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Biofuel futures in road transport – A modeling analysis for Sweden

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ABSTRACT

First and second generation biofuels are among few low-carbon alternatives for road transport that currently are commercially available or in an early commercialization phase. They are thus potential options for meeting climate targets in the medium term. For the case of Sweden, we investigate cost-efficient use of biofuels in road transport under system-wide CO_2 reduction targets to 2050, and the effects of implementation of targets for an almost fossil-free road transport sector to 2030. We apply the bottom-up, optimization MARKAL_Sweden model, which covers the entire Swedish energy system including the transport sector. For CO_2 reductions of 80% to 2050 in the Swedish energy system as a whole, the results of the main scenario show an annual growth rate for road transport biofuels of about 6% from 2010 to 2050, with biofuels accounting for 78% of road transport final energy use in 2050. The preferred biofuel choices are methanol and biomethane. When introducing additional fossil fuel phase-out policies in road transport (−80% to 2030), a doubling of the growth rate to 2030 is required and system CO_2 abatement costs increases by 6% for the main scenario. Results imply that second generation biofuels, along with energy-efficient vehicle technologies such as plug-in hybrids, can be an important part of optimized system solutions meeting stringent medium-term climate targets.

Introduction

The dependence on fossil fuels and the continuous increase of energy use in the transport sector have brought attention to transport biofuels as a measure to mitigate climate change and improve energy security. While biofuels currently only contribute a small share of the energy supply to the transport sector, several governments and intergovernmental organizations have declared policy targets which can lead to a significant increase in transport biofuel utilization. In the EU, energy from renewable sources in the transport sector should reach at least 10% by 2020 (EC, 2009). In addition, greenhouse gas (GHG) emissions should be reduced by 20% to the same year, and a long-term ambition of reducing GHG by 80–95% to 2050 has been stated (EC, 2011). In Sweden, the government has declared that the vehicle fleet should be independent of fossil fuels by 2030 while Swedish net emissions of GHGs should be zero by 2050 (Swedish Government, 2008).

Meeting stringent climate targets will in significant ways change the energy system and will involve a large scale integration of low-carbon fuels and technologies in the road transport sector. Due to limited resources, an increased

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utilization of alternative energy carriers in the transport sector can be expected to have system effects over sector boundaries. For instance, biomass is used as raw material in the forest product industry and in the chemical industry as well as for both biofuel production and heat/power production. Changes in biomass demand in any of these sectors will affect biomass markets and, thus, imply altered conditions for other biomass applications. In the analysis of efficient ways of meeting climate targets for transport and energy systems, a wide systems approach is therefore imperative.

This study investigates cost-efficient fuel and technology choices in the Swedish road transport sector in the presence of rigid climate policies in line with policy ambitions communicated nationally and by the EU. We focus on options that currently receive the major attention (and funding) in Sweden, and in the public debate are considered as feasible near-to-medium term options in Swedish context. In particular, we study prospects for first and second generation biofuels, but also electricity is included in the analysis as an alternative option to biofuels. The objective is to provide insights and analytical results to how these options can be utilized in road transport to meet stringent climate and energy security targets. The policy objectives in focus are CO_2 emission reductions for the national energy system as a whole and phase-out of fossil fuels in the road transport sector. The research questions are:

- To what extent could biofuels in road transport contribute to a cost-efficient achievement of stringent, system-wide CO_2 reduction policy targets to 2050?
- How does the attainment of an almost fossil-free road transport sector to 2030 affect cost-efficient fuel and technology choices and system costs?

To address the complex dynamic relationships between different sub-sectors of a national energy system, a systems modeling approach with an integrated view of the energy and transport system is applied. Important linkages between the transport sector and the rest of the energy system include the reliance on a common resource base in regard to biofuels and biomass-based heat and power, and the linkage between electricity generation and utilization of electric vehicles. A system-wide approach is also essential for the possibility to find cost-efficient GHG reduction strategies on an overall societal level and to avoid sub-optimized solutions. The study considers an array of technologies in all sectors of the energy system but, as indicated above, not all potential transport sector options are within the scope of the study. Examples of transport sector technologies and fuels that are not considered include: algae biofuels, hydrogen, electrofuels, fuel cell vehicles and electrified roads.

The number of systems studies that analyze the co-evolution of the stationary energy system and the transport sector has grown in the scientific literature in recent years. The geographical scope of these studies ranges from regional and national to global. Global studies focusing on the development of the transport sector as an integrated part of energy system include Takeshita (2012), Turton (2006), Gül et al.(2009), Azar et al. (2003), Grahn et al. (2009a,b), Hedenus et al. (2010), Gielen et al. (2003), Akashi and Hanaoka (2012), Van Ruijven and van Vuuren (2009), Kitous et al., 2010, Anandarajah et al. (2013), IEA (2008) and Kyle and Kim (2011). Studies with a national scope include Jablonski et al. (2010), van Vliet et al. (2011), Schulz et al. (2007), Martinsen et al. (2010) and Yeh et al. (2008) covering UK, Netherlands, Switzerland, Germany and USA, respectively. The focuses and results of the studies differ. In terms of transport biofuels, the future market penetration range from low to high levels. Most of the studies show low to intermediate transport biofuel market shares at the end of their studied time horizons (usually between 2050 and 2100), with levels below 40% for climate policy scenarios not applying sector-specific polices (see also review by Börjesson et al., 2013a).

In the case of Sweden, the future development of the energy and transport system has earlier been modeled by, e.g., Börjesson and Ahlgren (2012a,b) and Krook Riekkola et al. (2011). However, these studies do not investigate the recent and more ambitious policy targets, including an almost complete GHG emission and fossil fuel phase-out in the 2030–2050 timeframe. Further analysis in relation to these targets is thus required.

Method and data

In this section, the methodological approach is presented, including a general description of the model, main input data assumptions for the road transport sector and model scenarios.

