

# Bioenergy futures in Sweden – system effects of CO<sub>2</sub> reduction and fossil fuel phase-out policies

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## Abstract

Bioenergy could contribute both to the reduction of greenhouse gases and to increased energy security, but the extent of this contribution strongly depends on the cost and potential of biomass resources. For Sweden, this study investigates how the implementation of policies for CO<sub>2</sub> reduction and for phase out of fossil fuels in road transport affect the future utilization of biomass, in the stationary energy system and in the transport sector, and its price. The analysis is based on the bottom-up, optimization MARKAL\_Sweden model, which includes a comprehensive representation of the national energy system. For the analysis, the biomass supply representation of MARKAL\_Sweden is updated and improved by the use of, e.g., forestry forecasting modeling and through construction of detailed biomass supply curves. A time horizon up to 2050 is applied. The results indicate a potential for significantly higher use of bioenergy. In the main analysis scenario, in which CO<sub>2</sub> reduction of 80% by 2050 is imposed on the Swedish energy system, the total bioenergy utilization increases by 63% by 2050 compared to 2010. The largest increase occurs in the transport sector, which by 2050 accounts for 43% of the total primary bioenergy use. The high demand and strong competition significantly increase biomass prices and lead to the utilization of higher cost biomass sources such as stumps and cultivated energy forest, as well as use of pulpwood resources for energy purposes.

*Keywords:* biofuels, biomass, climate policy, energy system, greenhouse gas, MARKAL, model, scenario

*Received 16 March 2014; revised version received 5 September 2014 and accepted 7 September 2014*

## Introduction

Human activities have increased the concentration of greenhouse gases (GHGs) in the atmosphere, which is most likely causing the increase in global mean temperature and climate change (IPCC, 2007). The increase in atmospheric concentration of carbon dioxide (CO<sub>2</sub>), the most important GHG, is mainly due to the combustion of fossil fuels, but effects resulting from land-use change are also significant (IPCC, 2007). While the use of fossil fuels is too high from a climate perspective, any interference in the continuous supply of cheap energy also implies burdens for modern society. Sudden oil price increases are linked to inflation, increased unemployment, higher interest rates and, as a consequence, high societal costs (Kohl, 2004). A secure and diversified energy supply is thus of importance.

To reduce the risks of severe climate change, a substantial reduction of GHG emissions is required in the coming decades. To accomplish this, large changes to the energy system are necessary. Reduced energy use and a larger share of renewable and low-carbon energy in the energy system are important means to address this issue. A larger share of locally available renewable energy sources in the energy supply is also important to increase energy security and reduce dependence on imported energy such as oil.

Bioenergy is currently the largest source of renewable energy. In Sweden, bioenergy (including waste and peat) accounts for about one fourth of the total energy supply (SEA, 2011a). While bioenergy today is primarily used in the stationary energy sector for electricity and heat production, the use of biofuels in the transport sector has increased significantly in recent years. In 2012, biofuels accounted for 7.5% of domestic transport energy use (SEA, 2013a). Considering energy and environmental policy targets on both the national and EU level, a growing demand for bioenergy seems likely in the future. In the EU, GHG

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emissions should be reduced by 20% by 2020, and a long-term ambition of reducing GHG emissions by 80–95% by 2050 has been stated (EC, 2011). In addition, energy from renewable sources should account for at least 10% of the total energy use in the transport sector by 2020 (EC, 2009). In Sweden, the government has declared that the vehicle fleet should be independent of fossil fuels by 2030 and that Sweden should have no net emissions of GHGs by 2050 (Swedish Government, 2008). Although biomass is a renewable energy source, the annual potential is limited, ultimately due to land scarcity. An efficient and sustainable use of the available bioenergy potential is therefore imperative from both economic and environmental standpoints.

Increased use of bioenergy could contribute both to the reduction of GHG emissions and to increased energy security, but to what degree strongly depends on the cost and potential of biomass resources. This study investigates the potential future bioenergy utilization in Sweden and the effect of different climate and energy policies. In this study, we focus on domestic biomass resources and special attention is given to the relative distribution between biomass use in the stationary energy system and in the transport sector, respectively. The main research question is as follows:

- How will implementation of stringent CO<sub>2</sub> reduction and road transport fossil fuel phase-out policies affect the future utilization of biomass, in the stationary energy system and in the transport sector, and its price?

Options for efficient use of bioenergy have been studied from several perspectives and using different approaches (see, e.g., Gustavsson *et al.*, 2007, 2011; Börjesson, 2009; Börjesson & Ahlgren, 2010; Börjesson & Tufvesson, 2011; Forsell *et al.*, 2013). Often a static perspective on the comparison of bioenergy systems is applied. In other cases, a certain bioenergy chain, or a part thereof, is studied in great detail. More rarely, the competition between different bioenergy alternatives (in the same or different sectors) and with non-bio-based energy technologies, as well as their interaction with the surrounding energy system, is studied in a dynamic manner. When this is done, it is often at a global level (e.g., Azar *et al.*, 2003; Gielen *et al.*, 2003). While many modeling studies include bioenergy in the representation of the energy system, the representation of biomass supply and/or use is often fairly aggregated. National studies more specifically focusing on bioenergy include Jablonski *et al.* (2010), in the case of the UK, and Forsell *et al.* (2013), in the case of Sweden and France. Forsell *et al.* (2013) describe biomass supply in high detail, but competition with other energy technologies is less well

represented and biomass use is largely determined exogenously. There is thus a need for more general bioenergy studies not focusing on a particular application but adopting a holistic approach to the use of bioenergy in the national energy system, and including systemic effects of competition on bioenergy markets.

## Materials and methods

### *Steps of the analysis*

The analysis is based on a bottom-up, energy system modeling approach. We further develop a pre-existing model structure of the Swedish energy system, the so-called MARKAL\_Sweden model, and run the model with several different scenario set-ups. One part of the work focuses on the biomass resource supply representation of the model.

The work can principally be described and divided according to the following activities: (i) establishment of supply curves for biomass from forestry through forestry forecasting model simulations and spreadsheet calculations; (ii) establishment of biomass supply curves for agricultural biomass fractions through literature review and spreadsheet calculations; (iii) construction of input scenarios for the energy systems modeling analysis; (iv) integration of biomass supply curves into the energy system model; (v) other developments and updates of the energy system model (e.g., in regard to end-use demands); (vi) running of the energy system model; and (vii) analysis and interpretation of the model outputs. The work process is highly iterative and activities are to large degree carried out in parallel rather than in sequence.

The main model outputs of interest for the analysis are resulting biomass utilization levels (for different energy purposes) and biomass prices. In terms of biomass utilization levels, we consider three categories: total biomass use in the energy system as a whole; biomass use for heat and power production (Bio4HePo); and biomass use for transport biofuel production (Bio4Tran). The sum of Bio4HePo and Bio4Tran equals the total biomass use of the first category. Bio4HePo includes biomass use for district heating, electricity, process heat in industry and space and water heating in premises, but also heat and electricity production in biorefineries which also produce transport biofuels.

In the following sections, the utilized energy system model and data assumptions relating to the above activities are presented, including: key features of the energy system model; important input assumptions relating to the model technology representation and the end-use demands; the setting up of biomass resource data and biomass supply curves; and model input scenarios including energy policy assumptions.

### *General model description*

This study utilizes an application of the well-established MARKAL model generator (Lolou *et al.*, 2004). MARKAL is a widely applied, dynamic, optimization-based, partial equilibrium, bottom-up energy systems modeling framework, developed

within the Energy Technology Systems Analysis Program (ETSAP, [www.iea-etsap.org](http://www.iea-etsap.org)) of the International Energy Agency (IEA). The MARKAL application used in the present study represents the Swedish energy system (including transport) and is therefore referred to as MARKAL\_Sweden. Elastic demand (own-price) is applied in the model and the optimized model result represents the overall system solution that maximizes welfare within the limits outlined by the defined constraints (such as demand levels, resource and emission constraints) and conditions (such as technology characteristics) of the model. Welfare is defined as the sum of producer and consumer surpluses. The model optimization is achieved through a minimization of the total system cost, which is defined as the sum of the net present values of all costs arising in the technical energy system (mainly technology investment costs, operation and maintenance costs, fuel and resource costs and distribution costs) and losses in welfare due to reduced end-use demand, over the entire studied time horizon. Under the given conditions, the model delivers the cost-optimal combination of fuels and energy technologies meeting the energy demands of the system. Reference projections of end-use energy service demands and demand elasticities are provided to the model exogenously.

In the model, the price for a commodity is equal to the commodity's marginal system value, and is commonly referred to as the 'shadow price'. The marginal system value of a commodity, i.e., the shadow price, is equal to the marginal change of the optimized total system cost (the objective value) from a one-unit relaxation of the constraint managing the quantity of that commodity. The shadow prices of the model can differ from real world market prices for several reasons. Some of the more important assumptions in this regard are that the model assumes competitive markets and perfect foresight, e.g., implying that there is full knowledge (no uncertainty) about current and future parameter values. While acknowledging that differences exist, we will from now on refer to the 'shadow prices' simply as 'prices' and use the modeled values as competitive market price estimates.

MARKAL\_Sweden applies a time horizon from 1995 to 2050 divided into 5-year periods (each represented by one model year). Most flows of energy carriers are described on an annual basis, but heat is also tracked by three seasons, and electricity by three seasons and two diurnal periods. A discount rate of 6% is used. Throughout the paper, costs are given in the monetary value of 2010 and an exchange rate between Swedish Krona (SEK) and Euro (EUR) of 9 SEK/EUR is utilized.

