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Bioenergy futures in Sweden – Modeling integration scenarios for biofuel production

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ABSTRACT

Use of bioenergy can contribute to greenhouse gas emission reductions and increased energy security. However, even though biomass is a renewable resource, the potential is limited, and efficient use of available biomass resources will become increasingly important. This paper aims to explore system interactions related to future bioenergy utilization and cost-efficient bioenergy technology choices under stringent CO_2 constraints. In particular, the study investigates system effects linked to integration of advanced biofuel production with district heating and industry under different developments in the electricity sector and biomass supply system. The study is based on analysis with the MARKAL_Sweden model, which is a bottom-up, cost-optimization model covering the Swedish energy system. A time horizon to 2050 is applied. The results suggest that system integration of biofuel production has noteworthy effects on the overall system level, improves system cost-efficiency and influences parameters such as biomass price, marginal CO_2 emission reduction costs and cost-efficient biofuel choices in the transport sector. In the long run and under stringent CO_2 constraints, system integration of biofuel production has, however, low impact on total bioenergy use, which is largely decided by supply-related constraints, and on total transport biofuel use, which to large extent is driven by demand.

1. Introduction

An increased share of renewable energy in the energy system is critical to mitigate climate change as well as to handle other energy-related environmental challenges. For many countries and regions, renewable energy is also a way to improve energy security of supply through a more diversified energy mix and less reliance on imported energy carriers. Bioenergy is currently the largest source of renewable energy [21], and a further future increase in bioenergy demand is likely with increasingly ambitious climate and energy security targets. But even though biomass is a renewable resource, the annual potential is limited due to land scarcity. Efficient use of available biomass resources will thus be increasingly important.

Several potential future technologies, currently at the stage of research and development or early commercialization, have the ability to significantly increase the value and efficiency of bioenergy utilization. Advanced biorefineries based on conversion of lignocellulosic biomass to high value energy carriers such as transport fuels could be one key option. In contrast to *first-generation biofuels*, which primarily are based on traditional food crops, *second-generation biofuels* can be based on by-products from forestry and high yield energy crop alternatives, such as energy forest. Since second-generation biofuel production processes often have a relatively large net surplus of heat, integration with heat demands in district heating systems and/or existing industry can further increase the system efficiency and lower the costs (see e.g. Refs. [1,25]).

New advanced biorefinery technologies are linked to substantial development and capital costs. Further, integration of newly developed technologies in, e.g., industrial applications could imply risks for commercial activities. As a consequence, few actors are willing to take on necessary investments unless policies are in place ensuring long-term societal commitment for environmental targets and related initiatives. In turn, policymakers are in need of decision

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support for creation of long-term strategies leading in a beneficial direction for society. In addition to detailed technology assessments (e.g., on plant level), system analyses of potential technology options and identification of future cost-efficient technology pathways are therefore essential to enable future environmental and societal challenges to be met. While such studies involve broad approaches and aggregated views of the system, the risk of over-simplification of the representation of the underlying technological solutions must be carefully considered.

While it has been shown that the stringency of carbon targets is a significant determinant for future bioenergy utilization (e.g., Ref. [8]), the cost-effectiveness of different types of bioenergy utilization is likely to also depend on several other factors in the surrounding system. Factors of importance can be both of a direct and indirect character. For instance, changes in biomass supply and development of new bioenergy technologies may have a direct effect on the future bioenergy utilization, but also the development of competing non-bioenergy based technologies can have significant impacts. Through effects on biomass markets, seemingly unlinked developments in other parts of the energy system can give rise to system impacts over sector boundaries. The system dynamics are complex, and different factors can amplify as well as offset each other depending on the specific system situation and direction of change.

This paper aims to explore system interactions related to future bioenergy utilization and robust cost-efficient bioenergy technology strategies for the case of Sweden. Specifically, the study investigates possibilities for increased bioenergy conversion efficiencies through integration of advanced biofuel[1] production with district heating or industrial systems, and system effects of different developments in the electricity sector and biomass supply system. The main questions of investigation are:

- Under stringent CO_2 constraints, how can integration of second-generation biofuel production with existing industry or district heating systems influence future cost-efficient biomass utilization?
- To what degree is the biomass supply potential a critical determinant for cost-efficient biomass utilization in the medium to long term?
- How do large transitions in the electricity sector linked to non-biomass low-carbon electricity supply (e.g., nuclear power) and demand for electricity (e.g., through electricity export) impact cost-efficient biomass utilization?

The study is based on an energy system modeling approach applying a comprehensive view of the Swedish energy system and a long-term time horizon to 2050. It builds upon earlier work focused on the bioenergy system effects of CO_2 and fossil fuel reduction [8].

Broad, bottom-up energy system modeling studies, e.g., on national or global level, such as Refs. [7,8,16,28,35]; often have a comparably large selection of different types of energy technologies represented. However, while there are exceptions, focus is often put on stand-alone plants rather than integrated solutions with possibilities of higher system efficiencies. Further, much attention is often given to a relatively low number of future scenarios, which under certain conditions may be optimal from a cost perspective, but from other aspects (e.g., social, political, industry strategy-wise) might be unlikely. As previously highlighted (see e.g., Refs. [36,37,5,6]), it is of importance to utilize models not only to establish single optimal solutions but through parameter variations and broader set of assumptions analyze lessons to be learned of the dynamics of the studied systems and of alternative, "near-optimal" system developments.

In contrast to system studies at higher geographical scale, studies at a lower system level (plant level, etc.) could to a higher degree go into technological details regarding advanced bio-refineries and integration opportunities with other energy conversion systems, e.g., in industries, examples include Refs. [1,10,12,22]. However, such studies tend to have a strong dependence of exogenous scenario assumptions regarding, e.g., energy prices and marginal effects and they lack ability to capture system effects and interactions linked to biomass use at a higher system level.

This study seeks to bridge the gap between, on the one hand, high system level studies with lack of technological detail in regard to future options for advanced biomass use and, on the other hand, lower system level studies with simplified treatment of the dynamics of the surrounding system development.

2. Method and data

In the following sections, the model-based analysis approach and relevant input data are presented. Section 2.1 provides a brief description of the model; Section 2.2 presents the analysis approach applied as well as definition of model cases and scenario assumptions; Sections 2.3 presents technology data assumptions of special relevance for the study.

2.1. Model

The study is based on analysis with the MARKAL_Sweden energy system model. MARKAL_Sweden is an application of the well-established MARKAL model [26] and can be described as a dynamic, bottom-up, partial equilibrium energy system model. Through optimization, the model provides the overall welfare-maximizing system solution that meets the defined model constraints over the studied time horizon. Welfare-maximization implies that the cost of energy service supply and costs due to losses in consumer surplus are minimized. An important aspect is the models ability to invest in new technology capacity among the defined current and future technology options, if this lowers the overall system cost. Among other aspects, model constraints include energy service demands, emission restrictions and capacity constraints in supply and conversion technologies. Different versions of the MARKAL_Sweden model have been used in several earlier studies. The most recent, which the current study builds upon and from which additional model descriptions (and results) can be obtained, are Refs. [7,8].

MARKAL_Sweden applies a long-term time horizon reaching from 1995 to 2050.[2] The time horizon is divided in 5-year model periods, each represented by a model year (1995, 2000, …, 2050). Time resolution per model year differs between energy carriers: electricity is represented by three seasonal and two diurnal periods, heat is represented by three seasonal periods, and other energy carriers are represented on an annual basis. The model applies perfect foresight (no uncertainty of future developments) and, in the current study, a discount rate of 6% is applied.[3]

[1] The term *biofuel* is here used to denote biomass-based transport fuels (liquid or gaseous).

[2] Model costs are given in the monetary value of 2010. An exchange rate between Swedish Krona (SEK) and Euro (EUR) of 9 SEK/EUR is used.

[3] The discount rate has in the model no effect on the rate of CO_2 reductions in the system as this is handled through emission constraints for each respective model year (see Section 2.2). The chosen discount rate level is within the range commonly used in energy system modeling, although in the upper part of this range in order not to exaggerate the willingness to invest in capital intensive technologies.

The model applies a comprehensive view of the Swedish energy system and describes all relevant sectors including electricity, district heating, industry, transport, premises and services. The system is represented as a network of energy technologies and flows of energy carriers, covering fuel extraction and import, via energy conversion technologies and distribution systems to end-use energy demands, such as for transportation, space heat and industrial process heat. Technological learning is treated exogenously in the model, i.e., enhancement in technological features or lowering of technology costs are for relevant technologies assumed as a function of time.

Technology input data to the model include technology properties such as current capacities, investment costs, operation costs and conversion efficiencies for energy technologies in all parts of the national energy system. Reference projections for end-use energy service demands are inputs to the model, but own-price elasticity is applied for end-use demands making the resulting final demand levels scenario dependent (see also Ref. [8]). Input data also include prices for imported energy carriers and extraction costs and potentials for domestic energy resources, such as biomass.

2.2. Analysis approach and scenario assumptions

We study a selection of diverging developments of potentially critical factors for future bioenergy utilization. The identified factors are linked to options for increased bioenergy system efficiency through system integration of second-generation biofuel production (2.2.1), biomass supply (2.2.2) and transitions in the electricity system (2.2.3). For each factor, we define two contrasting developments, which we test in different combinations in multiple model runs (2.2.4). For transparency in analysis and results, a clear-cut division between the alternative developments are applied ("yes" or "no"), while acknowledging that a middle way development could be more likely in some cases. For each model case, we study the effects on relevant result parameters with focus on: total biomass utilization, production/use of biofuels, production of biomass-based electricity, and shadow prices (marginal costs) for biomass and CO_2.

