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Modelling emission and land-use impacts of altered bioenergy use in the future energy system

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ABSTRACT

Forest biomass is one of the few non-fossil and non-weather-dependent energy sources available in the Nordic countries. The future role of forest-based bioenergy is, however, unclear as biomass is a limited resource and has many alternative applications. This study analyses how fossil emissions and land-use is affected by forest bioenergy in the North-European heat and power sector, using an energy system model with endogenous capacity investments. The novelty of this paper lies in the detailed description of the substitution factors for different bioenergy levels toward a fully decarbonised energy system. The main results show that forest biomass remains important for heat production in the Nordic countries towards 2050 in a cost-optimal scenario. According to our model results, less use of forest biomass for heating will increase the use of fossil fuel, wind power, and power-to-heat in 2030, while in 2050 also solar PV will be used as a substitute for forest biomass. Implying that less use of forest biomass will increase the land use from wind and solar PV installation and increase and prolong the fossil carbon emission in the Nordic countries.

1. Introduction

Forest biomass is expected to play a major role in the future Northern Europe's low-fossil society. IPCC concludes that forests and forest biomass are important for reducing atmospheric carbon concentrations in multiple ways, of which the most important are afforestation, carbon storage in forests and use of bioenergy with and without CCS [1,2]. In the Nordic countries (Norway, Sweden, Finland, and Denmark), 51% of the surface area is covered by forests [3,4], and forest biomass contributes approximately 16% of electricity and district heat production [5]. Forest biomass is also likely to remain important in the future energy system [6,7] and will be used to balance the low-carbon energy system [8–11]. However, the future role of forest biomass is debated due to the potentially negative impacts from forest harvesting on biodiversity and recreational values, and so-called carbon debt arising from the fact that it may take several decades from a forest stand is harvested until the same amount of carbon is sequestered in the same stand. For these reasons, it is interesting to analyse the most likely substitutes for forest bioenergy in future energy systems.

In previous studies, different approaches have been used to estimate these substitution effects. The most common approach is to estimate biomass substitution for fossil fuel for a single plant, which has previously been estimated to be in the range of 0.11–1.33 tonnes of $CO2_{fossil}/MWh_{biomass}$ (0.27–3.3 $kgC_{fossil}/kgC_{biomass}$) [12–18] depending on the categories of fossil fuels that are replaced (highest for natural gas, lowest for oil condensing and lignite). Substitution factors above 1, in this case, indicate that the total carbon emissions in the atmosphere increase in the short term when forest biomass is used compared to fossil fuels. However, emissions may be reduced in a longer timeframe, depending on which product the biomass substitutes [19,20].

This plant-to-plant approach makes sense for converting existing production facilities, but a holistic system approach using a fine temporal resolution is needed to quantify how generation mixes and emissions are affected on a market scale. Generally, the fossil carbon substitution impact will be reduced when the overall carbon emissions are reduced [21–24]. Few studies have, however, explicitly focused on the system effect of forest biomass using holistic energy system models. Daioglou et al. [24] found that bioenergy can reduce emissions by 40% in 2100 given a carbon price of 500 €/tonne carbon. This was supported by Jåstad et al. [23] who estimated that the cost of delivering heat and electricity will increase by 0.2–0.7% in 2030 and that fossil fuel emissions would increase by 2–68% if all forest biomass is removed from the system.

A cost-efficient, low fossil-fuel energy system requires a large

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amount of wind and solar generation, leading to larger land requirements for energy infrastructure [25–28]. The social acceptability of this massive expansion of land-intensive electricity production is questionable [29]. It has previously been shown how more costly, but less land-intensive, scenarios may reduce land use significantly [27]. Using biomass for energy also entails large land-use impacts [30,31]. Sustainable forest management may, however, reduce the negative impacts [32].

In summary, most previous studies focus on the substitution effects of a single bioenergy plant or from the forestry/forest sector perspective. However, this is only part of the full picture, since a bioenergy plant will compete with all the other technologies in the market. This paper focuses on the effects of changing the use of biomass in the heat and electricity market in the Nordic countries and estimates the carbon emission substitution effects and land-use impacts at a system level. We estimate substitution factors for cases ranging from +50% to −100% compared to the cost-optimal bioenergy level up to 2050. We also focus on the time dimension of carbon emission impacts, since the substitution factors are likely to be reduced as emissions from the energy system decline. Few studies have focused on the substitution effects for the combined heat and electricity market, on the way to a fully decarbonised energy system by 2050. The novelty of this study is the quantification of carbon and land-use substitution factors in the Nordic energy sector as a function of the substituted amount and the overall emission levels.

2. Method

2.1. Balmorel

In this study, the partial equilibrium model Balmorel is used, which covers heat and power generation in Northern Europe (Norway, Sweden, Finland, Denmark, Estonia, Latvia, Lithuania, Poland, Germany, Netherlands, Belgium, France, and the UK). The model was originally created by Ravn et al. [33] and has been continuously updated since then [34]. The model has recently been used to estimate the effects of cross-border power transmission [35], social acceptance of generation technologies [29], EV charging flexibility [36], the displacement of fossil fuels by biomass in the power and heat sector [23], sector coupling [37], the impact of decentralised heating [10] within the Northern European power and heat market, the role of demand response [38] and the cost of reducing land-use conflicts [27]. The entire model code as well as the input data can be found at the Balmorel Community at GitHub Repository [39]. The model seeks to estimate the optimal combination of producing and delivering heat and electricity to different end-use sectors that overall minimises the costs given a set of techno-economic constraints. Fig. 1 shows a schematic flowchart of the model, with the main components.

In order to cover changes in the energy system, the next 30 years are presented as three representing years modelled in sequence, which may be interpreted as 2030, 2040 and 2050. For each year, 12 representative weeks with 72 timesteps have been modelled, giving a total of 864 timesteps for each year. For each timestep, the demand is fulfilled by estimating an optimal allocation between endogenous investment in new generation technology, exogenously defined generation capacity (Table 1), import or export of electricity to neighbouring regions or load or unload of energy storage that in total minimises the annual costs. During the time scope of this study, more stringent emission policies will be introduced in the European heat and power sector. A carbon price of 70 €/tonne is used in 2030 to cover the stricter regulations and 100 €/tonne in 2040, while we assume energy production will be fully renewable in the modelling area in 2050. Stricter emission policies and the techno-economic lifetime of the existing product units, mean that new investments will be needed. Endogenous investments made in 2030 and 2040 are assumed to be in the system in the following periods.

Stricter emission policies mean that regulated fossil fuels will be substituted with renewable options, which in many cases are variable. This leads to less production flexibility and may result in more use of demand-side flexibility, which in Balmorel is demand response in household and industrial sectors [38], smart charging schemes for electrical vehicles [36], endogenous power-to-heat production and energy storage. Table 2 shows the aggregate demand for electricity and heat in each of the modelled countries. The exogenously defined electricity demand is divided into electrical vehicles, residential demand, power-intensive industry and tertial demands. The demand is further disaggregated into 24 electricity regions (Fig. 2), which mainly follow the NordPool [42] regions and 52 heating regions that cover high-temperature heating in industrial processing and low-temperature district heating. Demand profiles vary according to the different user groups.

