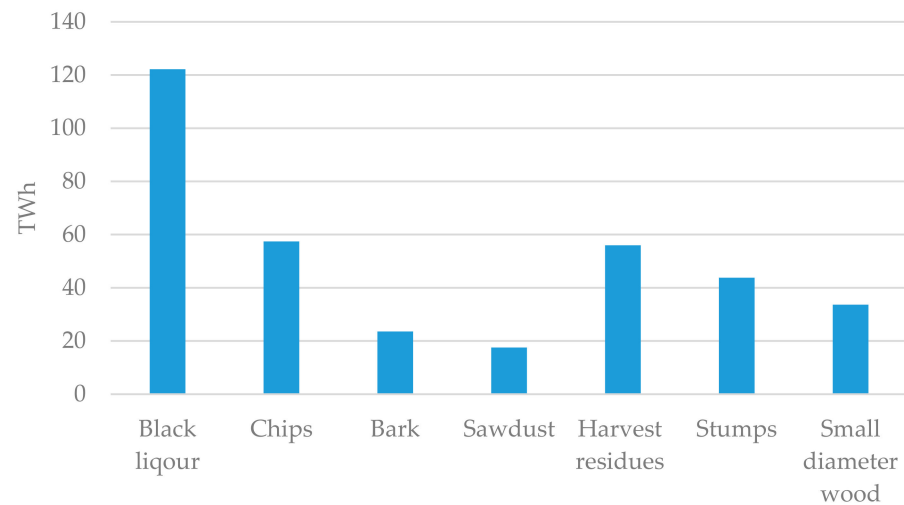
This paper takes a holistic approach to the prospects of forest-based biofuels by considering the demand for liquid fuels in a pathway toward a fossil-free Nordic transportation sector. At the same time, it provides a detailed analysis of the biomass competitions in the forest sector value chain. The overall objective of the paper is to provide a consistent assessment of whether, and how, forest-based biofuel industry may succeed in the Nordic countries while taking into account the rapid electrification of the transport sector and thus the biofuel market. We will address the following key questions:

- i What is a likely consumption level for biofuels in the Nordic countries when transport needs, policies and electrification are taken into account?
- ii How will different levels of Nordic biofuel production influence the forest sector and the biomass use in the heat and power sector?

The rest of the paper is organized as follows: The potential for forest biofuels is shown in Section 2. Section 3 describes the partial equilibrium model applied in the analyses as well as the data and scenarios in the model. Section 4 then presents the results. Section 5 discusses policy implications of these results, and the main conclusion is presented in Section 6.

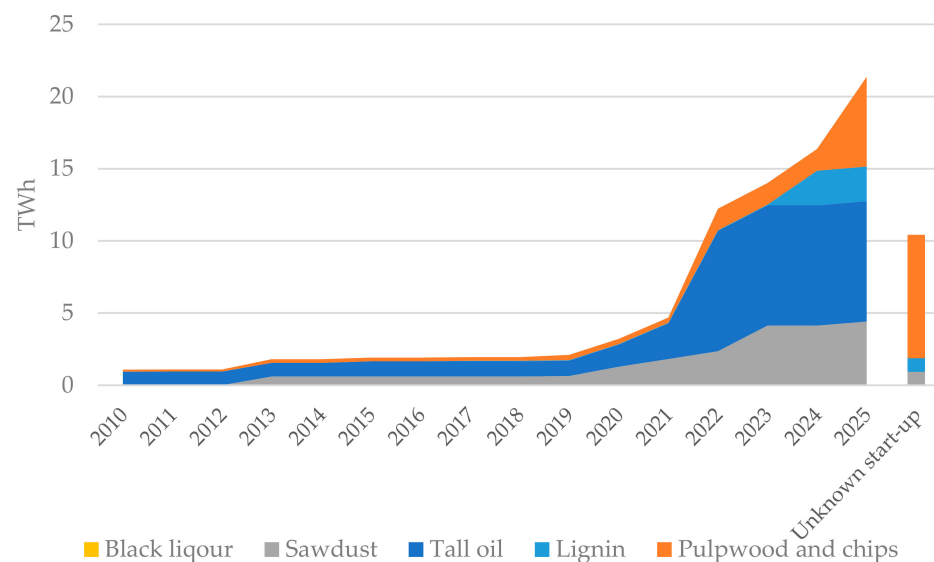
## 2. Biomass Potential in the Nordic Countries

In 2018, the domestic consumption of all primary solid biomass was 263 TWh and the total final energy consumption was 1066 TWh in the Nordic countries [9]. More than 20% of gross inland energy consumption in Denmark, Finland and Sweden is from biomass, compared to only 6–7% in Norway. The Nordic district heating sector delivers around 140 TWh each year [9], with about 45% coming from solid biomass. In addition, around 14.7 million m<sup>3</sup>, or 29 TWh, of firewood is used in households [28–31]. Wood biomass plays an important role in the Nordic countries because of a large resource base and long history of wood processing industries. Sweden and Finland are the major forest countries among the Nordics, with a harvest level of 76 mill and 64 mill m<sup>3</sup> industrial roundwood respectively in 2019, compared to 13 mill and 4 million m<sup>3</sup> in Norway and Denmark [32]. In total, 55 million m<sup>3</sup> of forest products are used for district heat production or burned in wood stoves in the Nordic countries. The large standing stock of wood coupled with the substantial forest industry activity implies that there is a significant biological potential for increased use of biomass for energy from low-quality logs, harvest residues and forest industry side streams. According to Pöyry and Nordic Energy Research [33], the overall Nordic biomass potential for energy amounts to some 450–500 TWh, of which 350 TWh is forest biomass (Figure 1). The largest biomass potential is in Sweden, followed by Finland. Black liquor, chips and harvest residues are the most important forest biomass resources in the Nordic context, when roundwood is not directly included.



**Figure 1.** Nordic forest biomass potential split on different biomass types except roundwood (TWh/year). Sources: Pöyry and Nordic Energy Research [33].

Forest biomass may be used to produce different qualities of liquid fuel. In 2019, 39 different forest-based biofuel projects in the Nordic countries were identified [34]. These projects have a total planned production capacity of 32 TWh of 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 of biofuel. 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. These forest-based biofuel projects amount to 32 TWh or approximately 3.2 billion L (Figure 2).

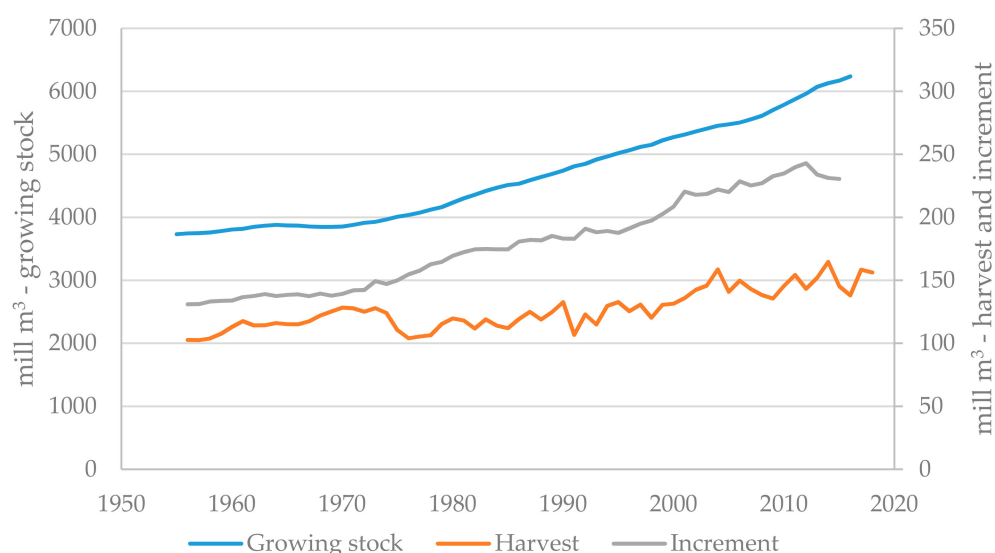


**Figure 2.** Identified planned liquid forest-based biofuel production capacity (accumulated) in Norway, Sweden and Finland for the period 2010–2025, and additional production capacity in projects with unknown start-up dates that may be regarded as uncertain. Source: [34].

