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

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ABSTRACT

The forest and energy sectors are heavily affected by the urgent need for global climate gas emission reductions. To fully understand the implications of a transition to a low carbon society, it is important to analyse the interactions between these sectors. We herein present a coupled/integrated modelling approach that integrates a Nordic Forest Sector Model (NFSM) and a North European energy sector model (Balmorel). Both models include endogenous investment in new production capacity and market prices obtained by market equilibrium in competitive markets. The new integrated model is used to investigate forest and energy sector impacts of a low carbon scenario in the Nordic countries. The results from the integrated model approach show a steady increase in use of forest resources for heat and power generation from 47 TWh in 2020 to 117 TWh in 2050, and a corresponding increase in biomass prices. Comparing these results with results from the two individual models suggests that the integration procedure provides more realistic biomass price and volume projections compared with standalone models.

1. Introduction

About 33% of the primary energy use in the Nordic countries comes from renewable sources [83]. The Paris Agreement may result in increased utilization of wind and solar power, but it will be difficult to complete the transition away from fossil fuel without extensive use of biomass in the heating, industrial, and transportation sectors. Since biomass has many alternative uses, the supply of biomass for energy is price sensitive. Although this sensitivity is generally accepted [7], few previous energy system analyses have addressed this topic. One exception is Oliver and Khanna [58], who used a model covering electricity from agricultural bioenergy with endogenous raw material prices. They found that biomass could provide 20% of the electricity needed in the US within 2030. Models covering biomass markets, like forest sector models, on the other hand, simplify the energy market in their partial approach. For example, Latta et al. [39] use a forest sector model and point out the dynamic relationship that exists between the forest and electricity production from biomass, but they do not have endogenously determined input of biomass in electricity production. Another method used to cover the relationship between energy and forest sector is to include different supply curves for biomass, as do Hoogwijk et al. [25], who estimate production costs of electricity based on different supply curves for biomass. They found that the production costs may vary between 40 and 100 USD_{2000}/MWh. A drawback of this study is that it does not include realistic market prices for electricity. Nguyen and Gustavsson [53] study co-generation of district heat, electricity, and biofuel production for varying heat demand. They found that the cost-optimum generation mix for each energy type varies according to district heat demand with co-generation being most profitable with high district heat production.

Integration of specialized models may be a way to improve modelling of biomass prices and volumes. Model integration is common in some field such as environmental studies [3]. Belete et al. [3] present a review of existing literature on model integration and present a roadmap for the integration process. Different models are integrated when an author believes it will increase our knowledge of the system under investigation. Energy system models have previously been integrated with macroeconomic models [46], general equilibrium models and climate models [37], Life cycle analysis (LCA) models [36], and health impact model [35], which all has increased our understanding of the relationship between different sectors. Historically, these integrated models have mainly been used to study different detailed demands or

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Table 1
Input data for biofuel production for the different allowed raw materials. Source: [8,9,63].

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

greenhouse gases (GHG) emissions effects. Welfle et al. [85] reviewed recent studies of bioenergy modelling and found that it is relatively common to use energy sector models or raw materials models to predict the role of bioenergy, but that it is more rare to combine different models within the field of bioenergy. Welfle et al. [85] conclude that the use of multiple models may lead to robust results, and that few studies have combined bioenergy with forestry and the forest industry. Forest sector models (i.e. forestry and forest industry) usually estimate raw materials used for heat production [5,80], and newer models usually also include material supply for forest-based biofuels [32,48,82], although bioheat demand is usually determined exogenously or follows a predefined price path.

Forest sector models have previously been linked to forest management models [26], as well as to bioheat models. For example, Karlsson and Wolf [34] integrated an hourly bioheat demand model into a traditional forest sector model. They studied the integration of a chemical pulp mills, sawmills, biofuel plants, and district heating systems and concluded that an integrated model gives better representation of the sector than a standalone system does. Mustapha et al. [51] present a hard-linking approach that combines an energy sector model and a forest sector model. They found that a 40% biofuel share in the Nordic countries resulted in a 50% reduction in heat and power produced from forest biomass, concluding that energy models that use constant exogenously determined biomass prices may overestimate the use of biomass in the future energy system. One drawback of the procedure applied by Mustapha et al. [51] is that the two models were optimized independently of each other and only two parameters were coupled.

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

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

2. Data and methods

2.1. NFSM

The Nordic Forest Sector Model (NFSM) is a partial equilibrium model covering forestry, forest industry, and forest-based bioenergy in the Nordic countries (Norway, Sweden, Finland, Denmark, and trade with third countries). Similar models have been used since Kallio et al. [33] introduced the Global Trade Model (GTM) in 1987. NFSM originates from the Norwegian Trade Model (NTM) (see Trømborg and Solberg [79], Bolkesjø et al. [4], and Trømborg and Sjølie [81], which itself was based on GTM. NFSM is previous developed and used in several studies [30,49,50]. In this chapter we present a brief description of NFSM. For a more complete description of the model see Jåstad et al. [31].

The aim of NFSM is to maximize consumer plus producer surplus (i.e. welfare) for each time step; the model is usually optimized each subsequent year in a recursive manner. NFSM provides market equilibrium prices and quantities for each region and time step and estimates roundwood supply, industrial production, consumption of end products, and trade between regions. The model includes growth and stock changes in forestry; using the previous period change in roundwood stock, the model calculates the shift in the timber supply curve for the following year. In total, the model includes seven different forest products: sawlogs and pulpwood from spruce, pine, and non-coniferous trees and harvest residues. A constraint ensures that the ratio of harvested sawlogs and pulpwood in a region follows historical and theoretical distributions, and that the amount of harvest residues does not exceed a theoretical limit for each region. The model has a total of 15 final products, including three types of sawnwood, cross laminated timber (CLT), three board grades, four paper grades, charcoal, biofuel, local produced heat, and district heat. CLT can be produced from spruce, pine, and non-coniferous sawnwood. The distribution of the three different types of sawnwood used as raw material for CLT can vary

Table 2
Base capacity for the biofuel plant, and base cost data, as well as the scale factors and learning rate. Source: [29,63].

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

Table 3
Base year harvest, industrial production, and unit electricity production in the Nordic countries in the reference year. Source: [6,12–16,18–20,38,41–45,48,54,56,57,60,64–66,70,71,78] and own estimate.

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

between years and regions, but at least half of the regional production must be from spruce sawnwood. We assume that 1.42 m^3 solid of sawnwood is needed to produce 1 m^3 solid of CLT, i.e. 30% is lost under manufacturing due to adjustment and cuttings of windows and doors. Paper can be produced from four grades of pulp: mechanical pulp, chemo-thermomechanical pulp, chemical pulp, and sulphite and dissolving pulp. Charcoal can be produced from all forest products (raw materials and by-products) in the model with an efficiency of 56% [84], but due to raw material costs, it would most likely be produced from sawdust, bark, and harvest residues. Charcoal producers may use different raw materials in different years without making new investments.

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

NFSM models both endogenous investments and decommissioning based on the demand for intermediate and final products. The model finds the optimal yearly production level to be between 0% and 120% of the reference production for pulp and paper and 0% to 140% for sawnwood technologies without investing in new production units. If it is economically sensible to increase production, an investment decision will be taken. The investment is assumed to be fully constructed the first year and producing 100% of the new production capacity already that year. If the model uses less than 70% of the installed capacity, we assume than that half of the unused capacity is decommissioned. The present model uses 2018 as the reference year and the reference data is shown in Table 3. The data were collected mainly from the same sources as in the previous updates described in Mustapha [48].