Apart from the strategy directions captured in the different model cases, all model cases apply the same policy situation, which for transparency reasons is greatly stylized compared to the flora of energy taxes and subsidies present in Sweden today. In the model, energy policies are principally limited to a CO_2 emission cap, which forces the CO_2 emissions in the Swedish energy system to be reduced by 80% from 1990 levels by 2050. The emission cap is gradually decreased from 2015 to 2050 in a linear manner. It is applied on the modeled system as a whole and no sector-specific emission restrictions are applied.

Assumptions on fossil fuel import prices are kept the same across all modeled cases, see Table 1. Since a national model is used, and Sweden has no domestic fossil fuel resources, fossil fuel prices are handled exogenously as inputs to the model. The availability of fossil fuels is considered "unlimited" for the studied system at the assumed market prices. However, the fossil fuel use is strongly indirectly constrained by the applied CO_2 emission constraint.

Table 1
Assumed fossil fuel prices at the border (EUR/MWh).

	2020	2030	2050
Crude oil	44.1[a]	44.1[a]	44.1[a]
Natural gas	30.1	30.4	31.3
Coal	9.2	8.1	6.6

Based on 450 scenario of World Energy Outlook 2010 [20] up to model year 2035 and kept constant for remaining time horizon.
[a] Equivalent to about USD 90/barrel.

2.2.1. Options for integrated biofuel production

Second-generation biofuel production processes often have a relatively large net surplus of heat. Integration of second-generation biofuel production with available heat demands could therefore improve the total system efficiency. However, such integration requires coordination and agreements between heat producers and fuel producers as well as placement of biorefineries adjacent to heat sinks, which may not always be optimal or achievable. The following contrasting development routes are therefore investigated regarding integration opportunities for second-generation biofuel production:

- *HEATINT-NO:* Second-generation biofuel production can only be invested in as stand-alone plants.
- *HEATINT-YES:* Second-generation biofuel production can be invested in both with and without connection to district heating and existing industry.

Black liquor gasification in the pulp and paper industry can be considered as a special case of industry integration and is handled as a separate option. Black liquor is an intermediate by-product in chemical pulp production, and is today used for process heat and electricity generation. Gasification of the black liquor for production of transport fuel (and/or increased electricity) could be a way to make better use of the resource. The process will not only imply heat integration with the pulp mill, it is also required to regenerate cooking chemicals (see further Section 2.3.2) and will thus to a larger extent be part of the mill process than if solid biomass gasification would be heat integrated to the mill.

Even if the development of black liquor gasification technologies would be successful, it is not obvious that the pulp and paper industry would choose such investment options – conventional technologies, safety of operation and the core business focus may be the industry's main priority. We therefore model two contrasting development routes:

- *BLG-NO:* Black liquor gasification technologies are not available as investment options.
- *BLG-YES:* Black liquor gasification technologies are considered possible investment options and are invested in if they lead to lower system cost than the alternatives.

Both regarding stand-alone and integrated plants, a number of different potential technology configuration alternatives and transport biofuel outputs are considered in the modeling (technology alternatives and data assumptions are presented in Section 2.3).

2.2.2. Biomass supply transitions

The amount of biomass available for energy purposes depends on several factors such as the total amount of biomass available, the development of the energy sector as well as of industry sectors using biomass as raw material or feedstock. For a national energy system, bioenergy supply depend both on availability of domestic resources and import possibilities.

Sweden is a forest-rich country with large per-capita biomass resources. Currently, Sweden is also an importer of bioenergy with annual imports estimated to 5–9 TWh (e.g., biopellets/briquettes and ethanol) [33]. To what extent, and to what price, biomass imports will be possible in the future is uncertain and depends, among other things, on the ambitiousness for greenhouse gas emission reductions on a global scale. To test the impact of different levels of future biomass supply available for energy purposes, we apply two diverging development paths for bioenergy imports:

- *BIOIMP-NO:* Import of bioenergy is not an option – biomass supply potential is based on estimations of domestic resources only.
- *BIOIMP-YES:* Biomass supply potential is based on domestic estimations of resources and the assumption that bioenergy imports could increase considerably (in particular bio pellets/briquettes, but also some amounts of ethanol and oilseeds).

Table 2 summarizes assumptions on bioenergy supply used in the study (for both BIOIMP-NO and BIOIMP-YES cases). The main domestic sources for bioenergy are forestry residues, industrial by-products and energy crops. For energy crops about 20% of the existing agricultural land in Sweden is here assumed to be available for energy crop cultivation (including energy forest). The domestic bioenergy potentials summarized in Table 2 are in the model represented with detailed supply curves, see also Ref. [8].

2.2.3. *Electricity system transitions*

To study the effects of large transitions in the electricity sector linked to (non-biomass-based) low-carbon electricity production as well as electricity demand, we define different developments for nuclear power generation and electricity export potentials.

The future of nuclear power depends to high degree on political decisions and the public opinion. In Sweden, nuclear power currently accounts for about 40% of the power generation [33], but whether current generation capacity will be replaced when the plants approach their technical lifetime is highly uncertain. While the Swedish ban on construction of new nuclear power has been removed [34], the political support for such investments are still low. Two alternative developments are tested:

- *NEWNUC-NO:* Existing capacity of nuclear power is phased-out with start from 2025 and fully achieved by 2035. No new investments in new capacity are allowed.
- *NEWNUC-YES:* Existing capacity is kept for its full technical lifetime and investments in new nuclear power to replace retired plants are allowed as well as a slight capacity increase.

Sweden and its Nordic neighbors are often described as a future potential exporter of electricity to continental Europe. This is, among other things, based on good conditions for renewable power generation in the region, such as hydro and wind power. Future possibilities and potentials for electricity export are, however, not obvious and depend also on the development in the importing countries. Two alternative routes are simulated:

- *ELEXP-NO:* No electricity export (for future years).
- *ELEXP-YES:* Unconstrained electricity export.

The export price of electricity is (in the same manner as fossil fuel import) handled with exogenously assumed prices, see Table 3. Electricity prices are calculated based on variable costs of power generation from for coal power and NGCC including fuel costs and CO_2 penalty (for the international electricity sector). For each year and season, the lowest cost alternative of these two options is chosen. Fossil fuel price assumptions are according to Table 1, and CO_2 penalties are assumed to rise from 40 EUR/ton in 2020 to 100 EUR/ton in 2035–2050 (based on CO_2 prices in the 450 scenario of [20]).

Table 2
Overview of costs and potentials for biomass available for energy resources in the model. Bioenergy imports are only available in the BIOIMP-YES cases.

	Potential [TWh/year]		Costs [EUR/MWh]
	2030	2050	
Domestic bioenergy (BIOIMP-YES & NO)			
Forest residues – tops and branches	14.0	17.1	14–30
Forest residues – stumps	18.1	21.3	19–40
Pulpwood, excl. bark	1.9 (74)[a]	9.4 (81)[a]	17–25
Energy crop – alternatives[b]			
Energy forest	17.1	17.1	17–80
Cereal crops	11.2	11.2	31–76
Ley/Grass crops	14.4	14.4	23–25
Oil seed crops	2.5	2.5	42–50
Straw	3	3	10
Organic waste	11	11	0–6
Industrial wood waste	27	27	0–5
Industrial liquors (black liquor)	50	50	–
Recovered wood	3	3	7
Firewood (single family houses)	11	11	1.5
Bioenergy imports (BIOIMP-YES)			
Import – wood pellets/briquettes	25	40	39
Imports – ethanol	3.4	3.4	74
Imports – oilseeds	1	1	42

Based on earlier published data and assumptions, see Börjesson et al. (in press) and references therein. Presented data apply for the entire modelled time horizon.

[a] Potentials without brackets refer to amounts available over and above the domestic pulpwood use in the pulp and paper industry for the assumed reference demand projection, i.e. resources which could be used for energy purposes without influencing feedstock supply to pulp and paper industry. Potentials within brackets refer to the full domestic pulpwood potential.

[b] Since energy crop alternatives compete for the same available agricultural land, 600,000 ha (about 20% of total in country), the full potentials of each energy crop alternative are not addable. However, different parts of the available agricultural land can be used for different crops.

2.2.4. *Summary of model cases*

To summarize, the analysis covers different developments of five factors with direct or indirect influence over future bioenergy use in the Swedish energy system:

(1) Second-generation biofuel production with heat integration (HEATINT);
(2) Second-generation biofuel production via black liquor gasification in the pulp and paper industry (BLG);
(3) Bioenergy import (BIOIMP);
(4) Nuclear power generation (NEWNUC); and
(5) Electricity export (ELEXP).

Under the assumption of stringent CO_2 constraints we investigate the influence of two diverging developments ("yes" or "no") for each of these five factors. To capture incremental system effects and interactions, we apply an approach with multiple model runs in which all combinations of the defined contrasting developments of the studied factors are tested. Five factors and two development paths per factor add up to a total of 32 model cases.

Table 3
Assumed international electricity prices for electricity export (EUR/MWh).

	2020	2030	2050
Winter	71	83	88
Spring/Autumn	62	87	88
Summer	55	87	88

2.3. Technology representation

The model includes representation of a large number of energy technologies in all parts of the energy system, current energy routes as well as potential future options. In the present work, special focus is given to technologies of relevance for biomass competition. The representation of different plant configurations for second-generation biofuel production and heat integration possibilities for such plants is presented in Section 2.3.1. The model representation of the integration possibilities in the pulp and paper industry is presented separately in Section 2.3.2. An overview of the model representation of heat and power technologies, including biomass-based options, is presented in Section 2.3.3.