General model description

The analysis is based on MARKAL_Sweden, a dynamic, bottom-up, partial equilibrium, energy system optimization model. The model is an application of the well-established MARKAL model generator (Lolou et al., 2004) and includes a comprehensive description of the Swedish energy system. Under the provided conditions, the model delivers the overall welfare-maximizing[1] system solution meeting all defined model constraints (e.g., regarding energy service demands and

[1] Welfare is here defined as the sum of producer and consumer surpluses. The welfare maximization is achieved by the (equivalent) minimization of the (discounted) total system cost, defined as the sum of the technical energy systems costs (investments, operation and maintenance, fuel costs, etc.) and the loss in welfare due to reduced end-use demand (Lolou et al., 2004).

emission restrictions) over the entire studied time horizon. The time horizon is from 1995 to 2050[2] and is divided in 5-year model periods, each model period being represented by a model year (1995, 2000, ..., 2050). While most energy carriers are represented on an annual basis, heat and electricity are further represented with three seasonal periods (heat and electricity) and two diurnal periods (electricity only). The model applies perfect foresight, which means that there is full knowledge about the future development in the optimization (no uncertainty). A discount rate of 6% is used. The current version of MARKAL_Sweden builds upon earlier MARKAL applications describing Sweden presented by, e.g., Bergendahl and Bergström (1981) and Unger and Alm (2000) but in particular on the more recent studies by Börjesson and Ahlgren (2012a,b) and Börjesson et al. (2014).

The model representation of the national energy system 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. The model depends on a large set of input data. Bottom-up technology data include technology costs and performance data such as operation and maintenance costs, investment costs and conversion efficiencies for technologies in all parts of the energy system. The technology representation includes supply technologies/processes (import of fossil fuels, cultivation/extraction of biomass, etc.), conversion technologies (heat and electricity generation, transport fuel production, etc.) and end-use technologies (industrial and residential heat boilers, vehicles, etc.) as well as energy distribution processes. Reference projections for end-use energy service demand over the studied period are inputs to the model, but own-price elasticity of demand applies, making the final demand levels scenario dependent outputs of the model. For road transport, end-used demands are divided in eight different vehicle classes: small and large cars, long and short distance buses, long and short distance heavy trucks, light trucks and motorcycles. End-use service demand elasticities for the road transport vehicle classes are between 0.2 and 0.6 in the model (Anandarajah et al., 2009).

In the model, all sectors of the national energy system are represented, such as heat and power production, transport, industry, and commercial and residential premises. Thus, the model allows for demands in different sectors to compete for limited energy resources. The transport sector of the model includes road transport, aviation, railway, shipping and working machines. However, road transport is the focus of the study and other modes are modelled in a less detailed manner. The model does not include endogenous modal shift, neither between road transport and other parts of the transport sector (e.g., from car to aviation) nor between different transport classes within road transport (e.g., from car to bus).

In the study, the limited supply of biomass resources constitutes an important model constraint. While a small increase in imports of biomass and biofuel are allowed in the model during the studied time horizon (based on SEA, 2013a; Swedish Government, 2010), the main biomass resource supply is based on estimates of domestic potentials. The main domestic sources of biomass for energy purposes in the model are forestry residues (tops and branches), wood product industry by-products and energy crops (including energy forest). For energy crops, 600 000 ha, or about 20% of the existing agricultural land in Sweden, is assumed to be available for energy crop cultivation (see e.g., Börjesson, 2007). Table 1 presents a summary of the biomass being available for energy purposes in the Swedish energy system as a whole (i.e., not only for transport biofuel production) in the model. If energy forest is produced on the available agricultural land (and pulpwood is being used in the pulp and paper industry according to the reference projection), the total bioenergy potential adds up to 178 TWh[3] for model year 2050. In the model, the domestic biomass potentials and biomass costs are represented by detailed supply curves (for more information on the biomass supply representation, see Börjesson et al., 2014).

Biofuel and vehicle technology representation

Several first- and second-generation biofuels for transport are included in the study: ethanol, biodiesel, biogas, synthetic natural gas (SNG), methanol, dimethyl ether (DME) and Fischer Tropsch (FT) liquids (synthetic gasoline, diesel and kerosene). Second-generation biofuels here refer to biofuels based on wood biomass as feedstock. For ethanol, two production routes are represented, based on wheat and on wood biomass, respectively. SNG and biogas are produced in different processes but are both methane-based gases.[4] An overview of the included biofuel processes and related technology data assumptions are given in Table 2 (for some parameters, altered conditions are tested in a sensitivity analysis, presented in Model scenarios). Properties refer to new plants built from the ground up with thermal input capacities of 200–250 MW, with the exception of biogas plants for which properties represent plant scales of 3 MW. Economical and technical lifetimes of 20 years are assumed for all processes. Table 3 presents assumed costs and energy penalties for distribution from the production site to filling stations and handling at the filling stations (while here presented as cost per energy unit, in the model, distribution costs are divided in investment cost and operation cost).

Since planning and construction of new biofuel production and infrastructure are linked to long lead times, in particular for large scale projects, the establishment of new production capacity in the near term is constrained in the model. For model year 2015, new biofuel production capacity is restricted to projects already underway (see Hansson and Grahn, 2013). For second generation biofuel production an upper constraint of 10 TWh on production capacity is applied also for model year

[2] 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.

[3] For comparison, the total energy supply in Sweden in 2010 was 616 TWh and the final energy use was 411 TWh (SEA, 2011a).

[4] In the paper, biogas and SNG will at times be referred jointly to as biomethane and, if also natural gas is intended, as methane.

Table 1
Summary biomass resources (excluding municipal combustible solid waste and peat) for model year 2050.