The annual growth in the Nordic forest sector increased from 134 million m<sup>3</sup> in 1960 to 230 million m<sup>3</sup> in 2015 (Figure 3). There are many reasons for this growth, the main drivers of which are a longer growing season, increased temperatures and changes in forest management (see Henttonen, et al. [35]). In the same period, the harvest has been relatively

stable, with 113 million m<sup>3</sup> in 1960 and 156 million m<sup>3</sup> in 2018. The harvest is divided evenly between sawlogs and pulpwood and this 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<sup>3</sup> to 6.1 billion m<sup>3</sup> (over the last 60 years. Consequently, the biomass in the Nordic forests has also increased. According to the proposed FRL, the Nordic countries might harvest on average up to 163 million m<sup>3</sup> each year between 2021 and 2030 without exceeding the sustainable level [36–39]. Climate change could extend the growing season even more. This is supported by Härkönen, et al. [40], who conclude that the stock of biomass in Northern Europe may increase by up to 30% toward 2030 as a result of longer growing seasons. This biomass might be available for energy production in the future.

As shown in Figure 3, forest resources are steadily increasing due to a modest harvesting level compared to the increment. There is thus an opportunity to increase harvest levels, and Rytter, et al. [41] found that forest growth can be further increased by 50–100% via change of tree species (including the use of non-native species), tree breeding, introduction of high-productive systems with the opportunity to use nurse crops, fertilization, and afforestation. It must be noted that the future amount of available roundwood is uncertain; for instance, drought, bark beetle and fire can substantially reduce the stock available for harvest.

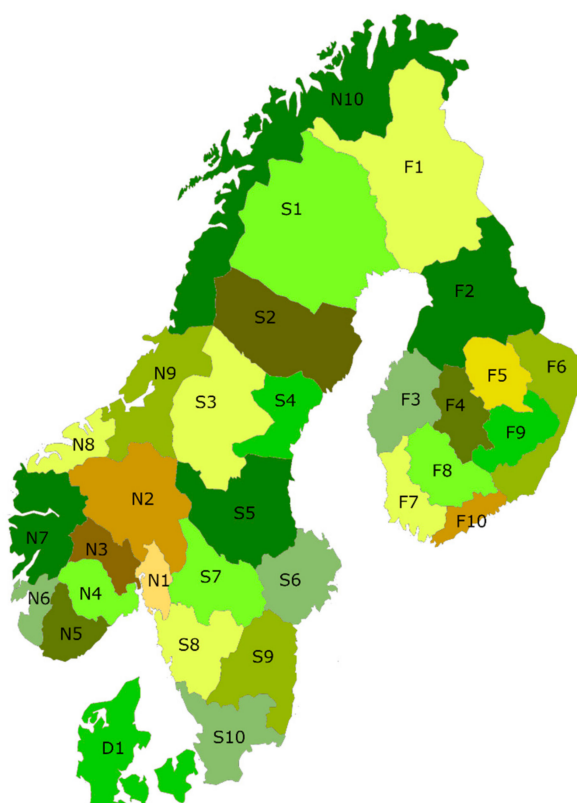


**Figure 3.** Nordic (Norway, Sweden and Finland) growing stock (left axis), yearly harvest (right axis) and increment (right axis). Source: [42–48].

### 3. Materials and Methods

#### 3.1. NFSM

The markets for inputs and outputs for the Nordic forest sector are highly interconnected [49–51]. In order to describe the cross-border roundwood balance between the Nordic countries, Mustapha [52] developed the Nordic forest sector model (NFSM). The NFSM is built on the Nordic Trade Model that was launched in 1995 by Trømborg and Solberg [53], and further developed by Bolkesjø, et al. [54], Bolkesjø, et al. [55], Trømborg and Sjølie [56], and Trømborg, Bolkesjø and Solberg [26]. The model covers 32 regions: 10 each in Norway, Sweden and Finland, one region in Denmark and one in the rest of the world (ROW) (Figure 4).



**Figure 4.** Regions in the Nordic forest sector model (N = Norway, S = Sweden, F = Finland, D = Denmark).

The NFSM seeks to maximize overall social welfare (i.e., consumers plus producers' surplus) in the Nordic forest sector—it is a partial equilibrium model. The model covers 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. The NFSM has 15 different aggregates of final products, 15 intermediate products and by-products, and 7 forest products. The NFSM includes:

- i Timber supply of different species and assortments, relating harvest to roundwood price and forest growing stock, with price and volume elasticities for given products and region.
- ii Forest industries and bioenergy production determining how timber and other wood resources are transformed into intermediate and end-products, and how capacity, locations, and production costs change over time.
- iii End-product demand based on price, volume, economic growth, and exchange rates, with direct price and GDP elasticities for given product and region.
- iv Trade between regions and countries, such that trade in each period takes place for each product whenever profitable.

The production of intermediate and final product creates derived demand for feedstock and intermediate products. Figure 5 shows a flowchart of the NFSM. The production for a given industrial product is defined in input-output relations where the use of wood, energy, and cost per produced unit is defined in a Leontief production function that implies that implies the factors of production will be used in fixed (technologically pre-determined) proportions, as there is no substitutability between factors. There is, however, built in substitution possibilities in the model to reflect substitution possibilities for feedstock in the production of biofuel, district heating, and board.

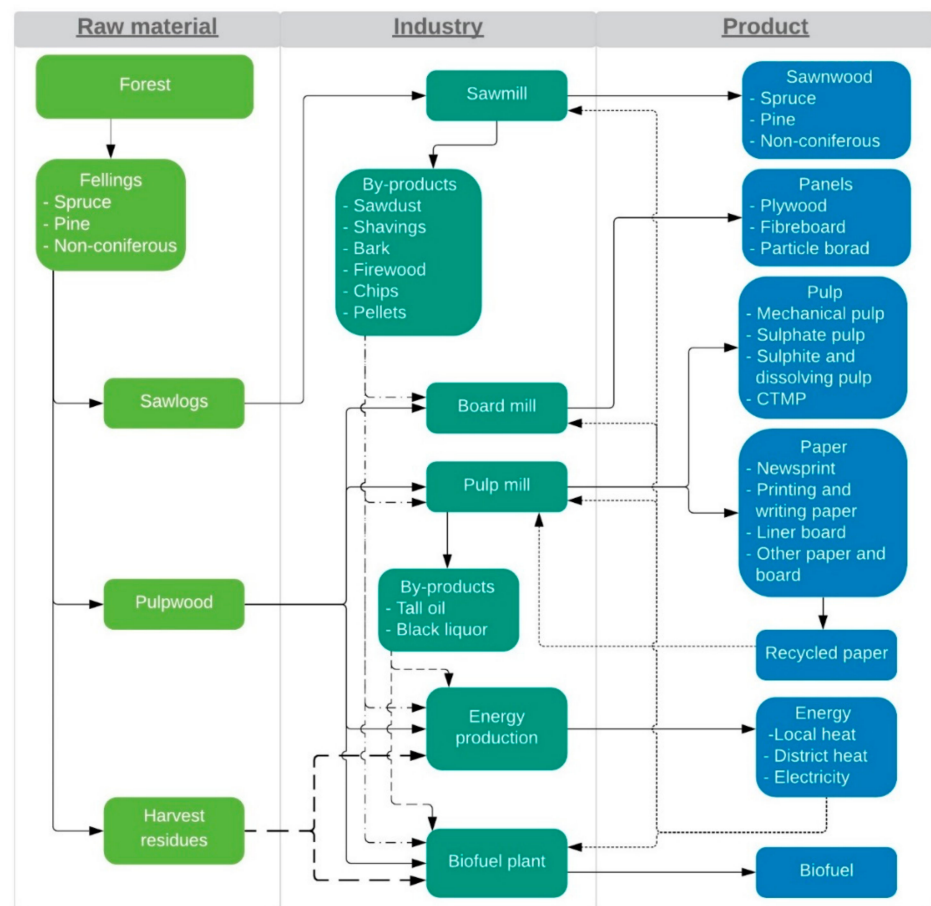


Figure 5. Schematic representation of the forest sector models.