2.3.1. Stand-alone and heat-integrated biofuel production options

In addition to fossil fuel options and electricity, the model includes a number of biofuels for the transport sector: ethanol, biodiesel, biogas, methanol, DME (dimethyl ether), FT (Fischer-Tropsch) liquids and SNG (synthetic natural gas). The transport subsectors using these fuels are represented by different end-use categories. For the road transport end-use categories (passenger cars, motorcycles, light trucks, heavy trucks and buses), the model includes a detailed representation of different vehicle technologies, including options such as hybrids, plug-in hybrids, and battery-powered electric vehicles as well as a large number of combinations of vehicle technologies and different transport fuels (see Ref. [7]). For other transport end-use categories (aviation, shipping, and working machines), the model has a simplified representation and a limited number of biofuel options (basically limited to FT-liquids and biodiesel).

The model includes a number of possible plant configurations for biofuel production, also for the same biofuel. Plant configuration differences include different degree of heat integration with industry and district heating systems, and, where applicable, the option of generation of more than one fuel in order to maximize efficiency. Table 4 presents the biofuel production technologies available in the model (excluding black liquor gasification options, which are presented in Section 2.3.2) and main input data for these. In line with the analysis approach (outlined in Section 2.2), not all options are available in all model runs (plants with heat integration are only included options in "HEATINT-YES"-cases; stand-alone plants are included in all cases).

2.3.2. Pulp and paper industry and black liquor gasification

Sweden has a large pulp and paper industry, which is a major user of biomass, both for feedstock and energy purposes. The sector can be divided in two main production routes, mechanical and chemical pulping.

Black liquor is an intermediate by-product in the chemical pulping process, which accounts for a large share of the chemical pulping industry's energy use. Today, the black liquor is combusted in the so-called recovery boiler of the mill for production of process

Table 4
Costs and energy balances for biofuel production technologies (excluding black liquor gasification-based options, see Table 5).

Type of fuel production	Type of feedstock	Energy input and output relations				Total efficiency[b]	Investment cost[c]
		Biomass (In)	Electricity (Net out)	Transport fuel(s) (Out)	Heat[a] (Out)		(MEUR/MW)
Stand-alone plants (HEATINT − YES & NO)							
Ethanol[f]	Wheat, etc.	1.0 + 0.23[e]	−0.06	0.55		0.43	0.9
Biodiesel[g]	Oilseeds	1.0 + 0.05[e]	−0.03	0.60		0.55	1.2
Biogas[h]	Org. waste, etc.	1.0	−0.08	0.57		0.53	1.4
MeOH[i]	Wood	1.0	−0.01	0.51		0.51	1.8
DME[i]	Wood	1.0	−0.04	0.59		0.57	1.7
FTD + FTG[i]	Wood	1.0	−0.01	0.33 + 0.12		0.44	2.2
SNG[j]	Wood	1.0	0.06	0.70		0.76	1.5
EtOH + Biogas[k]	Straw	1.0	0.07	0.30 + 0.11		0.48	1.2
EtOH[k]	Straw	1.0	0.06	0.47		0.56	1.2
EtOH[l]	Wood	1.0	0.13	0.34		0.47	2.1
EtOH + Biogas[l]	Wood	1.0	0.05	0.34 + 0.25		0.63	2.1
Plants with heat integration (HEATINT − YES)							
MeOH[i]	Wood	1.0	−0.02	0.51	0.12	0.61	1.8
DME[i]	Wood	1.0	−0.05	0.59	0.11	0.67	1.7
FTD + FTG[i]	Wood	1.0	−0.08	0.33 + 0.12	0.26	0.66	2.2
SNG[j]	Wood	1.0	0.04/0.02[d]	0.70	0.07/0.09[d]	0.81	1.5
EtOH + Biogas[k]	Straw	1.0	0.07	0.30 + 0.11	0.22	0.71	1.2
EtOH + Biogas[k]	Straw	1.0	0.05	0.47 + 0.03	0.15	0.70	1.2
EtOH[l]	Wood	1.0	0.12	0.34	0.40	0.85	2.1
EtOH + Biogas[l]	Wood	1.0	0.05	0.34 + 0.25	0.22	0.85	2.1

Efficiencies are based on LHV (lower heating value). Additional costs incorporated in the model include fixed O&M (operation and maintenance) costs of 3–4.5% of the investment cost annually and variable O&M of 1.5 EUR/MWh of fuel input. For several of the plant options, scaling is carried out when establishing the IC from based on references. The relationship Cost_2 = Cost_1*(Size_2/Size_1)^α and scaling factor α = 0.65 have been used. Presented data apply for the entire modelled time horizon.

[a] Heat delivery to district heating systems or as process heat to industry.
[b] Total efficiency = (Transport fuel_out + Electricity_out + Heat_out)/(Biomass_in + Electricity_in).
[c] Investment cost is given as cost per unit of feedstock input capacity and is based on assumptions of: 300 MW_input capacity for wood-based processes, biodiesel and first-generation ethanol production; 150 MW_input capacity for straw-based ethanol; 8 MW_input capacity for biogas production based on organic waste.
[d] District heat integration and industry process heat integration, respectively.
[e] Feedstock + process energy.
[f] Data are based on: EB (Energy balance), Ref. [9]; IC (Investment cost), Refs. [14,24].
[g] Data are based on: EB, Ref. [9]; IC, Ref. [15].
[h] Data are based on: EB, Ref. [9]; IC, Refs. [5,6].
[i] Data are based on: EB, Refs. [13,22,23]; IC, Ref. [13].
[j] Data are based on: EB, Ref. [18]; IC, Refs. [13,19].
[k] Data are based on: Ref. [14].
[l] Data are based on: EB, Refs. [2,24]; IC, Refs. [14,17,24].

heat and electricity. The recovery boiler also recovers the cooking chemicals in the black liquor required in the pulping process. Alternative technology options for future handling of the black liquor include gasification. Black liquor gasification units recover chemicals for the pulping process (as conventional recovery boilers) and gasify the black liquor into a syngas, which can be further processed into transport biofuels (or used for electricity generation).

In order to represent investments within the pulp and paper industry in an appropriate way, a comparably low level of aggregation is required. In the present study, the pulp and paper industry is disaggregated into the following sub-sectors: market chemical pulping, integrated chemical pulping, market mechanical pulping, integrated mechanical pulping, and paper production. In each subsector, relevant energy conversion technologies are represented (both current and potential investment options). The disaggregation allows more accurate technology representation since different technologies are relevant for different parts of the sector.

Fig. 1 presents a (simplified) overview of the chemical pulping sector representation in the model with investment options for biofuel production indicated. The end-use demands of the sector are divided in energy (electricity, process heat and direct fuel use), pulpwood and cooking chemicals. Black liquor could be used in the conventional way in recovery boilers or, alternatively, the model can choose to invest in gasification units, which will also supply the required cooking chemicals for the pulping process. As described

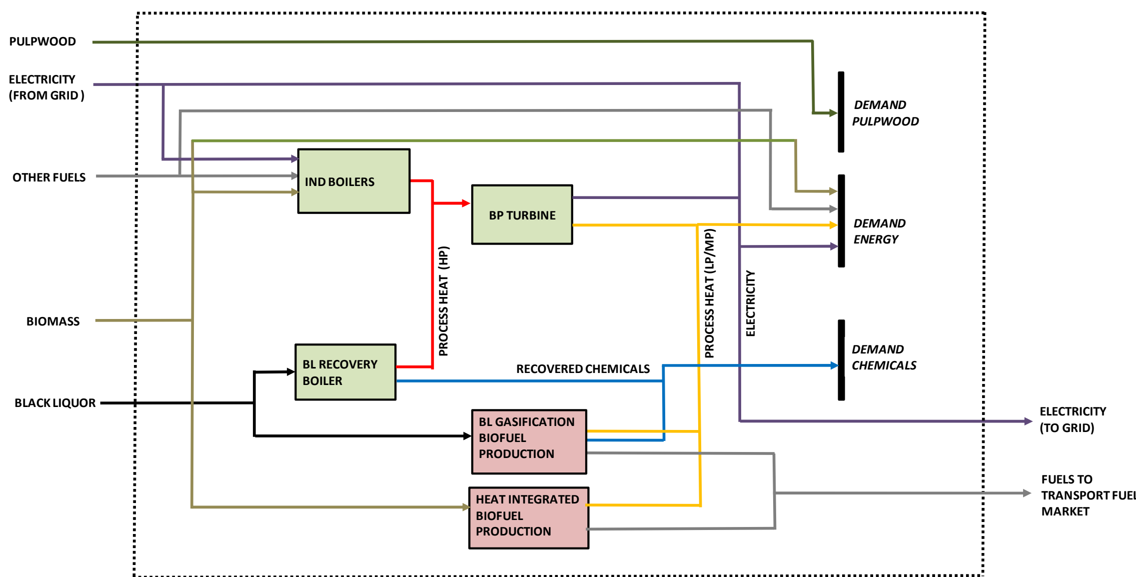

Fig. 1. Simplified overview of the model representation of the chemical pulp sector with investment opportunities for integrated biofuel production.

Table 5
Costs and energy balances for the main pulp and paper industry related processes in the model (for biofuel production with heat integration, see Table 4).