	Potential [TWh/year]	Cost [EUR/MWh]
Forest residues – tops and branches	17.1	14–30
Forest residues – stumps[a]	21.3	19–40
Pulpwood, excl. bark[a]	9.4 (81)[i]	17–25
Energy crop – alternatives[b,j]		
Energy forest	17.1	17–80
Cereal crops	11.2	31–76
Ley/Grass crops	14.4	23–25
Oil seed crops	2.5	42–50
Straw[c]	3	10
Organic waste[d]	11	0–6
Industrial liquors & wood waste[e]	77	0–5
Recovered wood[e]	3	7
Firewood (single family houses)[e]	11	1.5
Imports – wood pellets/briquettes[f]	4	39
Imports – ethanol[g]	3.4	74
Imports – oilseeds[h]	1	42

Based on:
[a] Börjesson et al. (2014).
[b] Börjesson (2007) and Rosenqvist (2011).
[c] Ekman et al. (2013) and Edwards et al. (2007).
[d] Linné et al. (2008), Börjesson and Ahlgren (2012c) and Björnsson and Lantz (2010).
[e] SEA (2013a) and Hagström (2006).
[f] SEA (2011a) and SEA (2013a).
[g] Swedish Government (2010) and SEA (2011a).
[h] SEA (2011a) and Hansson and Grahn (2013).
[i] Potentials without brackets refer to amounts available over and above reference demand in pulp and paper industry. Potentials within brackets refer to total domestic amount available. For total potentials, the total amount of pulpwood is not addable to the industrial residues potentials since they constitute partial sums of each other.
[j] Since energy crop alternatives compete for the same available agricultural land, 600000 ha (about 20% of total in country), the full potentials of each alternative are not addable. However, different parts of the available agricultural land can be used for different alternatives.

Table 2
Overview of transport biofuel production technologies in model.

Process	Fuel output	Energy input: bio/ other [MWh]	Energy output: fuel/other [MWh]	Investment cost (IC) [EUR/kW]	Fixed O&M cost [% of IC]	Variable O&M cost per input [EUR/MWh]
Fermentation of wheat[a]	Ethanol	0.98/0.02	0.41/-	650	3	1.5
Oil extraction and transesterification of rapeseed[b]	Biodiesel	0.91/0.09	0.54/-	200	3	1.5
Anaerobic digestion of organic waste/ energy crops[c]	Biogas	0.97/0.03	0.57/-	3000	10	-
Gasification of woody biomass[d]	SNG	0.96/0.04	0.69/0.15	1400	4.5	1.5
	Methanol	1/-	0.51/0.15	1500	4.5	1.5
	DME	1/-	0.51/0.15	1600	4.5	1.5
	FT liquids	1/-	0.38/0.15	2500	4.5	1.5
Fermentation of woody biomass[e]	Ethanol	0.99/0.01	0.34/0.03	1800	4.5	1.5

Based on previously published work (Börjesson and Ahlgren, 2012a,b).
Energy on lower heating value (LHV) basis. O&M cost, operation and maintenance cost (non-energy).
[a] "Bio" inputs are wheat grain (0.78) and woody biomass for process heat production (0.20). Input marked "Other" is electricity. Non-energy by-products of the process are DDGS (Distiller's Dried Grain with Solubles), which is used as animal feed and is here assumed to have an economic value of 12 EUR per MWh of produced ethanol.
[b] "Other" inputs are natural gas (0.05), methanol (0.03), and electricity (0.01). Non-energy by-products from the process are rapeseed cake (animal feed) and glycerol, which are assumed to have an economic value of 13 EUR per produced MWh of biodiesel.
[c] "Other" input is electricity.
[d] "Other" input for the SNG process is electricity. FT liquids are diesel, gasoline and kerosene. For the FT process, the "Other" outputs are electricity (0.09) and district heat (0.06). For SNG, methanol, and DME, the "Other" output is district heat.
[e] "Other" input is diesel; "Other" output is electricity.

Table 3
Assumptions made on transport fuel distribution (from production site to tank).

Transport fuel	Distribution costs (non-energy) [EUR/MWh]	Energy use (fuel + electricity) [%]
Diesel equivalents	11	1
Gasoline equivalents	12	1
Ethanol	14	1
Methanol	15	1
DME	20	1
Methane	28	3–4

Based on Ahlvik and Brandberg (2001, 2002), Petterson et al. (2006) and Benjaminsson and Nilsson (2009).

Table 4
Overview of fuel and vehicle technology combinations available for car and heavy truck vehicle classes in the model and assumptions on fuel consumption and additional vehicle costs. For heavy trucks, distinction between long distance (LD) and short distance (SD) traffic is made.

Technology	Fuel	Fuel consumption [kWh/vkm]; [% diff. to reference]			Vehicle incremental investment cost compared to reference [kEUR/vehicle]		
		2015	2030	2050	2015	2030	2050
Cars							
ICEV-SI (reference)	Gasoline	0.65	*0.54*	0.48	0	0	0
	Ethanol/methanol		*±0*		0.5	0.5	0.5
	Methane		*±0*		2	2	2
ICEV-CI	Diesel/FTD/biodiesel		*−15%*		1.4	1.4	1.4
	DME		*−15%*		2.8	2.8	2.8
	Ethanol/methanol		*−15%*		2	2	2
HEV	Gasoline		*−30%*		7.2	4.4	3.5
	Ethanol/methanol		*−30%*		7.7	4.9	4.0
	Methane		*−30%*		9.2	6.4	5.5
	Diesel/FTD/biodiesel		*−35%*		8.6	5.8	4.9
	DME		*−35%*		10	7.2	6.3
PHEV	Gasoline + Electricity		*−47%*		10	5.5	4.1
	Methanol/ethanol + electricity		*−47%*		11	6.0	4.6
	Methane		*−47%*		12	7.5	6.1
	Diesel/ FTD/biodiesel + Electricity		*−49%*		12	6.9	5.5
	DME + Electricity		*−49%*		13	8.3	6.9
BEV	Electricity		*−65%*		31	12	6.5
Heavy trucks							
ICEV (reference)	Diesel/FTD/biodiesel	3.8	3.6	3.5 (LD)	0	0	0
		2.6	2.5	2.4 (SD)			
	DME		*±0 (LD), ±0 (SD)*		20	13	9
	Ethanol/		*±0 (LD), ±0 (SD)*		10	5	2
	Methanol		*n/a (LD), ±0 (SD)*		10	5	2
	Methane		*±0 (LD), +10% (SD)*		28	18	13
HEV	Diesel/FTD/biodiesel		*−5% (LD), −25% (SD)*		60	30	20
	DME		*−5% (LD), −25% (SD)*		80	43	29
	Ethanol		*−5% (LD), −25% (SD)*		70	35	22
	Methanol		*n/a (LD), −25% (SD)*		70	35	22
	Methane		*−5% (LD), −17% (SD)*		88	48	33

Based on previously published work (Börjesson and Ahlgren, 2012a,b).