MARKAL\_Sweden builds upon earlier MARKAL model applications describing the Swedish energy and transport system (e.g., Bergendahl & Bergström, 1981; Unger & Alm, 2000; Börjesson & Ahlgren, 2012a,b). Recent developments of the model have, in particular, focused on the representation of the road transport sector (see also the concurrently performed study Börjesson *et al.*, 2014).

MARKAL\_Sweden represents all sectors of the energy system and allows for demands in different sectors to compete for finite energy resources (Fig. 1). The energy system representation is structured as a network of energy technologies and energy carriers, covering fuel extraction via different types of energy conversion technologies and distribution chains to end-use demands on energy services, such as transportation and heating. Each process or technology represented in the model is described by different types of data. Such data include technology costs and performance data (e.g., operation and maintenance costs, investment costs and conversion efficiencies) for technologies in all parts of the energy system, including supply technologies/processes (import of fossil fuels, cultivation/extraction of biomass, etc.), conversion technologies (heat and electricity production, transport fuel production, etc.), end-use technologies (industrial and residential heat boilers, vehicles, etc.) and distribution processes. Input assumptions are also required regarding demand projections and system limitations in regard to, e.g., resource supply, emission constraints or technology capacity.

#### Representation of stationary energy sectors

The stationary end-use energy sectors of the model can principally be divided in industrial, residential and commercial sectors. The end use demand from the industrial sector is subdivided into different industry branches as well as into demands for process heating, electric appliances, district heating, and fuels. The demands from the residential and commercial sectors are categorized into demands for heating (space and water) and electric appliances. Heat demands can be met by a number of end-use technology options, such as boilers with different fuel alternatives, electric boilers, district heat exchangers and heat pumps. District heat and electricity demands are linked to the district heat and electricity modules of the model, in which numerous technology options are represented.

The pulp and paper industry is a large user of biomass in Sweden, and is a sector that could be affected by an

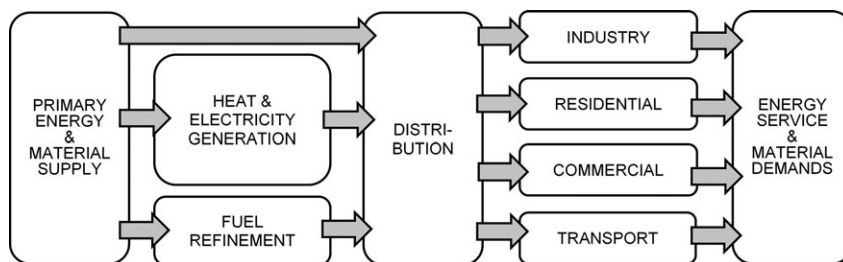


Fig. 1 Aggregated overview of sectors, processes and energy and material flows in MARKAL\_Sweden.

extensive use of bioenergy causing increased competition for the industry's raw materials. In order to capture a system-wide competition for pulpwood in the model, in addition to industry energy demands, the supply and demand for pulpwood in the pulp and paper industry are specified and also linked to bioenergy demands in other sectors of the energy system. The market for timber (timber is today primarily used for construction) could potentially also be affected by a future increase in bioenergy demand. However, due to the higher price of timber, the pulpwood market should be more exposed to such competition and therefore we do not consider timber in the present study.

Important assumptions for the stationary energy system include the handling of nuclear power, wind power potentials, and electricity import and export. Regarding nuclear power, only a minor increase in capacity is allowed during the modeled time horizon due to political considerations. An upper capacity limit is set at 10.1 GW, in line with assumption made by the Swedish Energy Agency (SEA, 2013b). The replacement of old nuclear power capacity with new is allowed when the technical lifetime of old plants is met in line with current Swedish government decisions (but in contrast to the previous ban on new reactors). For wind power, an upper annual production constraint of 30 TWh is assumed (based on Swedish government targets, see Swedish Government, 2008). Wind power is represented in the model by different cost classes. To reach the full potential, the establishment of comparably costly ocean-based wind farms is necessary. Concerning heat and electricity generation technologies, the main data sources for technology costs and technical performance are Nyström *et al.* (2011) and DEA, Energinet.dk (2010).

Since a national model is used, electricity trade is handled in a simplified manner. In order not to allow the model to meet national CO<sub>2</sub> reduction targets through large electricity imports, and by that simply moving emissions elsewhere, electricity imports are not allowed in the model for future model years. Electricity export is allowed in harmony with the visions of Sweden becoming a net electricity exporter articulated by government representatives and reflected in the long-term forecasts of the Swedish Energy Agency (SEA, 2011b, 2013b).

While the model includes a large number of technologies, both conventional technologies and potential future options, which are yet to be deployed at larger scale, there are also potential future options that are not represented. In the stationary energy sector, carbon capture and storage (CCS) and low-carbon alternatives to certain process fuel use in the process industry (primarily coke use in the iron and steel industry sector) are not represented in the model. As a consequence, the model cannot handle CO<sub>2</sub> emission reductions larger than about 90% (compared to the 1990 emission level).

### Representation of transport sector

The demand for road transportation is in the model defined by vehicle utilization levels, which for each model year are expressed as vehicle kilometers (vkm) traveled. Vehicle utilization is divided according to different vehicle classes, including

cars, light trucks, heavy trucks, buses and motorcycles. For each vehicle class, a number of vehicle technology and fuel options (and fuel production processes) are represented in the model. In addition to fossil oil-based transport fuels and natural gas, the model includes the following options for biofuels in road transport: ethanol, biodiesel, biogas, synthetic natural gas (SNG), methanol, DME and Fischer-Tropsch (FT) liquids (synthetic gasoline, diesel and kerosene). Regarding vehicle technologies, the model includes internal combustion engine (ICE) technology (both compression ignition, CI, and spark ignition, SI), hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs) and battery-powered electric vehicles (BEVs). Further details on road transport fuel and technology options (e.g., assumptions on cost and performance data) are given in Börjesson *et al.* (2014). Non-road domestic transport, including working machines, aviation and shipping, is also represented in the model but at a less detailed level, and low-carbon options only include synthetic fuels that are equivalent to conventional oil-based fuels. International transport is not included in the model. Some potential long-term low-carbon options for the transport sector are not within the scope of the study, including hydrogen, fuel cell vehicles, electrified roads, and algal biofuels.

### End-use demand projections

Figure 2 visualizes the assumed reference development for energy service demands aggregated to a few sectors (in the model, demands are more disaggregated). For the stationary energy system, the reference demand projections are based on long-term forecasts by the Swedish Energy Agency (SEA, 2011b, 2013b). These forecasts, however, only extend to 2030 and demand levels are thus kept constant for 2030–2050. For the pulp and paper industry, a slight increase in production, as well as in energy and pulpwood demand, under the studied time horizon is assumed based on the Swedish Energy Agency

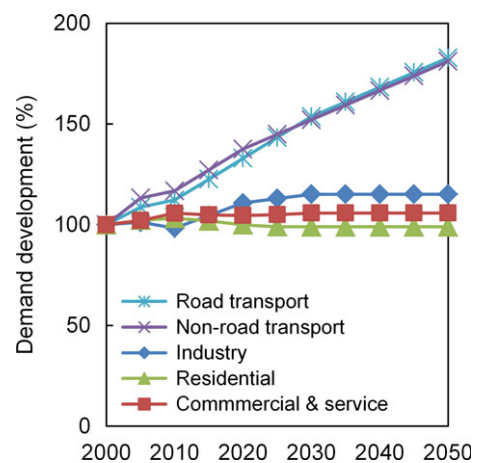


Fig. 2 Aggregated view of assumed reference energy service demand developments expressed with demand levels of 2000 as base.



forecasts (SEA, 2011b, 2013b). For transport, the demand projections are based on the reference case of the traffic capacity investigation by the Swedish Transport Administration (STA, 2012), which shows a significant travel increase. The distance traveled by cars increases by 65% from 2006 to 2050. Heavy-duty traffic increases at the same order of magnitude.

The reference projections represent a development based on current trends and policies. Since elastic demand is applied in the model, demand levels in model results can differ from the reference projections (except in the reference scenario, in which demand levels are completely exogenous). Assumed energy service demand elasticities, which are based on Anandarajah *et al.* (2009) and Henriksson & Lundmark (2013), are in the range of 0.2–0.6 for transport, 0.3–0.5 for industry and 0.25–0.35 for residential, commercial and service sectors. For pulpwood demand in the pulp and paper industry, an elasticity of 0.1 is assumed. This elasticity will, in conjunction with the endogenously determined biomass price, regulate to what degree pulpwood demand in the paper and pulp industry will diverge from the reference projection and consequently, to what degree pulpwood will be used for energy purposes.

### Forestry biomass resource data

Potentially available quantities of stemwood, logging residues and stumps for the period 2010–2059 are based on data collected in the Swedish Forest Inventory (SFI) from 2002 to 2006. Forest development is simulated by means of HUGIN, a calculation system that enables the forecasting of potential outcomes of stemwood, logging residues and stumps from harvesting operations (final fellings and thinnings) (Lundström & Söderberg, 1996). SFI consists of a network of more than 31 000 sample plots evenly spread over Sweden's entire forested area. In the simulation, a growth prognosis is produced for the trees in each individual sample plot. Each sample plot is used as the unit for decisions regarding different harvesting operations. An important assumption for the forecasting is that site productivity remains unchanged during the forecasting period.