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

	Electricity	Heat
Denmark	32	33
Finland	60	79
Germany	394	116
Netherland	110	19
Norway	117	13
Sweden	109	90
UK	311	18
Estonia	6	5
Latvia	5	6
Lithuania	8	8
Poland	105	66
Belgium	83	7
France	448	25

NFSM is written in GAMS as a linear mixed-integer programming model (MIP); the Appendix A shown the original functional shapes, which are nonlinear for consumption, harvest, and biofuel production. The nonlinear part of the model is implemented as a stepwise linearization, reasons of readability we only show the non-linear version of the model; for a detailed description of the linearized model see Jåstad et al. [31].

Table 5
Exogenously installed capacities in Balmorel for all countries, unit GW.

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

2.2. Balmorel

Balmorel is a partial equilibrium model covering the Northern European heat and power markets. The first version of Balmorel was described in 2001 by Ravn et al. [61]; since then, the model has been developed continuously [86]. The core model is available from the Balmorel community at Github Repository [22], where the background data is also available. The model is open access and published under an ISC license [59]. In this chapter, we briefly describe the Balmorel core model and the part of the model that is interesting for the integration procedure; for a more complete description of the model see Ravn et al. [61] and Wiese et al. [86].

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

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

The model covers district heat and electricity generation and

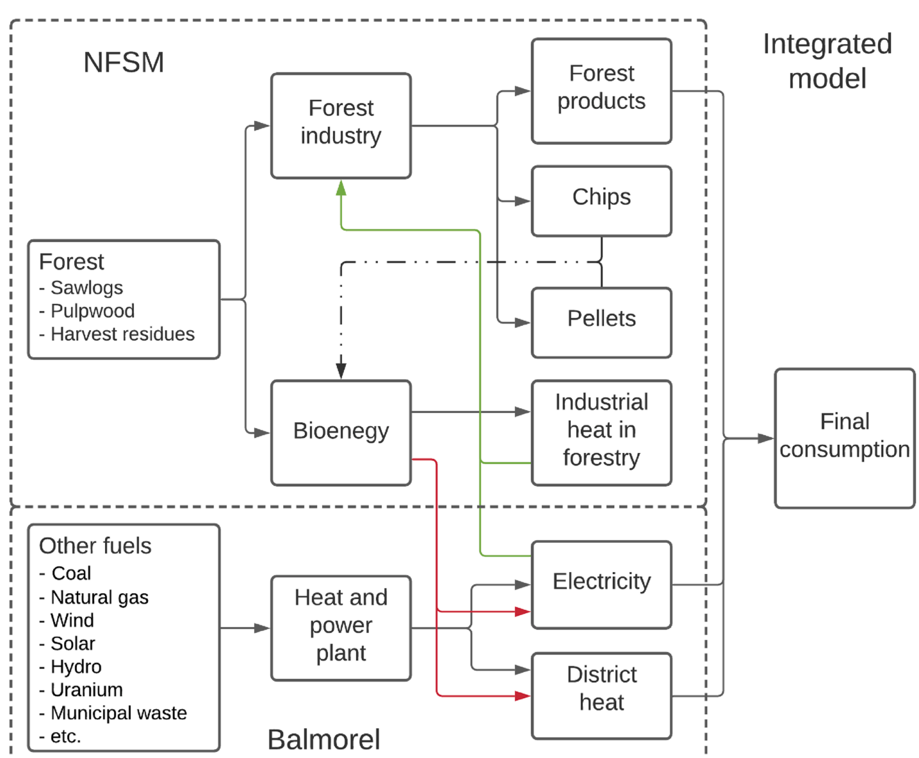

Fig. 1. Schematic representation of the integration procedure. Upper box shows the NFSM model and lower box shows the Balmorel model. The green line represents the electricity consumption in the forest industry, while the red line represents the heat and power produced from forest resources.

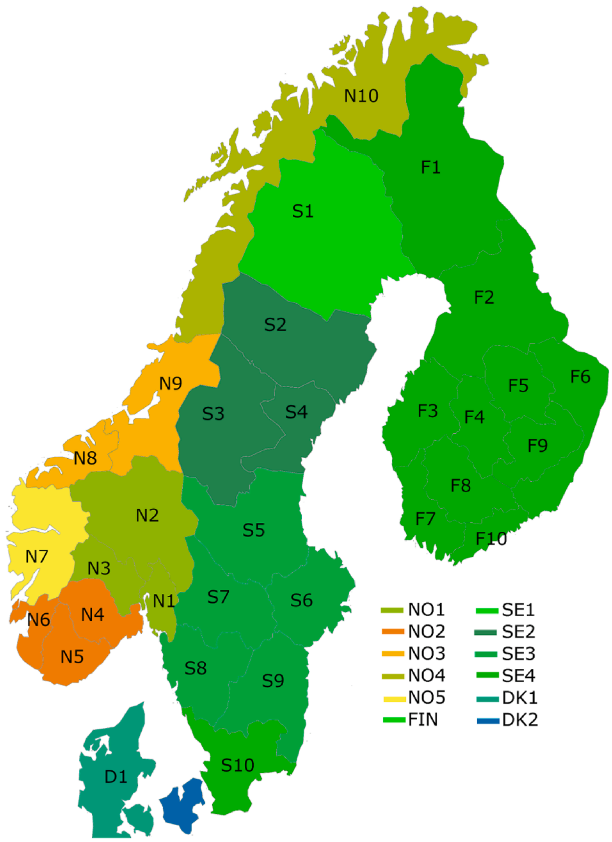

Fig. 2. Regions in NFSM (N1, N2, S1, S2, etc.) and Balmorel (same colour is within the same region) and where they are connected. The NFSM region 'rest of world' and Balmorel regions outside the Nordic countries are not shown.

consumption in Northern Europe (Belgium, Germany, Denmark, Estonia, Finland, France, Lithuania, Latvia, Netherlands, Norway, Poland, Sweden, and United Kingdom). Table 4 shows the electricity and heat consumption, except for the electricity consumption in the forest sector. Each country consists of one or more regions (Fig. 2); the model allows for transmission of electricity between regions, which mainly follow the NordPool regions [55]. We assume only exogenous investment in transmission capacities based on known investment plans. The model does not allow heat to be transmitted to neighbouring regions; thus, all heat produced must be consumed within the region where it is produced.

The temporal resolution in Balmorel is flexible and easy to adjust; the user can choose to model 1–8760 periods (hours) each year. It is possible to model each subsequent year, but since the computable cost of the model is relatively high, users often choose to only optimize every five or ten years. In this study we assume perfect foresight within the current year but no knowledge about the coming years. The data assumption in the Balmorel model is mainly from the [28], and data related to renewable production is mainly based on weather profiles from 2012. The most important factor for the transition to lower carbon emissions in the model is the use of a carbon price. In this study we assume an increase in carbon price from 23 €/tonne CO_2 in 2020 to 37 €/tonne CO_2 in 2030, 63 €/tonne CO_2 in 2040, and 82 €/tonne CO_2 in 2050 this follows Chen et al. [10]; in addition, we prohibit fossil energy production from 2040 in the Nordic countries (Norway, Sweden, Finland, and Denmark).

2.3. *Integration procedure*

Both Balmorel and NFSM are written in the General Algebraic Modelling System (GAMS) [21], and both are solved using the CPLEX solver [27]. Since both models have the same modelling environment, it is not necessary to perform new typing of the core models and all new coding is only related to connecting the two models. The modelling structure in Balmorel allows for easy extension of the code without changing the core model. This functionality is called add-ons and is described in Wiese et al. [86]. Since the Balmorel model is still undergoing rapid development, we find it most appropriate to integrate the models through the add-on framework; only minor changes are necessary in the core model of Balmorel. When doing the integration through the add-on structure, we are ensuring that both models can easily be extended independently while keeping the possibility of solving them together without further adjustment. In this chapter, we focus on the linking procedure between the two models, and the procedure used when optimizing the models. The two main connections between the forest sector and the energy sector are the forest sector's consumption of electricity and the given electricity price, and the use of forest biomass as raw material for energy production affecting the biomass balance in the forest sector.