2020 (based on that there are currently ongoing plans, at different levels of implementation, of about 8 TWh in the 2015–2025 timeframe, Hansson and Grahn, 2013). From model year 2025 no restrictions on new biofuel production capacity are applied.

The carbon intensity of transport biofuels is an important aspect in regard to their ability to mitigate CO_2 emissions. Emissions contributing to the carbon intensity can originate from fossil fuel-based energy use in different parts of the well-to-tank biofuel chain. Further, land use change effects related to production of the biomass raw material can be an important contributor. In the model, the input energy for production and distribution of biofuels can be based both on fossil and renewable sources, and is to a large degree determined endogenously. The carbon intensity linked to this energy use can thus vary between different time periods and scenarios. As mentioned previously (General model description and Table 1), the biomass resources available for energy purposes is to large extent by-products/residues from forestry and forest product industries, and in regard to energy crops, already established agricultural land is used. Since no major land-use changes are related to these biomass resources, carbon emissions related to this have been disregarded in the model.

Several different vehicle technologies are represented in the model, including: internal combustion engine vehicles (ICEVs) (both compression ignition, CI, and spark ignition, SI), hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs) and battery-powered electric vehicles (BEVs). Not all technologies are, however, available in all vehicle segments. PHEVs are only available for cars and BEVs are only available for about half of the car market (smaller cars). HEVs are available for light-duty vehicles (cars and light trucks) as well as for heavy-duty transport, although the fuel savings are comparably small for long-distance heavy-duty transport. Most combinations of represented fuel and vehicle technology options are included. However, methanol and compressed methane (CNG), i.e., biogas, SNG, and natural gas, are unavailable for long-distance heavy-duty transport due to its comparably low specific energy content. Liquefied methane (LNG) combined with 5% diesel (also synthetic diesel) is available for long-distance heavy-duty traffic. Assumptions on cost and performance data for cars and heavy trucks (which from an energy use perspective are the most important vehicle classes) are presented in Table 4. Further details regarding the vehicle technology part of the model are also available in earlier publications (Börjesson and Ahlgren, 2012a,b).

Model scenarios

For the analysis, several different input scenarios are developed: one main analysis scenario with "base assumptions" and ten alternative scenarios, which test the sensitivity of altered conditions compared to the main scenario. The main scenario applies stringent CO_2 reduction targets. General trends regarding end-use energy service demand development in different parts of the stationary energy system are in line with long-term forecasts by the Swedish Energy Agency (SEA, 2011b, 2013a). For the transport sector, reference demand projections are based on travel demand forecasts by the Swedish Transport Administration (STA, 2012), which for cars imply a 65% increase in vehicle kilometers (km) travelled from 2006 to 2050. The alternative scenarios simulate different developments in the stationary energy system as well as in the transport sector. In all scenarios, a stylized energy policy situation is applied; no energy or emission taxes or subsidies are included, but policy ambitions are instead represented as quantitative constraints regarding system-wide CO_2 emissions, renewable electricity generation and fossil fuel use in road transport. Table 5 shows an overview of the scenarios (see also Börjesson et al., 2014).

To investigate the system effects of aiming for a "fossil-independent", i.e., an almost fossil free, road transport sector to 2030, based on the declared Swedish government vision (Swedish Government, 2008), an additional fossil fuel phase-out constraint is introduced. Thus, for each of the scenarios (the main scenario as well the alternative scenarios), two model

Table 5
Overview of model scenarios. For the "alternative scenarios", only the difference to the "main scenario" is indicated.

Scenario	Description
Main scenario	
GLOB_CA	Global climate action: Sweden and the rest of world pursue ambitious climate targets. CO_2 emissions of the Swedish energy system as a whole (incl. transport) are reduced by 80% to 2050 compared to the 1990 emission level. A linear reduction from model year 2015 to 2050 applies in the form of an emission cap which gradually decreases for each model year. Further, based on the Swedish electricity certificate system for promotion of renewable electricity generation, a lower model bound ramping up renewable electricity generation in the Swedish energy system to at least 25 TWh by model year 2020 is applied (the bound is kept constant 2020–2035 but is then phased out; SEA, 2013b). Import fossil fuel prices are based on the "450 scenario" of IEA's World Energy Outlook (IEA, 2010), and a crude oil price of USD 90/barrel is assumed for 2015–2050
Alternative scenarios	
NAT_CA	National climate action: Ambitious climate targets applies in Sweden while the world at large show less ambitious targets, which results in higher import fossil fuel prices. 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
CO2_LR65; CO2_LR50	Low reduction of CO_2 emissions: Less ambitious CO_2 reduction levels are tested in two scenarios. In CO2_LR65, CO_2 emissions of the Swedish energy system as a whole (incl. transport) are reduced by 65% to 2050 and, in CO2_LR50, with 50% to 2050 (compared to the 1990 emission level)
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
EV_HC	High costs for electric vehicles: Cost reduction of electric vehicles, including HEVs, PHEVs and BEVs, are slower than with base assumptions; 50% higher incremental costs (compared to conventional vehicle technologies) are assumed
BIO_LS	Low supply for biomass: The potential for biomass from forestry is lower than with the base assumptions: stumps are assumed not to be available for energy purposes (e.g., due to ecological concerns)
MET_NO	No high blend methanol fuels: Additional restrictions for the use of methanol as transport fuel are assumed. Methanol can only be used as low blend in gasoline (reasons could, e.g., be its toxicity, low specific energy content and/or hesitant industry or public due to unsuccessful earlier ventures)
TRAD_SG	Slow travel demand growth: An alternative development with lower travel demand than with base assumptions is assumed: the travel levels in 2050 are here about the same as in 2005
NUC_PO	Nuclear phase-out: Nuclear power production is not allowed in Sweden after model year 2030
PULP_SD	Mechanical pulp shut-down: A less positive development for the Swedish pulp and paper industry compared to the base assumptions is assumed. Here, all mechanical pulp mills are closed down by 2030, which results in an 18% lower pulpwood demand and 36% lower electricity demand in the paper and pulp industry as a whole. More biomass can thus potentially be used for energy purposes