Concerning the potential of logging residues and stumps, environmental, technical and economic restrictions are taken into consideration (Athanassiadis *et al.*, 2009). The calculated

theoretical potential is reduced by excluding productive forest areas that are situated in areas of nature protection; in wet areas and peat soils with low bearing capacity; in areas that are located 25 m from a lake, sea, waterline or any ownership category other than forest; in areas that have an uneven ground structure and/or a slope of more than 19.6° according to the Swedish terrain classification scheme. Regeneration felling areas of less than 1 ha in size are excluded as well as hardwood stumps with attached root system.

For branches, tops and foliage, the system that is used comprises of forwarding to the roadside, chipping at roadside and transport to the industry by container truck. Stumps with attached root systems are forwarded to the roadside, transported by truck to the industry and chipped there.

Three forest biomass assortments are included in the study: pulpwood, logging residues and stumps – for which the following cost components are calculated: harvesting with a single tree harvester (pulpwood), extraction with a forwarder (pulpwood, logging residues and stumps), chipping by mobile chippers (logging residues), crushing by mobile shredders (stumps), compensation to forest owners, administrative costs and transport of machinery to the harvested site, transport by truck to the nearest heating plant or pulp mill. Every cost component is calculated separately and all relevant cost components are then added in order to form the total acquisition cost for each forest biomass assortment.

The biomass supply data, including costs and potentials for different biomass fractions from the HUGIN simulations and cost calculations, are utilized as input in the energy system modeling but these very high-detail data are first aggregated into step-wise supply curves, which is a suitable format for the MARKAL\_Sweden model. Figure 3 visualizes the step-wise supply curves for model year 2050 for tops and branches, stumps and pulpwood, respectively, as fed into MARKAL\_Sweden.

### Agricultural biomass resource data

For the construction of supply curves for energy crops, the arable land in Sweden is divided into eight different areas based on their production conditions. For each different area and energy crop alternative, yield levels and production costs are

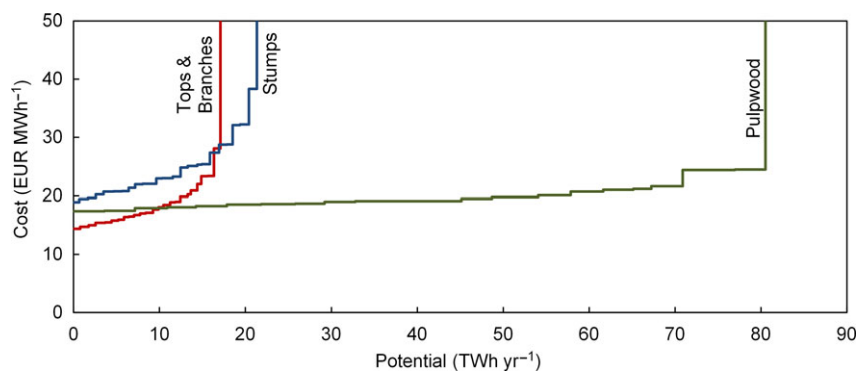


Fig. 3 Supply curves for different biomass types from domestic forestry as represented in model (model year 2050).

retrieved from Börjesson (2007) and Rosenqvist (2011), respectively, see overview in Table 1. It is assumed that the maximum area available for energy crop cultivation is 600 000 ha, or about 22% of the existing arable land in Sweden, and that this area is fully available from 2030 (see also Börjesson, 2007). This area is assumed to be distributed in the country in the same way as the currently existing arable land, i.e., no single production area can have a higher share of energy crop cultivation than 22% (see Table 1). Due to the risk for crop rotation diseases, cultivation of rapeseed is restricted to 150 000 ha. As can be seen in Table 1, for simplification, similar types of energy crops (such as different types of energy forest) usable for the same energy purpose are grouped together in the same category. Thus, in the model, four groups of energy crops are represented: energy forest, ley/grass crops, cereal crops and oil seed crops. Based on the data presented in Table 1, energy crop supply curves (visualized in Fig. 4) are constructed and integrated into the energy system model. For the annual full production potentials of the different energy crops presented in both Table 1 and Fig. 4, the full possible area for each of the crops is assumed, while in the model combinations of different energy crops can be chosen.

In addition to energy crop cultivation, several agricultural waste streams can be utilized for energy purposes. Straw from agricultural cereal and oilseed production can potentially be used for heat and electricity production as well as biofuel production. The total quantity of straw produced in Sweden amounts to 2.4 Mtons yr<sup>-1</sup>. The major use of straw is feed and bedding in animal husbandry (Ekman *et al.*, 2013). Very little is currently used for energy purposes. Ekman *et al.* (2013) estimate the annual amount of straw available for energy purposes at 0.83 Mtons (wet weight, 18% water content) or 0.68 Mton dry substance (DS). Assuming an energy content of 4.4 MWh ton<sup>-1</sup> DS (LHV) (Börjesson, 2007), this gives a total annual energy potential of about 3 TWh. The cost of straw for energy purposes is assumed at 10 EUR/MWh (Edwards *et al.*, 2007).

Waste fractions suitable for biogas production include sludge from sewage treatment plants, waste products from agriculture such as manure, food residues (from households, restaurants, super markets, etc.) and garden waste. While much of the current biogas production is located at sewage treatment plants using sludge as feedstock, the main future potential comes from the agricultural sector. In this study, the future feedstock potential for biogas production based on waste products is assumed at 11 TWh yr<sup>-1</sup> (Linné *et al.*, 2008). While straw is a potential feedstock option for biogas it is not included in this potential, since in the model it is represented as a separate energy source usable not only for biogas production but also for other energy purposes. There is assumed to be an additional cost involved for using the waste feedstock options for biogas production (logistic costs, etc.) of 0–6 EUR/MWh (Björnsson & Lantz, 2010; Börjesson & Ahlgren, 2012c).

#### *Other biomass fractions and biomass data summary*

Potentials for biomass sources not directly linked to forestry and agriculture, including industrial residues, firewood for single family houses, and recovered wood, are based on the

long-term forecasts by the Swedish Energy Agency (SEA, 2013b). The current study focuses on domestic biomass resources and the potential import amounts of biomass and biofuels are therefore restricted in the model. The permitted bioenergy import levels are assumed to be about the same as today's import levels, only a slight increase for some biomass fractions is allowed.

Table 2 summarizes model assumptions on biomass potentials and costs (excluding combustible municipal waste and peat). Note that not all biomass fractions can be used for the same purposes and also that the full energy crop potentials, as given in the table, are not addable. This is also the case for the full domestic pulpwood potential (within brackets) and industrial residues (since part of the industrial residues originates from the pulpwood potential). While utilization levels and price of biomass are scenario-dependent outputs of the model, the cost and potentials data of Table 2 are inputs to the model and the same for all modeled scenarios.

#### *Model scenarios and policies*

For the analysis, we develop several different input scenarios and cases. For the main analysis, these differ mainly in regard to the energy policies applied, basically in regard to CO<sub>2</sub> reduction levels (for the energy system as a whole) and in regard to fossil fuel phase-out policies (in the road transport sector). In the sensitivity analysis, we test different developments in the stationary energy system as well as in the transport sector compared to the base assumptions of the main analysis.

A stylized energy policy situation is applied in the study and no energy/emission taxes or subsidies are included. Policy ambitions are instead represented as quantitative constraints. In the study, three such quantitative policy constraints are included: (i) CO<sub>2</sub> reductions, (ii) increase of renewable electricity production and (iii) phase-out of fossil fuels in the road transport sector. CO<sub>2</sub> reductions are achieved by applying an emission cap to the model system, i.e., the entire Swedish energy system including the transport sector. The stringency of the cap differs between scenarios. Based on the Swedish tradable green certificate (TGC) system for the promotion of renewable electricity generation, a model constraint increasing renewable electricity generation in the Swedish energy system to at least 25 TWh by model year 2020 is applied (the constraint is then kept constant at 25 TWh until 2035 but is then removed, see SEA, 2013c). Further, to investigate the system effects of an almost fossil-free road transport sector by 2030 in line with the objective stated by the Swedish government (Swedish Government, 2008), a fossil fuel phase-out constraint for road transport is introduced. In the cases applicable, this constraint, which here is denoted the 'fossil fuel phase-out' (FFP) policy, is defined as an 80% reduction of fossil fuel use in the road transport sector by 2030 and a 100% reduction by 2050.

