Applied Energy 274 (2020) 115360

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

Eirik Ogner Jåstad*, Torjus Folsland Bolkesjø, Erik Trømborg, Per Kristian Rørstad

Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, NO-1432 Ås, Norway

HIGHLIGHTS

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

ARTICLE INFO

Keywords:
Bioenergy
Carbon reduction
Energy system models
Forest biomass
Partial equilibrium
Power and heat

ABSTRACT

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

1. Introduction

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

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

* Corresponding author.
E-mail addresses: eirik.jastad@nmbu.no (E.O. Jåstad), torjus.bolkesjo@nmbu.no (T.F. Bolkesjø), erik.tromborg@nmbu.no (E. Trømborg), per.kristian.rorstad@nmbu.no (P.K. Rørstad).

https://doi.org/10.1016/j.apenergy.2020.115360
Received 1 April 2020; Received in revised form 15 May 2020; Accepted 7 June 2020

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

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

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

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

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

2. Data and methodology

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

2.1. The Balmorel model and data

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

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

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

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

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

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

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

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

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

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

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

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

2.2. Forest biomass and biofuel

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

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

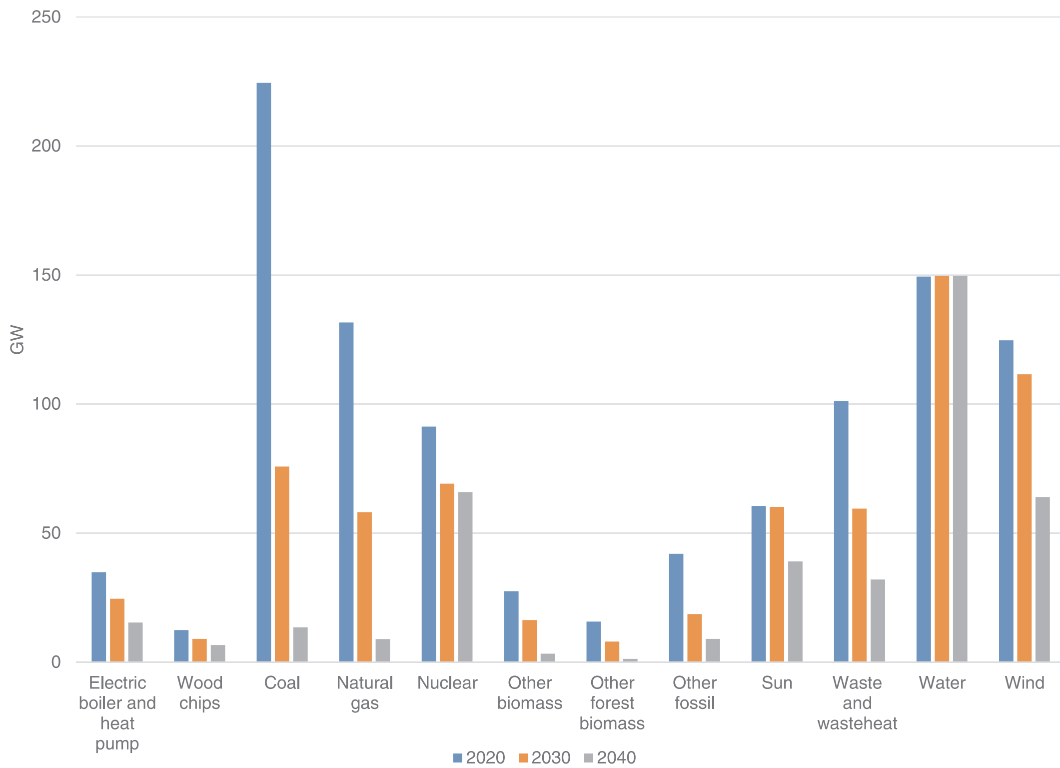

Fig. 1. Exogenous installed electricity and heat generation capacities by fuel/technology (GW), divided by fuel. The exogenous installed capacities in the model decreases following known phase-out plans and expected lifetime.