cases are carried out: one case without and one case with an additional constraint on road transport fossil fuel use. The additional constraint, here denoted the fossil fuel phase-out (FFP) policy, is defined as an 80% reduction of fossil fuel end-use in the road transport sector to 2030 and a 100% reduction to 2050. This exogenously determined constraint forces the system to replace fossil fuel use in road transport by an increased use of biofuels and/or electricity early on in the studied period.

As a reference for calculation of the incremental system costs linked to applied policies, model runs without CO_2 or fossil fuel use restrictions are also carried out.

Results

Road transport development – GLOB_CA

Scenario GLOB_CA shows (without implementation of the FFP policy) a gradual growth of road transport biofuel use throughout the studied time horizon (Fig. 1). The system-wide CO_2 emission cap, which implies an 80% emission reduction for the national energy system as a whole to 2050, leads to that no fossil fuels are used in road transport at the end of the studied period. In 2030, the use of biofuels in the road transport sector reaches 15 TWh (of which 11.5 TWh is domestic production) corresponding to 23% of total road transport final energy use. By 2050, road transport biofuel use is 42 TWh (of which 39 TWh is domestic production), corresponding to 78% of the final energy use of the sector. Electricity charged from the grid to PHEVs and BEVs accounts at this point for the remaining part, in total 12 TWh (22%).

Several different types of biofuels are utilized. Methanol becomes during the studied period the dominating fuel option for light-duty vehicles. In 2030, methanol use is 11 TWh and by 2040 it has increased to 15 TWh. However, as resource competition furthermore increases, more energy-efficient systems solutions are prioritized and, in 2050, methanol use has decreased to 12.5 TWh. At this point methanol is primarily used in PHEVs in the passenger car sector but also in hybrid light trucks and in short-distance heavy-duty traffic.

Methane is used from early on, but the origin of the gas changes. Driven by high oil prices and CO_2 penalties, fossil natural gas (NG) is for a large part of the studied period used as transport fuel, primarily in the heavy-duty sector and both in compressed (CNG) and liquefied form (LNG). As CO_2 constraints are tightened, natural gas is gradually phased out while biogas (based on anaerobic digestion) and SNG (based on biomass gasification) increase in importance. In 2050, biogas and SNG use reaches 6.5 TWh and 16.5 TWh, respectively. Organic waste resources with limited alternative use are utilized for biogas production; however, feedstock options that are more exposed to competition, such as grown crops, are not utilized.

Ethanol and FT liquids (FTL) in the form of synthetic gasoline and diesel also appear in the model results. The possibility for ethanol imports is utilized up to its assumed allowed amount throughout the studied period (3.4 TWh from 2020). Domestic ethanol production is, however, phased out at an early stage. In 2050, 3.5 TWh of FT liquids are used in road transport. A certain amount of diesel fuel is required for gas-fuelled heavy-duty CI-ICEVs, and FT diesel is at the end of the period chosen for this purpose over biodiesel or conventional diesel. Use of FT liquids in road transport is also promoted since FT liquids, in the model, are one of few low-carbon options for non-road transport (e.g., FT kerosene in aviation).

Despite the increase in travel levels, final energy use in road transport decreases significantly during the studied time horizon (Fig. 1) as consequence of the introduction of fuel-efficient vehicle technologies (Fig. 2). Compared to 2000, road transport final energy use is about 8% lower in 2030 and 25% lower in 2050. From 2030, PHEVs play a large role for passenger cars and from 2045 also BEVs are used to a significant degree. In 2050, BEVs account for 75% of the market in the in smaller car segment. HEVs dominate light truck transport as well as short-distance heavy-duty traffic, while CI-ICEVs dominate long-distance heavy-duty traffic for the entire time-horizon.

Fossil fuel phase-out policy – GLOB_CA (FFP)

The introduction of a rigid, sector-specific policy reducing use of fossil fuels in road transport by 80% already by 2030 (the FFP policy), significantly affects the road transport system, in particular in the shorter term (Figs. 3 and 4). The FFP policy

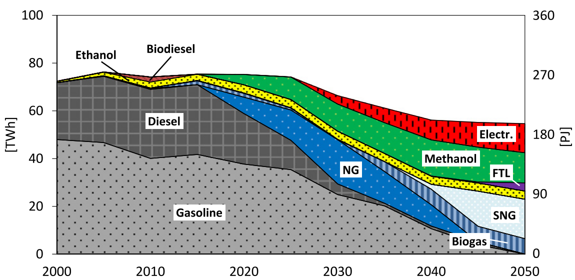

Fig. 1. Fuel use in road transport for scenario GLOB_CA.

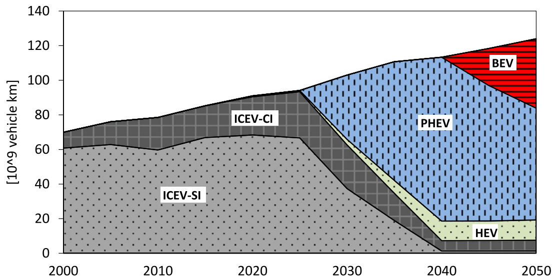

Fig. 2. Vehicle technology choices for scenario GLOB_CA (expressed in vehicle km travelled).