The following scenarios are included in the main analysis:

- A business-as-usual (BAU) scenario, which represents a development based on current trends and policies and without major technological changes in the energy

**Table 1** Assumed land availability, yield levels, and resulting annual potentials for energy crops (energy forest, ley/grass, cereal, and oilseeds). Land and potential figures are valid from model year 2030 when the assumed maximum available land availability of 600 10<sup>3</sup> hectare (kha) is reached

	Part of Sweden*								Total
	Gss	Gmb	Gns	Gsk	Ss	Ssk	Nn	Nö	
Land									
Available land for energy crops (kha)	74.1	69.6	101.2	110.4	138.8	43.9	35.6	26.4	600
Share of total arable land (%)	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4	22.4
Available land for oilseeds (kha)†	20.7	19.4	28.2	30.8	38.7	12.2			150
Share of total arable land (%)	6.2	6.2	6.2	6.2	6.2	6.2			5.6
Yield levels (MWh ha <sup>-1</sup> )‡									
Energy forest									
Salix	41.8	28.6	36.1	26.4	30.8	22.0			
Hybrid aspen	33.9	26.4	29.5	24.2	26.4	22.0	19.8		
Poplar	37.4	28.6	32.6						
Spruce (fertilized)							16.3	14.1	
Assumed mix	39.3	28.2	34.1	25.5	28.6	22.0	18.0	14.1	
Ley/grass crops									
Reed canary grass	24.3	23.4	22.5	20.7	21.6	20.3	18.9	18.0	
Ley crops	33.8	30.2	29.3	22.5	27.0	20.3	18.9	18.0	
Assumed mix	29.0	26.8	25.9	21.6	24.3	20.3	18.9	18.0	
Cereal crops									
Wheat (grain)	28.8	24.8	21.6		18.9				
Corn (grain)				13.5		12.6	9.0	8.1	
Assumed mix	28.8	24.8	21.6	13.5	18.9	12.6	9.0	8.1	
Oilseeds									
Rapeseed	19.9	18.5	18.5	17.0	14.2	14.2			
Potentials (TWh yr <sup>-1</sup> )§									
Energy forest	2.9	2.0	3.4	2.8	4.0	1.0	0.6	0.4	17.1
Ley/grass crops	2.2	1.9	2.6	2.4	3.4	0.9	0.7	0.5	14.4
Cereal crops	2.1	1.7	2.2	1.5	2.6	0.6	0.3	0.2	11.2
Oilseeds	0.4	0.4	0.5	0.5	0.5	0.2			2.5
Production costs (EUR/MWh)**									
Energy forest									
Salix	13.6	16.8	14.7	17.7	16.1	20.0			
Hybrid aspen	23.0	28.6	25.8	31.6	28.6	35.8	41.7		
Poplar	19.6	23.6	21.3						
Spruce (fertilized)							54.9	80.0	
Assumed mix	16.6	20.5	18.2	23.2	22.3	27.9	48.3	80.0	
Ley/grass crops									
Reed canary grass / Ley crops	23.0	23.3	23.8	24.7	24.2	24.9	24.9	24.9	
Cereal crops									
Wheat (grain)	31.2	34.7	37.7		41.0				
Corn (grain)				50.1		52.8	69.2	75.7	
Assumed mix	31.2	34.7	37.7	50.1	41.0	52.8	69.2	75.7	
Oilseeds									
Rapeseed	42.3	44.9	44.9	47.9	49.7	47.9			

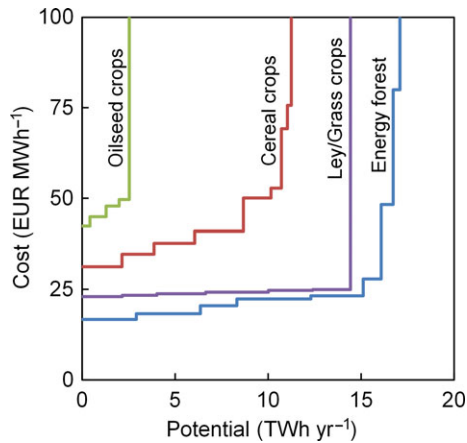
\*Gss, Plain districts in Götaland; Gmb, Central districts in Götaland; Gns, Plain districts in northern Götaland; Ss, Plain districts in Svealand; Gsk, Forest districts in Götaland; Ssk, Forest districts in central Sweden; Nn, Lower parts of Norrland; Nö, Upper parts of Norrland.

†'Available land for oilseeds' constitutes a subpart of 'Available land for energy crops'.

‡Yield levels are based on Börjesson (2007).

§Refers to maximum potentials if all of the available land were to be used for the same energy crop category. The provided full potentials within a certain area are thus not addable.

\*\*Production costs are based on Rosenqvist (2011).



**Fig. 4** Supply curves for energy crops (for model years 2030 to 2050). The different energy crop alternatives compete for the same land and the full potentials are thus not addable; however, different parts of the land can be used for different crops.

system. The BAU scenario is set as the reference scenario for which demands in the model's various end-use demand categories are exogenous and in accordance with the baseline projections presented earlier (Fig. 2). In the scenario, CO<sub>2</sub> emissions are kept constant at current levels (see also SEA, 2013b), corresponding to a 20% reduction compared to the 1990 emission level. Import fossil fuel prices are based on the 'current policy scenario' of IEA's World Energy Outlook (IEA, 2010), and a crude oil price of about USD 135/barrel is assumed for the latter part of the studied time horizon. For the transport sector, it is assumed that conventional fuels will continue to dominate and second-generation biofuels are not available options in the scenario.

- A no policy scenario (POL\_NO) in which no energy policies or CO<sub>2</sub> emission restrictions apply, i.e. fossil fuels can be used without any penalties of any kind. Similar to BAU, no second-generation biofuels are available. The main purpose of the scenario is to act as a comparison to the other scenarios of the analysis, rather than to represent a likely future development in itself.
- A main analysis scenario denoted GLOB\_CA (for GLOBAL Climate Action), which reflects a situation in which Sweden and the rest of the world pursue ambitious climate targets. CO<sub>2</sub> emissions should be reduced by 80% by 2050 compared to the 1990 emission level. Import fossil fuel prices are based on the '450 scenario' of IEA's World Energy Outlook (IEA, 2010), and a crude oil price of about USD 90/barrel is assumed.
- Two additional CO<sub>2</sub> reduction scenarios, which test the sensitivity to less ambitious CO<sub>2</sub> reduction levels than in GLOB\_CA. In scenario CO<sub>2</sub>\_LR65 and CO<sub>2</sub>\_LR50 (LR for Low Reduction), CO<sub>2</sub> emissions are reduced by 65% and 50% by 2050, respectively, compared to the 1990 emission level. Other assumptions are the same as for GLOB\_CA.

Parameters other than CO<sub>2</sub> reduction levels can also be of importance for biomass utilization and biomass allocation between sectors. A sensitivity analysis is therefore performed, testing alternative assumptions in regard to several different aspects. The alternative scenarios, presented in Table 3, simulate different developments in the stationary energy system as well as in the transport sector compared to the base assumptions. In Table 3, only differences to the main analysis scenario GLOB\_CA are presented, i.e. with regards to aspects not mentioned, conditions are the same as in GLOB\_CA.

The additional constraint on fossil fuel use in road transport, the so-called FFP policy, is applied for all scenarios with the exception of BAU and POL\_NO. Thus, for each of the scenarios (the main analysis scenario GLOB\_CA, the low CO<sub>2</sub> reduction scenarios CO<sub>2</sub>\_LR50 and CO<sub>2</sub>\_LR65 as well the alternative scenarios of the sensitivity analysis), two model cases are carried out: one case without FFP and one case with FFP. Table 4 gives an overview of the main differences between the scenarios, and Fig. 5 visualizes the CO<sub>2</sub> emission caps and the FFP policy constraints applied in the different model scenarios and cases. As mentioned, the CO<sub>2</sub> constraints apply for the entire national energy system (including transport) but the FFP policy constraint only applies to road transport.

## Results

### *Energy supply and final energy use*

To meet the increasingly stringent CO<sub>2</sub> reductions, several different measures are required across all sectors of the energy system. The developments in the energy system as a whole regarding total energy supply and final energy use are presented in Figs 6 and 7 for cases excluding the FFP policy. To reduce fossil fuel use, the scenarios present an increased use of biomass and other renewables as well as deployment of energy efficiency measures and lowered end-use demand.

For GLOB\_CA, use of biomass, waste and peat increase from 17% in 2000 to 32% in 2030 and 36% in 2050 expressed as a share of the total energy supply. Regarding the 'other renewables' category in Fig. 6, which also increases in importance, wind power is the main contributor. In 2050, wind power accounts for 26 TWh of electricity generation, i.e., considerably higher than the 0.5 TWh generated as of 2000. Bio-based electricity generation peaks in 2025 at a level of 23 TWh and then decreases to 13 TWh by 2050. The later decrease in the utilization of biomass in electricity generation can be explained partly by the increasing importance of bio-fuel use in the transportation sector moving towards the year 2050. That is, the results suggest that biomass – in the later time periods – is better used for biofuels than as a feed-stock for electricity generation. A similar pattern is seen for electricity export, which peaks at 25 TWh from 2030–2040 but only accounts for 10 TWh in



**Table 2** Summary of assumptions for biomass resources (excluding municipal combustible solid waste and peat)

	Potential (TWh yr <sup>-1</sup> )		Cost range (EUR/MWh)	Based on
	2030	2050		
Pulpwood (excl. bark)	1.9 (73)*	9.4 (81)*	17–25	See Section 'Forestry biomass resource data'
Forest residues – Tops and Branches	14.0	17.1	14–30	See Section 'Forestry biomass resource data'
Forest residues – Stumps	18.1	21.3	19–40	See Section 'Forestry biomass resource data'
Energy crop – Alternatives†				
Energy forest	17.1	17.1	17–80	Börjesson, 2007; Rosenqvist, 2011;
Cereal crops	11.2	11.2	31–76	Börjesson, 2007; Rosenqvist, 2011;
Ley/Grass crops	14.4	14.4	23–25	Börjesson, 2007; Rosenqvist, 2011;
Oilseed crops	2.5	2.5	42–50	Börjesson, 2007; Rosenqvist, 2011;
Straw	3	3	10	Ekman <i>et al.</i> , 2013; Edwards <i>et al.</i> , 2007;
Organic waste	11	11	0–6	Linné <i>et al.</i> , 2008; Börjesson & Ahlgren, 2012c; Björnsson & Lantz, 2010;
Industrial residues – Liquors	50	50	–	SEA, 2013b;
Industrial residues – Wood waste	27	27	0–5	SEA, 2013b; Hagström, 2006;
Recovered wood	3	3	7	SEA, 2013b;
Firewood (single family houses)	11	11	1.5	SEA, 2013b;
Imports – Wood pellets/briquettes	4	4	39	SEA, 2011a, 2013b;
Imports – Ethanol	3.4	3.4	71; 74‡	Swedish Government, 2010; SEA, 2011a;
Imports – Oilseeds	1	1	42	SEA, 2011a; Hansson & Grahn, 2013

\*Potentials without brackets refer to amounts available over and above the reference raw material demand in the pulp and paper industry. Potentials within brackets refer to total amount. The full pulpwood potential is not addable to the industrial residues potentials since they constitute partial sums of each other.