Type of process	Type of fuel/feedstock	Energy input and output relations				Total efficiency	Investment cost[a]
		Fuel (In)	Electr. (Net out)	Trans-port fuel (Out)	Process heat[b] (Out)		(MEUR/MW)
Boilers							
Industrial boiler[c]	Wood fuel/Peat	1.0	–	–	0.9 (HP)	0.90	0.8
Industrial boiler[c]	Coal	1.0	–	–	0.9 (HP)	0.90	0.7
Industrial boiler[c]	Fuel oil/ Natural gas	1.0	–	–	0.9 (HP)	0.90	0.1
Industrial boiler[c]	Electricity	1.0	–	–	1.0 (HP)	1.0	0.1
Recovery boiler[c]	Black liquor	1.0	–	–	0.9 (HP)	0.90	0.7
Turbines							
ST BP – existing stock	Steam (HP)	1.0	0.11	–	0.89 (LP)	1.0	–
ST BP – new[c]	Steam (HP)	1.0	0.22	–	0.78 (LP)	1.0	0.3
Gasification plants							
BLG CC CHP[d]	Black Liquor	1.0	0.38	–	0.34 (LP)	0.72	1.2
BLG MeOH[e]	Black liquor	1.0	−0.07	0.56	0.27 (LP)	0.77[b]	1.3
BLG DME[e]	Black liquor	1.0	−0.07	0.57	0.26 (LP)	0.76[b]	1.3
BLG FT liquids[e]	Black liquor	1.0	−0.07	0.45	0.28 (LP)	0.69[b]	1.6

Efficiencies are based on LHV (lower heating value). Additional costs incorporated in the model include fixed operation and maintenance (O&M) costs of 2% (for conventional technologies) and 4.5% (for black liquor gasification technologies) of the investment cost annually and variable O&M of 1.5 EUR/MWh of fuel input. Presented data apply for the entire modelled time horizon. Acronyms: BLG, black liquor gasification; BP, back-pressure; ST, steam turbine; HP, High pressure; LP, low pressure; CC, combined cycle.
[a] Specific investment cost given as cost per unit of feedstock input capacity.
[b] Total efficiency = (Transport fuel_out + Electricity_out + Heat_out)/(Biomass_in + Electricity_in).
[c] Data are based on: Refs. [11,12].
[d] Data are based on: EB (Energy balance), Ref. [27]; IC (Investment cost), Ref. [30].
[e] Data are based on: EB, Ref. [12]; IC, Refs. [12,13,31].

earlier (Section 2.3.1), there is also the possibility of heat integration of other biofuel production technologies. A certain level of competition for pulpwood between pulp and paper industry and the energy sector is included in the model (for more information on this, see Ref. [8]). Table 5 gives an overview of main input data for energy technologies related to the pulp and paper sector of the model.

2.3.3. Heat and electricity generation

MARKAL_Sweden includes a large number of technologies in the electricity and district heating sectors. Table 6 gives an overview of assumed properties of the most relevant technology options. Of special interest for the study are biomass-based options and nuclear power. In addition to conventional biomass-fueled power and CHP (combined heat and power) generation based on steam turbine cycle, biomass gasification-based options are also included. As pointed out in Section 2.2.3, investment of new nuclear power capacity is not an option in all model cases (only in NEWNUC-YES cases).

3. Results

In the following sections, the results generated by the model are presented. The effects on future bioenergy utilization from integrated biofuel production, electricity system transitions and biomass imports are here looked upon from different perspectives; in Section 3.1, from an overall system perspective; in Section 3.2, from a transport sector perspective; and in Section 3.3 from an electricity sector perspective. Further, Section 3.4 presents resulting developments of biomass prices and marginal costs of CO_2 emission reductions. Section 3.5 summarizes and gives an overview of the effects on main result parameters from the various input data variations captured in the modeled cases.

3.1. Overall bioenergy utilization

The model results show a significant increase in biomass use for energy purposes under the studied time horizon for all modeled cases. This is expected considering the stringent CO_2 constraint applied. Fig. 2 presents biomass use for heat, electricity and transport fuel production in (a) 2035 and (b) 2050. For cases without the possibility of bioenergy import (BIOIMP-NO), the total bioenergy use increases with 50–56% to model year 2035 and 71–75% to model year 2050 compared to year 2010. The total bioenergy use varies between cases in a small range, and the utilization is for all cases close to the full bioenergy potential (as defined in Table 2). When bioenergy import is allowed (BIOIMP-YES), this option is to large extent utilized, in particular in the later part of the studied period when the demand for low-carbon options is high. The increase in total bioenergy use for BIOIMP-YES cases is 50–75% to 2035 and 106–110% to 2050 compared to 2010.

In model year 2035, conventional bioenergy technologies for heat-only production and CHP generation account for a large share of the bioenergy use, 64–86% depending on case. First-generation biofuel production accounts for about 8–11% of total bioenergy use (to large extent organic waste used for biogas production). The share of bioenergy for production of second-generation biofuels is 4–27%. Black liquor gasification-based biofuel production shows in 2035 already significant production levels in relevant cases (BLG-YES). For cases without the option of black liquor gasification (BLG-NO), second-generation biofuel production is at this point increasing but still on comparably low levels.

In model year 2050, a significant increase in biomass use for second-generation biofuel production plants has occurred. At this point, this share corresponds to 30–48% of total bioenergy use. First-generation biofuel production is close to the levels in 2035, while more conventional use of bioenergy has decreased to a share of 43–61%.

Second-generation biofuel production with heat integration is preferred over stand-alone options, which can be observed by the shift in Fig. 2 from cases when heat integration is not an option (HEATINT-NO), to cases when it is an option (HEATINT-YES). First, heat integration with industrial process heat demands is chosen and, second, integration with district heating systems. As a consequence, the use of, in particular, industrial biomass CHP plants is lower in heat integration cases (HEATINT-YES) than in

Table 6
The most relevant electricity, CHP and HOB (heat-only boiler) technologies available in model and related assumptions on cost and energy performance data.

Type	Energy input and output relations			Total efficiency	Investment cost		Operation & maintenance	
	Fuel (In)	Electr. (Net out)	Heat (Out)		($MEUR/MW_e$)	($MEUR/MW_f$)	Fixed (%)	Variable (EUR/MWh_e)
Electricity								
Bio ST condensing	1.0	0.36	–	0.36	2.4	0.9	2	4.2
Bio IGCC condensing	1.0	0.48	–	0.48	2.4	1.2	4.5	3.1
NGCC condensing	1.0	0.58	–	0.58	0.8	0.5	3	2.8
Coal ST condensing	1.0	0.45	–	0.45	1.7	0.8	2	3.3
Nuclear power	1.0	0.36	–	0.36	4.2	1.5	–	12
Wind power	–	–	–	–	1.3–2.7	–		15–19
Hydro power – large	–	–	–	–	2.2	–	–	11
Hydro power – small	–	–	–	–	2.8	–	–	14
CHP (district heating)								
Bio ST CHP (large)	1.0	0.31	0.74	1.05	2.7	0.9	2	4.7
Bio ST CHP (small)	1.0	0.28	0.77	1.05	4.4	1.2	2	5.0
Bio IGCC CHP	1.0	0.43	0.47	0.90	2.7	1.2	4.5	3.5
NGCC CHP	1.0	0.50	0.34	0.84	1.1	0.5	2	2.8
HOB (district heating)								**(EUR/MWh_f)**
Bio HOB	1.0	–	1.05	1.05	–	0.8	2	1.5
Coal HOB	1.0	–	0.90	0.90	–	0.7	2	1.5
Gas HOB	1.0	–	0.90	0.90	–	0.1	2	1.5
Oil HOB	1.0	–	0.90	0.90	–	0.1	2	1.5

Efficiencies are based on LHV (lower heating value). Data based on Refs. [11,12,27,30]. For bio-based options, investment costs have been adjusted to appropriate plant sizes using a scale factor of 0.65; specific investment cost data for Bio ST condensing, Bio IGCC condensing, bio ST CHP (large) and Bio IGCC CHP are based on a 300 MW input plant size. Presented data apply for the entire modeled time horizon.