The NFSM is multi-periodic and recursive, as the equilibrium for one year is found before solving for the next; despite being multi-periodic, however, the model is static and deterministic, giving equilibrium solutions that should be equal each time given equal input. The model solution of a particular period is used to update the model input for the subsequent period for consumption, timber supply, prices, changes in production costs, and available technologies. Thereafter, a new equilibrium is computed subject to the new demand and supply conditions, new technologies, and new capacities. As such, the dynamic changes from year to year are modelled using a forward recursive programming approach, meaning that the long-run spatial market equilibrium problem is broken up into a sequence of short-run problems (one for each year). The model is suitable for short- to long-term projections of changes within the forest sectors, as well as for validating the effects of large shocks within the forest sector.

The NFSM has been used in several studies in recent years covering a wide range of topics within biofuel production and the effects of biofuel production on the Nordic forest sector, including: techno-economical costs of biofuel production [57], the physical location of biofuel production facilities [58], biofuel-induced effects on the traditional forest sector [59] estimation of the policies level needed to make biofuel production profitable [60], quantification of different scenarios as outcomes from a Delphi study [61], and both hard-linked [24] and integrated [62] with the energy sector model Balmorel.

The NFSM is written in The General Algebraic Modelling System (GAMS) [63] and solved with the use of the CPLEX solver [64], under which the objective and main equations are shown. A detailed and mathematical description of the model can be found in Jåstad, Bolkesjø, Trømborg and Rørstad [62].

### 3.2. Data

Tables 1 and 2 presents the main data used in the NFSM in aggregated figures; for data on a disaggregated level place, see Jåstad [65].

**Table 1.** Harvest, industrial production and unit electricity production in in the base year (2018). Source: [65].

	Unit	Norway	Sweden	Denmark	Finland	Average Unit Electricity Consumption [MWh/unit]
Harvest						
Spruce sawlogs	mill m <sup>3</sup> solid ub.	4.6	22.6	0.7	13.3	-
Spruce pulpwood	mill m <sup>3</sup> solid ub.	4.1	17.6	1.7	10.4	-
Pine sawlogs	mill m <sup>3</sup> solid ub.	1.5	13.8	0.2	10.7	-
Pine pulpwood	mill m <sup>3</sup> solid ub.	1.6	10.7	0.5	16.8	-
Non-conifers	mill m <sup>3</sup> solid ub.	1.8	12.0	2.6	12.4	-
Harvest residues	mill m <sup>3</sup> solid	0	3.2	0.1	3.0	-
Energy production						
Local heat	TWh	3.9	12	10	9	-
District heat	TWh	1.5	15	11	18	-
Industrial heat	TWh	2.3	69	1.1	46	-
Pulp production						
Sulphite and dissolving pulp	mill tonne	0.15	0.36	0	0	1.77
Sulphate	mill tonne	0	8.29	0	7.76	0.87
CTMP	mill tonne	0.14	1.29	0	0.69	0.59
Mechanical pulp	mill tonne	0.12	2.22	0	2.61	2.25
By products from pulp mill						
Tall oil	mill tonne	0	0.383	0	0.338	
Black liquor	mill tonne	0.24	16.77	0	14.79	
Production of energy carriers						
Chips	mill m <sup>3</sup> solid	2.2	13	2.1	8.2	-
Firewood	mill m <sup>3</sup> solid	2.3	5.1	2.3	5.0	-
Pellets	1000 tonne	55	1994	136	385	0.12
Sawnwood production						
CLT	1000 m <sup>3</sup> solid	60	145	0	140	0.07
Non-coniferous sawlogs	1000 m <sup>3</sup> solid	1.4	108	89	303	0.07
Pine sawlogs	mill m <sup>3</sup> solid	0.63	8.3	0.09	5.6	0.07
Spruce sawlogs	mill m <sup>3</sup> solid	1.9	13	0.30	6.4	0.07
Paper production						
Newsprint	mill tonne	0.5	1.1	0	0.5	1.04
Linerboard	mill tonne		2.9	0.02	1.4	0.49
Other paper and paperboard	mill tonne	0.2	4.0	0.3	4.4	0.72
Printing and writing paper	mill tonne	0.5	3.0	0.1	5.0	0.81
Board production						
Particle board	1000 m <sup>3</sup>	405	550	346	100	0.21
Plywood	1000 m <sup>3</sup>	0	120	80	1030	0.15
Fibreboard	1000 tonne	172	0	2.5	24	0.71



**Table 2.** Price and GDP elasticity for the various end products. Source: [66].

Product	Price Elasticity	GDP Elasticity
Sawnwood	−0.17	0.24
Cross laminated timber	−0.17	0.34
Fiberboard	−0.54	0.92
Plywood	−0.61	0.72
Particle board	−0.51	0.59
Newsprint	−0.04	0
Printing and writing paper	−0.53	0
Linerboard	−0.45	0.4
Other paper and board	−0.45	0.4
Charcoal	−10	0

In the production of biofuel pulpwood, sawdust, harvest residues, tall oil, and black liquor may be used. The assumed energy efficiencies/fuels use and costs for biofuel production are shown in Table 3. The scale factors are set to 0.795 for operation and management costs, 0.755 for investment cost, 0.645 for labour cost and the learning rate is set to 0.92 for all feedstocks. The total biofuel production is set by scenario whereas the location of the plants is defined by endogenously modelled regional feedstock costs including transport costs, investments and production costs and scale factors. Once established, a biofuel plant produces at the same capacity with the same raw material for the remainder of the modelling period.

**Table 3.** Main input parameters for biofuel production used in the analyses. Source: [20,67,68].

Raw Material	Base Investment Cost [mill €]	Base Size [MWh Biofuel]	Base Labour Cost [€/man year]	Energy Efficiencies	Hydrogen [MWh/MWh Biofuel]
Chips	287	367,920	44,473	58%	0.60
Dust	287	367,920	44,473	58%	0.60
Harvest residues	287	367,920	44,473	42%	0.60
Black liquor	27	257,544	35,579	60%	0
Tall oil	16	257,544	35,579	82%	0

Both endogenous investments and decommissioning of plants are modelled in NSFM. These choices are based on the demand for intermediate and final products. The yearly production levels are constrained to be between 0–120% of the reference production for pulp and paper and 0–140% for sawnwood technologies disregarding new investments. If it is profitable to increase production, an investment is modelled. The construction period is assumed to be less than one year and producing at capacity the first year. If a model plant is producing at less than 70% of capacity, it is assumed that half of the unused capacity is decommissioned. The year 2018 is used as the reference year, and Table 1 shows the most relevant data for the reference year.

### 3.3. Scenarios for Biofuel Demand

We estimate future demand (i.e., consumption) for forest-based biofuel in the Nordic countries based on the estimated demand for liquid fuels, blending requirements of biofuel and the share of forest-based biofuel. The total number of vehicles and the total driving distances are based on historical figures [69–72] and it is assumed that they remain constant throughout the period in question. It is assumed that the vehicle retirement age follows historical figures [73], and each retired vehicle is replaced with either an electric or a fossil fuel-powered vehicle with an estimated probability function for year of wracking [74–76]. In Norway, the stated policy is that all new private vehicles must be zero emission from 2025, and the country aims to fully electrify all other new vehicles by 2035 [74]. Sweden does not have such clear goals, but Svenskt Näringsliv [75] 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.