Due to the heterogeneous nature of bioenergy fuels, the land-use

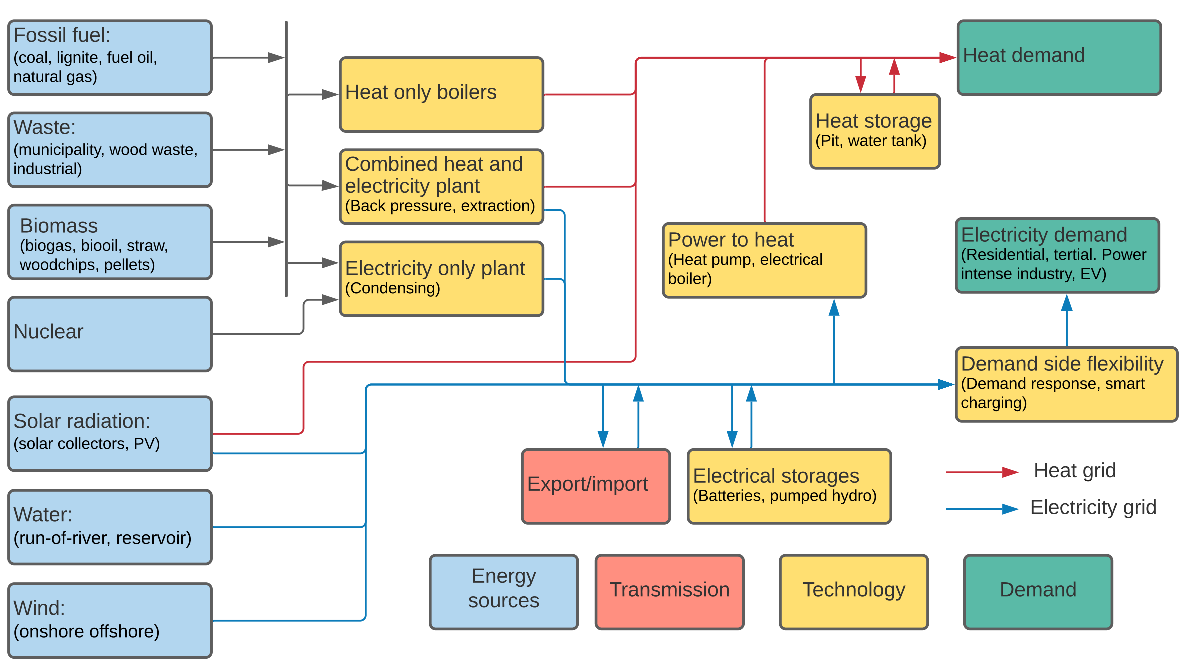

Fig. 1. Flowchart of the model with the main technologies and raw materials.

Table 1
Exogenous capacity for each modelling year [GW] and average land-use requirements for generation equipment [km^2/GW]. Nordic countries are Norway, Sweden, Finland, and Denmark, while ROW is the rest of the modelled counties (Estonia, Latvia, Lithuania, Poland, Germany, Netherlands, Belgium, France, and the UK). Sources: [27,31,40,41].

	Nordic countries			ROW			Land-use requirements
	2030	2040	2050	2030	2040	2050	
Electricity for heating	1	0	0	0	0	0	0.70
Forest biomass	9	7	5	22	17	17	0.37
Fossil fuel	16	7	0	185	72	0	0.03
Hydro	55	56	57	175	174	174	
Nuclear	12	8	3	67	59	21	1.0
Offshore wind	2	1	0	31	22	1	136
Onshore wind	19	10	0	82	33	0	200
Other biomass	3	2	1	13	8	7	0.60
PV	2	2	1	92	82	30	18
Waste and heat	55	31	19	4	3	3	2.0

Table 2
Exogenously defined energy demand in the modelled countries. Electricity demand includes electric vehicles, residential demand, power-intensive industry and tertial demands. Unit: TWh. Source: [44–46].

	Electricity demand			Heat demand		
	2030	2040	2050	2030	2040	2050
Belgium	90	98	107	7	7	7
Germany	586	640	694	143	143	143
Denmark	53	72	91	32	32	32
Estonia	8	9	9	5	5	4
Finland	94	101	108	59	58	54
France	497	560	623	33	33	33
Latvia	6	7	8	7	6	5
Lithuania	11	12	13	6	6	7
Netherlands	124	147	170	31	31	31
Norway	159	174	189	7	7	8
Poland	144	156	168	77	88	98
Sweden	161	179	197	114	112	99
UK	340	408	476	43	43	43

factor (Table 1) for the different technologies is estimated without raw material extraction. We further assume that forest biomass for energy production comes from residue from timber harvest or sawmilling, and hence, does not directly increase the harvest levels. Moreover, we exclude land-use requirements related to hydropower. While the land-use factor for the other technologies is estimated based on [27,31,40,41]. The land use from wind power is assumed as the disturbed area which is equivalent to the area with noise and on-ground visual impact (including roads and grid connection).

Electricity transmission is an important part of the current energy system in Northern Europe. In this study, we allow electricity transmission in line with existing and known expansion in transmission lines between neighbouring regions [43]. From 2040, we also allow endogenous investments in interconnectors restricted upwards to 1 GW between and from the Nordic countries, and 2.5 GW between regions outside the Nordic countries. The model is only allowed to invest in new transmission lines as expansions of existing or known lines.

The model includes energy production from all frequently used energy sources, including wind (onshore and offshore), solar (solar collectors and PV), hydropower (run-of-river, reservoir and pump), biomass (biogas, bio-oil, straw, woodchips and pellets), fossil fuels (coal, lignite, fuel oil and natural gas) and other fuels such as waste and nuclear power (Fig. 1). Fuel prices (Table 3) are based on IEA [47] and nuclear generation costs are from Entso-E [46], other generation costs are mainly collected from IEA [45] and Energistyrelsen [40]. For wood chips and pellets, a stepwise price is assumed for each country based on the calibration prices given in Table 3, where a 25% increase in biomass consumption results in 12.5% higher costs. We assume that the variable costs for electricity to heat producers are the endogenous electricity prices plus the grid rent and taxes shown in Table 4. The availability of

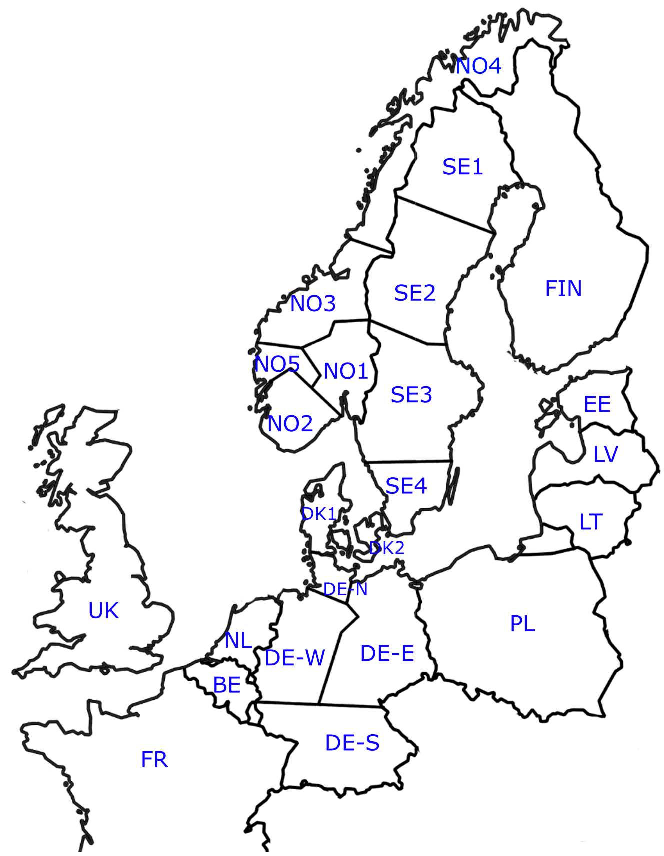

Fig. 2. Electricity regions in Balmorel, with several heat regions within each electricity region.