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

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

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

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

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

2.3. Scenarios

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

3. Results

3.1. Fuel and technology mix

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

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

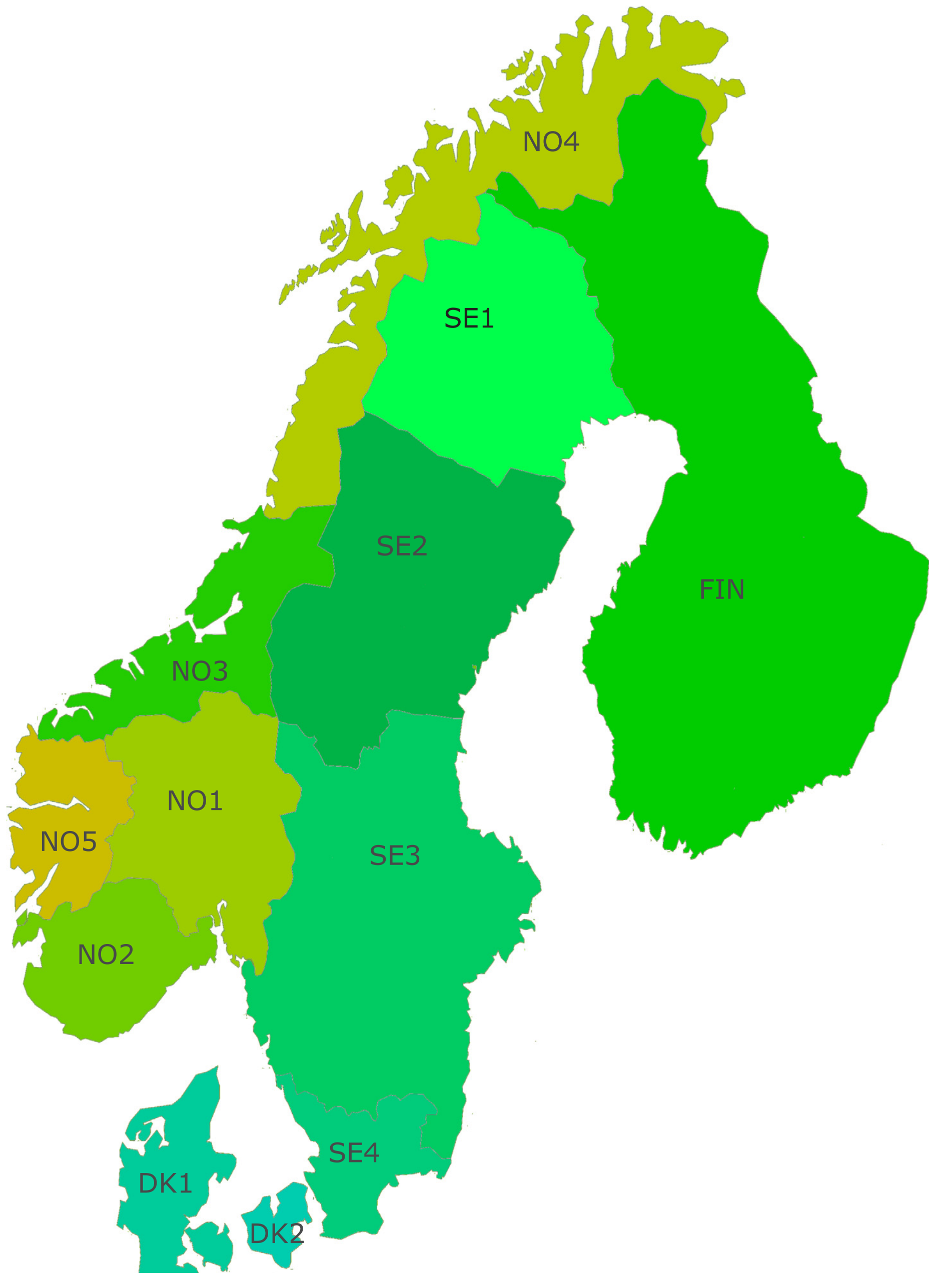

Fig. 2. Regions in the Nordic countries, in addition is Germany divided into 4 regions and Estonia, Latvia, Lithuania, Poland, Belgium, France, the Netherlands, and the United Kingdom dividend into one region each.

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

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

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

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

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

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

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

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

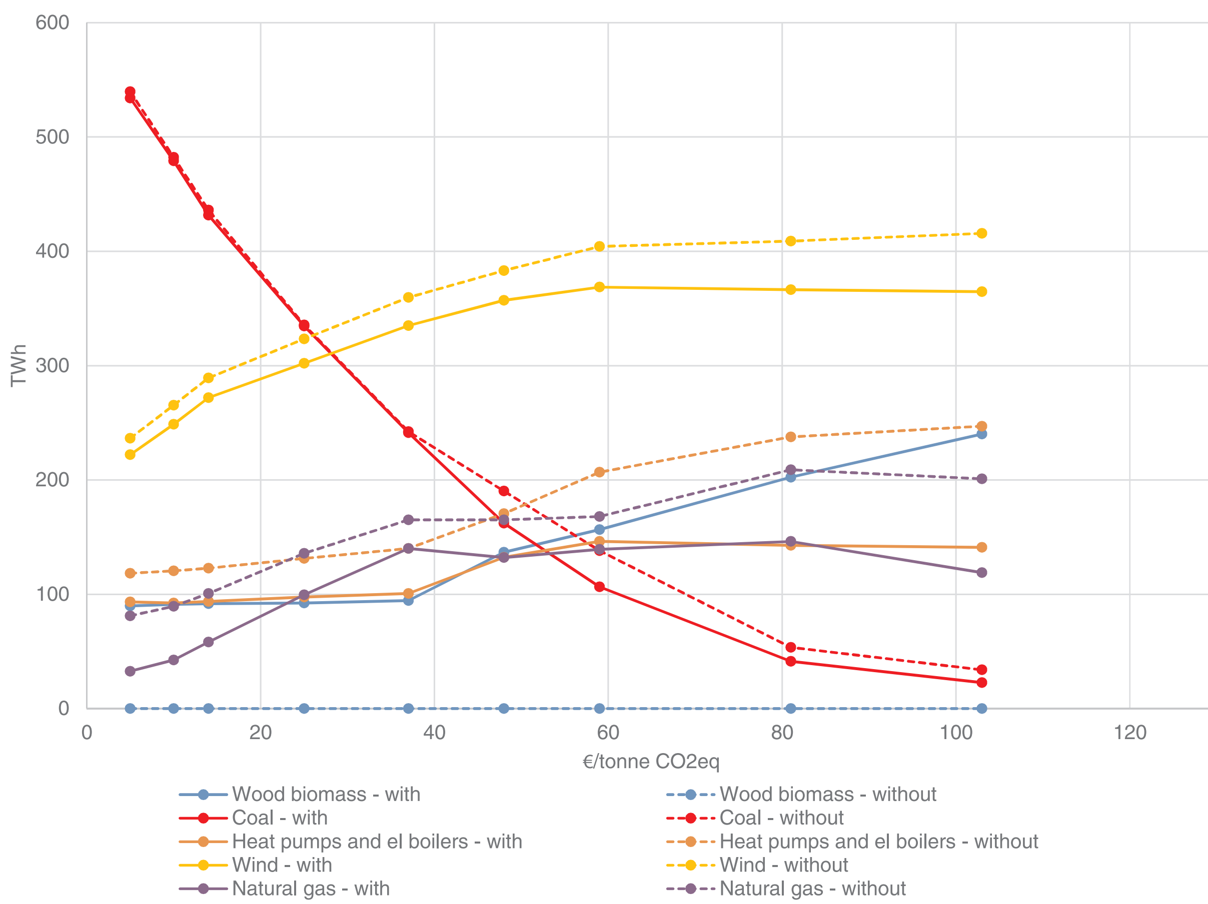

Fig. 3. Modelled production of electricity and heat deliveries in Northern Europe, production mix for different carbon prices, only the main fuel categories are shown. Dotted lines are scenarios without wood chips, while solid lines are with wood chips, for year 2030.