†Since energy crop alternatives compete for the same available agricultural land, the full potentials of each alternative are not addable. However, different parts of the available agricultural land can be used for different alternatives.

‡For 2030 and 2050 respectively.

2050. In GLOB\_CA, the remaining fossil fuels in 2050 consist of fossil fuel use in industry, in particular coke use in the iron and steel industry, and oil use in non-road transport (aviation, shipping, working machines), which only partly switches to biofuels under the assumed conditions. As a result of increased use of more efficient energy technologies, lower end-use demand levels as well as lower electricity export (10 TWh compared to 19 TWh), GLOB\_CA shows a 15% (95 TWh) lower total energy supply than BAU in 2050.

#### Total biomass utilization

With the exception of the POL\_NO scenario, all scenarios show an increasing use of biomass in the energy system throughout the studied period (Fig. 8). The BAU scenario shows an increase in biomass use of 29% from 2010 to 2030 and 43% from 2010 to 2050. With higher CO<sub>2</sub> reductions, the utilization is even higher and in GLOB\_CA, the increase in biomass use is 41% from 2010 to 2030 and 63% from 2010 to 2050. In GLOB\_CA, almost the full biomass potential, as defined in the model, is utilized.

The substantial increase in biomass use means that the supplied quantity of most of the different biomass fractions increases, see Fig. 9 for GLOB\_CA. While not all biomass fractions can be used for all purposes, in general, the low-cost biomass fractions, such as, e.g., industrial residues, are utilized before more expensive options such as energy forests are introduced. However, due to the cost structure of several of the different biomass options, a mix of different biomass sources is utilized at any point in time. Among the biomass fractions that show the largest increase in utilization during the studied period are forestry residues, in particular stumps but also tops and branches, and energy crops in the form of energy forest. Further, an increase in the use of pulpwood for energy purposes is seen as well as in organic bio-waste for biogas production. The high demand for biomass in the energy system leads to less pulpwood use in the pulp and paper industry in GLOB\_CA compared to the exogenous reference demand projection of the BAU scenario, see Fig. 10.

As Fig. 9 shows (indicated by the dotted line), the implementation of the FFP policy increases the biomass supply by up to 10 TWh yr<sup>-1</sup> in the middle of the

**Table 3** Overview of alternative scenarios for sensitivity analysis (only differences to GLOB\_CA are described)

Scenario	Description
2GEN_HC	High cost for 2nd generation biofuels: Investment costs for second-generation biofuel production are assumed to be twice as high as with the base assumptions (which, e.g., for methanol production implies 3000 EUR/kW instead of 1500 EUR/kW, see Börjesson <i>et al.</i> , 2014).
EV_HC	High costs for electric vehicles: Cost reductions of electric vehicles, including HEVs, PHEVs and BEVs, are assumed to be slower than with base assumptions, 50% higher incremental costs (to conventional vehicle technologies) are assumed (which, e.g., for BEVs in 2050 imply an incremental cost of 9.8 kEUR/car instead of 6.5 kEUR/car, see Börjesson <i>et al.</i> , 2014).
BIO_LS	Low supply for biomass: The potential for biomass from forestry is lower than in the base assumptions: stumps are assumed not to be available for energy purposes. It is uncertain if a large-scale usage of stumps will take place in Sweden as ecological considerations are raised. The concern is that large-scale stump harvesting will increase the losses of soil carbon and nutrients due to increased soil disturbance and decrease the habitat areas for micro-organisms.
TRAD_SG	Slow travel demand growth: Based on potentials for reduced travel demand growth by measures that are not captured by the model (e.g., city planning; modal shift to bicycle, trains, shipping, etc.; and parking policies/tariffs), an alternative development with lower travel demand levels is assumed (based on Swedish Transport Administration; STA, 2012). In this alternative development, the travel demand levels in 2050 are similar as in 2005.
NUC_PO	Nuclear phase-out: The scenario addresses the much debated issue of a nuclear power phase-out in Sweden and tests the effects of, in addition to climate targets, not allowing nuclear power generation after model year 2030.
PULP_SD	Mechanical pulp mills shut-down: The scenario reflects a less positive development for the Swedish pulp and paper industry and assumes that all mechanical pulp mills, due to increasing international competition, are closed down by 2030. This results in an 18% lower pulpwood demand and 36% lower electricity demand by the paper and pulp industry as a whole (based on Nilsson, 2004; Wiberg, 2007).
NAT_CA	National climate action: The scenario reflects a situation in which ambitious climate targets apply in Sweden while the world at large shows less ambitious targets. This results in higher import fossil fuel prices; prices are based on the “current policy scenario” of IEA’s World Energy Outlook (IEA, 2010) and a crude oil price of USD 135/barrel is assumed for the latter part of the studied time horizon.

**Table 4** Summary of differences between scenarios

Scenario		CO <sub>2</sub> reduction*	FFP policy	TGC	Fossil fuel prices‡	2nd gen biofuels	End-use elasticity
Business-as-usual	BAU	Yes, -20%	No	Yes	High	No	No
No policies	POL_NO	No	No	No	High	No	Yes
Global climate action	GLOB_CA	Yes, -80%	Yes & No†	Yes	Low	Yes	Yes
Low CO <sub>2</sub> reduction	CO <sub>2</sub> _LR65	Yes, -65%	Yes & No†	Yes	Low	Yes	Yes
	CO <sub>2</sub> _LR50	Yes, -50%	Yes & No†	Yes	Low	Yes	Yes
Sensitivity scenarios (see Table 3)		Yes, -80%	Yes & No†	Yes	Low / High§	Yes	Yes

\*CO<sub>2</sub> reduction to 2050 compared to the 1990 emission level.

†Two different cases are run for each scenario.

‡‘High’ refers to fossil fuel prices based on the ‘current policy scenario’ of IEA’s World Energy Outlook (IEA, 2010) with an oil price around USD 135/barrel. ‘Low’ refers to fossil fuel prices based on the ‘450 scenario’ of IEA’s World Energy Outlook (IEA, 2010) with an oil price around USD 90/barrel.

§Fossil fuel prices depend on scenario (see Table. 3).

studied period (model years 2025–2035) for GLOB\_CA. In particular, the utilization of organic waste in biogas production is higher during this period compared to the case without the FFP policy applied. The biomass supply at the end of the studied period is similar in both cases, i.e., both with and without the FFP policy

applied. For the lower CO<sub>2</sub> reduction scenarios (CO<sub>2</sub>\_LR50 and CO<sub>2</sub>\_LR65), the effect of the FFP policy on biomass use is relatively higher than for GLOB\_CA and, in these cases, the biomass use is essentially the same as in GLOB\_CA with FFP (i.e., as the dotted line in Fig. 9).

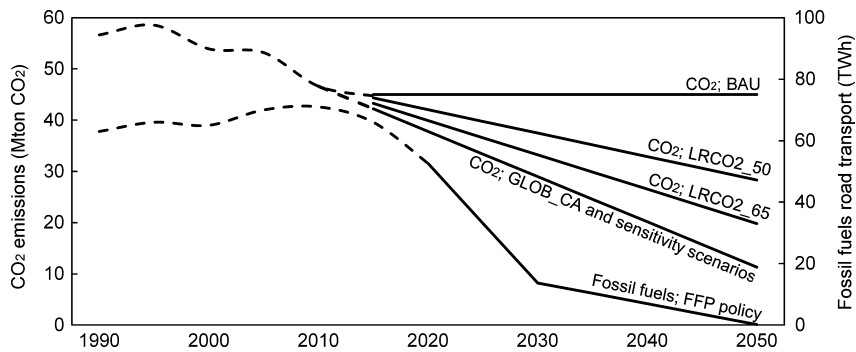


Fig. 5 CO<sub>2</sub> emission and FFP policy constraints (solid lines) as applied in different scenarios.

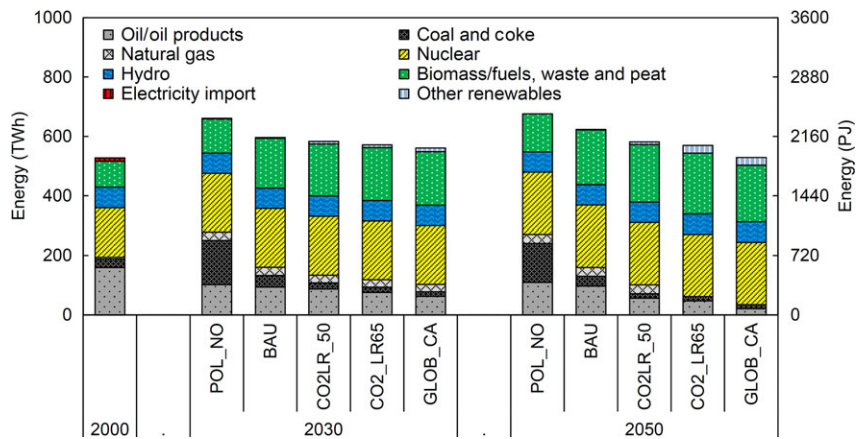


Fig. 6 Total energy supply for model years 2030 and 2050. Nuclear power is represented in gross values (input energy).