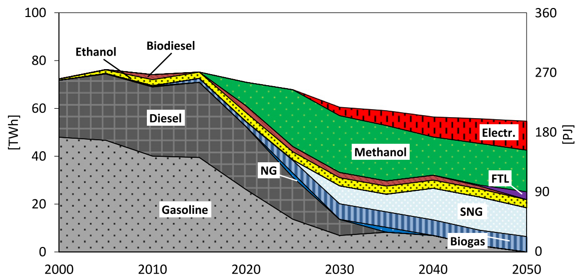

Fig. 3. Fuel use in road transport for scenario GLOB_CA with FFP policy.

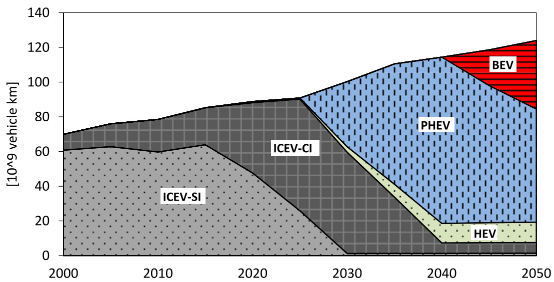

Fig. 4. Vehicle technology choices for scenario GLOB_CA with FFP policy (expressed in vehicle km travelled).

target is met by a large deployment of second generation biofuels, substantially brought forward in time compared to the case without FFP policy, and a larger use of the more fuel-efficient CI-ICE vehicles. Further, slightly lower travel demand levels (2–3%) are noted in 2020–2030 compared to the case without FFP policy.

With the FFP policy applied, biofuel utilization reaches 43 TWh already in 2030 (40 TWh domestic production) and accounts at this point for 72% of final energy use of the sector. A marginal decrease in transport biofuel use to 42 TWh in 2050 then occurs, but the share of final energy use of the sector increases to 78% by the end of the studied time period due to the increasing use of fuel-efficient vehicle technologies.

A large part of the FFP policy is met through a larger use of methanol; already in 2025–2035, methanol shows utilization levels in the road transport sector of 23–24 TWh. Natural gas is utilized only in very small amounts in this case. Instead, the FFP policy promotes an earlier increase of biogas and SNG in the gas mix and their combined use reaches 14 TWh in 2030. Due to the inertia of the system and the early establishment of large methanol utilization, the FFP policy case shows larger use of methanol at the end of the period and a smaller use of biomethane compared to the case without the policy. In 2050, methanol use is 17.5 TWh, or 5 TWh higher than without FFP policy, and biomethane use is 18.5 TWh, or 4.5 TWh lower than without FFP policy. The electricity use is basically the same in both cases (12 TWh).

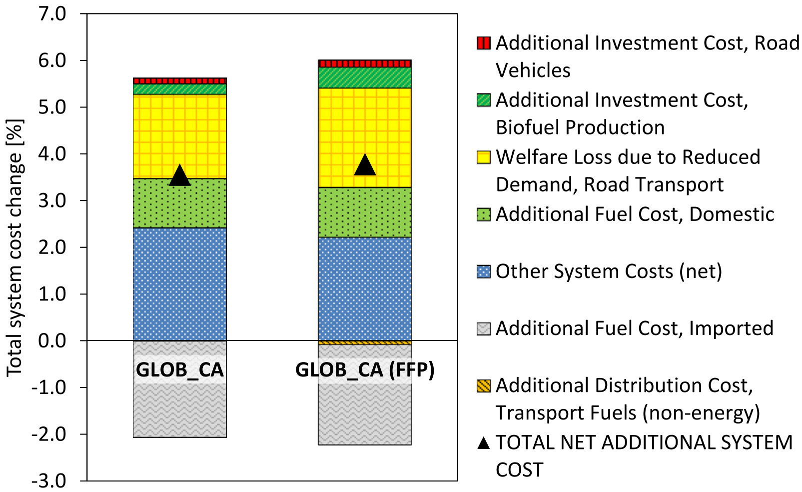

Fig. 5. Increase in total system costs (including welfare loss due to reduced demand) with implementation of 80% CO_2 reduction (GLOB_CA) and with 80% CO_2 reduction and FFP policy jointly (GLOB_CA (FFP), compared to a situation without emission or fossil fuel use restrictions.

The use of HEVs, PHEVs and BEVs is similar to the case without the FFP policy. These technologies are assumed to experience decreasing costs during the studied time horizon (see Table 4), and the fact that they are not used at an earlier stage suggests that the assumed cost levels are not competitive until the latter part of the studied time horizon.

System costs

By definition, further restraining of the system implies higher system costs. Thus, an early phase-out of fossil fuels in road transport in addition to system-wide CO_2 reductions, as with the FFP policy, increases system costs (Fig. 5). For GLOB_CA without FFP policy, the CO_2 constraint reducing emissions by 80% for the Swedish energy system to 2050 increases the total system cost by 3.6% compared to a situation without CO_2 restrictions ("total net additional system cost", in Fig. 5). The introduction of the FFP policy gives a total system cost increase for both CO_2 and FFP policy of 3.8% compared to a situation without CO_2 restrictions. Put differently, the implementation of the FFP policy increases total system-wide CO_2 abatement costs by about 6%.

Travel demand levels (distance traveled) are for future model years about 10% and 11% lower for GLOB_CA and GLOB_CA (FFP), respectively, compared to a situation without CO_2 restrictions. The reduced travel demand will reduce the consumer surplus, and this constitutes a welfare loss that is a significant part of the additional system costs (Fig. 5). Higher investment costs for road vehicles with alternative technologies as well as investments in biofuel production also contribute to an increase in system cost. However, even though the specific distribution costs (per energy unit) generally are higher for the alternative transport fuels (see Table 3), there is no increase in total distribution costs for the system as a whole in GLOB_CA. For GLOB_CA (FFP), the total system distribution costs are even somewhat lower than without CO_2 restrictions (i.e., additional costs are negative). The reason for this is that the total amount of transport fuels is significantly lower in these scenarios compared to the situation without CO_2 restrictions, due to higher use of energy efficient vehicles and lower travel levels. Further, for the system as a whole, the costs of imported energy decrease while the costs of domestic energy increase. The "Other System Costs" category of Fig. 3 summarizes the net effect of a number of cost items, such as investments in the stationary energy sector, operation and maintenance costs and welfare loss due to demand reductions in other parts of the energy system than road transport.