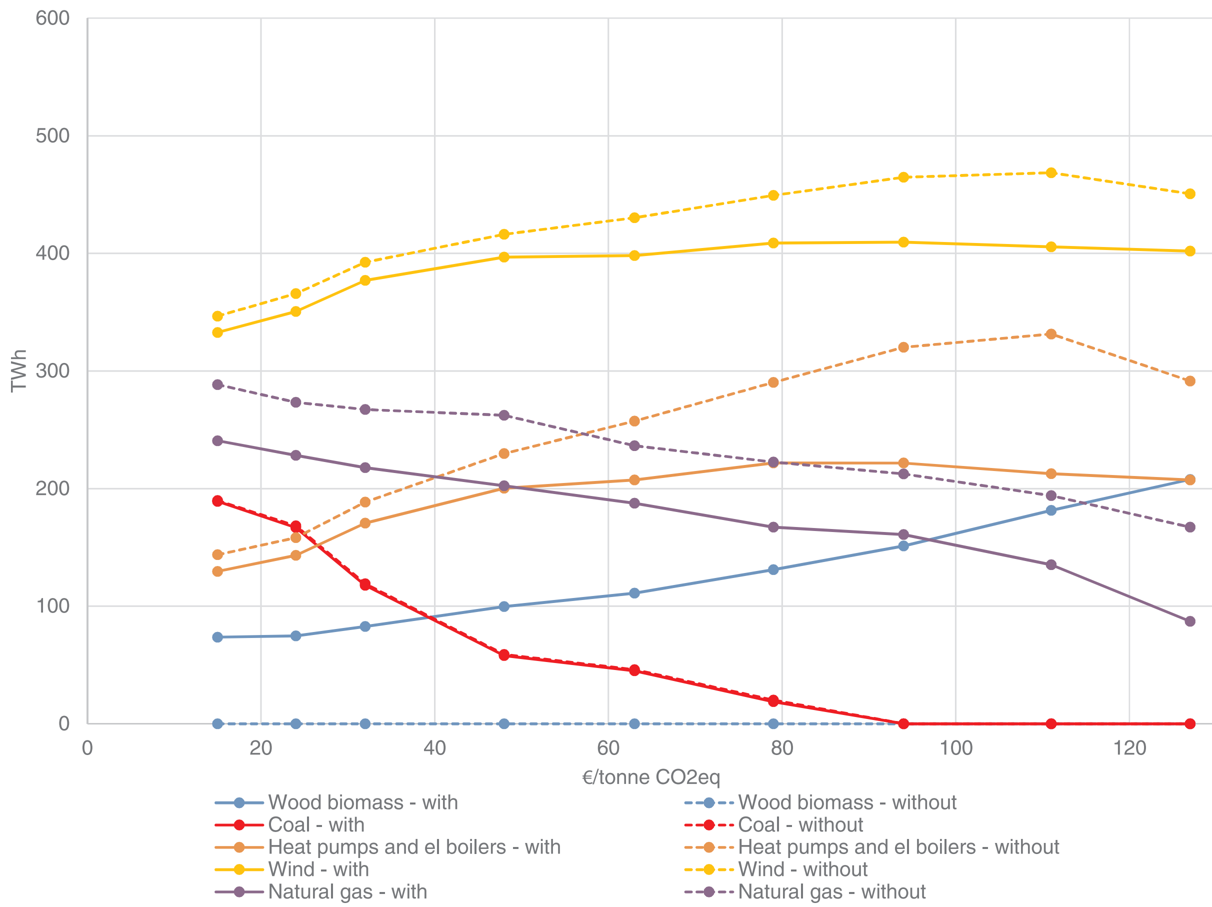

Fig. 4. Modelled production of electricity and heat deliveries in Northern Europe, production mix for different carbon prices, only the main fuel categories are shown. Dotted lines are scenarios without wood chips, while solid lines are with wood chips, for year 2040.