We have assumed a constant energy output in non-road transportation for both electric and internal combustion engines. To convert between liquid fuel and electricity, average engine effectivity is used [74]. 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% for electrical charge losses. Railroad transportation is assumed to 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 [77]. Further, from 2025 domestic ferries will be fully electrified and the potential for shore supply will be fulfilled. In domestic aviation, we assume a constant jet fuel demand until 2030; while for 2040, it is assumed that electricity delivers 20% of the base line energy use in domestic aviation. This is in line with Avinor [8].

As stated above, Norwegians have a 20% blend-in target for road fuels in 2020 [78]; of this, we assume that 1.75% of the total is forest-based biofuel. For advanced biofuels, the volumetric share will increase to 10% by 2030 [74]; all of this biofuel will be forest-based in our scenarios. It is also assumed that the obligation will increase to 20% in 2035 and to 100% in 2050. All types of transportation have to meet the same regulation.

The Swedish biofuel policy is a GHG reduction goal, not a not a blend-in obligation; the aim is to reduce the transportation emissions by 40% by 2030, as specified in [79]. Based on [80] we assume a GHG emissions reduction of 95% from Nordic forest-based biofuel compared to fossil fuel. Assuming the same forest-based biofuel share of the total biofuel mix as in Norway, we get 1.2% forest-based biofuel of the total liquid fuel 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 [81,82]. The blending requirements in road traffic implied by the policies above are summarized in Table 4.

**Table 4.** Blending requirements in road traffic by country. Assumed forest-based share of total in parentheses.

	2018	2020	2030	2035	2050
Norway	10%	20% (1.75%)	40% (10%)	(20%)	(100%)
Sweden	12%	13% (1.2%)	42% (10.5%)	(20%)	(100%)
Finland	15%	20% (1.8%)	30% (7.5%)	(20%)	(100%)
Denmark	7%	10% (0.9%)	30% (2%)	(20%)	(100%)

We have assumed constant transport demand/transport distances and that:

- All railroads are electrified by 2025 in Sweden, Norway and Finland and by 2030 in Denmark.
- Domestic coastal marine transport, ferries, and fisheries are electrified in 2025 in Norway and in 2029 in the other Nordic countries. International shipping is not included.
- Domestic aviation is assumed to reduce their consumption of liquid fuels between 2030 and 2040 by 80%. International aviation is not included.
- Construction machines follow the trends for busses and heavy-duty vehicles.
- Hydrogen is assumed to not influence the demand for biofuels in the transport sector until 2050.

Based on the above assumptions, we have developed three different scenarios for the use of biofuels in the Nordic countries toward 2050:

- (i) A base scenario (Base Electric), where investments in electric vehicles follow known trends in each country (as described above), the probability of the wracking of combustion cars and driving distances follow Norwegian historical trends and the use of

biofuel in combustion road vehicles follows estimated policy until 2030, after which the biofuel share follows a linear trend and reaches 100% in 2050.

- (ii) A rapid electrification scenario (Rapid EI), where all countries follow Norwegian investment levels for electrical vehicles from 2022, all buses and heavy-duty vehicles are 100% electric from 2030 (base in Norway: 2033 and 2035) and the scrapping probability for cars above 10 years increases by 5–8 for vehicles aged 10–14 years and 21% for vehicles above 15 years.
- (iii) A slow electrification scenario (Slow EL), where the year for a 100% new electrical vehicle ratio is postponed by 5 years, combustion vehicles are used 5 years longer before scrapping and the driving distances for cars above 10 years of age increases by 2000 km/year

Biofuel production outside the Nordic countries follow the same trends and the assumed increased use of forest biofuels cannot be imported.

### 3.4. Scenario for Industrial Development

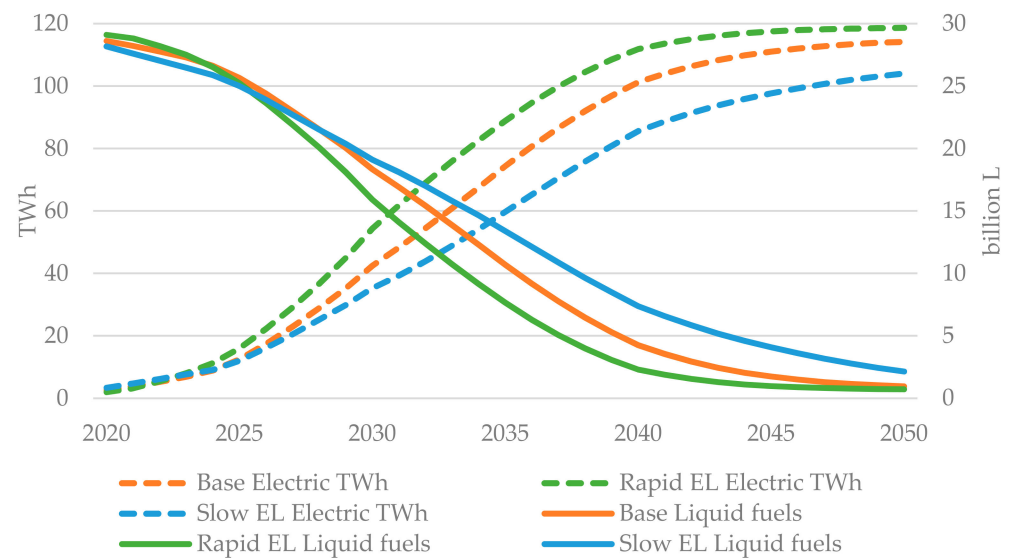
The availability biomass as well as the impact of increased biofuel production on the forest sector depend on several factors. Central assumptions regarding the development in the forest, heat and power sectors applied in this study are:

- Sawnwood demand increases by 1% p.a.
- Increased use of cross laminated timber (CLT) by 10% p.a. until 2025; after 2025, by 5% p.a.
- Printing and writing paper decreases by 2% p.a.
- Newsprint decreases by 3% p.a.
- Demand for remaining products according to assumed GDP growth and GDP elasticities.
- Charcoal demand increases by 0.002 million tonnes/year between 2022–2025, by 0.044 million tonnes/year between 2026–2036, by 0.030 million tonnes/year between 2036–2040, and by 0.296 million tonnes/year between 2041–2050.
- Increased use of pulpwood in other industrial processes:
  - Norway: 0.1 mill m<sup>3</sup> p.a. between 2022–2030, 0.3 mill m<sup>3</sup> p.a. between 2031–2040, and 0.5 mill m<sup>3</sup> p.a. between 2041–2050.
  - Sweden and Finland each: 0.2 mill m<sup>3</sup> p.a. between 2022–2030, 0.4 mill m<sup>3</sup> p.a. between 2031–2040, and 0.6 mill m<sup>3</sup> p.a. between 2041–2050.
  - A 2.5% p.a. increase in district heat in the Nordic countries.

## 4. Results

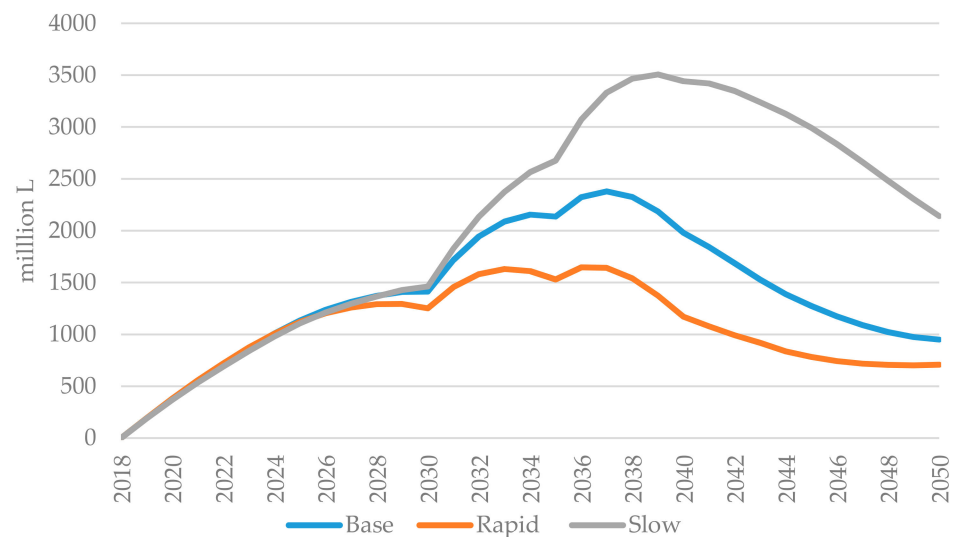
### 4.1. Demand for Biofuels

Figure 6 shows the estimated future demand for liquid fuel and electricity in the transportation sector in the Nordic countries. Figures until 2030 are based on likely trends, adopted policies and announced policies, while figures after 2030 are mainly based on the extrapolation and harmonization of Nordic goals; a 100% renewable transportation sector by 2050 is assumed. All scenarios give an increased use of electricity and a corresponding reduction in the total use of liquid fuels. The total electricity consumption in the transport sector is 104 TWh by 2050 in the slow electrification scenario, 114 TWh in the base scenario and 119 TWh in the rapid electrification scenario, e.g., about a 25% increase in the Nordic electricity production. 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.