renewables is geographically restricted, based on techno-economic assumptions and social acceptance. We assume that new investments will be made in the most economically attractive locations available in the model. We further assume that all coal and lignite plants will be closed by 2040 and all other fossil fuel plants by 2050, even though they may have a remaining techno-economic lifetime.

2.2. Biomass scenarios

In order to calculate the substitution effects of forest biomass in the energy sector, we first have to find the optimal amount of forest biomass consumption. Thereafter, we rerun the model with exogenously defined levels of forest biomass. We test alternative biomass utilisation levels from 0 TWh to +50% compared to the optimal amount. In the base

Table 3
Fuel prices in the model, unit: €/GJ. Sources: [40,45–47].

	2030	2040	2050
Biogas	12.7	12.7	12.7
Coal	2.4		
Fuel oil	9.3	11.0	
Lignite	0.9		
Municipality waste	−3.3	−3.3	−3.3
Natural gas	6.9	8.1	
Nuclear	0.8	0.8	0.8
Peat	1.9	1.8	
Shale	2.0	2.0	
Straw	5.9	6.1	6.4
Surplus heat	0.1	0.1	0.1
Wood chips	6.2	6.4	6.7
Wood pellets	7.9	8.1	8.3
Industrial residual biomass	0.7	0.7	0.7

Table 4
Grid rent and taxes that apply to electricity to heat producers. Source: [48].

Country	Grid rent and taxes [€/MWh]
Belgium	61
Denmark	155
Germany	119
Estonia	40
France	42
Latvia	61
Lithuania	48
Netherlands	41
Poland	54
Finland	30
Sweden	34
Norway	21
UK	52

scenario, we only restrict forest biomass consumption within the Nordic countries, while the model can freely optimise the use of forest biomass outside the Nordic countries.

We also perform model runs where we exogenously define forest biomass use for the full Northern Europe region. This implies that a higher level of forest biomass is removed from the system, and the remaining level of forest biomass is used where it is most needed in the Northern Europe energy system. The main findings from this sensitivity analysis are the substitution factors given competition for the remaining biomass between the different Northern European countries.

2.3. Sensitivities

Sensitivity analyses are performed to test the robustness of some of the model assumptions. The following sensitivities use the same forest biomass level as in the base scenario as a basis for the calculations. The sensitivity analyses are shown in Table 5.

Table 5
Sensitivity description, only deviations from the base scenario are explained.

Scenario name	Brief description	Implementation in the model
Base	Base scenario	Carbon price: 2030: 70 €/tonne, 2040: 100 €/tonne, 2050: infinite. Natural gas price: 2030: 6.9 €/GJ, 2040: 8.1 €/GJ, 2050: infinite. Cap on onshore wind production in Norway: 2030: 22 TWh, 2040: 25 TWh, 2050: 35 TWh.
Fossilfuel_High	Less strict emission policy	Carbon price: 2030: 50 €/tonne, 2040: 80 €/tonne, 2050: 150 €/tonne. Natural gas price: 2030: 5.5 €/GJ, 2040: 6.5 €/GJ, 2050: 7.2 €/GJ.
Fossilfuel_Low	Stricter emission policy	Carbon price: 2030: 120 €/tonne, 2040: 150 €/tonne, 2050: infinite. Natural gas price: 2030: 8.3 €/GJ, 2040: 9.8 €/GJ, 2050: infinite.
Transmission_zero	No new investment in interconnectors	Prohibition of new interregional transmission lines, except known lines.
Transmission_inf	Optimal new investment in interconnectors	The endogenous optimal level of new transmission lines.
GridRent_High	Higher grid rent for power-to-heat producers	50% increase from the base (Table 4).
GridRent_low	Lower grid rent for power-to-heat producers	50% reduction from the base (Table 4).
HeatDemand_High	Higher heat demand	20% increase in heat demand from the base (Table 2).
HeatDemand_Low	Lower heat demand	20% decrease in heat demand from the base (Table 2).
Wind_High	High onshore wind production in Norway	Cap on onshore wind production in Norway: 35 TWh from 2030.
Wind_Low	High onshore wind production in Norway	Cap on onshore wind production in Norway: 20 TWh from 2030.
Nuclear_High	More nuclear capacity in the system	Nuclear capacity in Sweden 10 GW, Finland 10 GW, France 50 GW, and UK 17 GW for all modelled years.

3. Results and discussion

3.1. Base scenarios

According to the model results, Nordic power generation increases from 521 TWh in 2030 to 600 TWh in 2050 (Fig. 3), mainly as a result of assumed growth in electricity demand. While the Nordic countries have a net export surplus (22 TWh/year) in the base scenario in 2030, the results suggest that the region will have an import need of 21 TWh/year in 2050. Typically, the Nordic countries would import low-priced electricity during summer and export hydro and wind power during the winter months. Hydropower remains the largest source of electricity in the Nordic countries up to 2050, followed by wind, nuclear and solar PV. Hydropower accounts for 45% of the electricity production in 2030 and 38% in 2050. The decline is due to limited remaining potential for hydropower in the Nordic countries and increasing wind power generation. For thermal electricity production, forest biomass is the main raw material providing 22 TWh of electricity in 2030 and 21 TWh in 2050.

The modelled Nordic heat generation decreases slightly from 166 TWh in 2030 to 154 TWh in 2050, due to the expected reduced need for heat in households and more use of heat pumps. Fossil fuels account for 11% of the heat production in 2030, which drops to zero in 2050. The modelled use of forest biomass remains high but reduces from 135 TWh in 2030 and 131 TWh in 2040 to 126 TWh in 2050.