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

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

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

3.2. Emissions impacts

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

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

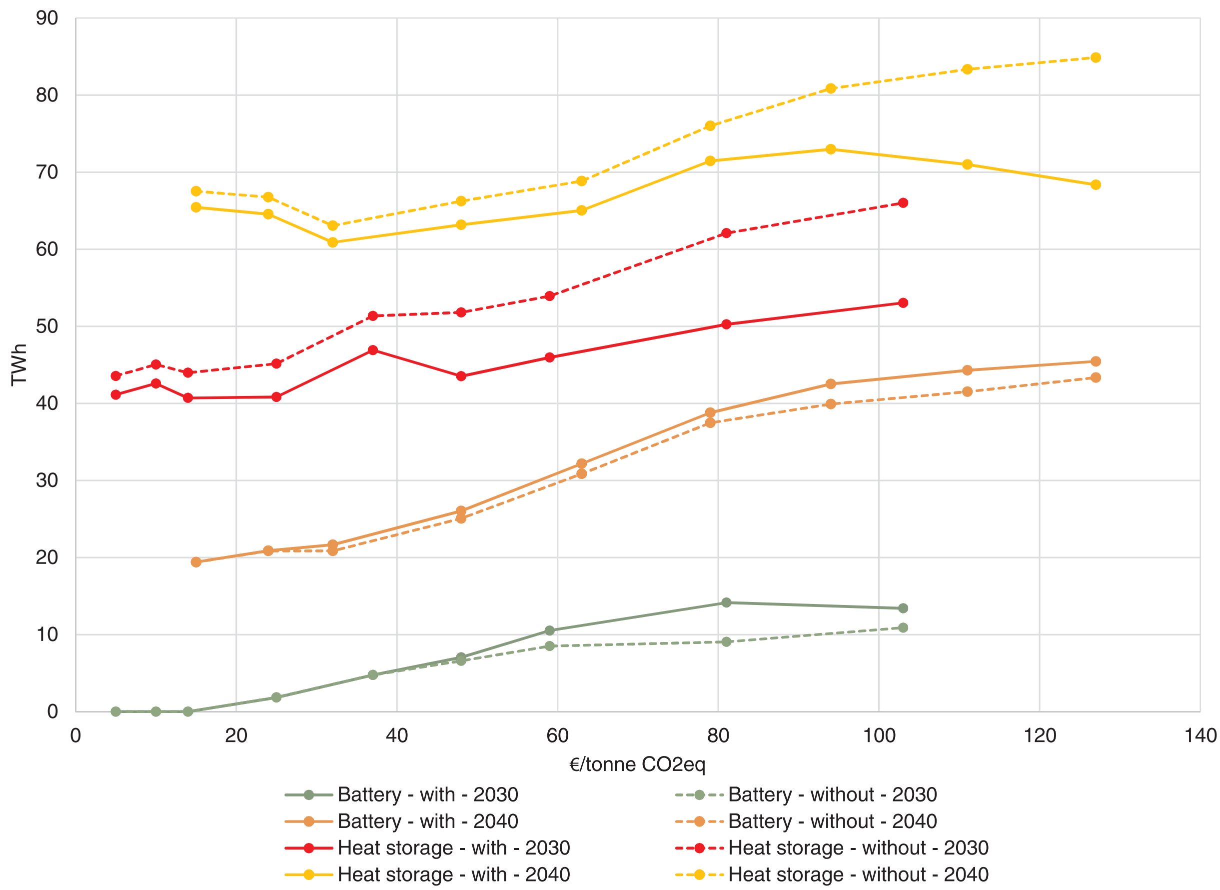

Fig. 5. Modelled energy from batteries and heat storages in Northern Europe, with and without use of wood chips, in 2030 and 2040, for different carbon prices.

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

3.3. System costs and energy prices

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

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

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

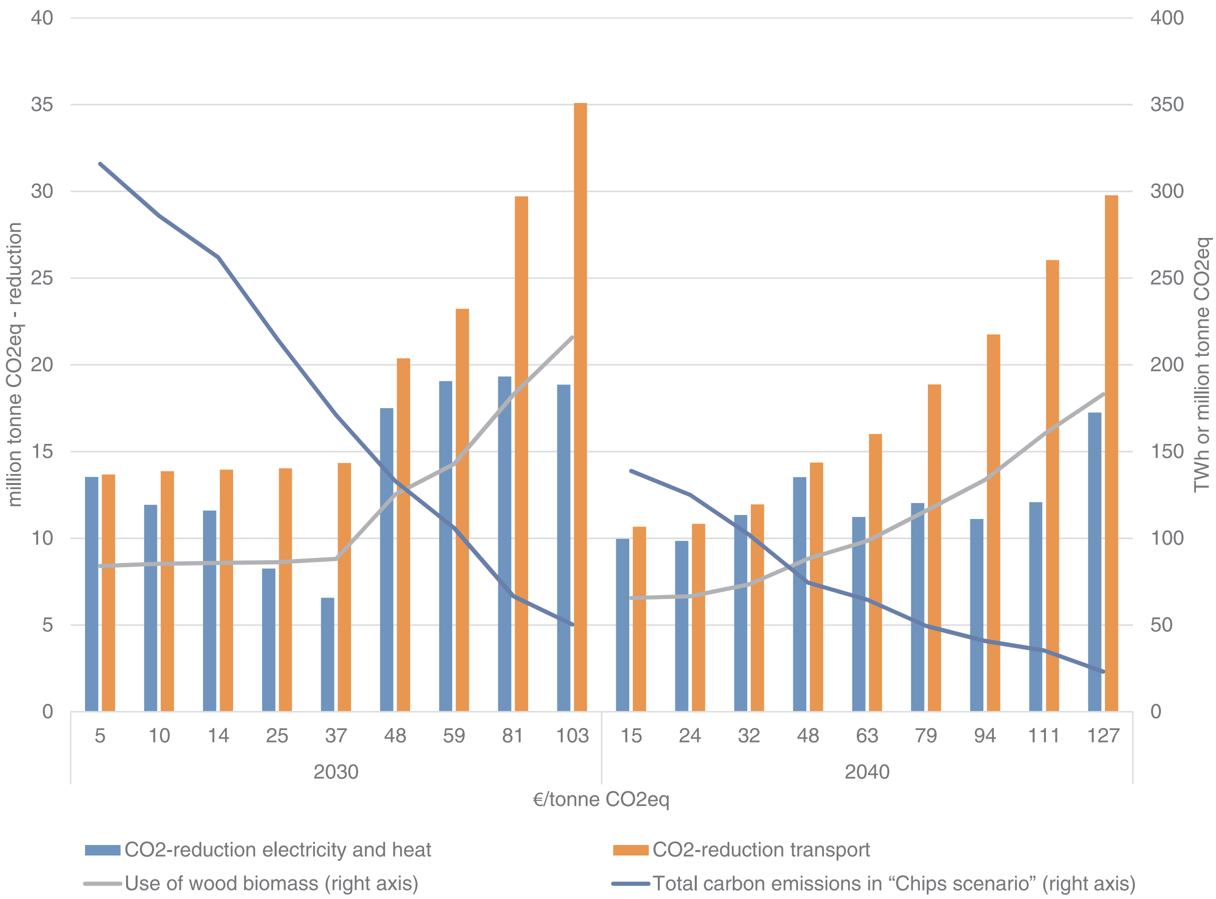

Fig. 6. Modelled use of wood chips (right axis), CO_2 reduction from electricity and heat production (left axis), total emissions when wood chips are included (right axis) from heat and electricity production, and theoretical CO_2 reduction if all wood chips that was used in the model were used for biofuel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

observed.