Fig. 1 shown a schematic representation of the integration procedure, the main interaction is that forest resources is used for producing heat and electricity that is used in the energy balance (red line). And the electricity consumption in the forest industry is produced at the same levels as electricity for end consumption. If the forest industry starts to consume more electricity will the overall consumption of electricity increase, which will increase the total production of electricity. Some of this electricity may come from a bioenergy plant, which will increase the use of chips or pellets, and the plant may produce heat that reduce the need for producing district heat from other fuels.

2.3.1. *Time resolution*

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

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

2.3.2. *Geographical resolution*

Balmorel has 24 regions that follow the NordPool regions in the Nordic countries, i.e. five regions in Norway, four in Sweden, two in Denmark and one in Finland. For the countries outside the Nordic countries, Balmorel has one region each for Lithuania, Latvia, Estonia, Poland, United Kingdom, Netherland, Belgium, and France and four regions for Germany. NFSM has 31 regions that cover all of the Nordic countries (Fig. 2) and one region that covers rest of the world (ROW). In

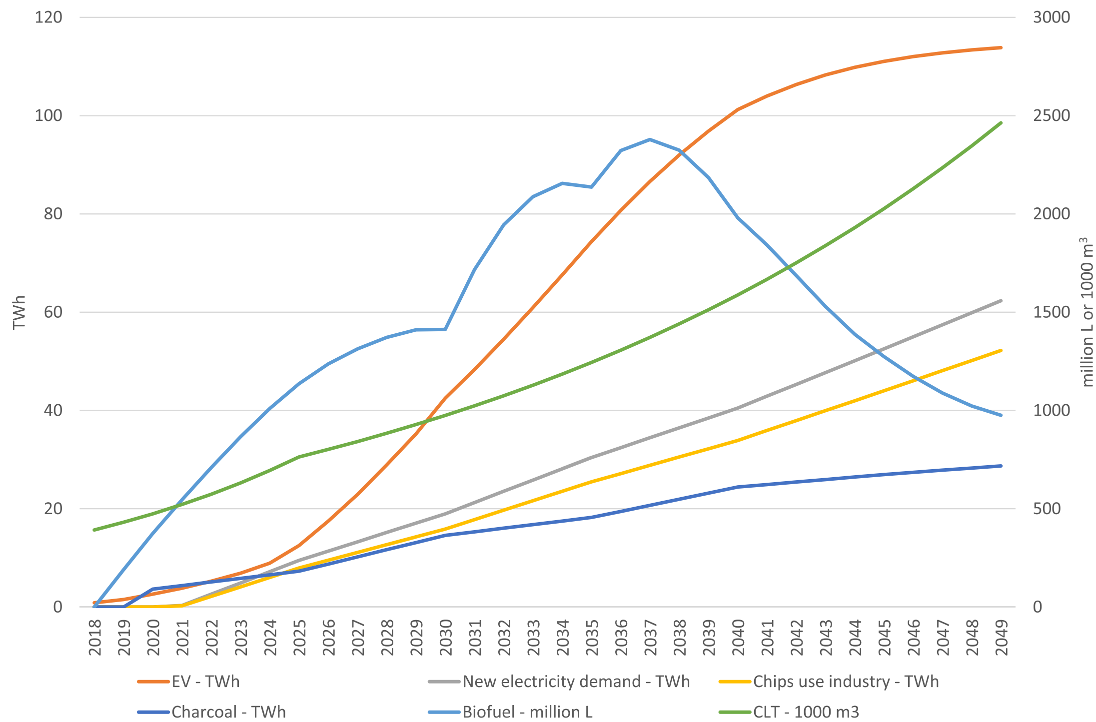

Fig. 3. Exogenously determined development of demand used in this study, electricity consumption in electric vehicles (EV) and new electricity demand in industrial processes, chips and charcoal use for industrial processes (left axis), biofuel demand for road transport (right axis), and demand for CLT in construction (right axis).

the integration procedure, we assume that the NFSM ROW region follows the weighted average costs in Germany, Lithuania, Latvia, Estonia, and Poland. Each of the NFSM regions is placed inside one of the Balmorel regions as shown in Fig. 2, except NFSM region D1, which is divided equally between Balmorel regions DK1 and DK2. When allocating fuel consumption from Balmorel to the NFSM regions, we disaggregate the consumption according to the reference distribution.

2.3.3. Electricity demand and supply

Electricity consumption in NFSM is assumed to be allocated equally over a year. This may be a feasible assumption for pulp and paper mills since they normally do not ramp their production [24], but less so for sawmills, which tend to have higher activity during the daytime. In the years that NFSM is solved alone, the unit electricity cost is assumed constant, and for years with endogenous unit electricity costs are decided by the model with use of the Eq. (I.1). Each time the full model is solved, the regional unit electricity prices in NFSM are updated using the average yearly electricity prices found in the full model. For subsequent years, the new electricity cost is applied until the next time the full model is solved. This ensures that the forest sector faces changes in electricity costs.

The electricity consumption in the forest sector is added to the electricity balance, shown in Eq. (B.3) in the Appendix A, in the seventh term

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

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

2.3.4. Heat demand and supply

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

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

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

The integrated model covers input in bioheat plants in all regions

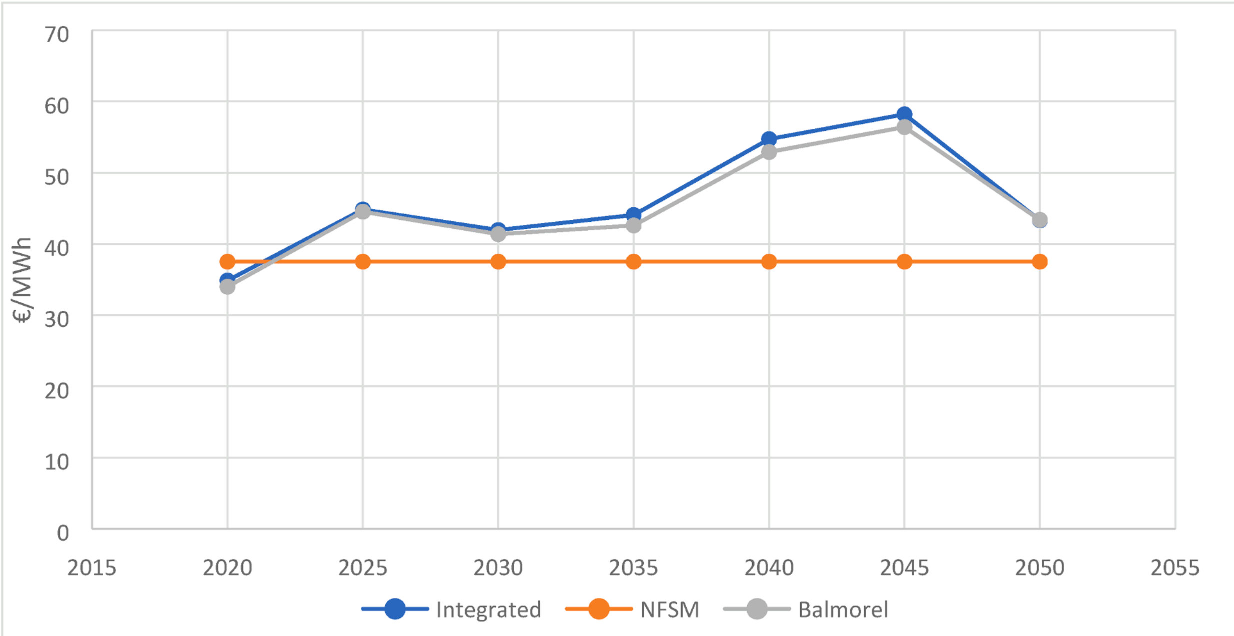

Fig. 4. Modelled average electricity prices in Finland, Norway, and Sweden for NFSM, Balmorel, and the integrated model.