3.2. Nordic perspective

3.2.1. Fuels and technologies

Fig. 4 shows the modelled changes in heat and power production for the different energy sources when the use of forest biomass is modified. Fossil fuels are the main substitutes in 2030 and the average substitution factor is 0.22 TWh/TWh of forest bioenergy removed. Most of the consumed forest biomass is used for heat generation resulting in increased production from power-to-heat when the amount of forest biomass is reduced, with an average change of 0.45 TWh per reduced TWh of forest bioenergy. The increased power-to-heat usage results in increased electricity production, which gives wind power an average substitution factor of 0.14 TWh per reduced TWh. The substitution

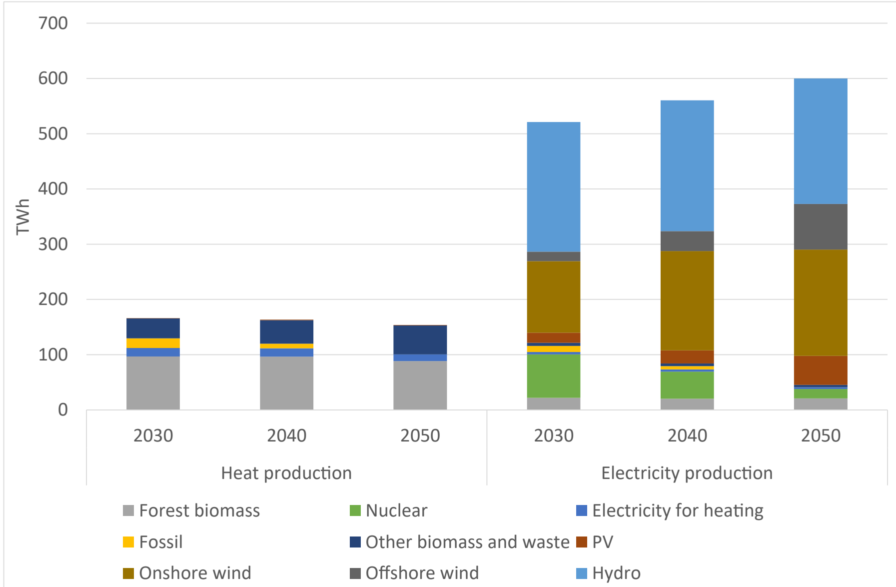

Fig. 3. Modelled heat and electricity production in the Nordic countries.

factors for wind power are highest for increased biomass usage with a peak marginal substitution factor of 0.21 TWh/TWh for a 40% increase in forest biomass, while the marginal importance is lower for a reduction in forest biomass demand (0.14 TWh/TWh). Fossil fuel has a relatively stable substitution effect of 0.21–0.31 TWh/TWh for a reduction in bioenergy production but is lower for an increase in biomass (0.05–0.22 TWh/TWh). This implies that a 50% reduction in forest bioenergy increases the consumption of fossil fuels by 51%. As expected, the results clearly show that higher volumes of fossil fuels are needed as well as emission-free technologies to substitute forest biomass. In addition to the changed generation mix within the Nordics, a significant part of changed forest biomass use is carried through to changed net electricity exports to neighbouring regions (0.06 TWh change in net import/TWh reduced forest bioenergy).

The substitution effects change substantially in 2050, if we assume a fully decarbonised Nordic heat and power production. In 2050, wind and solar power are the main substitutes for forest biomass. For 2050, the model results also show that less use of forest biomass entails a need for significantly more power-to-heat (P2H) as well as energy storage. The number of hours of electricity imports also increases.

3.2.2. *Fossil carbon emissions*

The model results indicate an increase in fossil carbon emissions of 0.02–0.06 million tonnes of CO_2/TWh forest biomass (Fig. 5). The substitution factors are lower for cases where we drive in more forest biomass than is economically optimal (0.01–0.05 million tonnes of CO_2/TWh). The fossil carbon emission impacts declined from 2030 to 2050 as expected and also depend on the amount of biomass removed. When more than 10% biomass is removed, the substitution factor is relatively constant at 0.05 million tonnes CO_2/TWh in 2030 and 0.03 million tonnes CO_2/TWh in 2040. As a result, fossil emissions increased from 7 million tonnes of CO_2 for optimal usage of forest biomass to 15 million tonnes of CO_2 in a system without forest biomass. For countries outside the Nordics, the emissions are insignificant with the use of forest biomass in the Nordic countries.

3.2.3. *Land use*

As mentioned above, land-use estimates assume that forest-based bioenergy does not have a land-use impact since forest biomass for energy is usually residue from timber harvest or sawmilling. In the model runs, wind and solar PV accounts for approximately 99% of the new land use, excluding raw material extraction and hydropower. The need for additional land use in the Nordic countries is a 2.7–18 km^2/TWh change in forest biomass, depending on the year and substitution level (Fig. 6).

The need for additional land for energy generation declines relatively linearly with the increased use of forest biomass for energy at an average rate of approximately 13 km^2/TWh bioenergy. As seen in Fig. 6, the graph to the right, substantial land areas is also saved in other Northern European countries when Nordic forest biomass demand increases.

3.2.4. *Impacts on electricity and heat prices*

Fig. 7 shows the price duration curves for the average Nordic heat and power prices in 2040. The average Nordic power prices increase from 32.3 €/MWh in 2040 with the optimal amount of forest biomass to 35.9 €/MWh with full substitution of forest biomass, while prices increase to 32.7 €/MWh for a 50% increase in biomass demand. As expected, biomass reduces prices more during periods of high prices.

The price effects of reduced forest biomass use are more significant in the heat market since forest biomass has a larger market share in heating than in the power system. According to the model results, the median price for heat increases by approximately 13 €/MWh for full substitution of forest biomass, while the prices are reduced by 0.4 €/MWh for a 50% increase in biomass use (Fig. 7).

3.3. *Northern Europe perspective*

When we extend the scope to include altered forest biomass use in all model countries, the optimal forest biomass use is 285 TWh in 2030, 301 TWh in 2040 and 399 TWh in 2050, according to the model results.

In these model runs, the modelled fossil carbon emission impacts in the Nordic countries are 0–0.03 million tonnes of CO_2/TWh reduced biomass (Fig. 8), which is around half the value observed when only substituting forest biomass in the Nordic countries (Fig. 5). This implies that the model finds it more cost-efficient to reduce bioenergy production outside the Nordic countries first, resulting in a lower emission factor within the Nordic countries. However, when calculating the global emission impacts by all model countries, the model results indicate that forest biomass may replace approximately 0.10 million tonnes of CO_2/TWh biomass.

When altering forest biomass use in all countries, the land-use impact is estimated to be 7.4–20 km^2/TWh for the entire model in 2030 and