3.4. Endogenous transmission line investment

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

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

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

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

4. Discussion

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

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

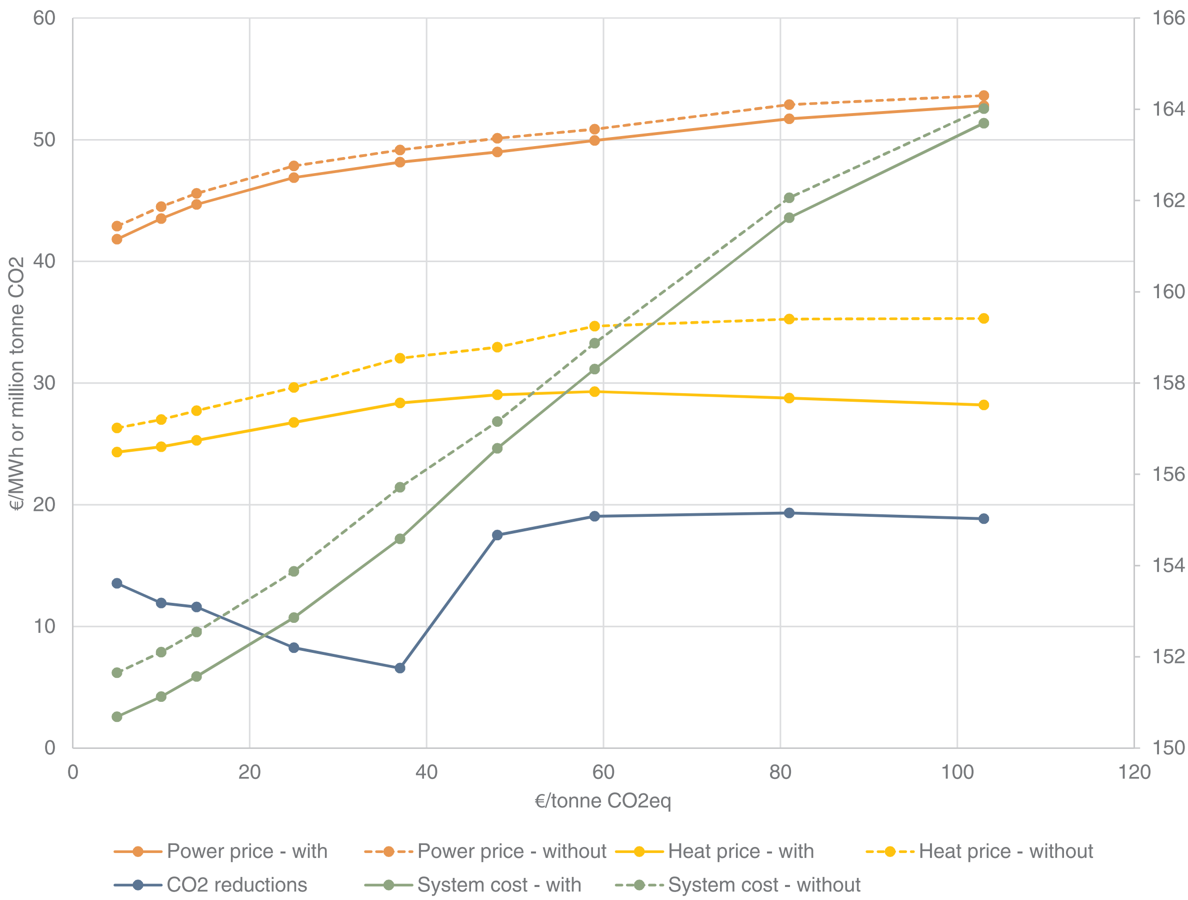

Fig. 7. Modelled weighted power and heat prices (€/MWh), system cost corrected for emission taxes (billion €), and carbon reduction if wood chips re used for heat and electricity production (million tonne) in Northern Europe, for scenarios with and without use of wood chips, in 2030, plotted against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