**Figure 6.** Nordic use of fuels in the transport sector, by scenario.

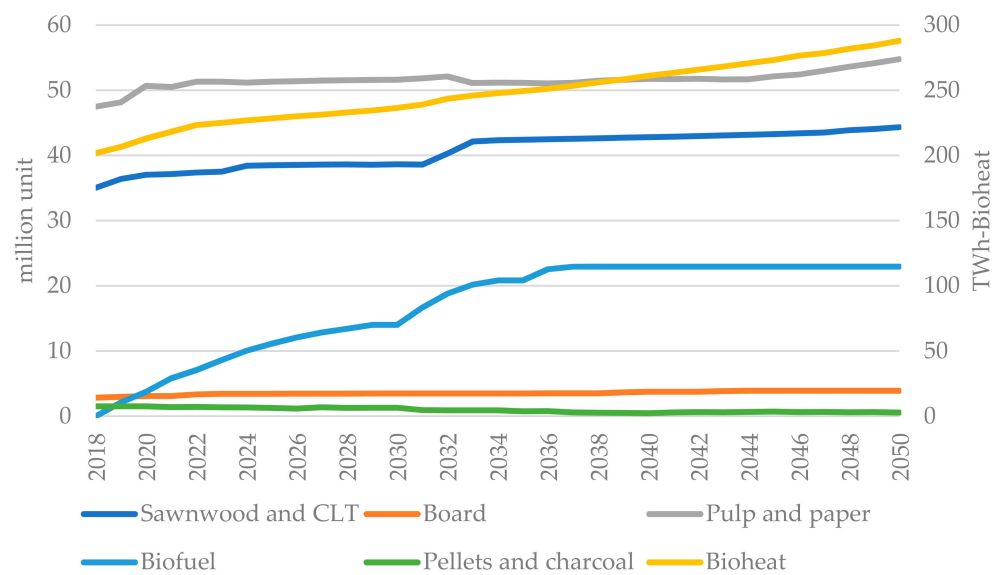
The increasing share of electricity implies that the potential use of forest-based biofuels in the domestic Nordic market will reach a peak in 2037 of 2400 mill L in the base scenario and 1650 mill L in 2036 in the rapid electrification (EL) scenario (Figure 7). These volumes are based on the slow EL scenario, giving a peak for forest-based biofuels of 3500 mill L in 2039. These volumes correspond to a solid biomass use of about 13, 18 and 27 mill m<sup>3</sup>, respectively, when assuming a 60% efficiency from wood to fuel. The total roundwood harvest in the Nordic countries was about 150 mill m<sup>3</sup> in 2020.



**Figure 7.** Use of forest-based biofuel in the Nordic countries, by scenario.

#### 4.2. Forest Sector Impacts

The modelled production in the Nordic forest industries in the base scenario is shown in Figure 8. This estimated production is based on the consumption of liquid fuel shown in Figure 7 and the assumed blend-in requirements in Table 4 as a basis for the minimum biofuel production levels, and that the blend-in requirements of forest-based biofuel will reach 100% in 2050.



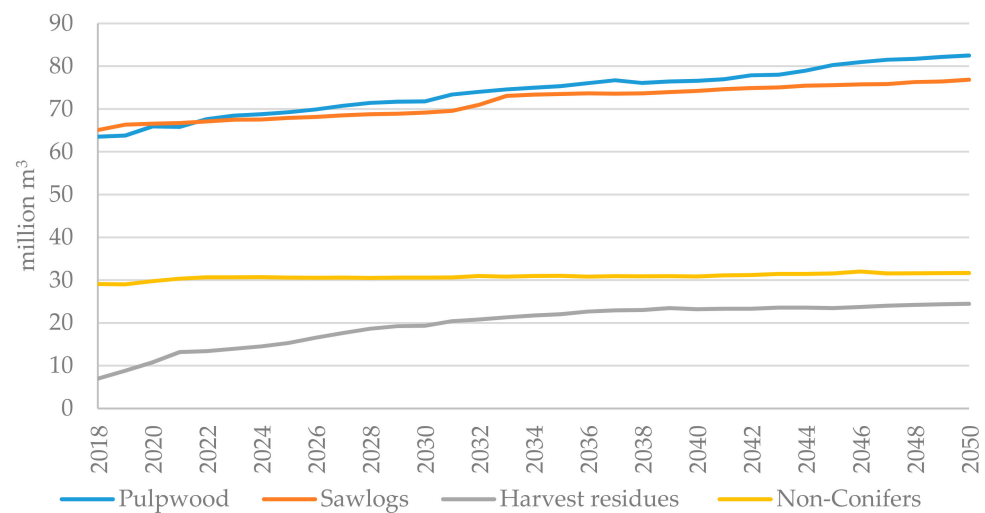
**Figure 8.** Modelled Nordic production of the main categories. Bioheat includes district heat, local heat and industrial heat. Biofuel in million L on the left axis and bioheat in TWh on the right axis.

The maximum biofuel volume produced is 22.5 TWh (approx. 2.25 billion L) from 2037. It is assumed that when a biofuel plant is constructed, it will produce the same amount of biofuel for the rest of the studied period. The feedstocks used are 32% tall oil, 21% chips and pulpwood, and the rest (47%) is sawdust. More than half (56%) of the biofuel production is located in Sweden, while Finland produces 32%, Norway 11% and Denmark 1% of the Nordic production. Tall oil is the most profitable feedstock and all accessible tall oil in the Nordic countries is used for biofuel production; tall oil diesel increases the profit in chemical pulping slightly. The salient points in 2030 and 2035 for biofuel production are due to a change in policy periods for those years.

As a consequence of the changes in paper demand, the Nordic pulp and paper industry undergoes a transition from producing 10.7 million tonnes of newsprint, printing and writing paper in 2018 to 7 million tonnes in 2050, whereas the production of other paper grades, including packaging, increases from 13 million tonnes in 2018 to almost 20 million tonnes in 2050. These changes result in a reduction of 20% in the production of mechanical pulp, an increase of 25% in chemical pulp and 36% increase in chemical-thermomechanical pulp (CTMP) capacity. These changes give an increased availability and use of tall oil for biofuel production.

The production of sawnwood increases from 38 million m<sup>3</sup> in 2032 to 41.5 million m<sup>3</sup> in 2034, due to the assumed increase in the demand. The increased production of bioheat is caused by the assumed increase in district heat of 2.5% per year and results in an increase from 45 TWh in 2018 to 100 TWh biomass use in district heating in 2050.

Due to the changes in production mix (Figure 8), the total harvest including harvest residues from the Nordic forest increases from 164 million m<sup>3</sup> to 215 million m<sup>3</sup> (Figure 9). Most of the increase is constituted by harvest residues used for heating. The removal of harvest residues increases from 11% to 33% of the theoretical potential of harvest residues. Extensive removal of harvest residues can reduce biodiversity and long-term productivity especially on low productive soil types. The annual harvest of roundwood is lower than the annual growth throughout the analysed period, which results in a relatively constant roundwood price for all qualities due to the positive shift in the supply.