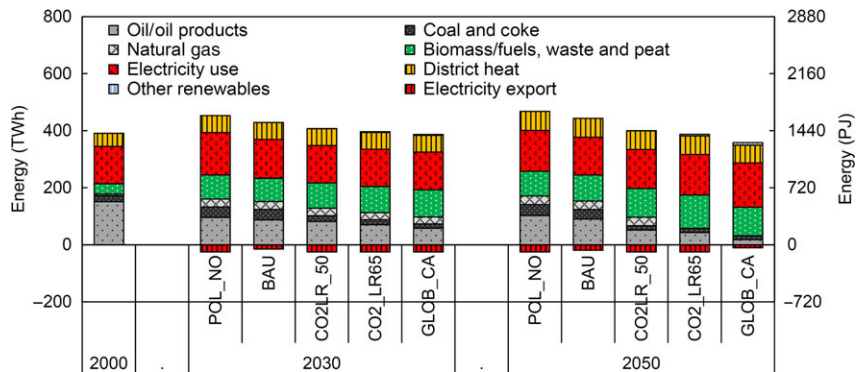


Fig. 7 Final energy end use for model years 2030 and 2050.

*Biomass allocation between sectors*

While the bioenergy supply to the energy system as a whole increases steadily throughout the studied time horizon for all scenarios applying CO<sub>2</sub> emission constraints, the use of biomass develops differently depending on energy system sector. Utilization of biomass resources for Bio4HePo and Bio4Tran (see definitions in ‘Steps of the analysis’) are presented in Figs 11

and 12, respectively. Results are presented without (a) and, for relevant scenarios, with (b) the FFP policy applied.

Without the FFP policy, Bio4HePo shows an increasing trend in the first half of the studied period. For GLOB\_CA, Bio4HePo peaks during 2025–2030 at a level of 132 TWh (Fig. 11a). After 2030, the utilization level decreases to 104 TWh in 2050. Bio4Tran shows a different development (Fig. 12a); a comparably modest

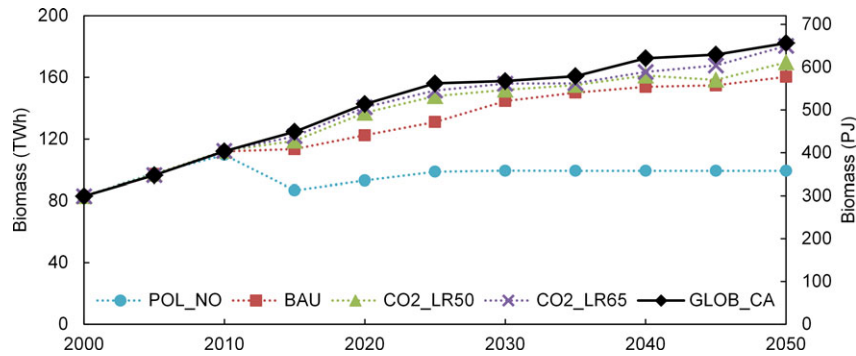


Fig. 8 Total biomass utilization in the energy system as a whole.

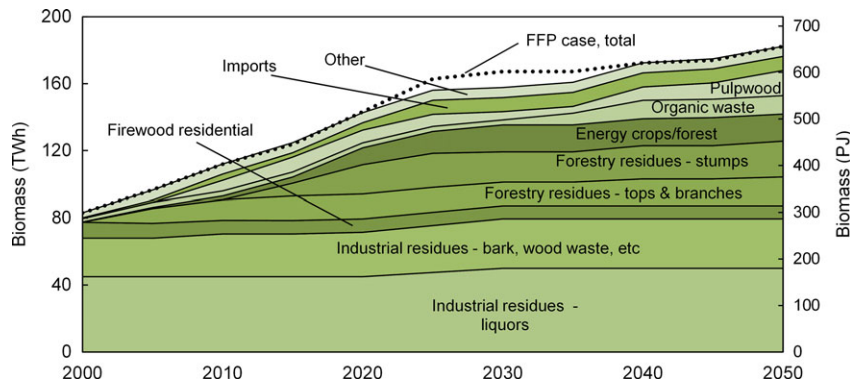


Fig. 9 Biomass utilized for energy purposes divided in supply categories (excluding peat and combustible municipal waste) for scenario GLOB\_CA. The dotted line shows the total utilization with the FFP policy applied.

increase is seen up to 2030, when about 26 TWh is utilized for this purpose, but then a faster increase takes off and the utilization reaches 79 TWh in 2050.

While the application of the FFP policy has a comparably small influence on the total biomass supply (Fig. 9), it has a large influence on the allocation of biomass between sectors. Compared to the case without FFP, a larger biomass use is noted for Bio4Tran at an earlier stage during the studied period (Fig. 12b), while a lower use is noted for Bio4HePo (Fig. 11b). For GLOB\_CA with FFP policy, utilization of Bio4HePo increases to 115 TWh in 2015–2020. It then declines somewhat but stays in the range of 101–112 TWh for the 2025–2050 period. In contrast, Bio4Tran utilization starts out with a sharp increase from 2015 and then stabilizes around 2030. For 2030 to 2045, utilization in this category is within the range of 61–67 TWh and increases to 80 TWh in model year 2050 (i.e., for 2050, utilization is very close to that of the case without FFP policy).

The CO<sub>2</sub> reduction level is of large significance for the allocation of biomass. Scenarios applying less stringent reduction targets (CO<sub>2</sub>\_LR50, CO<sub>2</sub>\_LR65) show large differences to GLOB\_CA in several respects. Without FFP, lower CO<sub>2</sub> reductions result in less Bio4Tran

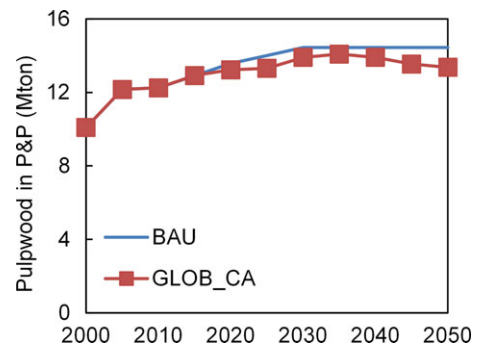


Fig. 10 Use of domestic pulpwood in pulp and paper industry in GLOB\_CA compared to reference development in BAU.

utilization but higher Bio4HePo utilization in comparison to GLOB\_CA (Fig. 12a and Fig. 11a, respectively). For instance, while the scenario CO<sub>2</sub>\_LR50 (without FFP) shows a very low Bio4Tran utilization of 21 TWh in 2050, it shows a very high level for Bio4HePo of 148 TWh. Further, for CO<sub>2</sub>\_LR65 and CO<sub>2</sub>\_LR50, the effect of introducing the FFP policy is much larger than for GLOB\_CA, since the Bio4Tran levels in these cases are low without the policy. As previously indicated, if no



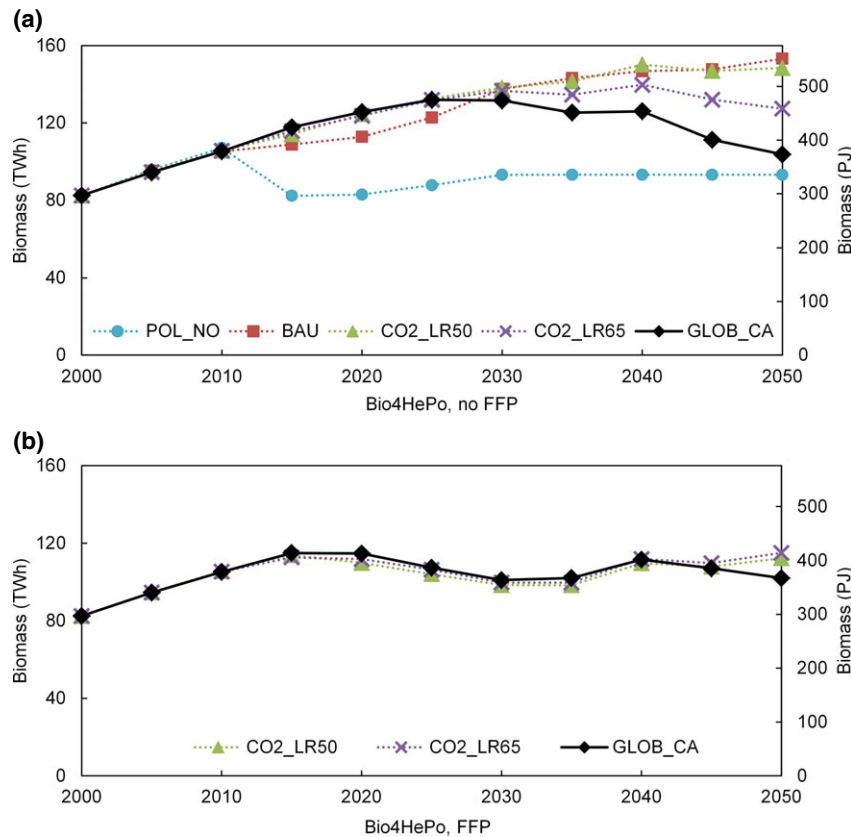


Fig. 11 Biomass utilized for heat and power production (Bio4HePo), without FFP policy (a) and with FFP policy applied (b).