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

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

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

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

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

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

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

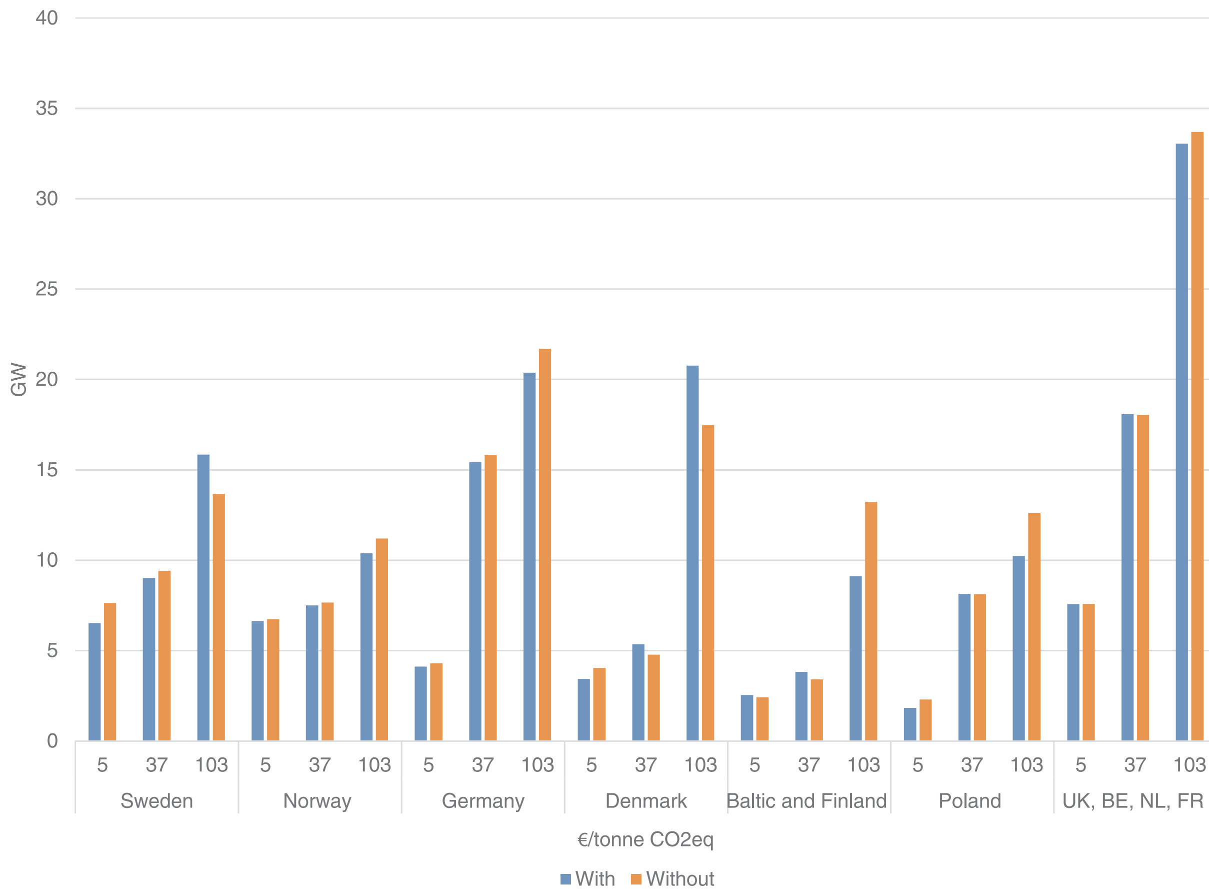

Fig. 8. Investment that exceeds the known planned investment in international cross-border transmission lines in the endogenous transmission investment scenarios in Northern Europe, with and without use of wood chips for selected carbon prices, in 2030.

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

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

5. Conclusion

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

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

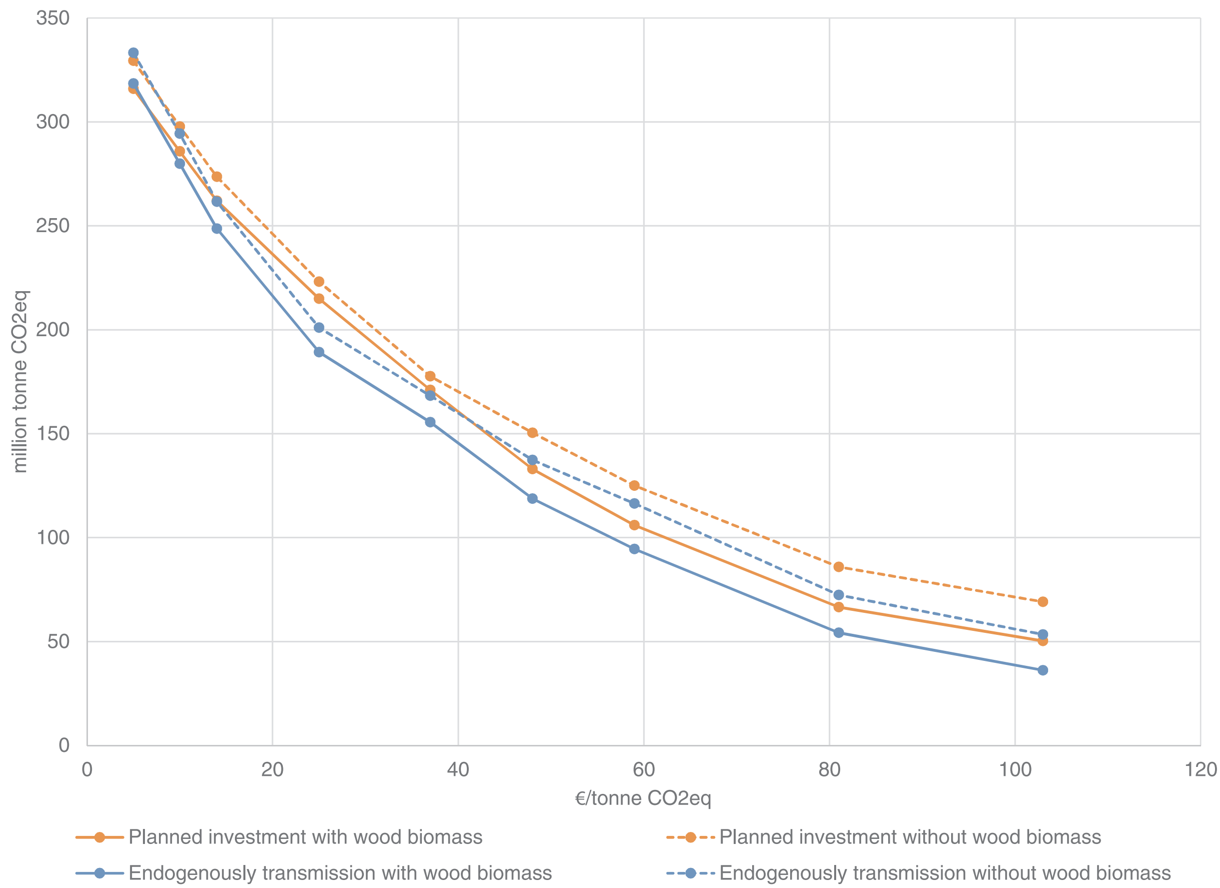

Fig. 9. Modelled total carbon emissions from the energy system if wood chips are included in the system in Northern Europe for the scenario with only planned transmission line investment, with and without wood chips, and endogenous transmission investment, with and without wood chips.