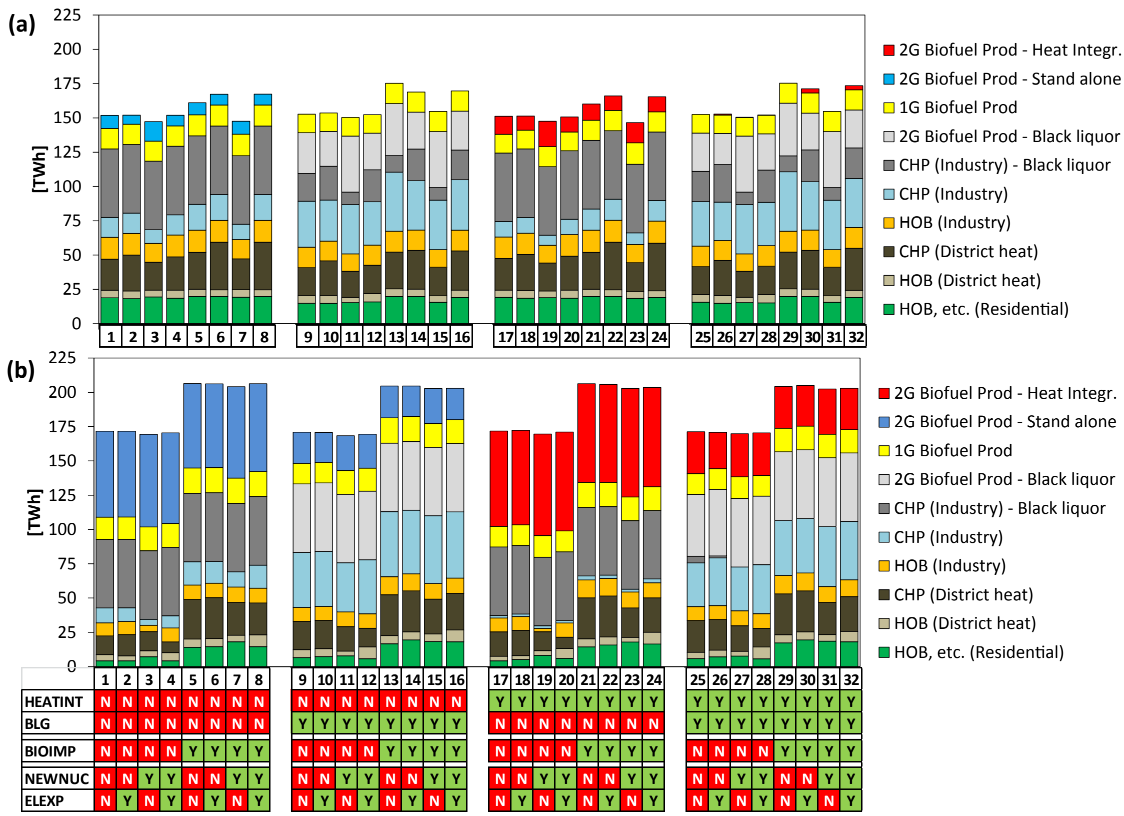

Fig. 2. Biomass use for heat, electricity and biofuel production in (a) 2035 and (b) 2050.

corresponding cases without heat integration (HEATINT-NO), since part of the process heat demand then is supplied by the biofuel production plants. The impact on biomass CHP generation in district heating systems are not as clear-cut and differs between cases; on the one hand, heat integration with district heating systems reduces the "space" available in the district heating systems for CHP; on the other hand, a more efficient usage of biomass on a system level allows more biomass to be used per unit of heat produced, thus enabling a shift from heat-only boilers (HOBs) to CHP. Biomass gasification technology (incl. black liquor gasification) is not utilized for the purpose of electricity generation in any of the cases.

Black liquor gasification for production of biofuels is chosen in cases in which this alternative is available (BLG-YES); this option is chosen over stand-alone plants as well as (other) heat-integrated plants. When black liquor is used for biofuel production, other alternatives are required to fill up need for process heat in the pulp and paper industry. Consequently, use of solid biomass for process heat production is higher compared to corresponding cases without black liquor gasification available (BLG-NO). Also when black liquor gasification is an option, significant other heat-integrated biofuel production occurs in 2050 (i.e., in cases with both BLG-YES and HEATINT-YES), since there is a limited amount of black liquor available.

3.2. Transport sector

Fig. 3 presents final energy use in the transport sector for model years (a) 2035 and (b) 2050. Non-road transport fuel use (aviation, shipping, rail and working machines) is presented in aggregation, divided in fossil and biofuel use only, while road transport fuel use is divided into different biofuels used.[4]

All cases show a mixture of fuel choices in the model results. Biofuel options that are used at some point during the studied time horizon include biogas, ethanol, biodiesel, SNG, methanol and FT-liquids (mainly FT-diesel). Domestic first-generation biofuel production based on cultivated crops (wheat-ethanol and rapeseed-biodiesel) is phased-out early on in the studied period (and is not seen in Fig. 3). In contrast, biogas based on anaerobic digestion of organic waste is used throughout the model time horizon in all cases. However, the feedstock potential is limited and maximum use from this production route is about 6–7 TWh. Imported ethanol is used in all cases allowing bioenergy import, i.e. BIOIMP-YES cases (also here, an upper ethanol import limitation of 3.4 TWh per year is applied). The main second-generation biofuels chosen in road transport are SNG, methanol and ethanol, but the used amounts differ significantly between cases. In order to use methane fuel (SNG and biogas) in diesel engines (rather than lower-efficiency Otto engines), a 5% addition of diesel fuel is required. Therefore, a small amount of FT-diesel is also noted in the results for model year 2050. Additionally to biofuels, electricity becomes an important low-carbon option. At the end of the studied time horizon, battery-powered vehicles and plug-in hybrids (often in combination with biofuels) are used to the maximum extent possible within the assumed model constraints.

[4] As mentioned (see Section 2.3.1), the selection of biofuels in non-road transport is modeled with less detail, and potential insights regarding biofuel choices in this sector based on model results are thus limited.

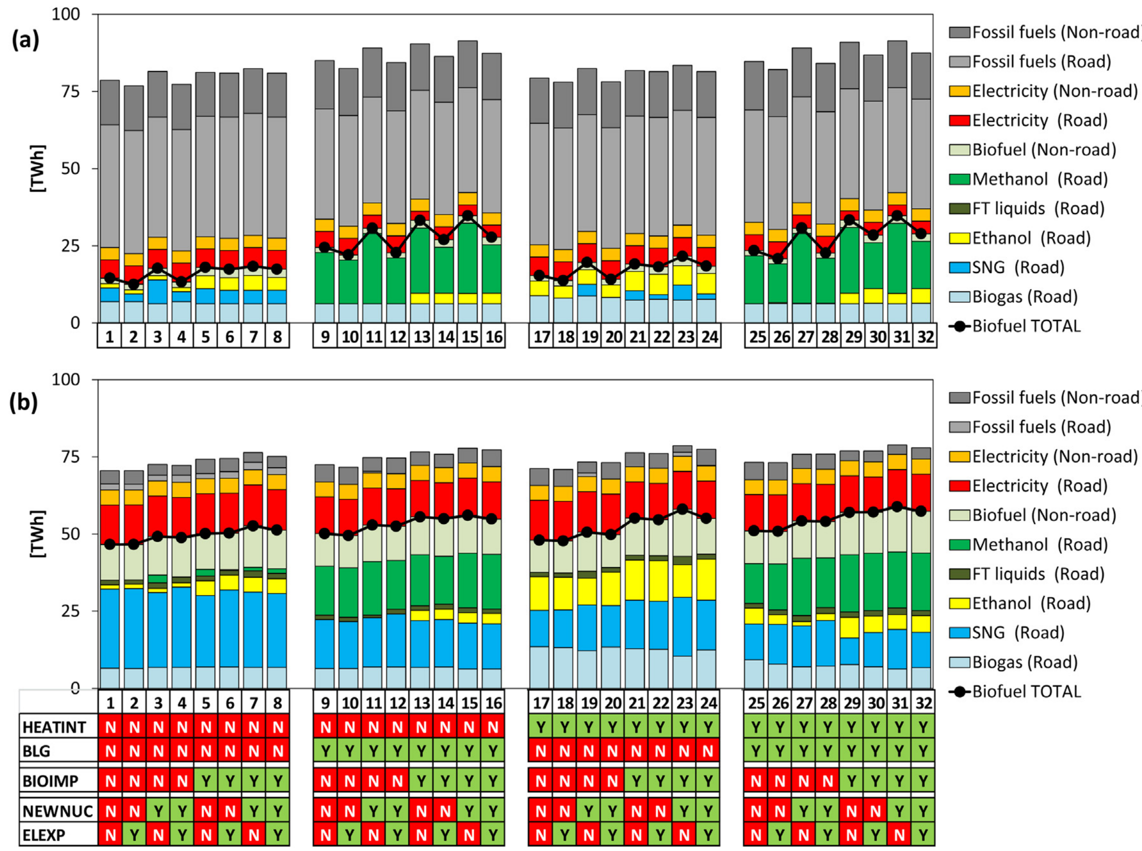

Fig. 3. Transport fuel use in (a) 2035 and (b) 2050.

Whether integration opportunities are included or not have large significance for which biofuel options that are chosen in the model, as well as for at which point in time investments in second-generation biofuel production occur. SNG accounts in all cases for a significant part of the fuel supply, but faces significantly harder competition in cases with integration possibilities (HEATINT-YES and BLG-YES) than in cases without such options (HEATINT-NO and BLG-NO). SNG has a high efficiency in production, also for stand-alone configurations, which is the main reason for its high cost-competitiveness. Straw-based ethanol is used in almost all cases; however, the straw potential is limited and the option therefore only accounts for a minor share (about 1.5 TWh).

Heat-integration possibilities (HEATINT-YES) increase the competitiveness of wood-based second-generation ethanol. Plants with combined production of ethanol, biogas and heat has a high total efficiency and, in these cases, ethanol (and electricity) is the preferred choice in the passenger car sector while heavy traffic primarily use SNG (for long haul, in liquefied form).

For cases with black liquor gasification (BLG-YES), the first larger investments in second-generation biofuel production occur in model year 2025, which is 10 years (two model periods) earlier than in corresponding cases without black liquor gasification possibilities. In the model, methanol is the preferred option for biofuel production based on black liquor gasification. In cases when both heat integration and black liquor gasification is allowed (HEATINT-YES + BLG-YES), production routes for wood-based ethanol face harder competition than in corresponding cases without black liquor gasification options available (HEATINT-YES + BLG-NO), and the use of this option is smaller.

3.3. Electricity sector

Sweden has currently an electricity generation, which is essentially free from fossil fuels; about half of the generation is based on hydro power and the other half is based on nuclear power. CHP and wind power account for small, but increasing shares [33]. Fig. 4 presents model results for the electricity generation in model years (a) 2035 and (b) 2050. The situation of today with large shares of hydro and nuclear is to high degree kept also in the long run for cases in which investments in new nuclear power is allowed after the existing capacity has been retired (NEWNUC-YES). However, a significant increase in wind power for cases in which unlimited electricity export is allowed is observed (ELEXP-YES). A phase-out of nuclear power (NEWNUC-NO) is, in the model results, primarily met by increased wind power generation, increased end-use efficiency, and low (or no) electricity export.