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

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

$$\sum_{t,q}\varphi_{q,t,i,y}\Lambda_{q,t,u}\Omega_u = \varsigma_{i,u}\sum_{t,u_2}\varphi_{q,t,i,y}\Lambda_{q,t,u_2}\Omega_{u_2}\forall i,u \tag{I.3}$$

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

2.3.5. Objective function

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

$$addon = -1,000,000{*}\max[\cdots] \tag{I.4}$$

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

2.4. Assumptions for modelled scenarios

To find the advantages and disadvantages of the integrated modelling approach, we develop a scenario for the Norwegian forest and energy sector where the assumptions are used as input to model runs in NFSM and Balmorel, as well as in the integrated model. The main assumption regarding the demand for various energy commodities and services for the main scenario is shown in Fig. 3. The investments in electric vehicles follow known plans and goals [47,74,76]. The demand for liquid fuel and electricity is estimated using estimated investments in electrical vehicles; for example, Norwegian policy states that all new private vehicles have to be electric from 2025 [47]. Total number of vehicles (electric and liquid fuel), yearly driving distances, probability of scrapping, and energy demand are all based on historical figures for the Nordic countries [47,68,69,72,75,77].

For non-road transportation, it is assumed that the energy output is constant regardless of whether the uses electricity or liquid fuel. It is assumed that railway transportation is fully electrified within 2025, while the electricity demand from short distance marine increases by 0.3 TWh each year between 2020 and 2025 [73]; and from 2025 it is assumed that all domestic ferries are electric and the potential for shore supply is fulfilled. For domestic aviation, a constant liquid fuel demand is assumed until 2030, and from 2040 the liquid demand decreases to 20% of the 2018 values, while 80% of the energy demand is fulfilled with electricity [1].

The Norwegian blend-in obligations for biofuel state that 20% of the liquid fuel sold for road transportation in 2020 should be biofuel, and of this at least 1.75% should be advanced biofuel [40]. The share of advanced biofuel is assumed to increase to 10% in 2030 [47]. We assume that the entire advanced biofuel share is fulfilled with Nordic forest-based biofuel. In 2030, we assume that the blend-in obligation will increase to 20% and further increase to 100% in 2050. We assume the same blend-in mandate for all types of liquid fuel. The Swedish biofuel policy is not a blend-in obligation, but a GHG reduction goal: the

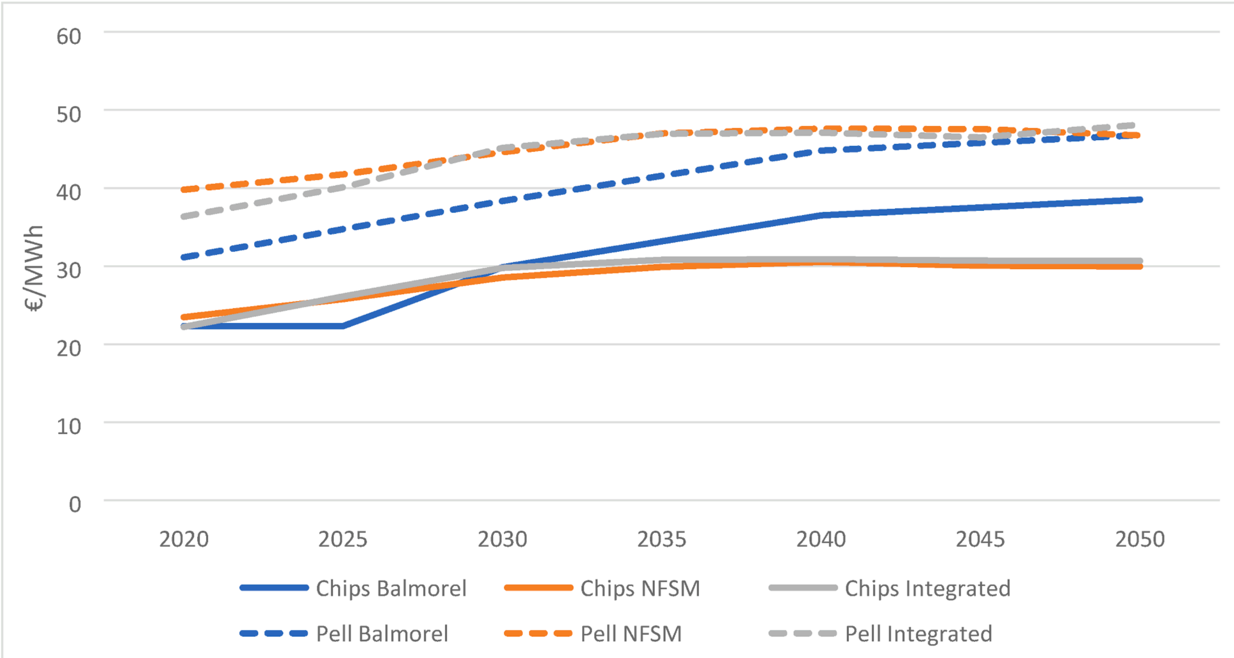

Fig. 5. Modelled average chips and pellets prices in Norway, Sweden, and Finland for NFSM, Balmorel, and the integrated model.

goal is 40% reduction for all liquid fuel for transportation in 2030 [62]. We assume that Nordic forest-based biofuel reduces the GHG emissions by 95% [40] compared to fossil fuel. With the same assumptions for the forest-based biofuel share in the total biofuel mix as in Norway, we get 1.2% forest-based biofuel in 2020, 10.5% in 2030. 20% in 2035, and 100% in 2050. It is assumed that the Finnish and Danish transportation sectors follow the same assumptions as Sweden, but 2018 and 2019 values follow historical investments.

We assume that all the fossil fuel used for energy generation (173 TWh), both in electricity and heat generation and in industrial processes, is replaced with 80 TWh electricity toward 2050 [73]; the rest of the energy demand is assumed to be covered by 67 TWh of chips and 3.6 million tonnes of charcoal. And finally, the Nordic consumption of cross laminated timber (CLT) in 2018 is estimated to be 392,000 m^3 solid [11,17,67]; we assume that the consumption of CLT will increase by 10% yearly in the period 2018–2025 and 5% thereafter. This will give a Nordic demand of 2.6 million m^3 solid CLT in 2050. The introduction of CLT may reduce the demand for cement and steel in the building sector by up to 1.23 tonnes cement and 0.14 tonne steel per m^3 solid CLT [23]. In a Nordic context, this is equivalent to an emissions reduction of 0.66 tonne CO_2 per m^3 solid CLT [83].

3. Results

3.1. Power prices

In NFSM, the electricity prices are given exogenously for each region and the prices for electricity delivered at mills are held constant for all years. The electricity prices vary between regions: the average electricity price is 38 €/MWh in Norway and Sweden, 37 €/MWh in Finland, 42 €/MWh in Denmark, and 43 €/MWh in ROW. Balmorel has endogenously determined electricity prices in each region based on the production costs and demand for each period. The estimated average electricity prices in Finland, Sweden, and Norway are shown in Fig. 4. For the Balmorel model, the electricity prices will increase from 2030 to 2045 due to increasing investment and costs related to high carbon prices. The main reason for the increased electricity price in years 2040 and 2045 is an increase in investment in electricity storage, which in turn is forced into the system due to increased carbon prices. In 2050, all the necessary investments are made and the cost of investing in electricity storage is not shown directly at the marginal production costs.