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

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

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

6. Data availability

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

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

Acknowledgement

Funding for this study was provided by the Norwegian Research Council through the 'Norwegian Centre for Sustainable Bio-based Fuels and Energy (Bio4Fuels)' [NRF-257622] and 'The role of bioenergy in the future energy system (BioNEXT)' [NRF-255265].

References

[1] European Commission. Clean energy for all Europeans. Available at: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans; 2019a [accessed: 22.01.19].
[2] EEA. Trends and projections in Europe 2018. EEA Report No 16/2018, 16 (ISBN

978-92-9480-007-7); 2018. doi: https://doi.org/10.2800/931891.
[3] Tveten ÅG, Bolkesjø TF, Martinsen T, Hvarnes H. Solar feed-in tariffs and the merit order effect: A study of the German electricity market. Energy Policy 2013;61:761–70. https://doi.org/10.1016/j.enpol.2013.05.060.
[4] Hirth L, Ziegenhagen I. Balancing power and variable renewables: Three links. Renew Sustain Energy Rev 2015;50:1035–51. https://doi.org/10.1016/j.rser.2015.04.180.
[5] Suškevičs M, Eiter S, Martinat S, Stober D, Vollmer E, de Boer CL, et al. Regional variation in public acceptance of wind energy development in Europe: What are the roles of planning procedures and participation? Land Use Policy 2019;81:311–23. https://doi.org/10.1016/j.landusepol.2018.10.032.
[6] Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? Appl Energy 2019;233–234:1027–50. https://doi.org/10.1016/j.apenergy.2018.08.109.
[7] Szarka N, Scholwin F, Trommler M, Fabian Jacobi H, Eichhorn M, Ortwein A, et al. A novel role for bioenergy: A flexible, demand-oriented power supply. Energy 2013;61:18–26. https://doi.org/10.1016/j.energy.2012.12.053.
[8] IEA. Nordic Energy Technology Perspectives 2016. Available at: http://www.nordicenergy.org/project/nordic-energy-technology-perspectives/; 2016.
[9] Welfle A, Gilbert P, Thornley P, Stephenson A. Generating low-carbon heat from biomass: Life cycle assessment of bioenergy scenarios. J Cleaner Prod 2017;149:448–60. https://doi.org/10.1016/j.jclepro.2017.02.035.
[10] Booth MS. Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. Environ Res Lett 2018;13(3):035001https://doi.org/10.1088/1748-9326/AAAC88.
[11] Searchinger TD, Beringer T, Holtsmark B, Kammen DM, Lambin EF, Lucht W, et al. Europe's renewable energy directive poised to harm global forests. Nat Commun 2018;9(1):3741. https://doi.org/10.1038/s41467-018-06175-4.
[12] Reid WV, Ali MK, Field CB. The future of bioenergy. Glob Change Biol 2020;26(1):274–86. https://doi.org/10.1111/gcb.14883.
[13] Gustavsson L, Truong NL. Bioenergy pathways for cars: Effects on primary energy use, climate change and energy system integration. Energy 2016;115:1779–89. https://doi.org/10.1016/j.energy.2016.04.018.
[14] Dwivedi P, Khanna M, Sharma A, Susaeta A. Efficacy of carbon and bioenergy markets in mitigating carbon emissions on reforested lands: A case study from Southern United States. Forest Policy Econ 2016;67:1–9. https://doi.org/10.1016/j.forpol.2016.03.002.
[15] Guo J, Gong P, Brännlund R. Impacts of increasing bioenergy production on timber harvest and carbon emissions. J Forest Econ 2019;34(3–4):311–35. https://doi.org/10.1561/112.00000500.
[16] Soimakallio S, Saikku L, Valsta L, Pingoud K. Climate change mitigation challenge for wood utilization—the case of Finland. Environ Sci Technol 2016;50(10):5127–34. https://doi.org/10.1021/acs.est.6b00122.
[17] Yan Y. Integrate carbon dynamic models in analyzing carbon sequestration impact of forest biomass harvest. Sci Total Environ 2018;615:581–7. https://doi.org/10.1016/j.scitotenv.2017.09.326.
[18] Holmgren P, Kolar K. Reporting the overall climate impact of a forestry corporation-the case of SCA; 2019.
[19] Rentizelas AA, Li J. Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co-firing. Energy 2016;114:129–42. https://doi.org/10.1016/j.energy.2016.07.159.
[20] Clancy JM, Curtis J, Ó'Gallachóir B. Modelling national policy making to promote bioenergy in heat, transport and electricity to 2030 – Interactions, impacts and conflicts. Energy Policy 2018;123:579–93. https://doi.org/10.1016/j.enpol.2018.08.012.
[21] Khanna M, Dwivedi P, Abt R. Is forest bioenergy carbon neutral or worse than coal? Implications of carbon accounting methods. Int Rev Environ Resour Econ 2017;10(3–4):299–346. https://doi.org/10.1561/101.00000089.
[22] Durusut E, Tahir F, Foster S, Dineen D, Clancy M. BioHEAT: A policy decision support tool in Ireland's bioenergy and heat sectors. Appl Energy 2018;213:306–21. https://doi.org/10.1016/j.apenergy.2017.12.111.
[23] Yang J, Song K, Hou J, Zhang P, Wu J. Temporal and spacial dynamics of bioenergy-related CO2 emissions and underlying forces analysis in China. Renew Sustain Energy Rev 2017;70:1323–30. https://doi.org/10.1016/j.rser.2016.12.031.