Bio-based power production ranges between 8 and 24 TWh in 2050, i.e., it accounts for a comparably small share of the total electricity generation. On average, cases without bioenergy import (BIOIMP-NO) show a small decline from 2035 to 2050 (about −2 TWh), while cases with bioenergy import (BIOIMP-YES) show a small increase (about +1 TWh). In addition to biomass import, electricity export is a factor that, in 2035, increases the cost-efficient level of biomass-based power generation in the results. In contrast, the possibility of new nuclear power gives a negative effect. Integration possibilities for biofuel production do not have a clear-cut impact and results differ between cases; basically, there is a small positive effect on power generation from CHP in district heating systems while a small negative effect on generation from CHP in industry.

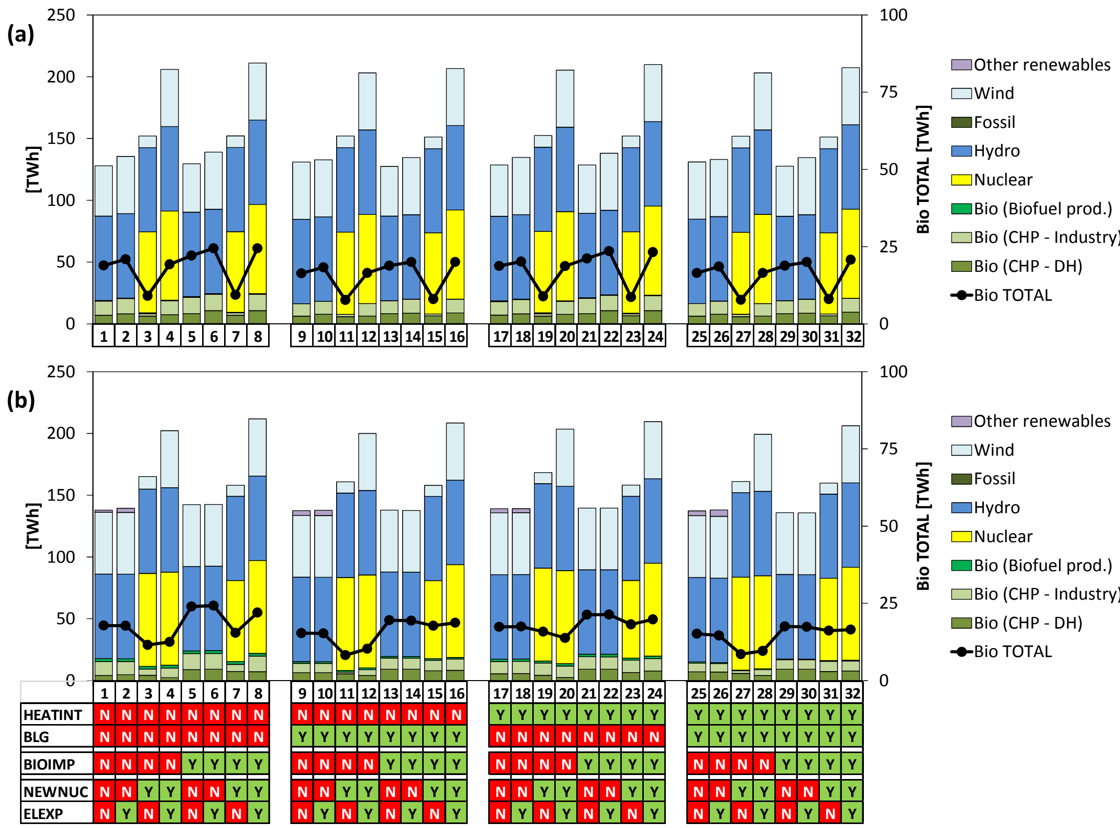

Fig. 4. Electricity generation in (a) 2035 and (b) 2050. Total bio-based electricity generation is given on right axis.

The availability of, and level of competition for, biomass is of significance for cost-competitiveness of biomass-based power. As indicated, there is an increasing competition for bioenergy under the studied time horizon as an increasing share of the available biomass potential instead gets allocated to production of biofuels. The reason for this is essentially that the electricity sector has better possibilities for cost-competitive non-biomass low-carbon options than the transport sector.

3.4. Shadow prices — biomass and CO_2

In the model optimization, shadow prices are generated for constrained variables. The shadow price indicates the marginal value (marginal utility or marginal cost) of a commodity from a system perspective, and can basically be thought of as a proxy for a market price. Figs. 5 and 6 present the shadow prices for wood-biomass (unrefined) usable for energy purposes and the shadow prices for CO_2 emissions respectively. For the case of CO_2 emissions, the interpretation of the shadow price could be the price of an

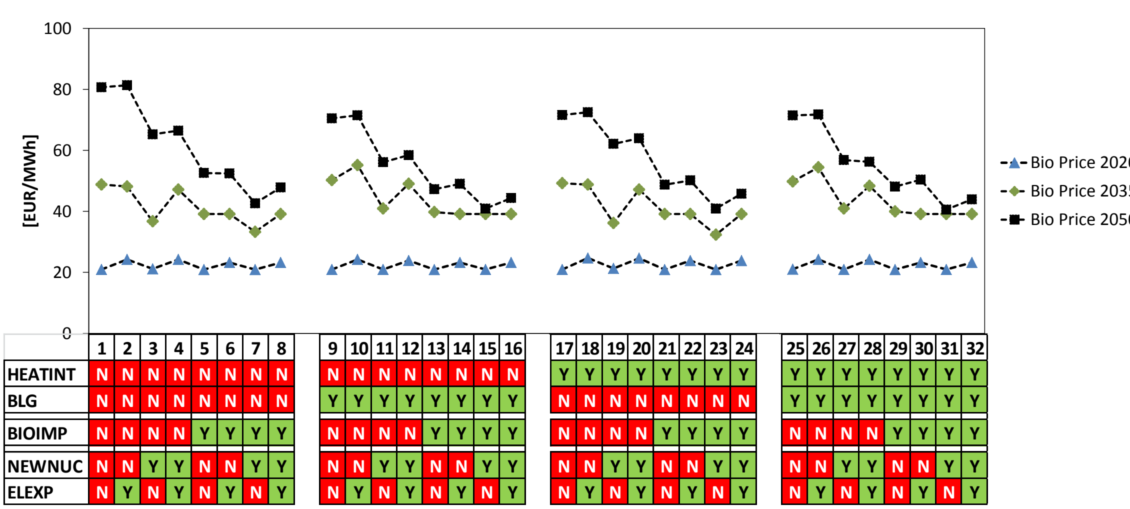

Fig. 5. Unrefined wood-biomass shadow price for model years 2020, 2035 and 2050.

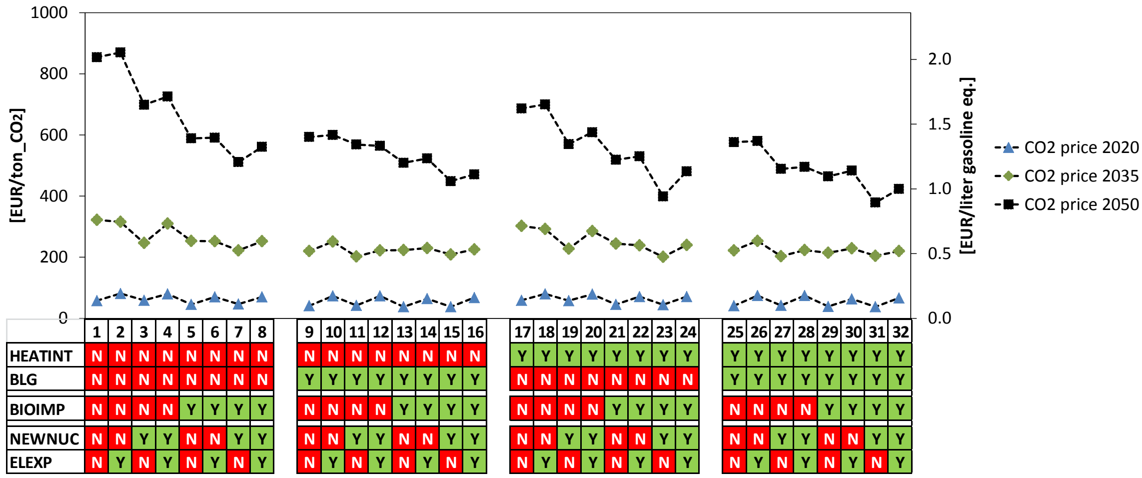

Fig. 6. CO_2 shadow price for model years 2020, 2035 and 2050.

emission permit in a cap-and-trade system or the required CO_2 tax (or fuel tax) to reach the assumed emission reductions. Results are given both as cost per ton of CO_2 emissions and as cost per unit of gasoline equivalent.