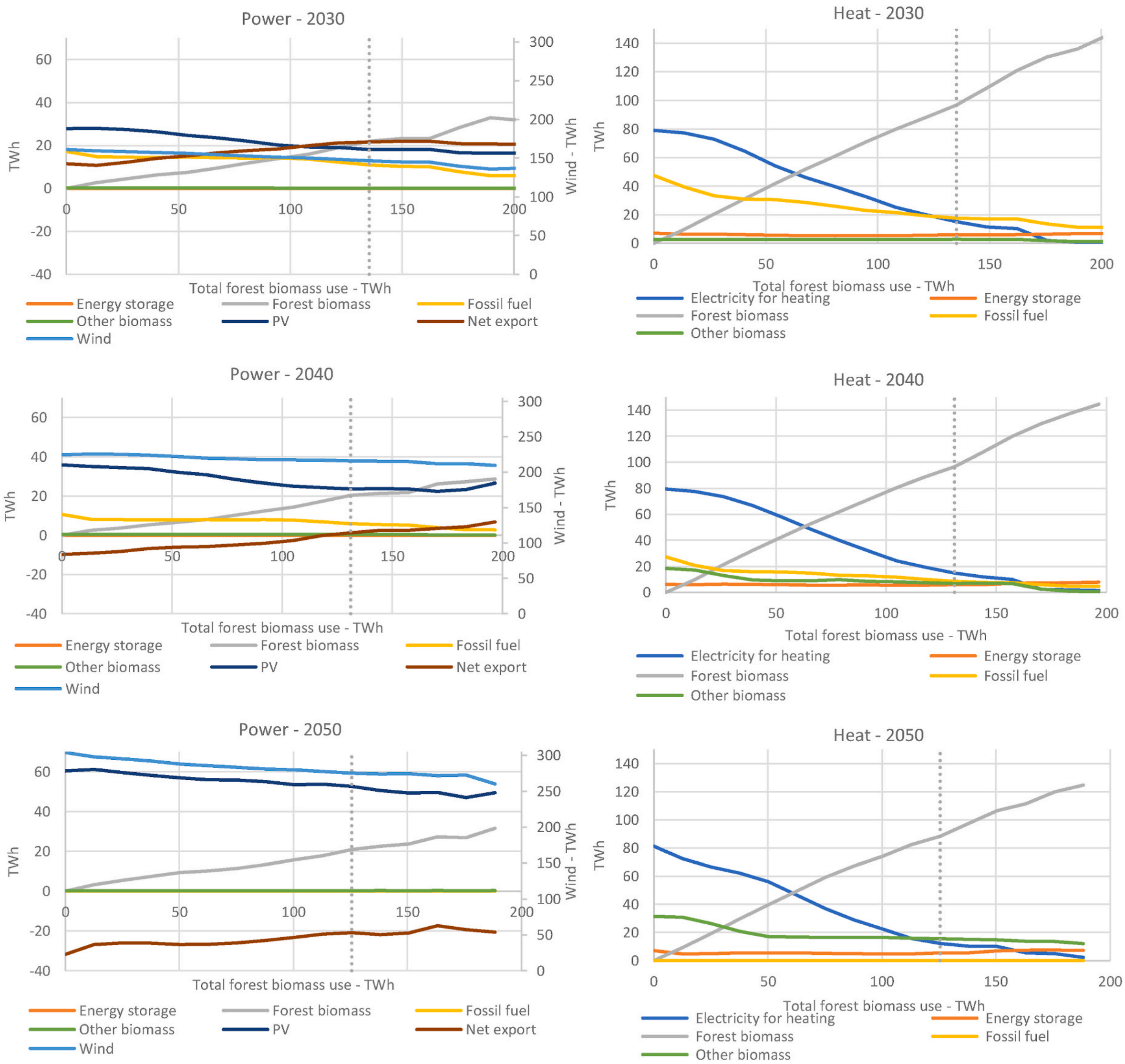

Fig. 4. Modelled change in power (left) and heat (right) production for the different fuel categories in the Nordic countries for different forest biomass levels (input). The economically optimal amount of forest biomass is shown as a dotted vertical line. Shown for the different modelled years. The use of hydropower, nuclear power and waste is not shown since they are used at an exogenous capacity limit for all forest biomass levels.

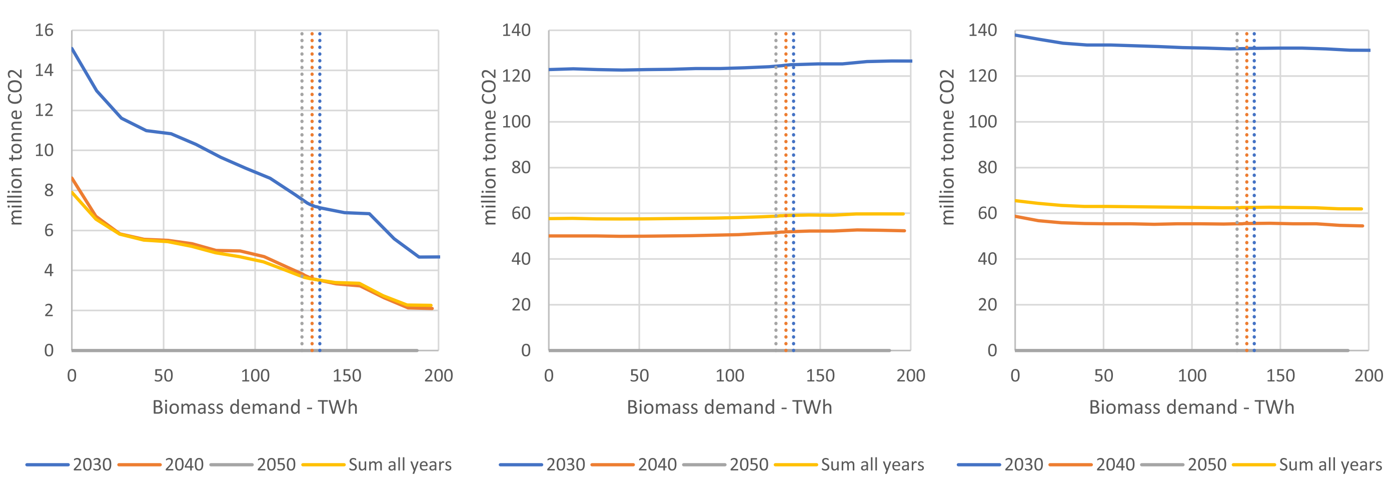

Fig. 5. Modelled fossil carbon emission effects of different forest biomass levels in the Nordic countries (left) for the other modelled countries (central), and for all modelled countries (right). The economically optimal amount of forest biomass is shown as a dotted vertical line.

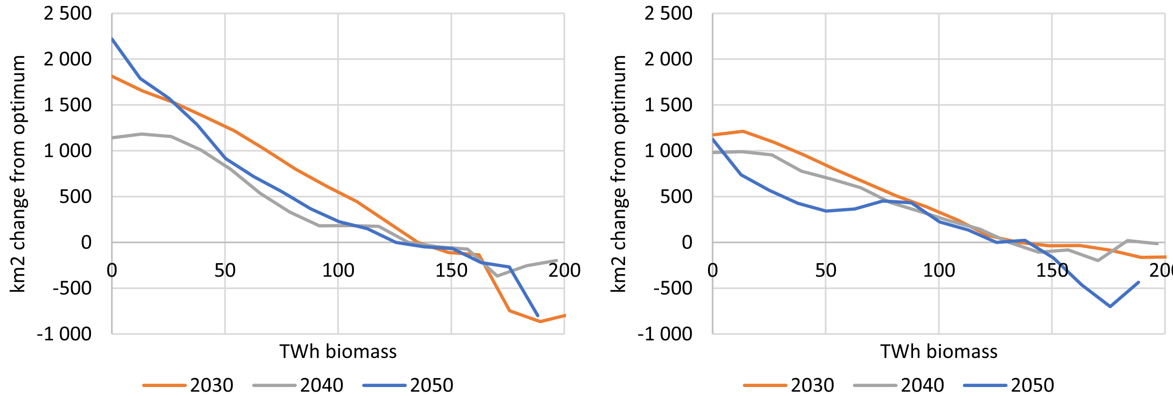

Fig. 6. Estimated accumulated land-use change from the optimal biomass level both in the Nordic countries (left) and the rest of the modelled countries (right).