CO<sub>2</sub> policies are applied, such as for POL\_NO, the incentives for bioenergy are very low and, not surprisingly, the utilization of both Bio4HePo and Bio4Tran are both considerably lower than in GLOB\_CA.

#### Price of biomass

For all scenarios applying CO<sub>2</sub> constraints (i.e., all scenarios except POL\_NO), significantly increasing biomass prices are observed for the studied time horizon. Fig. 13 presents the model price development for unrefined wood biomass used for energy purposes (wood chips).

For GLOB\_CA without the FFP policy applied, biomass prices increase from 19 EUR/MWh in model year 2010 to 43 EUR/MWh in 2030 and, further, to 66 EUR/MWh in 2050 (Fig. 13a), i.e. the price more than triples. With FFP, the price increase is sharper in the early part of the period, showing a value of 49 EUR/MWh in 2030 (Fig. 13b). However, the price increase then halts and in 2050 the level is similar with and without the FFP policy. The lower CO<sub>2</sub> reduction levels of CO\_LR50 and CO2\_LR65 imply lower biomass prices, in particular at the end of the studied time horizon. However, the price still more than doubles from 2010 to 2050 in the

CO<sub>2</sub> LR50 scenario, also without the FFP policy. The BAU scenario shows a more modest development with a biomass price stagnating around 30 EUR/MWh in the later part of the studied period. Not surprisingly, POL\_NO shows lower prices for future model years than today.

#### Sensitivity analysis

For many of the alternative scenarios, the general trends in regard to the development of biomass utilization are similar to GLOB\_CA. Generally, for all scenarios without the FFP policy applied, the results indicate that CO<sub>2</sub> reduction levels are required to reach about 40–50% for Bio4Tran to take off at a faster rate. For the alternative scenarios, this emission reduction level occurs in the 2025–2030 period. At this point in time (and at this CO<sub>2</sub> reduction level), most scenarios also show a stabilization or initial decline in Bio4HePo.

The sensitivity analysis highlights that parameters other than the CO<sub>2</sub> reduction level can also be of importance for the biomass utilization of the energy system and the biomass allocation between energy sectors. Figure 14 presents the total biomass use, Bio4HePo,

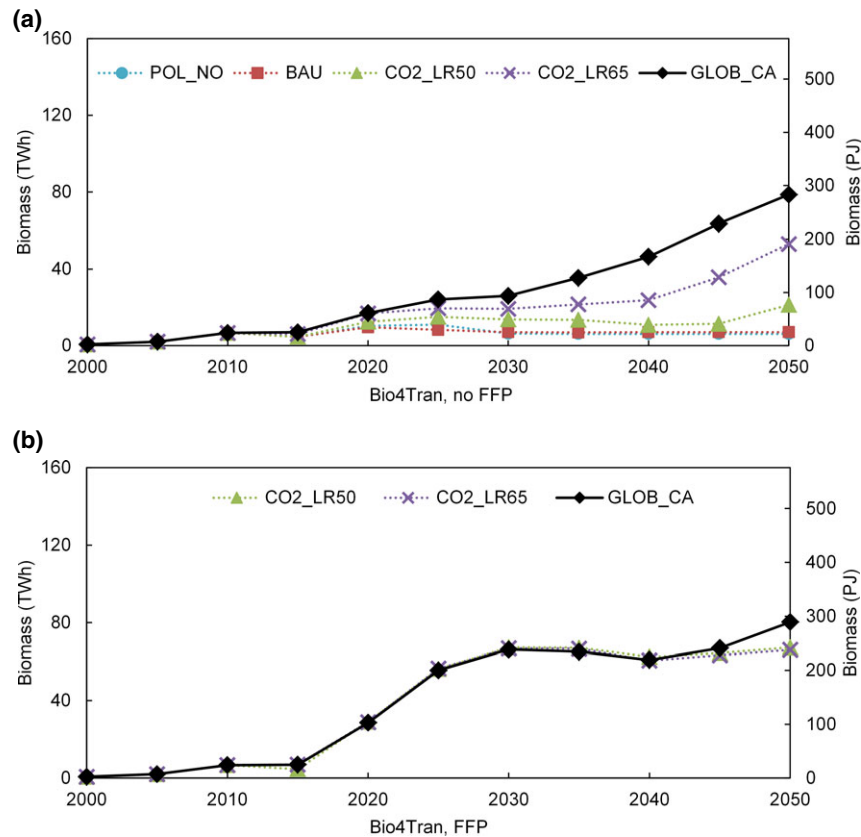


Fig. 12 Biomass utilized for transport biofuel production (Bio4Tran), without FFP policy (a) and with FFP policy applied (b).

Bio4Tran and price of biomass in relation to GLOB\_CA for all of the alternative scenarios, in (a) without FFP and in (b) with FFP. The cost development of low-carbon alternatives to transport biofuels is a parameter of large significance. The scenario EV\_HC, in which electric vehicles experience a slow cost reduction development, stands out as one of the scenarios with the largest difference to GLOB\_CA regarding Bio4Tran utilization, with 2030 levels about 40% higher for the case without FFP (Fig. 14a). Further, the lower transport demand growth development of scenario TRAD\_SG and higher cost of second-generation biofuel production according to scenario 2GEN\_HC also show comparably large differences to GLOB\_CA. Without FFP, both these scenarios show Bio4Tran levels about 25% lower than GLOB\_CA for the 2030–2050 period seen as a whole (Fig. 14a). A lower Bio4Tran utilization than GLOB\_CA is also observed for the scenarios BIO\_LS (low supply of biomass) and NUC\_PO (nuclear phase-out); for 2030–2050, levels are 10–15% lower than for GLOB\_CA (without FFP). In contrast, NAT\_CA (national climate action) and PULP\_SD (shut-down of part of the pulp and paper industry) show higher Bio4Tran levels than GLOB\_CA. However, differences are rather small (+6% and +3% for

NAT\_CA and PULP\_SD, respectively, for the 2030–2050 period without FFP).

The percentage difference in Bio4Tran utilization for the alternative scenarios in comparison to GLOB\_CA is generally smaller with the FFP policy applied (Fig. 14b) than without the FFP policy (Fig. 14a). This is expected, considering that the development of the transport sector is determined exogenously to a higher degree when the FFP policy is applied.

In terms of biomass prices, the alternative scenarios show results that are generally close to GLOB\_CA, with differences around 10% or less in 2050. However, NUC\_PO shows significantly higher levels. The scenario's combination of stringent CO<sub>2</sub> constraints and nuclear power phase-out pushes biomass prices up to above 90 EUR/MWh at the end of the studied period.

## Discussion

In this study, future developments of biomass utilization in Sweden are investigated. Costs and potential availability of biomass resources are first established by a combination of a forestry forecasting simulation (forest residues and pulpwood) and a literature review

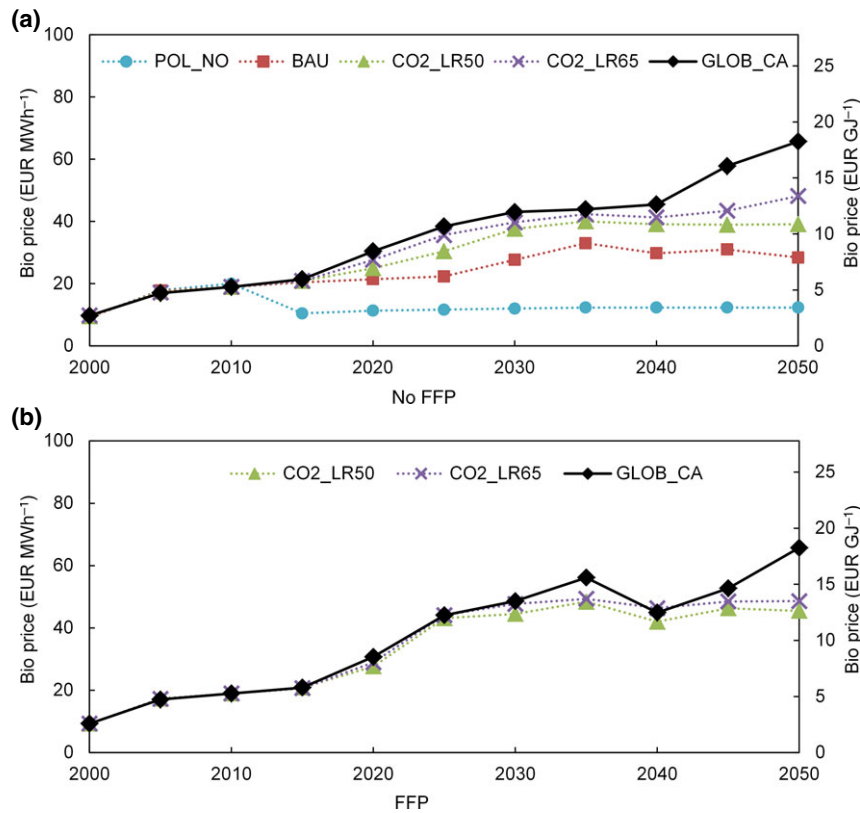


Fig. 13 Wood biomass price, without FFP policy (a) and with FFP policy applied (b).