[24] Tsiropoulos I, Hoefnagels R, van den Broek M, Patel MK, Faaij APC. The role of bioenergy and biochemicals in CO2 mitigation through the energy system – a scenario analysis for the Netherlands. 2017; 9(9): 1489–1509. doi: https://doi.org/10.1111/gcbb.12447.
[25] Tsiropoulos I, Hoefnagels R, de Jong S, van den Broek M, Patel M, Faaij A. Emerging bioeconomy sectors in energy systems modeling – Integrated systems analysis of electricity, heat, road transport, aviation, and chemicals: a case study for the Netherlands. 2018; 12 (4): 665-693. doi: https://doi.org/10.1002/bbb.1881.
[26] Hagberg MB, Pettersson K, Ahlgren EO. Bioenergy futures in Sweden – Modeling integration scenarios for biofuel production. Energy 2016;109:1026–39. https://doi.org/10.1016/j.energy.2016.04.044.
[27] Szarka N, Eichhorn M, Kittler R, Bezama A, Thrän D. Interpreting long-term energy scenarios and the role of bioenergy in Germany. Renew Sustain Energy Rev 2017;68:1222–33. https://doi.org/10.1016/j.rser.2016.02.016.
[28] Welfle A, Thornley P, Röder M. A review of the role of bioenergy modelling in renewable energy research & policy development. Biomass Bioenergy 2020;136:105542https://doi.org/10.1016/j.biombioe.2020.105542.
[29] Ravn H, Hindsberger M, Petersen M, Schmidt R, Bøg R, Gronheit PE, et al. Balmorel: a Model for Analyses of the Electricity and CHP Markets in the Baltic Sea Region (2001); 2001. Available at: http://www.balmorel.com/index.php/balmorel-documentation.
[30] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strategy Rev 2018;20:26–34. https://doi.org/10.1016/j.esr.2018.01.003.
[31] Github Repository. balmorelcommunity, Balmorel. Available at: https://github.com/balmorelcommunity/balmorel; 2019 [accessed: 21.06.19].
[32] World Nuclear Association. Nuclear Power in Belgium. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/belgium.aspx; 2019a [accessed: 13.05.19].
[33] World Nuclear Association. Nuclear Power in the European Union. Available at: http://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx; 2019b [accessed: 13.05.19].
[34] NordPool. Historical Market Data. Available at: http://www.nordpoolspot.com/historical-market-data/; 2018 [accessed: 16.08.2018].
[35] Eurostat. Volume of timber (source: FAO - FE) [for_vol]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=for_vol&lang=en; 2019c [accessed: 09.05.19].
[36] Eurostat. Roundwood, fuelwood and other basic products [for_basic]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do; 2019a [accessed: 07.05.19].
[37] European Commission. Renewable energy directive. Available at: https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive; 2019b [accessed: 22.01.19].
[38] Serrano GdA, Sandquist J. Comparative analysis of technologies for liquid biofuel production from woody biomass. In: Sintef (ed.). Trondheim, Norway: Sintef; 2017.
[39] Chen YK, Hexeberg A, Rosendahl KE, Bolkesjø TF. Long-term trends of nordic power market: A review. Wiley Interdiscip Rev: Energy Environ 2020. [submitted for publication].
[40] Eurostat. Supply, transformation and consumption of oil and petroleum products [nrg_cb_oil]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_cb_oil&lang=en; 2019a [accessed: 14.05.19].
[41] Birdsey R, Duffy P, Smyth C, Kurz WA, Dugan AJ, Houghton R. Climate, economic, and environmental impacts of producing wood for bioenergy. Environ Res Lett 2018;13(5):050201https://doi.org/10.1088/1748-9326/AAB9D5.
[42] Gustavsson L, Haus S, Ortiz CA, Sathre R, Truong NL. Climate effects of bioenergy from forest residues in comparison to fossil energy. Appl Energy 2015;138:36–50. https://doi.org/10.1016/j.apenergy.2014.10.013.
[43] Laganière J, Paré D, Thiffault E, Bernier PY. Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. GCB Bioenergy 2017;9(2):358–69. https://doi.org/10.1111/gcbb.12327.
[44] McKechnie J, Colombo S, Chen J, Mabee W, MacLean HL. Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environ Sci Technol 2011;45(2):789–95. https://doi.org/10.1021/es1024004.
[45] Sandbag. EUA Price Available at: https://sandbag.org.uk/carbon-price-viewer/; 2019 [accessed: 07.06.19].
[46] Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33. https://doi.org/10.1016/j.rser.2017.03.114.
[47] Brown TW, Bischof-Niemz T, Blok K, Breyer C, Lund H, Mathiesen BV. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'. Renew Sustain Energy Rev 2018;92:834–47. https://doi.org/10.1016/j.rser.2018.04.113.
[48] Energistyrelsen. Teknologikataloger. Available at: https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger; 2020.
[49] AGFW. AGFW-Hauptbericht 2016. Available at: https://www.agfw.de/zahlen-und-statistiken/agfw-hauptbericht/; 2016.
[50] AGEB. Energieverbrauch in Deutschland im Jahr 2016. Available at: https://www.ag-energiebilanzen.de/; 2017.
[51] FAOSTAT. Forestry Production and Trade. Available at: http://www.fao.org/faostat/en/#data/FO; 2019 [accessed: 08.02.19].