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

3.2. Raw material consumption in bioheat production

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

Balmorel finds the optimal allocation of raw material consumption for all available raw materials in the model, including electrical heating. Balmorel estimates a peak in forest resource use of 146 TWh in 2025, and the amount drops to 104 TWh in 2050, mainly due to increased use of heat pumps and electrical boilers. The difference between Balmorel and the integrated model in 2025 comes from the different wood chips prices, which encourage more use of natural gas instead of investment in new chips units. Balmorel has a less detailed representation of the forest recourses than NFSM. For this reason, in the integrated model, we split the wood chips category in Balmorel into four different grades of forest raw materials: bark, chips, sawdust, and harvest residues. Results from the integrated model show increasing consumption of forest raw material, from 47 TWh in 2020 to 117 TWh in 2050, most dominated by harvest residuals, bark, and chips.

The exogenous chips price in Balmorel increases from 22 €/MWh in

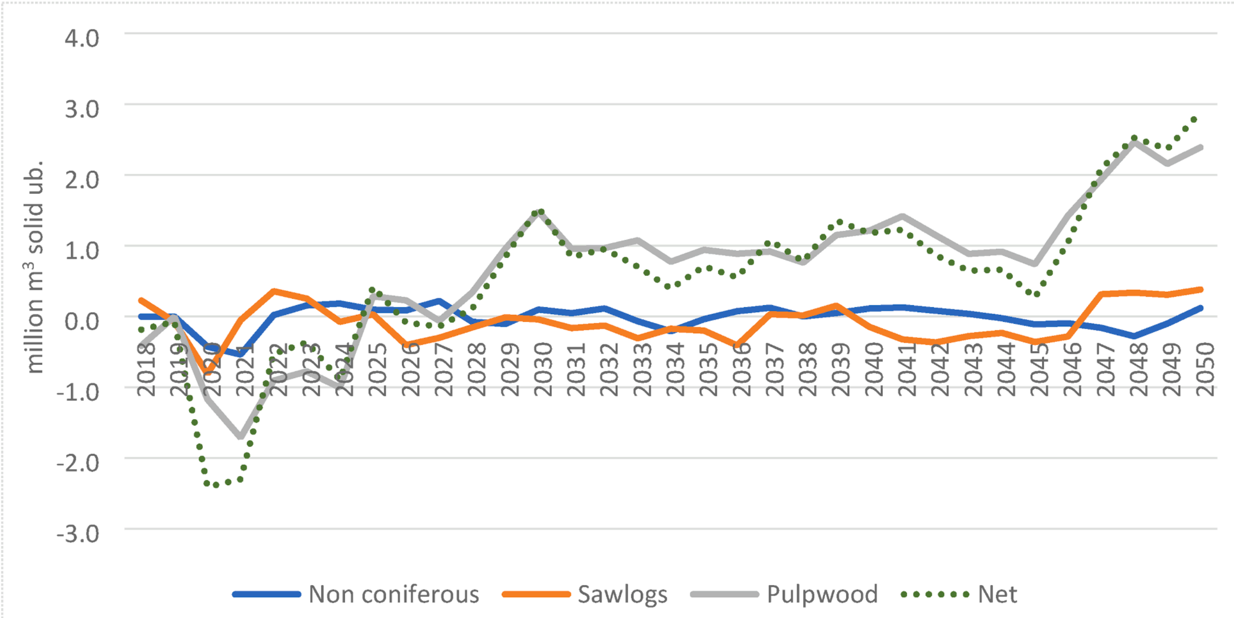

Fig. 6. Modelled difference in roundwood harvest levels between the integrated model and NFSM in Norway, Sweden, and Finland; positive number is higher harvest in the integrated model, while negative number is lower harvest in the integrated model.

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

3.3. Forest sector

In this section, we describe forest sector effects in Norway, Sweden, and Finland, which are the main forest regions in NFSM. The integration procedure also affects Denmark and the ROW region, but because the

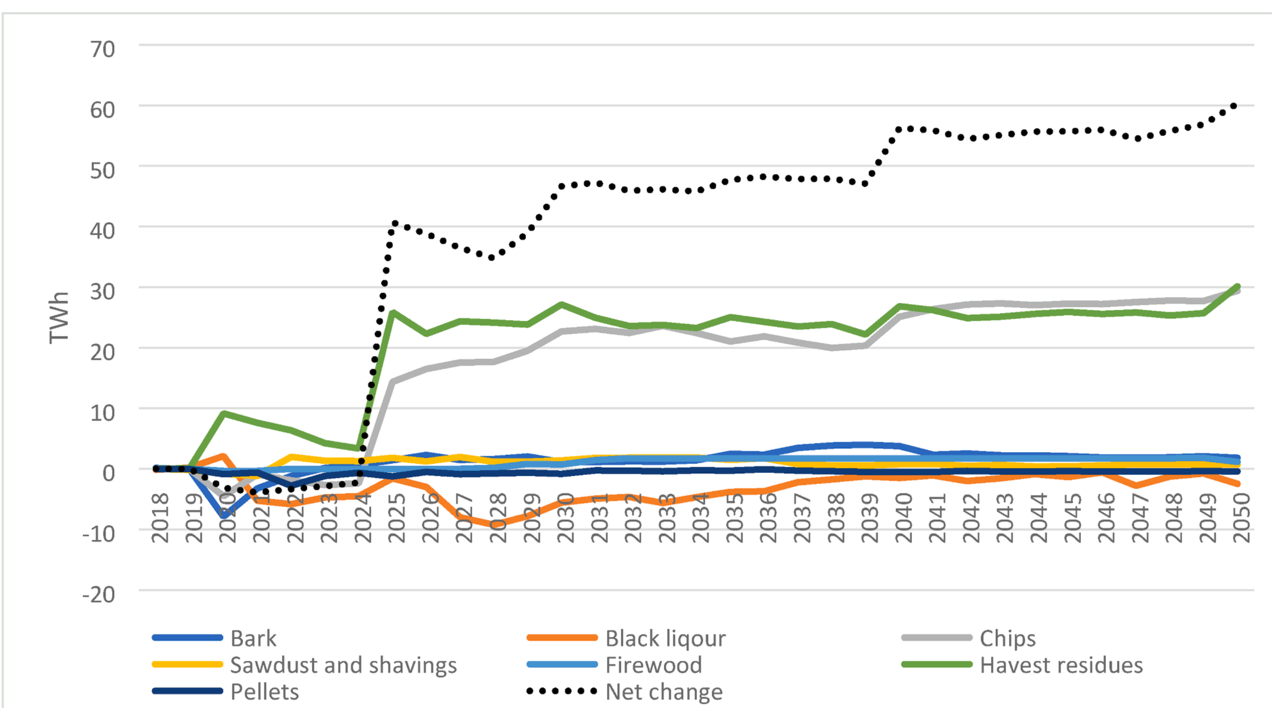

Fig. 7. Modelled difference in raw material input in district heat, industrial heat, and locally produced heat between the integrated model and NFSM in Norway, Sweden, and Finland; positive number is greater input in the integrated model, while negative number is lower input in the integrated model.