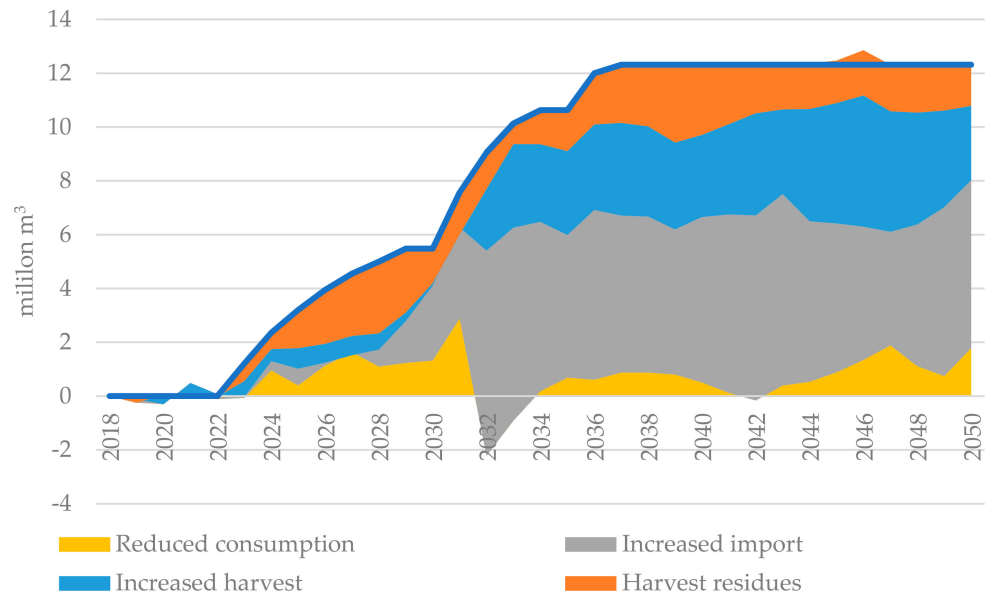


**Figure 9.** Modelled Nordic outtake from forests in the base scenario. Non-Conifers is pulpwood and sawlogs of mainly birch.

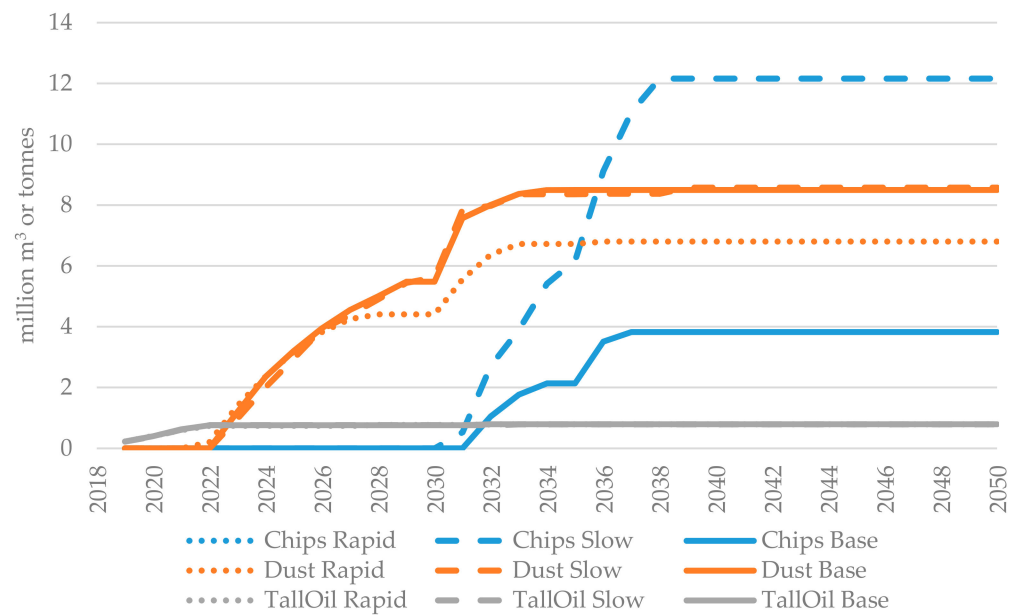
Biofuel production in the base scenario would require up to 12.3 million m<sup>3</sup> wood. This amount comes from an increase in harvest, the use of harvest residues, increased import, and/or a reduction in biomass consumption in other industrial processes. Figure 10 shows the difference between the base scenario and a corresponding scenario without biofuel production. This figure shows that the main biomass usage for biofuel in the first years (until 2030) is mainly due to increased use of harvest residues. After 2030, the raw material mix is heavily dominated by increased import and harvest. The reason for this is that chips and pulpwood are first used as feedstock for biofuel production in 2032 and most of the easily available harvest residues are used for district heat production from 2030. Before 2032, only by-products (sawdust and tall oil) are used for biofuel production, which implies small changes in harvest levels. The difference between roundwood consumption for biofuel production and availability of raw materials will be filled by reduced roundwood consumption in other processes. The highest reduction in the use of roundwood in the traditional forest industry is up to 2.8 million m<sup>3</sup>. Most of the reduction is in the production of charcoal and pellets, which are mainly exported. The increase in the production of sawnwood results in increased sawlog consumption between 2032 and 2034, compared to a scenario without biofuel production. The biofuel production increases the demand and price for by-products from sawmilling, which improves the profitability and hence volume of sawnwood production.

#### 4.3. Alternative Biofuel Demand Scenarios

In the base scenario, the peak in forest-based biofuel production is observed in 2037 with a production of 23 TWh. If we assume a more rapid electrification of the transportation sector, the peak will be in 2033 and the production level for biofuel will be 16 TWh. A slow electrification will imply a peak biofuel production in 2039 with a corresponding production level of 37 TWh. These differences in biofuel production influence the forest sector. The merit order for the different raw materials for biofuel production is similar for the three scenarios (Figure 11); all available tall oil is first used for biofuel production, followed by the use of sawdust, and finally chips and pulpwood. The latter two are used after 2031 in the slow EL scenario, and after 2032 in the base scenario, while chips and pulpwood are not used in the rapid scenario since the demanded biofuel volume is lower and it is not as cost-competitive as feedstock for biofuel compared to sawdust and tall oil.

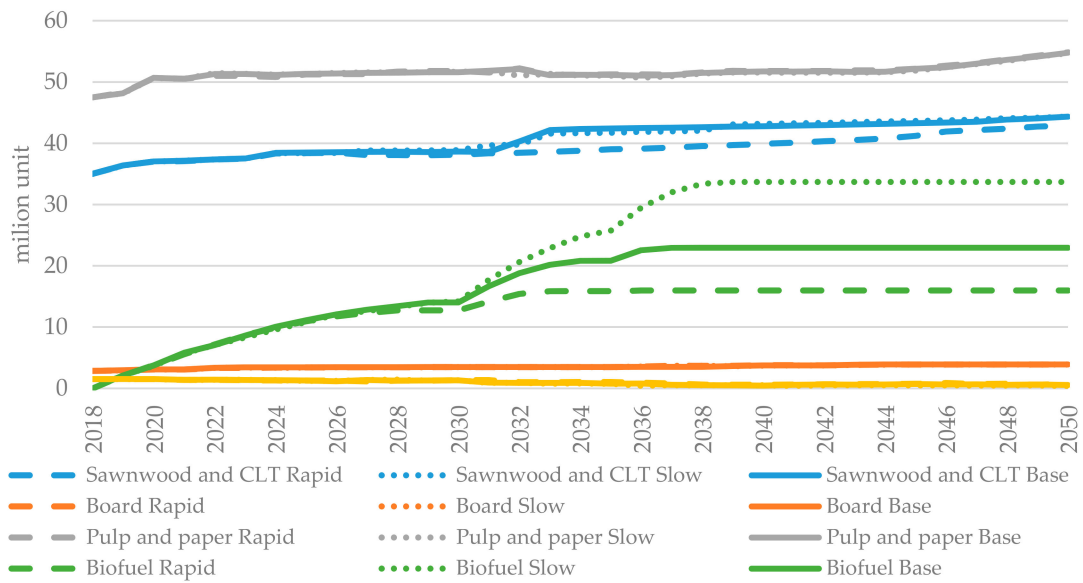


**Figure 10.** Change in harvest, use of harvest residues, and increased import (stacked) and forest raw material demanded for biofuel production in the Nordic countries. The figure shows the difference between the base and a similar scenario without biofuel production.