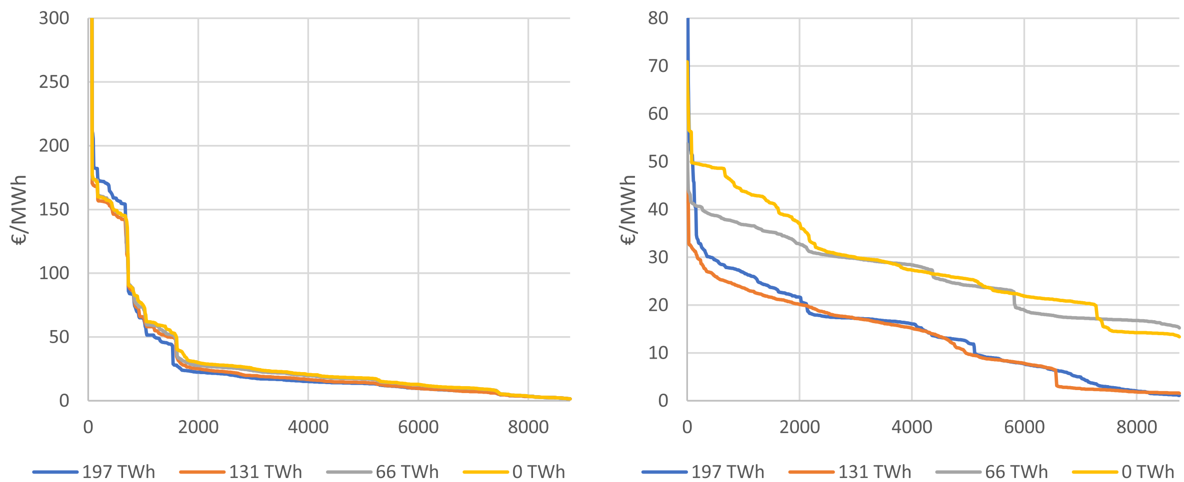

Fig. 7. Modelled price duration curves for the average Nordic prices with the optimal amount of forest biomass (131 TWh), without forest biomass (0 TWh) and 50% increase (197 TWh) and reduction (66 TWh). Electricity prices (left) end heat prices (right). The y-axis for electricity prices is cut at 300 €/MWh, for electricity for 2040, 7 h are above 300 €/MWh. Note the different y-axes.

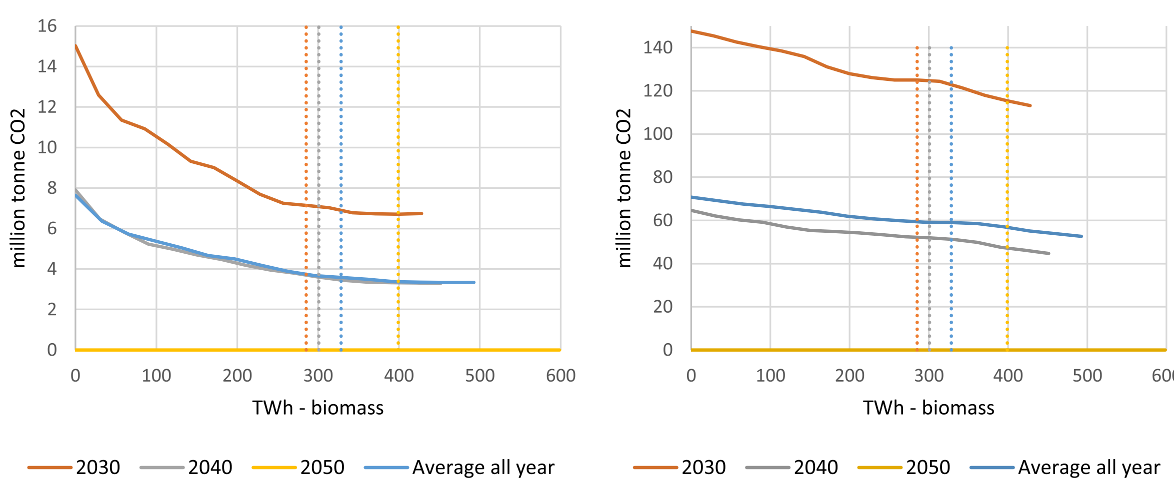

Fig. 8. Carbon emission impacts in the Nordic countries (left) and the rest of the model (right) when forest biomass is reduced in all countries. The optimal amount of forest biomass is shown as a dotted vertical line.

18–47 km^2/TWh in 2050, indicating that reduced biomass use may have larger impacts on land use for energy infrastructure on the continent than in the Nordic countries (Fig. 9).

3.4. Sensitivities

3.4.1. Carbon emission impacts

The sensitivity analyses performed show carbon emission impacts in

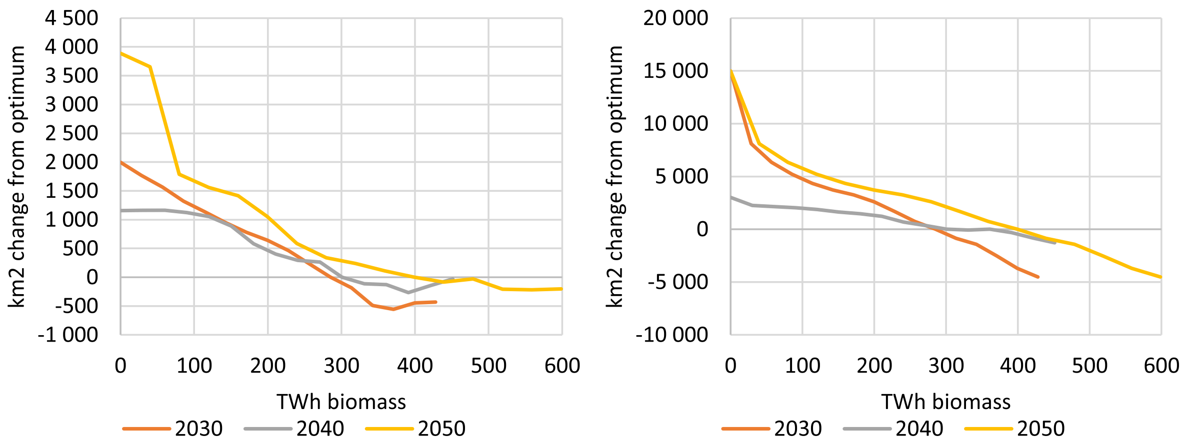

Fig. 9. Estimated accumulated substitution effects of land use both in the Nordic countries (left) and the rest of the modelled countries (right).

the same range as in the base scenario (Table 6), but the emission impacts increase to 0.03–0.07 million tonnes of CO_2/TWh reduced biomass when lower fossil fuel costs are assumed. In many cases, increased nuclear capacity leads to negative emission impacts of increased biomass use. The reason for this is that higher nuclear capacity reduces the need for fossil fuels, showing a more constant net export of electricity from the Nordic countries compared with the base (Fig. 4). In 2040, the carbon emission impacts are lower, but the difference between the sensitivities is virtually identical to 2030.