(biomass from agriculture, industrial residues, etc.) combined with spreadsheet calculations. Detailed supply curves were established and integrated into the bottom-up energy system model MARKAL\_Sweden, which provides optimized future developments of the national energy system. The potential availability of forest biomass resources was estimated by using the HUGIN system that is primarily used for forecasting of future forest biomass yields under different forest management practices. The forecasting uncertainty involves the precision of forest tree growth functions (which are constructed from data from the Swedish National Forest Inventory), the assumption that site productivity remains unchanged during the forecasting period, the inability to take into consideration storm effects and other natural calamities as well as behavior of the forest owners when the market situation changes (i.e., forest owners tend to harvest more when market prices are high).

Results of the study show that CO<sub>2</sub> emission reductions considerably increase the cost-efficient amount of biomass in the energy system. In the main scenario (GLOB\_CA), in which a system-wide CO<sub>2</sub> reduction of 80% by 2050 compared to the 1990 emission level is imposed, the total bioenergy utilization increases by

63% by 2050 compared to 2010. Also, in scenarios with comparably modest CO<sub>2</sub> reduction levels, e.g., 20–50% by 2050 compared to 1990 (BAU and CO<sub>2</sub>\_LR50), the use of bioenergy increases significantly from current levels. However, without sector-specific policies, major CO<sub>2</sub> reductions of about 50% and above are required for transport biofuel production to take off. With higher reduction levels, the cost-efficient levels of transport biofuel production and use rise, and with stringent CO<sub>2</sub> reduction constraints, e.g., reduction of 80% by 2050, the model results show the largest increase in bioenergy use in transport biofuel production (in the main scenario GLOB\_CA, 43% of the total primary biomass use is due to transport biofuel production in 2050). This is explained by increasingly stringent CO<sub>2</sub> restrictions and biomass availability constraints implying an upward pressure on the biomass market price. As a consequence, sectors more easily able to switch to other energy sources or feed-stocks will do so (within the constraints of the model and scenarios). Since, under the assumed conditions, there are more economically viable ways to generate electricity and heat based on non-bioenergy sources than transport fuels, we thus see a decreasing utilization of bioenergy for electricity and heat as the price increases and, e.g., wind power

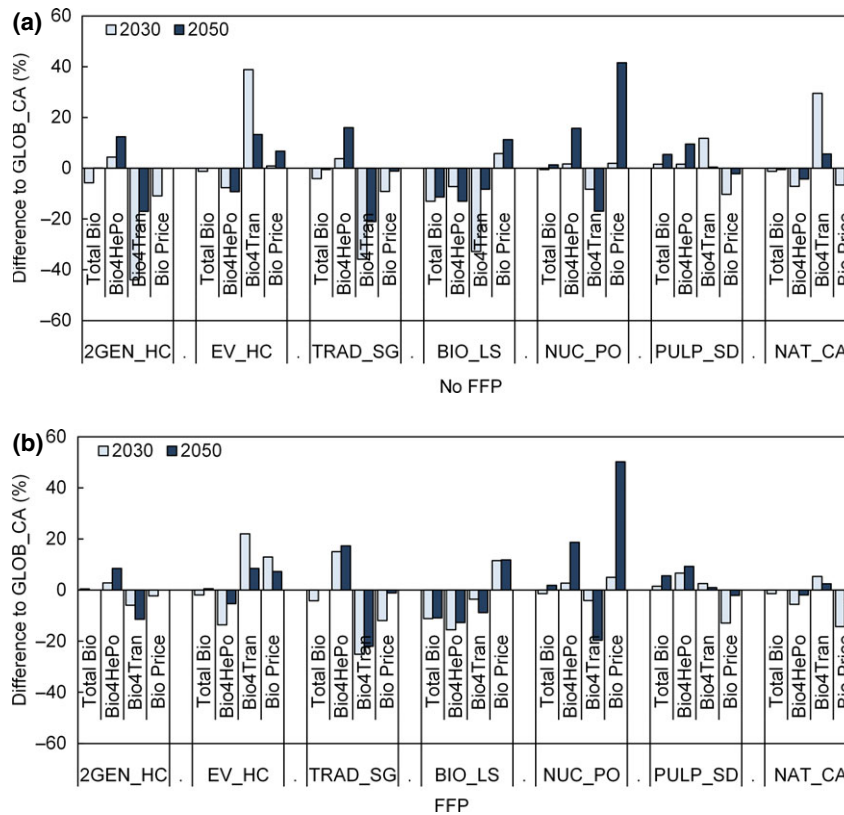


Fig. 14 Percentage change in total bioenergy utilization, Bio4HePo, Bio4Tran and biomass price in the sensitivity scenarios compared to GLOB\_CA, without FFP policy (a) and with FFP policy applied (b).

becomes more cost-efficient in the stationary energy system.

The introduction of a sector-specific policy, which reduces fossil-fuel use in road transport by 80% by 2030, leads to a large share of the biomass resources being allocated to transport biofuel production in the middle of the studied period. This fossil fuel phase-out policy leads to a 5% higher total system-wide use of bioenergy but a 20% lower bioenergy use for heat and power during the 2025–2035 period in the main scenario (GLOB\_CA).

Several other energy system modeling studies show a potential to increase the cost-efficient use of bioenergy under GHG constraints. At the national and regional levels, similar results are obtained by, e.g., Jablonski *et al.* (2010) in the case of the UK, van Vliet *et al.* (2011) in the case of the Netherlands, Forsell *et al.* (2013) in the cases of Sweden and France, and Blesl *et al.* (2010) for Europe. At a global scale, e.g., Gielen *et al.* (2003), Azar *et al.* (2003), and Grahn *et al.* (2009) also present a growing trend for future bioenergy use. That the largest increase in biomass use, under stringent CO<sub>2</sub> constraints, will be in production of biofuels for transport is also seen in studies by, e.g., Blesl *et al.* (2010) for Europe and Gielen *et al.* (2003) at a global scale while other

studies show a different development with very little transport biofuel use, see, e.g., Grahn *et al.* (2009) and Azar *et al.* (2003). Reasons for differences in this regard have been investigated and include, among other factors, the modeled time horizon, the level of CO<sub>2</sub> reductions and model technology representation in the stationary energy system as well as in the transport sector (see Grahn *et al.*, 2007; Börjesson *et al.*, 2013). Adding (cost-competitive) non-biomass low-carbon options in either the transport sector or in the stationary energy sector could shift biomass use to the other sector. In the present study, some potential future low-carbon options are not included, for instance, hydrogen as a transport fuel, electrified roads and CCS.

A strong biomass competition is likely to significantly increase future biomass prices compared to today's levels; substantial increases in biomass prices are seen across all modeled scenarios applying CO<sub>2</sub> emission constraints. For the main analysis scenario (GLOB\_CA), biomass prices more than triple from 2010 to 2050. Increased stress on the system in the form of additional policy measures, such as early fossil fuel phase-out in road transport or a nuclear power phase-out, or other factors such as slower than anticipated development and cost reduction of electric vehicles further pushes up



biomass prices. The model results suggest that the simulated policy targets can be achieved while the increasing price for biomass indicates that the costs involved are not insignificant and that this needs to be thoroughly assessed before policy actions are taken.

Due to the national approach applied, bioenergy trade over national borders is in this study represented in a simplified manner, and only allowed a small increase in bioenergy imports compared to current levels. In reality, higher imports could dampen the biomass price increases seen in the model results, but the effects of possible imports are uncertain in a climate-conscious world since a sharp global biomass demand increase is then expected. Only in the NAT\_CA scenario are the climate ambitions in the surrounding world, and thus the demand for low-carbon fuels, assumed to be lower than in Sweden. From a security-of-supply perspective, it might be relevant with domestic transport biofuel production but the social cost of achieving security-of-supply should be compared to fuel import costs. The increasing domestic marginal cost of a higher utilization of biomass might suggest that, at a certain price level, imports become more attractive than domestic production.

A future high demand for biomass leads to the utilization of higher-cost biomass resources such as stumps and cultivated energy forest in the model results. To some extent, pulpwood is also used for energy purposes. The increasing price of biomass might affect the profitability and, ultimately, the survivability of the pulp and paper industry. While the bulk of the increasing utilization of bioenergy is using harvesting residues, stumps and other biomass fractions not competing as a feedstock with the pulp and paper industry, in a competitive policy-driven situation, even slight changes need to be assessed. On the other hand, an increased demand for biofuels and 'green' electricity may also present an opportunity for an industry with well-established biomass supply-chains and mills, which, using new technologies, can be re-constructed to energy poly-generation plants with multiple outputs. Black liquor gasification for production of biofuels or electricity has received attention in recent years and can be an interesting option. Although liquors from the pulp and paper industry constitute an available resource in the model, the full potential benefits of this kind of industry-integrated polygeneration opportunities are not captured in the current model version.

The study shows that under stringent climate targets, even in a biomass-endowed country like Sweden, the utilization of biomass resources will be constrained. Measures for efficient utilization as well as for increasing biomass supply, e.g., through amplified growth of energy forest cultivation, will be important to cost-efficiently meet stringent climate objectives.

## Acknowledgements

This article is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Center is a nationwide center, which through cooperation and a systems approach contribute to the development of sustainable fossil-free fuels for transportation. The center is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see [www.f3centre.se](http://www.f3centre.se)). Funding was also provided by the Swedish Energy Agency through the Fuel Program Sustainability. We also thank Bio4Energy, a strategic research environment appointed by the Swedish government, for supporting this work.

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