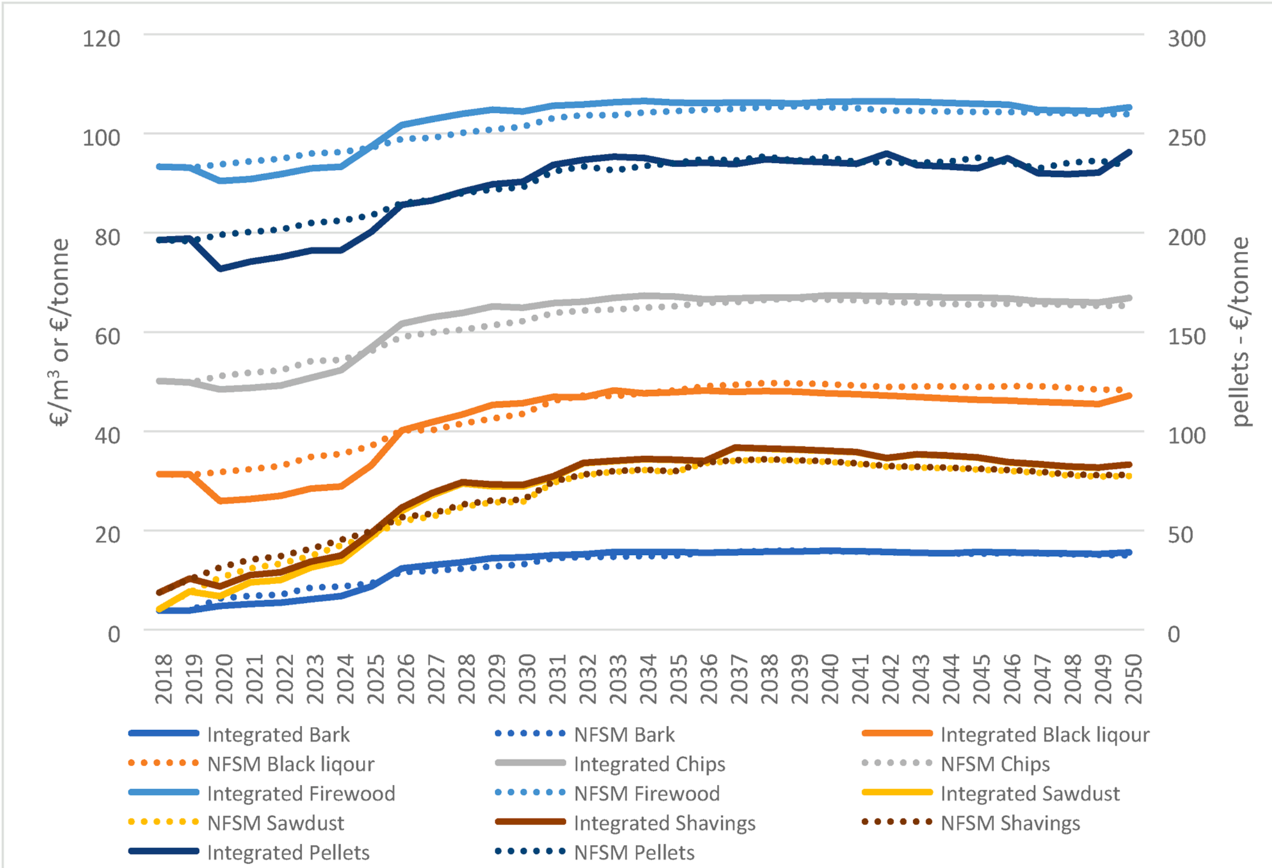

Fig. 8. Modelled unit market price for secondary forest products and by-products for the integrated model (solid line) and NFSM (dotted line) in Norway, Finland, and Sweden; pellets price is shown on right axis.

Danish forest sector is relatively limited and the ROW region has many specific assumptions, these results are not shown here.

In 2018, the total harvest in Norway, Sweden, and Finland was 153 million m^3 solid ub. where 66 million m^3 solid ub. was spruce and pine sawlogs and 61 million m^3 solid ub. was spruce and pine pulpwood. The remaining (26 million m^3 solid ub.) was different grades of non-coniferous roundwood. NFSM shows an increase in total harvest of 16%, from 153 million m^3 solid ub. in 2018 to 178 million m^3 solid ub. in 2050. When the models are integrated, the harvest increases by an additional 2.9 million m^3 solid ub. in 2050 (Fig. 6). The main reason for the additional increase in harvest is the increased use of forest resources for energy production. The harvest of sawlogs is relatively similar (-0.8–0.4 million m^3 solid ub. or −1.2–0.5%) in both models, since electricity accounts for a small share of the total cost at sawmills compared to pulp and paper mills and sawmills get a net increased income from selling by-products which partly compensates for the increased electricity costs. NFSM and the integrated model give similar results for harvest of non-coniferous roundwood. In total, the yearly variation in harvest level is between −1.5% and +1.6% of the NFSM harvest. The difference between the two models is highest in the year that both models are optimized; the main reason for this is the change in raw materials used for heat production (Fig. 7). If we include collection of harvest residues, the total outtake from the forest increases by up to +7%. The total harvest, including harvest residues, is stable between 2020 and 2024 due to a decreased use of forest raw materials for heat production in the integrated model compared to NFSM, along with a slight increase in industrial heat. The changes in roundwood harvest (Fig. 6) are lower than the increased input of forest raw material in heat production due to slightly less pulp and paper production in the Nordic countries in the integrated model.

The use of forest biomass in the production of industrial heat increases in a relatively similar fashion in the integrated model and in NFSM since the assumed demand for industrial heat in industrial production follows the same pattern in both models. We find an increased use of forest resources in district heat generation. Fig. 7 shows the difference between the two models in terms of the amount of raw materials used for heat production. The total consumption of forest raw materials changes each time both models are optimized (2020, 2025, 2030, 2035, 2040, 2045, and 2050) since the model finds a new optimal level of forest heat production. The same years also show a peak in the total changes due to the integration procedure whereas the Balmorel model has different efficiency coeffects for the different plants and NFSM has one efficiency parameter for each fuel. The small peaks in Fig. 7 are mainly explained by the shift between the use of bark to the use of sawdust in the production of charcoal, trade with the ROW region, and less collection of harvest residues. The peaks do not give significant short time changes in the raw material prices (Fig. 9). The increase between 2024 and 2025 is due to the increased use of forest biomass for district heat production between 2020 and 2025.

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

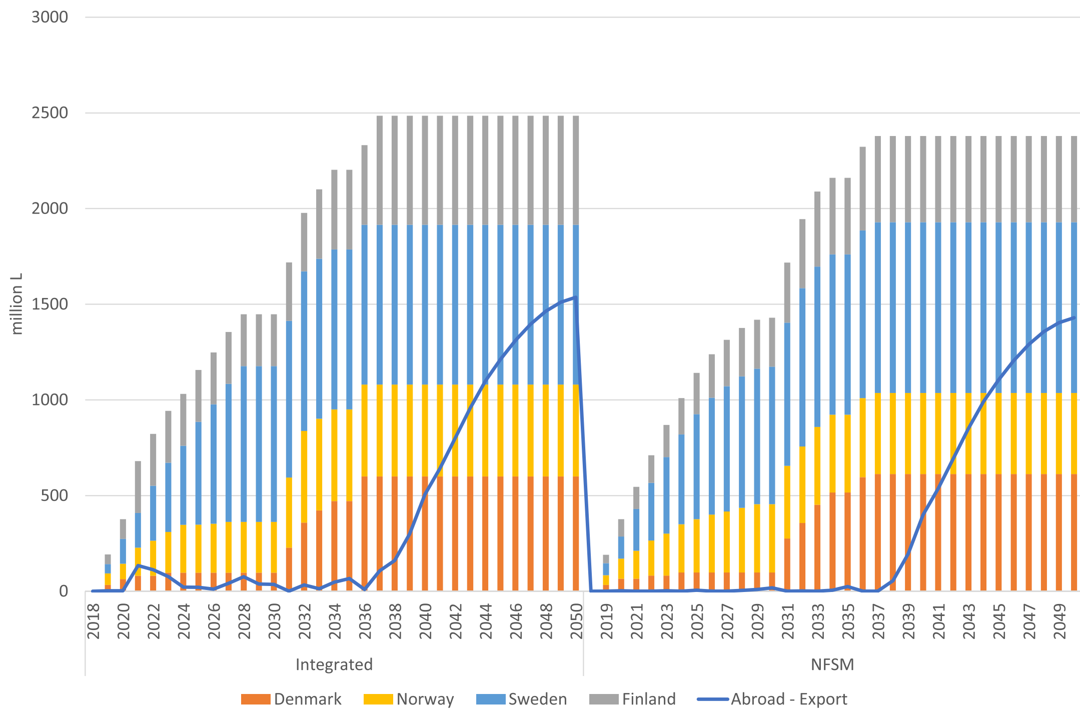

Fig. 9. Country-specific production of biofuel and export to rest of the world for the integrated model and NFSM.