As a result of more stringent CO_2 constraints and increasing demand levels, the biomass and CO_2 shadow prices both increase significantly during the studied period for all modeled cases. In particular, very high prices are reached in cases when nuclear investments and bioenergy imports are not allowed. Possibilities for electricity export also push prices in an upward direction. In the long run (2050), biofuel production integration (HEATINT-YES and BLG-YES) has a downward effect on the shadow

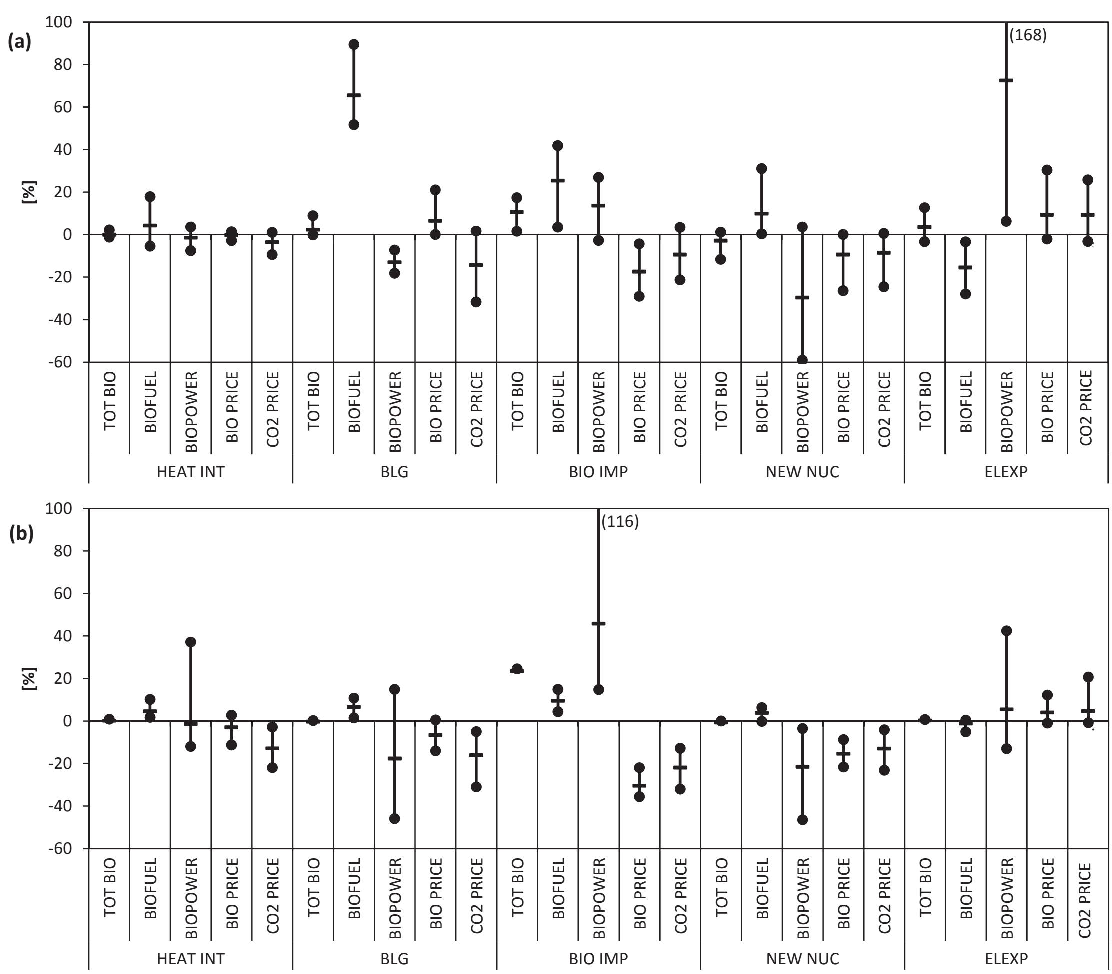

Fig. 7. Percentage change in result parameter values when going from "NO" to "YES" for studied factors (HEATINT, BLG, BIOIMP, NEWNUC, and ELEXP), for model years (a) 2035 and (b) 2050. Highest, lowest and the average percentage change are marked.

prices. The effect is larger for CO_2 than for biomass and is also larger for black liquor gasification integration (BLG-YES) than for heat integration (HEATINT-YES). However, in comparison with the total increase seen over the studied time horizon due to the CO_2 reduction constraint, the effects induced by the integration options on CO_2 and biomass shadow prices are relatively modest.

3.5. Factor impacts – summary

Fig. 7 summarizes the results and presents the relative impact of the five studied factors (heat integration, black liquor gasification, biomass import, new nuclear power generation, and electricity export) on the main result parameters: total bioenergy utilization (TOT BIO), total biofuel use (BIOFUEL), biomass-based power production (BIO POWER), wood-biomass shadow price (BIO PRICE), and CO_2 shadow price (CO_2 PRICE) as percentage change when each respective factor is "activated", i.e., when going from the "No"-cases to the "Yes"-cases. For each factor, 16 results are obtained with different combinations of conditions regarding the other four factors. Thus a range is presented (with the highest, lowest and average change indicated for each factor and result parameter), which clarifies the direction and size of system effects (within as well as across sector boundaries) as well as robustness of results in regard to the tested alternative developments (a small range indicates robust results).

The effects observed in Fig. 7 have in many aspects been touched upon in earlier sections, but a few things could be further pointed out. Effects on bio-based power generation stand out for some factors (BIOIMP, ELEXP and NEWNUC) with large percentage changes. Further, in the long term (2050), the only factor affecting total bioenergy use to any significant degree is change in supply of biomass (BIOIMP). Also in regard to total biofuel use, the percentage change in the long run is small between "Yes"- and "No"-cases. Biomass and CO_2 emissions valuation are affected to a somewhat higher degree.

4. Discussion and conclusions

In this study, system interactions linked to future bioenergy utilization and cost-efficient bioenergy technology strategies are studied. Special focus is put on opportunities for system integration of second-generation biofuel production with industry and district heating, system effects of large transitions in the electricity system, and influence of different levels of biomass supply.

The analysis is based on bottom-up energy systems modeling of the Swedish energy system. All energy sectors (including transport) are represented in the model, and competition for scarce resources, such as biomass, over sector boundaries are captured. The study applies an explorative modeling approach and system effects and interdependencies of studied factors are investigated through a systematic, multiple model run assessment enabling an analysis identifying robust solutions.

While energy systems models of the type used in the present study have many capabilities, there are also shortcomings, which should be considered in the interpretation of the model results. A partial equilibrium approach is applied and only direct costs are taken into consideration. This means that effects on the macroeconomic level are essentially not captured (although end-use demand price elasticity is included). For example, a higher use of domestically produced biofuels rather than imported oil-based fuels could have potential macro-economic impacts. Such development could imply effects on, e.g., job creation, and in such way lower the national societal costs associated with these solutions. The (direct) cost optimization also means that different types of intangible values which may influence technology choice are not captured and that new technologies only compete on the basis of cost. This could work in both ways in terms of the timing of introduction of new technologies in the results; neither "early adopters" nor "laggards" are represented. However, when system cost savings are achieved, technological change occurs instantly and system inertia is in this sense low compared to reality. Related to this is also the fact that the model does not take market issues such as asymmetric information or financing problems into account. While the perfect foresight feature of the model implies that uncertainty linked to future developments is not captured, the approach of using a large set of scenarios in the analysis to some extent addresses this.

The model results suggest that integrated biofuel production can be a cost-efficient option for meeting of stringent CO_2 constraints. Under the assumed conditions, such technology solutions increase system efficiency, lower the production cost of biofuels and the overall system cost. Integrated alternatives are chosen over stand-alone options under all modeled conditions, including large transitions in the electricity system and different levels of biomass supply. However, while the direction of the impact is clear, the magnitude of the effect differs from comparably large effect in some cases to small effects in other cases. Among the tested system-integration alternatives, biofuel production through black liquor gasification shows high cost-competitiveness under the assumed conditions. In the long run (2050), cases with heat integration (HEATINT-YES) show 3–22% lower CO_2 marginal reduction cost than corresponding cases without heat integration possibilities. Corresponding values for black liquor gasification cases (BLG-YES) are 5–31% (Fig. 7). Although on another system level (plant level), similar results showing potentials for increased efficiency from a cost- and/or energy perspective of integrated biofuel production compared to stand-alone options have been presented by, e.g., Refs. [1,25].

The CO_2 shadow prices generated by the model suggest that significant penalties (e.g., taxes) on fossil fuels are required to achieve CO_2 reductions of 80% by 2050 (compared to the 1990 emission level). Compared to current CO_2 prices in the EU emission trading system, the long-run CO_2 prices in the model results are exceptionally high. However, since the marginal reduction costs here are determined by reductions in the transport sector (while, e.g., the electricity sector is completely fossil free), a more relevant comparison is with current taxes in this sector. Today, the gasoline taxes in Sweden are about 0.65 EUR/liter (5.85 SEK/liter) [32] (including CO_2 and energy tax but excluding value added tax). Under the assumed conditions, the results suggest that these levels in the long run needs to at least be doubled while keeping biofuels tax exempt if the modeled emission reductions and technology transition should occur. Considering the low system inertia of the modeled system, the real required levels may be even higher. Note, however, that several other sectors than transport show lower marginal CO_2 reduction costs. Long run CO_2 shadow prices of the current study are largely in a similar region as levels presented in several studies with comparable modeling approaches on European level (see, e.g., Refs. [3,4]).

Interactions linked to biomass utilization differ depending on time horizon. In the medium term (2035), heat/industry integration of biofuel production has a positive impact on the cost-efficient amount of biofuels in the transport sector as well as on the total bioenergy use in the energy system. Electricity-system transitions that have a positive effect on bio-based power generation, such as an increased possibility of electricity export or a phase-out of nuclear power, have a negative impact on transport biofuel production due to effects on biomass markets. The effect on bio-based power production of integrated biofuel production differs between cases, but is generally negative as potentials for power generation in CHP plants decrease as a larger share of the heat demand is met by excess heat from transport fuel production. In the long term (2050), the dynamics of the system change. The stringent CO_2 constraint allows smaller flexibility in the system, and the effects from factor variations on biofuel use and total bioenergy use becomes more limited. In the transport sector, biofuel is the only low-carbon option besides electricity (and reductions in distance traveled) in the model. Since electricity at the end of the period basically is used to its defined maximum capacity in the transport sector, biofuels are forced into the system in an amount to a large degree given by the stringency of the CO_2 constraint. At this point, the amount of biomass available for energy purposes is almost fully utilized, which means that the bioenergy supply is the main decisive factor for total bioenergy use. Thus, possibilities to increase supply, e.g., through biomass import, have a direct impact on bioenergy use, but other factor variations have a small impact.