**Figure 11.** Raw materials used for biofuel production in the different scenarios.

The differences in the production of biofuel lead to only moderate differences in production volumes for other product categories (Figure 12). The main difference is found for sawnwood production after 2031. In the slow and base scenario production, volumes increase, while in the rapid scenario no significant increase in sawnwood production is found. The reason for this is that in the base and slow scenarios, the production volume is so high that they increase the profitability of sawmilling residues, while in the rapid scenario the increase in the value of sawmilling residues is not high enough to make it profitable to increase the sawmill capacities.

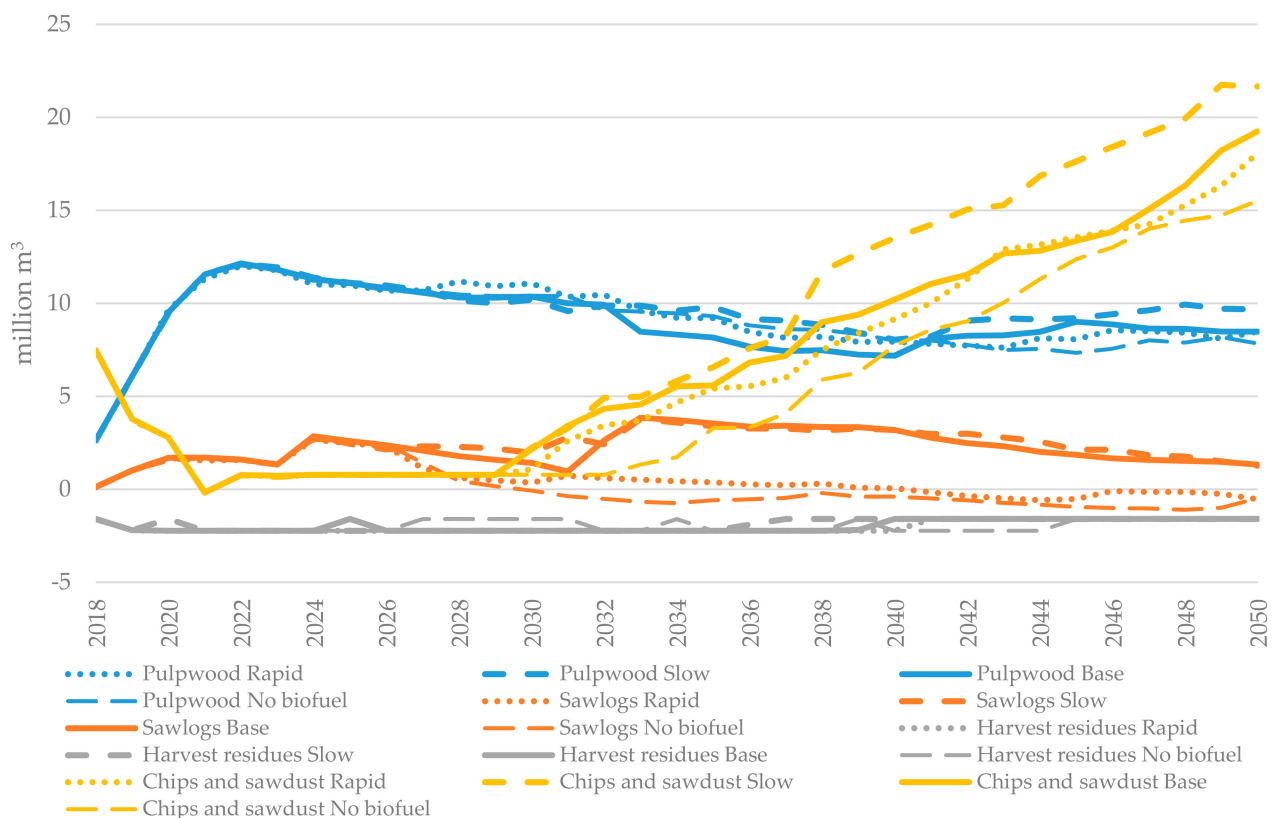


**Figure 12.** Modelled production of the main industrial products in the Nordic countries for the base, rapid electrification and slow electrification scenarios.

The main trends between the scenarios are that a rapid transition reduces the amount of biomass use, especially after 2030, whereas a slow transition leads to higher harvesting levels compared to the base scenario. The most significant change from the base scenario is found for the sawlogs harvest in the rapid scenario, as sawmilling is less profitable in the rapid scenario compared to the base scenario, but differences are only up to 4.5% lower than the base. The relatively small changes in harvest levels lead to small changes in sawlogs and pulpwood prices.

There are significant differences in biofuel production between the scenarios, resulting in limited differences in the harvest and production of forest industry products, but greater differences in net biomass import to the Nordic countries. Figure 13 shows the net import to the Nordic countries from the ROW region. As shown, trade is similar for all raw materials until 2030, where the biofuel production is also relatively similar across all scenarios. A general trend is that the import is highest in the slow transition scenario and lowest in the rapid transition scenarios.





**Figure 13.** Modelled net import of wood biomass to the Nordic countries for the base, rapid and slow electrification scenarios.

## 5. Discussion and Policy Considerations

The potential for increased use of biomass for energy in the Nordic countries is significant. Forest biomass represents the main feedstock potential for biofuel in the Nordic countries and the results of this study indicate that, from a resource viewpoint, a 100% fossil-free Nordic transportation sector based on electrification and biofuels is feasible. It will, however, require a massive buildout of renewable electricity capacity and increased utilization of wood resources in the coming decades.

The realization of this potential requires the deployment of cost-competitive biofuel conversion pathways. The purpose of this study is not to evaluate different forest-based biofuel technology options, but to analyse the impact of forest-based biofuel deployment. Production of the estimated future demand for biofuels is exogenously defined in the model and means that the profitability of the production is not analysed in this study. There are, however, large uncertainties regarding future costs of forest-based biofuels compared to first-generation biofuels and advanced biofuels already on the market, e.g., biofuels produced from used cooking oil, animal waste, and tall oil. Apart from biofuels from tall oil, technologies for advanced biofuels from lignocellulosic feedstock are in a development phase and more costly than commercialized biofuels. Though there is a potential for cost reduction through learning and scale, Witcover and Williams [83] have noted that production cost estimates are higher in later than in earlier publications, primarily due to higher costs for feedstock and capital expenditure components.

The modelling is based on several assumptions regarding developments in the forest sector that define the business environment for forest-based biofuel production. The assumptions are decisive for the results and magnitudes and directions are thus more important than exact figures. A main challenge in this type of modelling is to model or foresee major decisions regarding capacity expansions or closures. The advantages of recursive programming as included in NFSM, compared to perfect foresight forest sector models are discussed in Latta, et al. [84]. While influence of expected changes in the

future business environment can be better captured in dynamic models, the investment behaviour with a not so perfect foresight might be relative well modelled in recursive multiperiodic model like NFSM. Uncertainty is partly included by sensitivity/scenario analyses in this study. Stochastic models might better reflect actual investment behaviour but add significant complexity and data requirements.

The expected decrease in paper production due to decreased demand for printing paper will likely increase the availability of Nordic biomass for biofuel production, thereby maintaining harvest levels below annual increments. The feedstock supply data used in the NFSM are uncertain as supply depends on several factors. Price and availability (e.g., standing volumes) are important parameters and included in the model. The price elasticities used for timber supply are based on [60,85,86] and own econometric estimates and may not accurately represent future quantity-price relations. A central limitation of the modelling of the supply of harvest residues is the lack of compelling data to accurately represent engineering bottom-up collection costs and forest-owner rationale in response to changing demand. Higher feedstock costs will increase the marginal production cost of biomass heat- and power-generating facilities, moving these further up the merit order.