The production of non-energy forest products is relatively constant across the two models and across the years since the integration does not lead to significant changes in demand and supply of roundwood. The greatest change is found for paper production after 2040 where the production is reduced by 3–8%; the main reason for this is the increased price of market pulp driven by increased electricity prices. While the market price for secondary forest products increases over time; this is due to the large production of biofuel, up to 2.3 billion L from 2036, and is the same in the integrated and standalone models. All secondary forest products have lower prices in the integrated model in the years 2020 to 2025 (Fig. 8) because of a slightly lower demand for forest resources for heat production (Fig. 7).

3.4. Energy sector

The modelled climate gas emissions from fossil fuels decrease from 2020 to 2050 due to increasing carbon prices. For Norway, Sweden, and Finland, the modelled emissions are 62% higher in the integrated model than in Balmorel for 2025. The main reason for this is the higher chips price in the integrated model, which implies that fossil fuels are more competitive (Fig. 5). The Nordic countries do not emit carbon from power and heat generation after 2035. For the countries outside the Nordic countries, we find a reduction in carbon emissions of up to 20% when the model is integrated, with the largest reduction in 2045. The reason for this is that the chips price is up to 42% lower in the regions outside the Nordic countries in the integrated model than in the Balmorel model.

For the period 2020–2030 the modelled generation of electricity and heat from chips is lower when the models are integrated than when Balmorel is optimized alone. After 2030 more chips are used in the integrated model than in Balmorel. The change in chips consumption mainly affects the use of natural gas for the period 2020–2035 and electrical heating after 2030. The reason for this is that chips price (Fig. 5) is lower in the year (2020–2035) for the integrated model, this gives more use of natural gas when the model is integrated. The use of natural gas decreasing from 2020 to 2050 due to the assumed increasing in carbon prices, which reduces the competitiveness of gas power relative to renewable power. Around 78% of the difference in the produced energy from chips is allocated as heat. This fraction is almost equal in periods with reduced production and periods with increased production; the reason for this is that most of the CHP plants that use chips for fuel have a constant distribution between heat and power.

The modelled electricity prices in Balmorel and the integrated model show similar yearly changes, but the prices in the integrated model vary between −1% and 3% more than in Balmorel, except in 2050 where the electricity prices decrease by 6%. The highest increase happens in Finland, which also has the highest electricity consumption in the forest sector. While, also the heat prices are relatively stable for the integrated model and standalone Balmorel but tend to increase in Balmorel and decline in the integrated model. The reason for this is that the integrated model has a more stable chips price which gives a more stable heat production cost in the Nordic counties; chips account for 20–63% of the heat production in the integrated model. In the integrated model, we also find a small increase in the price of heat for 2040 and 2045 in Norway; the reason for this is that 2040 is the first year that the Nordic energy sector will become carbon neutral, which trigger more investment and use of electrical boilers at industrial sites in western Norway.

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

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

As shown in Fig. 3, the Nordic countries may consume up to 2.4 million m^3 solid CLT in 2050, with most of the CLT being produced within the Nordic countries. In the integrated model, Norway will have a bigger share of the total production after 2035 than in NFSM, and the reason for this is a slight reduction in sawnwood prices in Norway, which again are the result of a smaller increase in electricity prices in the Norwegian sawmills compared to Sweden and Finland. We assume that at least half of the CLT production must be from spruce sawlogs; this is a binding constraint for all countries and years. The reason for this is that pine sawlogs have a lower estimated market price than spruce sawlogs.

It is assumed that the Nordic biofuel demand will peak in 2037 (Fig. 3), which the Nordic biofuel demand will start to decline. Since a biofuel plant is assumed to have a longer lifetime than the modelled period, the Nordic countries will start to export forest-based biofuel to ROW after 2037. In the period 2020–2025, when the demand for forest biomass in heat production declines in the integrated model, it will be beneficial to invest in more biofuel plants than in Nordic consumption, which will result in export of biofuel to ROW (Fig. 9). This shows that declining low-grade forest resources can be caught by other industries, and lock-in is a potential risk with such short-term declines.

4. Discussion

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

Even though the geographical focus in this study is the Nordic countries may the results be relevant to other countries as well. The Nordic countries is a special interesting area since the region is dominated by large supply of renewable energy, both wind, hydro, biomass is easily available in all countries. The thematic focus is to better model the energy and forest sector, which is relevant for all regions with boreal forests, forest industry, and have a large district heat sector. It is likely that energy sector and forest sector modelling in those areas will profit on using the integration procedure explained in this study.

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

The most significant difference between Balmorel and NFSM is the time resolution. In forest sector analyses, it is not beneficial to increase the time resolution, since forests have a long-term cyclic nature with growth mainly in the summer period and harvest all year around, while forest industrial products, unlike electricity and heat, can be stored for a shorter period without significant costs or losses. The pulp and paper industries normally produce pulp and paper without breaks, except for some shorter maintenance periods, and it can be assumed that pulp and paper mills do not optimize their production based on short-term variation in the electricity price; but according to Helin et al. [24] there may be a significant potential for demand response at mechanical pulp mills. For sawmills, it can be beneficial to increase the resolution of the model to a include daytime, night-time, and weekends, since they do not have as high start and stop costs as pulp and paper mills, but it is unlikely that the sawmills optimize their production according to electricity costs alone, since only a marginal fraction of the total costs is related to electricity. But for bigger sawmills that sell surplus heat, there may be a connection to the heat market. Finally, bioenergy production in the integrated model is modelled with hourly resolution, while raw material usage is modelled with a yearly resolution. Dividing output and input this way ensures that the bioenergy producers are connected to both markets. Nevertheless, it is sensible to use an hourly resolution for the electricity and heat markets since short-term variation in electricity generation and demand is an essential part of the energy market.

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

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

The consumption levels of locally produced heat from wood stoves are assumed to be independent of the district heat and electricity markets. This is a simplification since consumers that use wood stoves may change to electrical heating or connect to a district heat network in the long term. However, Nesbakken [52] reports that short-term cross price elasticity between wood stove heating and electricity prices is relatively low, while the long-term elasticity is probably higher. The main contribution to yearly and seasonal variations in district heat, electricity for heating, and wood stove use is the outdoor temperature, which will affect all sectors at the same time. For this reason, it is likely that firewood consumption and electrical heating will be more connected in the future, which means that local heat production should be included in the integration procedure in the future.

We find that when using the integrated model, bioheat production is lower than was the case with Balmorel for some years and higher for others. This is in contradiction to Mustapha et al. [51], who stated that studies using fixed biomass prices overestimate the bioenergy production. We find that when the model can use low-grade forest resources for bioenergy production, the amount of bioenergy produced may increase due to the lower price of the raw materials. This shows that when a model can be flexible in terms of the way biomass is used, the total produced bioenergy will increase and we will get better use of the raw materials.

We have assumed no co-generation between charcoal, biofuel production, or bioheat production; this is a simplification since some biofuel technologies have a side stream that can be turned into charcoal or sold as district heat. As shown by Nguyen and Gustavsson [53], surplus heat from co-generation is only likely to be profitable for bigger biofuel plants connected to bigger district heat networks. This show that while the effects of these simplifications may be assumed to be low overall, they may nevertheless be interesting to investigate in a later study.