Sensitivity analysis – alternative scenarios

The sensitivity analysis shows that cost-efficient fuel choices in road transport, in general, and biofuel utilization, in particular, are sensitive to changes of some parameters while quite robust to other parameter changes. Changes in fuel use for each respective alternative scenario compared to the main scenario GLOB_CA are visualized for model year 2030 and 2050 in Fig. 6, in (a) for cases without FFP policy and in (b) for cases with FFP policy. In general, since road transport fuel use under the FFP policy (Fig. 6b) to a higher degree is constrained, the differences between GLOB_CA and the alternative scenarios are smaller than in absence of the FFP policy (Fig. 6a).

In addition to biofuels, the only options to achieve CO_2 and fossil fuel reduction in the model are increased electricity use and reduction of travel levels. Thus, mainly scenarios representing futures with considerably more costly electric vehicles (EV_HC), reduction of travel demand growth (TRAD_SG) or less stringent CO_2 policies (CO2_LR65, CO2_LR50) show notable differences in transport fuel futures compared to the main scenario (GLOB_CA). In particular, less stringent CO_2 policies for

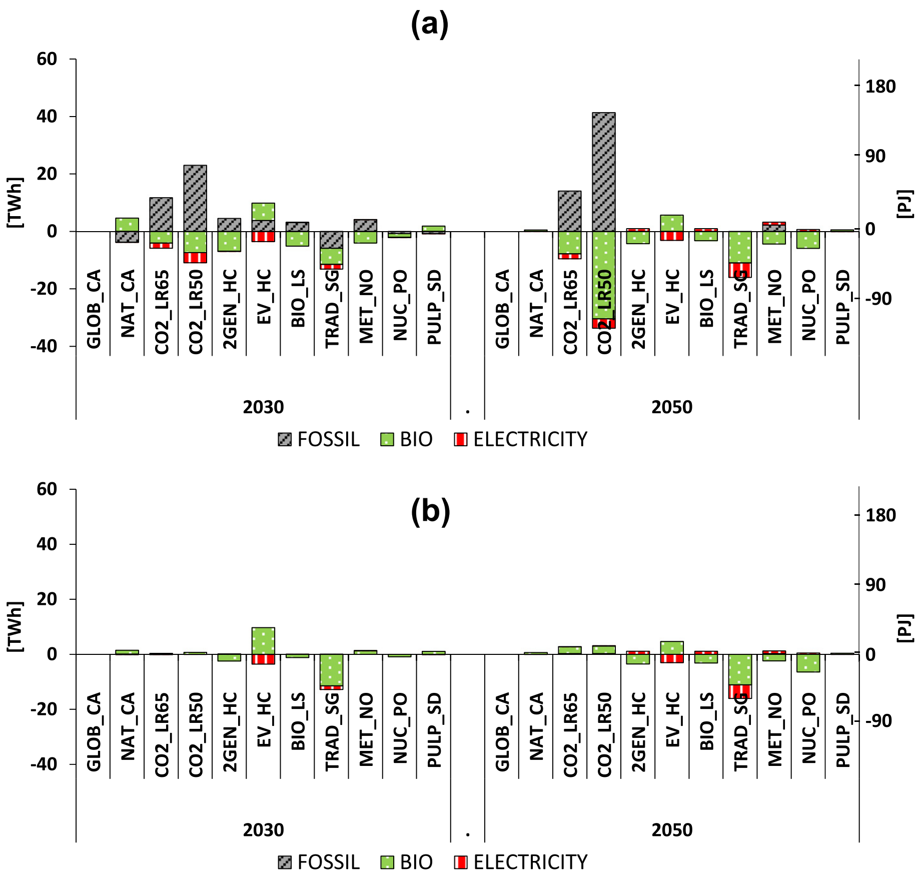

Fig. 6. Difference in road transport fuel use for alternative analysis scenarios compared to GLOB_CA, in (a) without FFP and in (b) with FFP.

the national energy system as a whole (CO2_LR65 and CO2_LR50) result in significantly lower use of transport biofuels in absence of the FFP policy (Fig. 6a). With the FFP policy, transport biofuel use in CO2_LR65 and CO2_LR50 is slightly higher than for GLOB_CA (Fig. 6b) due to lower competition for biomass from the stationary energy system in these cases. Not surprisingly, a lower travel demand growth (TRAD_SG) requires less transport fuels, including biofuels, while a slow cost reduction (EV_HC) of electric vehicles leads to higher biofuel use.

With the exceptions of low CO_2 reduction (CO2_LR65 and CO2_LR50) and low travel demand growth (TRAD_SG) scenarios, the road transport biofuel use of the alternative scenarios only differ in a range of ±15% (±6 TWh) compared to GLOB_CA in 2050 both with and without FFP policy. The percentage change in road transport biofuel use compared to GLOB_CA is generally higher for model year 2030 than for model year 2050 for cases without FFP, while generally lower for cases with FFP policy. With stringent CO_2 reductions, high investment costs for second generation biofuels (2GEN_HC) lead to the lowest biofuel use for 2030 without FFP policy, almost 50% lower than in GLOB_CA.

Scenario NAT_CA shows higher road transport biofuel use than GLOB_CA. The high oil price in NAT_CA implies a larger incentive for replacing oil with biofuels. Further, this scenario shows an advantageous situation for electricity imports, which imply less demand for biomass in the stationary energy system.