The results show indirect impacts of increased biofuel production. Increased biomass consumption increase prices which result in reduced paper consumption, changed use of biomass in district heating and increased biomass import. The energy sector impacts of Nordic biofuel production are analysed in in Jåstad, Bolkesjø, Trømborg and Rørstad [62]. They note that bioheat has favourable GHG results compared to biofuel in the short run, but also potential to be replaced by renewable power. Earles, et al. [87] identify and estimate indirect economic and environmental impacts of increased wood use for bioethanol production in the US by combining a partial equilibrium model and a life cycle assessment model in a consequential life cycle assessment approach. They found increased greenhouse gas emissions from natural gas could offset reductions obtained by substituting biofuels for gasoline, but relatively low environmental impacts across related forest product sectors. Plevin, et al. [88] analyse how the impacts of carbon intensity standards can be modelled. Both geographical and sectoral system boundaries are important to consider when direct and indirect impacts of biofuel production shall be analysed. Data availability and complexity versus the magnitude of potential impacts are trade-offs in the choice of modelling approach. Technological developments including renewable alternatives to biofuels in aviation and shipping, trade offs between short run and long term GHG-effects, sound management of forest in climate mitigation and biodiversity perspectives and the potential for carbon negative bioenergy solutions are important topics related to biofuel, but outside the scope of our study.

Policy initiatives have triggered a transition to biofuel in the Nordic countries, but as noted by Midttun, et al. [85], biofuel has mainly created dynamic change in the petroleum sector, where retailers and refineries have adopted cheap imported biofuel to diversify out of an exclusive reliance on petroleum, leaving forest-based biofuel unable to compete. While public policy may influence commercial conditions, it does not—in a market economy—dictate the industrial strategy, which is hard to predict, especially when it moves beyond existing sector boundaries. However, the recent adjustment in biofuel policy, in part a response to ecological critique, may represent a more promising opportunity for forest industry participation in the future. Directing more biomass toward energy production will likely have some distributional effects in the forest sector value chain. For example, the profits within pulp and paper production may be reduced due to increased competition for wood. On the other hand, biofuel can also be a side stream from higher-value-creating products. Forest owners will profit from increased energy production due to the increasing wood demand.

It is not straightforward to determine which types of policies will be most suitable for promoting 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 obligations or feed-in premiums; still

others may affect both biofuel and electrical vehicles, such as increasing fossil fuel taxes. The rapid expansion of biofuels in the Nordic market is largely based on feedstock import and dominated by petroleum refineries, which have been required by legislation to provide increasing quantities of renewable fuels. Biofuel could be an important part of their future strategy, as a new green add-on in the transformation to multi-energy stations. In this way, the companies are scoring a double bonus: diversifying feedstock while going green, as they gradually de-couple from their role as monolithic petroleum vendors. In response to the new biofuel policy, which includes so-called double counting, there has been a stronger forest industry engagement in biofuel, but often in collaboration with the petroleum industry. Crossover engagements between the two sectors appear to have stimulated a dynamic coupling between consumption and production, as well as a complementary mobilization of joint refining capabilities [85]. The plants are often based on flexible feedstock so that they can take advantage of various market opportunities. The success of forest-based biofuel is highly contingent on its ecological and social sustainability. The attack on biofuel for displacing food crops, and the discussion about biofuel's possible short-term negative impact on CO<sub>2</sub> absorption from forests, has led to policy setbacks. Any successful boost to forest-based biofuel production is therefore dependent on the industry convincingly documenting its sustainability in competition with other green alternatives.

The biofuel production increases competition for low-value feedstocks in the forest sector. There are forest resources for increased and sustainable production of biofuels, but the biofuel production will to some extent reduce the production of other industrial products. The biofuel production in the Nordic countries consumes about 8% of the total wood consumption in the most expansive scenario analysed in our study. The EU Bioeconomy Monitoring System [88,89] estimates that 22% of the EU biomass supply in 2015 was used for energy compared to 22% for materials and 57% for food purposes including inputs. The value added is comparatively low for energy production, but in biorefineries, by cascading and use of by-products and residues it will supplement the profitability of the higher value products.

## 6. Conclusions

The present study develops a pathway toward a fossil-free Nordic road transport in 2050 based on electrification and wood-based biofuels. The study shows that, from a resource viewpoint, a 100% fossil-free Nordic transportation sector based on a combination of these two options is feasible, but it will require a massive build-out of renewable electricity capacity and increased utilization of wood resources in the coming decades. Due to technological progress in battery technologies and electric vehicles, we foresee a strong electrification of the transport sector resulting in a demand for biofuels of approximately 2.5 billion L in 2035 and 1 billion L in 2050, in a 100% fossil-free base scenario. Despite an expected increase in wood demand from pulping industries, it seems likely that the Nordic forest sector can deliver the demanded amounts of biomass for biofuels while at the same time keeping harvest levels below annual forest growth. However, the transition will come with some major implications to the forest sector value chain. First, the simultaneous increase in demand from pulping industries and biofuel will cause an overall increase in wood use (pulpwood, chips and sawdust) consumption of approximately 40 mill m<sup>3</sup>, of which the biofuels share is approximately 20–25% in our base-scenario (the current Nordic harvest level is approximately 160 mill m<sup>3</sup>). Second, the tall oil produced in pine-based pulp mills is almost exclusively used for biofuels. Third, the utilization of harvest residues will increase more than 300% compared to the current level, since biofuel production reallocates some of the current raw material used in bio-heating. From a techno-economic viewpoint, forest-based biofuels are not cost-competitive to fossil alternatives, and biofuel blending requirements will likely be a needed policy instrument to achieve the fossil-free 2050 target. Due to the increasing electrification, the biofuel consumption in road transport will likely reduce after 2040. It is, however, likely that the declining domestic demand will be replaced by increasing demand from international biofuel markets in aviation and

shipping. Future import possibilities for forest biomass are uncertain, as they depend on biofuel policies in the exporting countries. There are established systems for the use of harvest residues in Sweden and Finland, but the cost and availability for increased use represent uncertainties in the results.

Finally, it should be stressed that biofuels based on lignocellulosic feedstock are still marginal contributors to the current biofuels market. Most of the technologies have not reached commercial scale of production and the uncertainties regarding future costs and profitability for these technologies are considerable. In addition, public acceptance of the close to 100 TWh of new renewable electricity production needed in the scenarios presented represents another major uncertainty.

The modelling approach applied here quantifies direct and indirect effects of increased biofuel production on the forest and bioenergy sectors in the Nordic countries. Forest biomass represents the main potential for increased biomass use in this region. In other regions where agricultural resources are more important for future biofuel production, inclusion of more biomass types in the modelling approach should be considered. There are, however, important trade-offs between the complexity regarding products, technologies, biomass types, sectors, and geographical cover, versus the research questions to be analysed by the model, and these need to be taken into account.

**Author Contributions:** T.F.B., P.K.R., E.T.: Conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, writing—original draft, reviews; E.O.J.: data curation, formal analysis, investigation, methodology and modelling, writing—original draft, reviews; A.M., J.S.: investigation, writing—original draft. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was provided by the Norwegian Research Council through the ‘Norwegian Centre for Sustainable Bio-based Fuels and Energy (Bio4Fuels)’ [NRF-257622], ‘The role of bioenergy in the future energy system (BioNEXT)’ [NRF-255265] and ‘Enabling the green transition in Norway (Enable)’ [NRF-2473427].

**Acknowledgments:** We also wish to thank our industry partners Avinor, Statkraft, Moelven, and Glommen-Mjøsen Skog for valuable contributions in the BioNEXT project.

**Conflicts of Interest:** The authors declare no conflict of interest.

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