The results show that different availability of integration options can have a significant impact on which biofuel that shows the best cost-competitiveness. Regarding second-generation biofuels, SNG is chosen to a comparably large extent in all cases. In cases with only stand-alone second-generation biofuel plant configurations available (HEATINT-NO, BLG-NO), SNG gets a dominating position. Due to its high production efficiency, SNG is an advantageous option despite comparably high distribution and vehicle costs. However, when black liquor gasification is available (BLG-YES), this option is utilized for methanol production. Benefits of methanol include low costs in distribution and end-use compared to gaseous fuels. Note that SNG production based on black liquor gasification is not an option in the model due to low methane content in the syngas (for the black liquor gasification technology here considered). Heat integration cases (HEATINT-YES) have primarily a positive impact on ethanol production, for which available polygeneration plant configurations show high efficiency.

It should be noted that there are still no large-scale commercial second-generation biofuel production plants available and assumed technology costs are linked to uncertainty. This also relates to the relative cost differences between different types of conversion routes, such as thermochemical (gasification-based fuels) and biochemical (ethanol) routes. Compared to studies applying earlier versions of the MARKAL_Sweden model (e.g., Ref. [7]), investment costs for second-generation biofuel production have in the current study been adjusted upwards in line with recent estimates (see references given in Table 4). The main effect of this is that investments occur later in the studied time horizon. As mentioned above, lack of alternative options in the transport sector will in the long run (under stringent CO_2 constraints) push biofuels into the transport sector regardless of cost. However, availability of other, non-biomass based, low-carbon transport options, currently not represented in the model, could alter this result. Such options could include hydrogen from electrolysis, other electrofuels, and increased possibilities of direct use of electricity in the transport sector, e.g., through electrified roads supplying heavy-duty long-haul transport. Investigations into the potentials of such options can be relevant future research directions.

Biomass prices can under stringent CO_2 constraints be expected to increase significantly from current levels. Use of integrated biofuel production, with higher system efficiency, can to some extent dampen such increase. If higher biomass supply than what is assumed in the present study is possible, this could also keep prices down. From a national perspective, biomass import is one option to increase supply. However, not all nations can rely on biomass imports if significant CO_2 emission cuts should be achieved globally. From this perspective it is highly questionable that a biomass-rich country like Sweden in the future could depend on large net imports of bioenergy.

Acknowledgment

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References

[1] Andersson J, Lundgren J, Marklund M. Methanol production via pressurized entrained flow biomass gasification – techno-economic comparison of integrated vs. stand-alone production. Biomass Bioenergy 2014;64:256–68.
[2] Barta Z, Reczey K, Zacchi G. Techno-economic evaluation of stillage treatment with anaerobic digestion in a softwood-to-ethanol process. Biotechnol Biofuels 2010;3(21):1–11.
[3] Blesl M, Kober T, Bruchof D, Kuder R. Effects of climate and energy policy related measures and targets on the future structure of the European energy system in 2020 and beyond. Energy Policy 2010;38:6278–92.
[4] Blesl M, Kober T, Kuder R, Bruchof D. Implications of different climate protection regimes for the EU-27 and its member states through 2050. Clim Policy 2012;12:301–19.
[5] Börjesson M, Ahlgren EO. Modelling transport fuel pathways: achieving cost-effective oil use reduction in passenger cars in Sweden. Technol Forecast Soc Change 2012a;79:801–18.
[6] Börjesson M, Ahlgren EO. Cost-effective biogas utilization – a modelling assessment of gas infrastructural options in a regional energy system. Energy 2012b;48:212–25.
[7] Börjesson M, Ahlgren EO, Lundmark R, Athanassiadis D. Biofuel futures in road transport – a modeling analysis. Transp Res Part D 2014;32:239–52.
[8] Börjesson M, Athanassiadis D, Lundmark R, Ahlgren EO. Bioenergy futures in Sweden – system effects of CO_2 reduction and fossil fuel phase-out policies. GCB Bioenergy 2015;7:1118–35.
[9] Börjesson P, Tuvfvesson L, Lantz M. Livscykelanalys av svenska biodrivmedel [Life cycle analysis of Swedish biofuels]. Malmö: Swedish Gas Technology Centre (SGC); 2010 [In Swedish].
[10] Consonni S, Katofsky RE, Larson ED. A gasification-based biorefinery for the pulp and paper industry. Chem Eng Res Des 2009;87:1293–317.
[11] Danish Energy Authority. Technology data for energy plants. Copenhagen: Danish Energy Agency and Energinet.dk; 2012.
[12] Ekbom T, Berglin N, Lögdberg S. Black liquor gasification with motor fuel production – BLGMF II. Stockhom: Nykomb Synergetics AB; 2005.
[13] Ekbom T, Gåverud H, Rehnlund B. Marknadsförutsättningar för biodrivmedel – Konkurrenskraft för SNG i förhållande till alternativa förnybara drivmedel [Market conditions for biofuels – Competitiveness of SNG in relation to alternative renewable fuels]. Malmö: Grontmij and E.ON. Gasification Development; 2012 [In Swedish].
[14] Ekman A, Wallberg O, Joelsson E, Börjesson P. Possibilities for sustainable biorefineries based on agricultural residues – a case study of potential straw-based ethanol production in Sweden. Appl Energy 2013;102:299–308.
[15] EUBIA. Biodiesel. Website information, available at:. 2014. http://www.eubia.org/index.php/about-biomass/biofuels-for-transport/biodiesel.
[16] Gül T, Kypreos S, Turton H, Barreto L. An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model GMM. Energy 2009;34:1423–37.
[17] Hamelinck CN, Faij APC. Outlook for advanced biofuels. Energy Policy 2006;34:3268–83.
[18] Heyne S, Harvey S. Assessment of energy and economic performance of second generation biofuel production processes using energy market scenarios. Appl Energy 2013;101:203–12.
[19] Heyne S, Harvey S. Impact of choice of CO_2 separation technology on thermo-economic performance of Bio-SNG production processes. Int J Energy Res 2014;38:299–318.
[20] IEA. World energy outlook 2010. Paris: International Energy Agency (IEA); 2010.
[21] IEA. Renewables. Website information. Available at:. 2015. https://www.iea.org/topics/renewables/ (2015-06-01).
[22] Isaksson J, Pettersson K, Mahmoudkhani M, Åsblad A, Berntsson T. Integration of biomass gasification with a Scandinavian mechanical pulp and paper mill – consequences for mass and energy balances and global CO_2 emissions. Energy 2012;44:420–8.
[23] Johansson D, Franck P-Å, Pettersson K, Berntsson. Comparative study of Fischer-Tropsch production and post-combustion CO_2 capture at an oil refinery: economic evaluation and GHG balances. Energy 2013;59:387–401.
[24] Lindstedt J. Swedish experience – from demo to production scale of cellulose based ethanol. In: Presentation at the first international conference on lignocellulosic ethanol 2010-10-13/15, Copenhagen; 2010.
[25] Ljungstedt H, Pettersson K, Harvey S. Evaluation of opportunities for heat integration of biomass-based Fischer-Tropsch crude production at Scandinavian kraft pulp and paper mill sites. Energy 2013;62:349–61.

[26] Lolou R, Goldstein G, Noble K. Documentation for the MARKAL family of models. Energy Technology Systems Analysis Programme (ETSAP). Paris: International Energy Agency; 2004.
[27] Marbe Å, Harvey S, Berntsson T. Biofuel gasification combined heat and power – new implementation opportunities resulting from combined supply of process steam and district heating. Energy 2004;29:1117–37.
[28] Martinsen D, Funk C, Linssen J. Biomass for transportation fuels – a cost-effective option for the German energy supply? Energy Policy 2010;38:128–40.
[30] Nohlgren I, Herstad Svärd S, Jansson M, Rodin J. El från nya och framtida anläggningar 2014 [Electricity from new and future plants]. Stockholm: Elforsk; 2014 [In Swedish].
[31] Pettersson K, Harvey S. Comparison of black liquor gasification with other pulping biorefinery concepts – systems analysis of economic performance and CO_2 emissions. Energy 2012;37:136–53.
[32] SBPI. Statistik [Statistics]. Website information. Available at:. 2015. www.spbi.se (2015-05-21).
[33] SEA (Swedish Energy Agency). Energy in Sweden 2013. Eskilstuna: Swedish Energy Agency; 2013.
[34] Swedish Government. Kärnkraften – förutsättningar för generationsskifte [Nuclear power – preconditions for generation shift]. Government bill 2009/10:172. Stockholm: Swedish Government; 2009 [In Swedish].
[35] Takeshita T. Assessing the co-benefits of CO_2 mitigation on air pollutants emissions from road vehicles. Appl Energy 2012;97:225–37.
[36] Trutnevyte E. Does cost optimization approximate the real-world energy transition? Energy 2016;106:182–93.
[37] Trutnevyte E. EXPANSE methodology for evaluating the economic potential of renewable energy from an energy mix perspective. Appl Energy 2013;111:593–601.