As shown in Table 6, the global carbon emission impacts are relatively unaffected by the sensitivities indicating that the carbon leakage plus the local effects are relatively equally balanced across the sensitivities. Large effects are identified if the scope is limited to the Nordic countries (Fig. 10). For example, increasing the grid rent for power-to-heat producers by 50% increases the carbon emission impacts to 0.02–0.08 million tonnes of CO_2/TWh. Correspondingly, a lower grid rent gives a lower substitution factor of 0.0–0.05 million tonnes of CO_2/TWh. The reason for this is that a higher cost for power-to-heat production results in more use of natural gas when reducing biomass consumption, while a lower cost for power-to-heat results in less use of natural gas and more use of wind power instead. Reduced heat demand also reduces carbon emissions, since less fossil fuel is needed in the system, and a higher heat demand simultaneously results in a higher substitution factor, implying that more costly areas for wind power have to be developed to cover increased heat demand.

3.4.2. Land use

The average land-use impact in the base scenario is a -3.2–14 km^2/TWh increase in forest biomass use in the Nordic countries (Fig. 6). Most of the sensitivity scenarios have lower or similar land-use impacts (Fig. 11). The land-use factor is generally lower for increased biomass demand than for reduced demand, due to the low amount of electricity for heating in the base scenario, and the even lower amount for higher biomass use. The highest land-use effects are found for the scenario without endogenous investment in transmission lines where the land-use substitution factor is up to 33 km^2/TWh. Restricting interconnector capacities to those currently planned reduces the Nordic countries' possibility to import electricity for balancing purposes and increases the need for domestic backup power. This is particularly important in 2050 when no fossil fuels are left in the system. On the other hand, we find the lowest land-use impacts across all scenarios (0.6–8 km^2/TWh) when investments in new interconnectors are unrestricted. This shows that more transmission lines may reduce the land use impact of phasing out forest biomass, since other parts of North Europe may help balance the system in periods where biomass is most needed. However, the land use impact from grid infrastructure is not included in this study, resulting that the land use impact of transmission line investment is still unknown.

Table 6
Global carbon emission impacts in the full model for all sensitivities. Unit: million tonnes of CO_2/TWh reduced forest biomass.

	2030			2040		
	min	average	max	min	average	max
Fossilfuel_High	0.03	0.05	0.07	0.02	0.04	0.07
Fossilfuel_Low	−0.01	0.01	0.03	−0.01	0.00	0.01
GridRent_High	0.00	0.02	0.06	0.00	0.01	0.03
GridRent_low	−0.02	0.01	0.03	−0.02	0.00	0.03
HeatDemand_High	0.01	0.03	0.08	−0.01	0.01	0.05
HeatDemand_Low	−0.01	0.01	0.04	−0.02	0.00	0.02
Nuclear_High	−0.04	0.00	0.03	−0.03	−0.01	0.02
Transmission_inf	−0.02	0.01	0.04	0.00	0.01	0.03
Transmission_zero	−0.02	0.01	0.04	−0.01	0.01	0.03
Wind_High	−0.01	0.01	0.04	−0.01	0.00	0.02
Wind_Low	−0.01	0.01	0.04	−0.01	0.00	0.03
Base	−0.02	0.01	0.04	−0.01	0.00	0.02

3.5. Discussion and limitations

The primary geographical coverage area in this paper is the Nordic countries, but the results may be interesting for other regions as well. The reduction in biomass demand is likely to be substituted in the short term by fossil fuels and, in the longer term, by variable renewables, which is relevant for many other regions. A prerequisite for transferring the results is that the regions need a large biobased heating sector, which is the case for most countries in the mid and higher latitudes.

The study was built on an assumption that the fossil emission for electricity and heat production reach zero in 2050. But how realistic this approach is still open for discussion. Recently policy papers in the EU, such as REPowerEU [49], may speed up the transition to a renewable energy system quicker than what was assumed in this study. If the transmission goes faster than what we expect will the fossil substitution factor goes to zero faster implying that the land use substitution will be more important than the fossil substitution in a shorter timeframe. As a result, the land use conflicts of not using forest biomass for energy production may be harsher earlier than what this paper show. On the other hand, the land-use conflicts and the consequences of more volatile electricity prices may do the EU not reach zero emissions by 2050. In this case, it still will be some fossil substitution factors also in 2050.

As is the case for all modelling studies, this study also has some limitations and simplifications that may affect the outcomes. First, since the model uses a partial approach, the model will not be able to cover alternative use of forest biomass, which limits the possibility of finding the overall best biomass usage. This is especially relevant for higher