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

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

As well as the case with most modelling studies is also this study dependent on uncertain aggregated or disaggregated input data. In this study is the main uncertainty related to the data on single plant level, both within the forest sector and energy sector. The input/output from the different technologies on aggregated level is close to the actual figures, but the figures is more uncertain when disaggregated to plant level. Similarly, the regional demand for forest product is highly uncertain since it is based on a mass balance disaggregated to regional level with use of population size, and further that all actors is assumed to be perfect price takers. Following will the investment costs for new plants and future carbon price be highly uncertain. Even though the input data is uncertain, we believe that it does not contribute to unacceptable output uncertainty.

5. Conclusion

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

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

The study shows that it is important to be aware of the interaction between the forest, energy, and bioenergy sector when optimizing bioenergy production. We strongly recommend studying the spill over effects between the sectors when making long term projections. The integrated model will strongly improve different policy scenarios, for example may further work focus on carbon price effects in both sectors. Finally, we can conclude that although the solving time and complexity increase when we integrate the models, we recommend including endogenous biomass prices in energy sector models and endogenous power prices in the forest sector model.

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

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Data availability

Model Balmorel related to this article can be found at https://github.com/balmorelcommunity, hosted at Github (Github Repository, 2019).

Appendix A

Symbol list

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

NFSM equations

NFSMs objective function is shown below and all symbols are briefly explained in Table 6:

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

Symbol	Description	Unit	Model
Set			
i, j	Regions		NFSM
f	Final products		NFSM
k, k_2	All products, i.e., final products, intermediate products, and roundwood categories		NFSM
y	Year		NFSM
w	Roundwood category		NFSM
t	Technology		NFSM
tb	Biofuel technology		NFSM
kb	Biofuel		NFSM
e	Electricity		NFSM
u, u_2	Raw material used for energy production		NFSM
q	Heat production		NFSM
Y	Current year		Balmorel
A, A_1	Regions		Balmorel
AI	Import to region		Balmorel
AE	Export from region		Balmorel
G	Technologies		Balmorel
GH	Hydropower with reservoir technologies		Balmorel
GSH	Storage technology heat		Balmorel
GSE	Storage technology electricity		Balmorel
GB	Heat pumps and electrical boilers technologies		Balmorel
F	Fuels		Balmorel
S	Week		Balmorel
T	Hour		Balmorel
Variable			
γ	Consumption	Tonne, m^3, MWh	NFSM
θ	Harvest	m^3	NFSM
ε	Harvest residues	m^3	NFSM
φ	Production	Tonne, m^3, MWh	NFSM
ω	Trade	Tonne, m^3, MWh	NFSM
Θ	Downgrading of roundwood category	m^3	NFSM
VF	Fuel consumption	MWh	Balmorel
VE	Electricity produced	MW	Balmorel
VH	Heat produced	MW	Balmorel
VG	Endogenously capacity	MW	Balmorel
VX	Transmission	MW	Balmorel
VC	Endogenously defined transmission capacity	MW	Balmorel
VS	Loading of energy storage	MW	Balmorel
Parameters			
ζ	Reference consumption	Tonne, m^3, MWh	NFSM
Γ	Reference price	€/unit	NFSM
τ	Price elasticity		NFSM
β	Econometrically estimated roundwood supply elasticity		NFSM
α	Roundwood supply shifts periodically according to changes in growing stock via this parameter	€	NFSM
χ	Reference harvests	m^3	NFSM
ϕ	Growing stock	m^3	NFSM
κ	Growing stock rate	%	NFSM
μ	Harvest residues intercept	€/m^3	NFSM
υ	Harvest residues slope	€/$(m^3)^2$	NFSM
ι	Exogenous input price	€/unit	NFSM
Λ	Input of product	Unit/unit	NFSM
D	Transportation costs	€/unit	NFSM
LB	Labour costs biofuel	€/MWh	NFSM
VC	Variable costs	€/MWh	NFSM
IC	Investment costs	€/MWh	NFSM
ξ	Base production size for biofuel plant	MWh	NFSM
SL	Scale factor labour costs		NFSM
SV	Scale factor variable costs		NFSM

(*continued on next page*)

Table 6 (*continued*)

Symbol	Description	Unit	Model
SI	Scale factor investment costs		NFSM
Ψ	Controlling the regions in NFSM and Balmorel		Integration
Ω	Energy content in energy products	MWh/unit	Integration
ϖ	Historical allocation of heat production between NFSM regions in a Balmorel region	%	Integration
ς	Fraction of raw material input previous year	%	Integration
FP	Unit fuel price	€/GJ	Balmorel
OM	Variable operation and maintenance costs	€/MWh	Balmorel
EG	Exogenously capacity	MW	Balmorel
FC	Fixed operation costs	€/MW	Balmorel
HP	Hydro storages costs	€/MWh	Balmorel
XC	Transmission costs	€/MWh	Balmorel
IC	Investment costs	€/MW	Balmorel, NFSM
An	Annuity		NFSM
IX	Investment cost in transmission lines	€/MW	Balmorel
EL	Emission per consumed unit	kg/GJ	Balmorel
EC	Emission costs	€/kg	Balmorel
DH	Demand heat	MWh	Balmorel
HT	Heat demand profile	%	Balmorel
DL	Distribution losses	%	Balmorel
EF	Fuel efficiency	%	Balmorel
DE	Demand electricity	MWh	Balmorel
ET	Electricity demand profile	%	Balmorel

$$\max\left[\sum_{i,f}\left[\left\{\Gamma_{i,f}{}^{*}\left(1-\frac{1}{\tau_{i,f}}\right)\right\}\gamma_{i,f,y}-\frac{1}{2}\left\{\frac{\Gamma_{i,f}}{\zeta_{i,f,y}\tau_{i,f}}\right\}\gamma_{i,f,y}^{2}\right]-\sum_{i,w}\frac{\alpha_{i,w,y}}{\beta_{i,w}+1}\theta_{i,w,y}^{\beta_{i,w}+1}-\sum_{i}\mu_{i}\varepsilon_{i,y}+\frac{1}{2}\upsilon_{i}\varepsilon_{i,y}^{2}-\sum_{i,t,k,k2}\left(\iota_{i,k2}\Lambda_{k,t,k_2}\right.\right.$$
$$\left.\left.+An_{i}{}^{*}IC_{k}\right)\varphi_{i,k,t,y}-\sum_{i,j,k}D_{i,j,k}\omega_{i,j,k,y}-\sum_{i,tb,kb}\left\{LB_{i,tb,kb}\left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}}\right)^{SL_{tb}}+VC_{tb,kb}\left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}}\right)^{SV_{tb}}+An_{i,kb}VI_{tb,kb}\left(\frac{\varphi_{i,kb,tb,y}}{\xi_{kb}}\right)^{SI_{tb}}\right\}\right] \tag{N.1}$$

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

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

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

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

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

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

The main equation in NFSM is the material balance equation:

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

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

Balmorel equations

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

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

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

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

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

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

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

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

The first term describes production of electricity (*VE*) in region *A*, with use of technology *G*, in week *S*, and hour *T*. The second term describes the electricity that is consumed in heat pumps and electrical boilers, where *VH* is the produced heat and *EF* is the efficiency of the heat pump and the electrical boilers with technology *GB*. The third term describes imported electricity (*VX*) from region A_1 to region *A*, corrected for distribution losses. The fourth term describes exported electricity (*VX*) from region *A* to region A_1. The fifth term describes electricity that is stored (*VS*), both short and long-term storage, with technology *GSE*. The sixth term describes hourly electricity demand, where *DE* is the yearly demand and *ET* is the demand profile in region *A*, in week *S* and hour *T*, corrected for transmission losses. The seventh term is available for different user-defined add-ons to the core model.

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