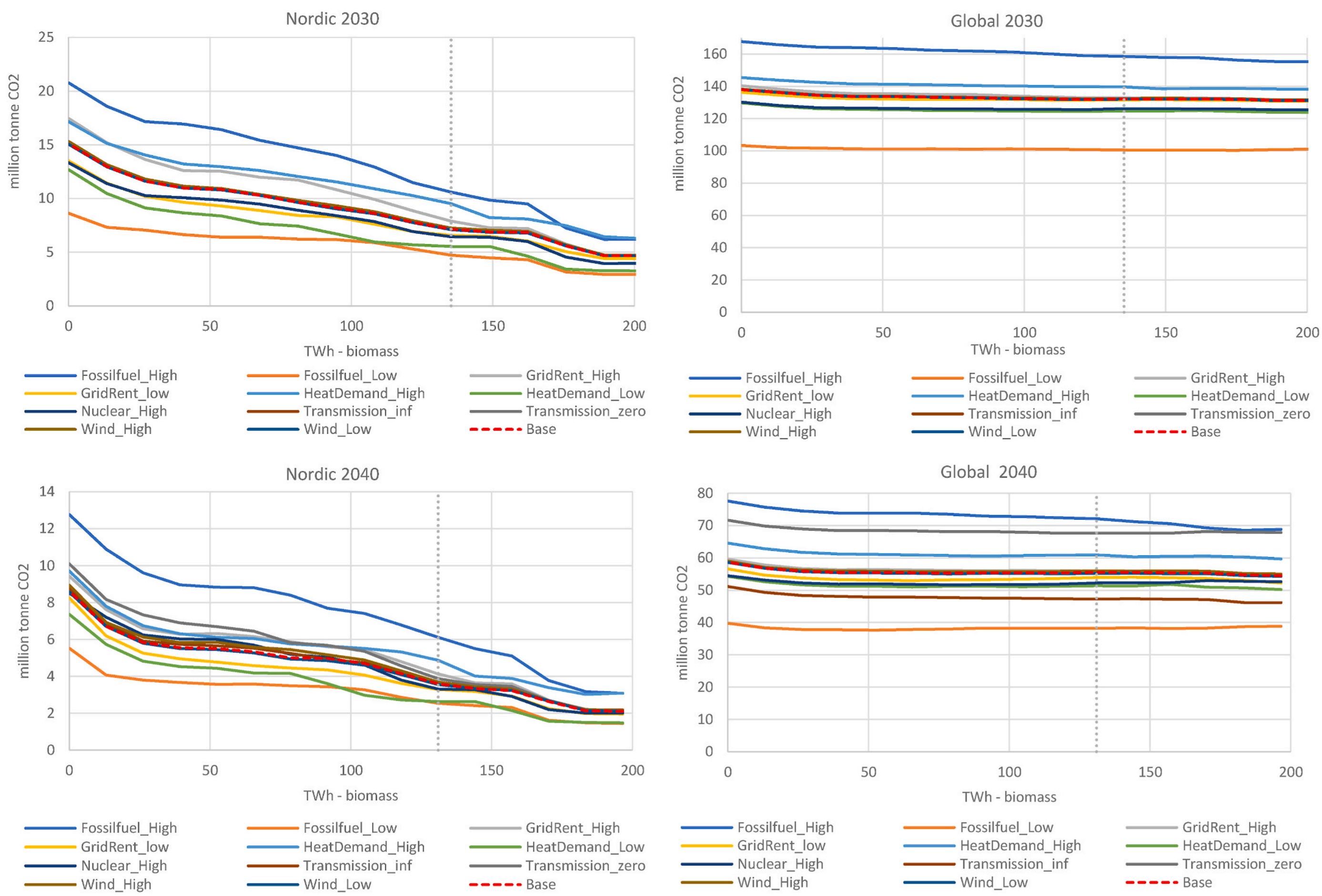

Fig. 10. Modelled carbon emission impacts in the Nordic countries (left) and all modelled countries (right), for all sensitivities. The optimal amount of forest biomass is shown as a dotted vertical line.

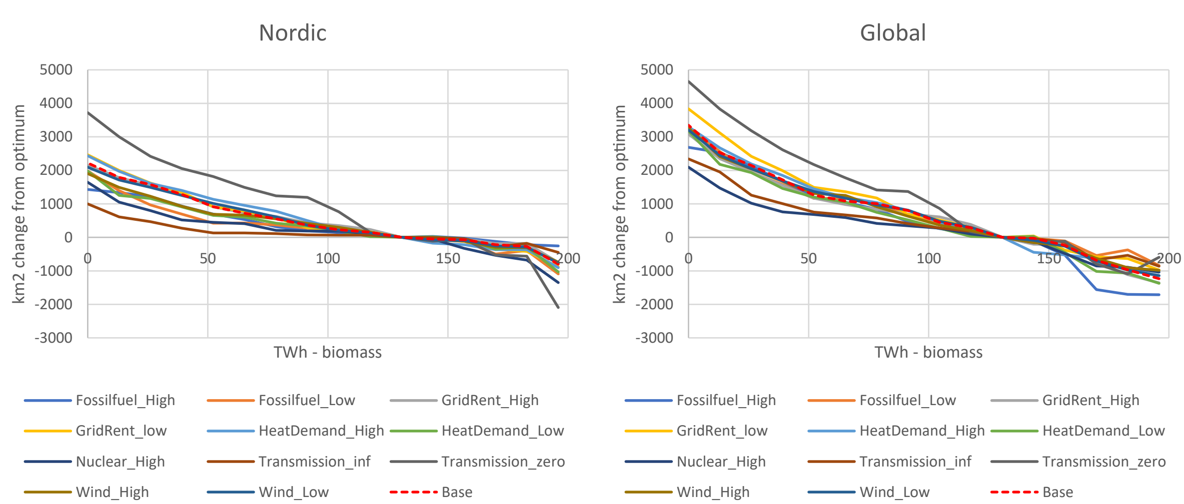

Fig. 11. Estimated accumulated change from the optimal land use both in the Nordic countries (left) and all modelled countries (right).

carbon prices, which are likely to increase the use of forest biomass within other sectors, which may reduce the availability of biomass for energy production. However, the main raw material for bioenergy normally comes from waste and low-quality biomass, which is likely to have lower competition from other forest industries. In the calculation of emission factors, we do not include biogenic carbon emissions since we assume it is recaptured in the forest within a rotation cycle. However, the short-term effect of increased biogenic carbon emissions is an overall increase in carbon concentration, due to the long rotation times for forest biomass. We avoid this problem by only focusing on fossil fuel emissions. This brings us to the next simplification, which is that we do not include CCS in this study. Implementation of CCS has two indirect effects on bioenergy, first, it may increase the use of fossil fuels and thereby reducing the need for biomass to balance the system, and second, it may, if used for BECCS, increase the profitability of biomass production since it will give truly negative emissions. The land-use impact is further simplistic as it is calculated from average land-use factors, which may not be accurate for specific projects. If other land-use factors had been included, the land-use substitution factor might have increased or decreased linearly compared to the findings in this study. Particularly important parameters to include in further studies may be raw material extraction and the footprint of grid investments.

This study focuses on the effect on energy systems for different levels of forest biomass demand. As shown, fossil emissions and land use will increase if bioenergy use is reduced. Whether it is beneficial to remove bioenergy from energy production in a greater perspective is still uncertain. To determine the overall effects, alternative uses of forest products must be studied. This is, however, outside the scope of this study. The biggest reductions in carbon emissions are likely to be achieved if the biomass is used for other long-lived products such as building materials and reused instead of being used for energy production. Köhl et al. [13] estimate that the displacement factor may be in the range of 1.5–7.5 tC/tC, showing a significant carbon reduction if biomass is used for building materials. Another important aspect is whether the biomass is left in the forests and therefore used as carbon storage. However, most of the biomasses used for energy production are not primary forest products since the high-quality products are usually used for products other than energy. In future studies, it may be beneficial to include the biogenic emissions. In such analyses, it is, however, important to assess the alternative uses of the particular biomass being used for energy. The total biogenic emission to the atmosphere might increase or decrease depending on the type of biomass, the alternative use and not least the time horizon considered.

4. Conclusion

This study quantifies the cost-optimal use of biomass in the North European energy system and thereafter quantifies the effects on the generation mix, fossil fuel emissions and land use for different pre-determined levels of forest-based bioenergy generation. The results suggest that forest biomass will remain an important fuel in heat generation in the Nordic countries up to 2050. The study shows that excluding forest biomass from the energy sector will increase costs, emissions and land use for electricity generation infrastructure in the modelled countries. According to the results, the impacts of reduced forest biomass use change during the period 2030–2050. In 2030, a reduction of 1 TWh of bioenergy results in increased production from 0.25 TWh of fossil fuel, 0.14 TWh of wind power and 0.53 TWh of delivered heat from power-to-heat producers. For 2050, assuming no use of fossil fuels, 1 TWh of forest bioenergy is replaced by 0.23 TWh of wind power, 0.62 TWh of power-to-heat, 0.10 TWh of increased import and 0.10 TWh of PV.

The impacts on fossil emissions are modelled to be in the range of 0.02–0.06 million tonnes of CO_2 per TWh reduced forest biomass in 2030. Reduced use of fossil fuels results in increasing land use for wind and solar power generation. In 2050, the land-use effect of reduced forest biomass use is estimated to be in the range of 2.7–18 km^2/TWh forest biomass. Here, we assume no additional land use from using forest residues for energy. A similar number for the entire model is in the range of 2.1–27 km^2/TWh, showing that bioenergy in the Nordic countries has a substantial effect on the entire Northern European power and heat market.

Forest biomass use affects power prices only marginally, with an average price effect of 0–0.05 €/MWh/TWh forest biomass. The impact on heat prices is greater and estimated to be 0.01–0.15 €/MWh/TWh of forest biomass.

Credit author statement

Eirik Ogner Jåstad: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.; **Torjus Folsland Bolkesjø**: Conceptualization; Funding acquisition; Supervision; Validation; Visualization; Writing - review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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