Scenario NUC_PO and BIO_LS imply a hardening of the competition for available biomass resources. For NUC_PO this is due to a higher demand for other low-carbon energy sources in the stationary system as nuclear power generation is phased out, while for BIO_LS it is due to lower biomass supply. Scenario MET_NO, which do not allow high blend methanol fuels, implies that higher cost biofuels needs to be used. For all three of these scenarios, total transport biofuel use is somewhat lower than in GLOB_CA. Marginally higher use of transport biofuels compared to GLOB_CA is noted for PULP_SD as a shutdown of part of the Swedish paper and pulp industry implies that more biomass (pulpwood) is available for energy purposes.

Regarding biofuel choices, several scenarios show the same inertia effect when introducing the FFP policy as seen in GLOB_CA. That is, with FFP policy a larger use of methanol is seen also at the end of the period (2050) compared to the case without the policy, while the use of SNG is smaller. Such scenarios include 2GEN_HC, BIO_LS, NUC_PO and PULP_SD. For CO2_LR50 and CO2_LR65, use of both methanol and SNG increases with FFP policy applied, while EV_HC, TRAD_SG and NAT_CA only show small changes in regard to this. For MET_NO, the restrictions on methanol results in a higher use of other options, in particular SNG but also FT liquids as well as DME, which is an option not seen in any of the other cases; adding FFP increases use of SNG while decreasing gasoline use (which for this scenario still is present in 2050 without FFP policy).

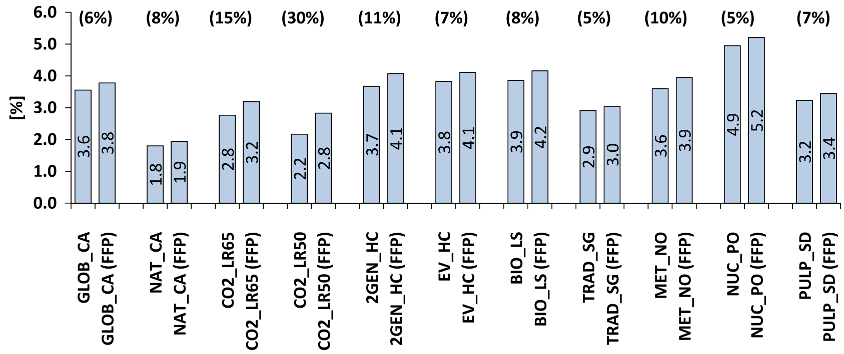

Fig. 7. Incremental system cost for CO_2 reduction, as well as for CO_2 reduction and FFP policy jointly, expressed in relation to corresponding situation without CO_2 or fossil fuel restrictions. Within brackets, the percentage increase in incremental system cost for adding FFP.

In Fig. 7, the incremental total system cost, or system CO_2 abatement cost, for CO_2 reduction as well as for CO_2 reduction and FFP policy combined, in relation to the corresponding situation without policy restrictions, are visualized for all scenarios (with bars). In addition, the percentage increase in incremental system cost when adding FFP policy to CO_2 reduction is given (at the top of the figure within brackets). In general, the more stress that is put on the system, e.g., regarding higher cost for alternative technologies or less supply of biomass or low-cost electricity, the higher the incremental system cost. Scenarios which compared to GLOB_CA imply narrowed options for the system include: NUC_PO, 2GEN_HC, BIO_LS, EV_HC and MET_NO. The highest values are noted for scenario NUC_PO.

Scenario conditions that, in comparison to GLOB_CA, put less stress on the system imply lower incremental system costs. Such scenario conditions include lower required CO_2 emission reductions (CO2_LR65, CO2_LR50), more biomass available for energy purposes (PULP_SD) or lower travel demand (TRAD_SG). Among the scenarios that pursue the 80% CO_2 reduction target, NAT_CA shows the lowest cost increase. This is due to the high fossil fuel prices assumed in this case, making the additional cost of choosing low-carbon options smaller.

While the increase in incremental system costs of implementing the FFP policy for scenarios applying a CO_2 reduction of 80% to 2050 are in the range of 5–11%, scenarios with lower CO_2 reduction requirements show higher levels, 15–30% (CO2_LR65, CO2_LR50). This is line with results showing a low deployment of alternative fuels in these scenarios when FFP policy is not applied (Fig. 6a).

Discussion

The results of the study show that biofuels in the road transport sector can make an important contribution to the achievement of stringent CO_2 emission reductions and fossil fuel phase-out targets without considerable system cost increases or excessive reliance on biofuel imports.

The methodological approach is of importance for the interpretation of the results and a few notes can be made. The methodology applied is based on scenario analysis supported by bottom-up energy system modeling. The model represents both the transport sector and the stationary energy system (heat and power generation, etc.) and, in such way, important linkages between these sectors are captured. The model provides cost-optimal systems solutions, taking a large number of conditions into account, and give insights about future potentials and related system effects of technologies and policy strategies. Due to its partial equilibrium approach, macroeconomic effects are essentially not captured by the model; however, own-price elasticity is applied for end-use service demands. The model only represents technological learning in an exogenous manner, and do not capture any potential requirements for learning investments that could be required to achieve the assumed technology cost development. This can to great extent be motivated by the national scope of the study, but is still of significance for the interpretation of the model results.

The model calculations are based on direct technological costs and with full knowledge of future developments (perfect foresight), and do not account for, e.g., future uncertainties, lack of information or financing issues. Due to the model features of optimization and perfect foresight, the system inertia regarding technological change is lower than in the real world. In the model, technological change occurs instantly as one option gives a lower system cost than the other; there are no "slow adopters" delaying such a change. However, as it is seldom cost-efficient to retire a technology before its technical lifetime is met and due to the technological age structure of segments, technological change still takes time; e.g., in the model results, the shift from ICEVs to PHEVs in the passenger car segment takes about 15 years (see Figs. 2 and 4).

The analysis provides several insights on future cost-efficient use of transport biofuels. While there are previous estimates on biofuel potentials (see, e.g., compilation of biofuel visions for Sweden by Hansson and Grahn, 2013), few have utilized a dynamic modeling approach as in the present study. Instead, most rely on static calculations based on (exogenous) appraisals of the amount of biomass resources not used currently and therefore potentially available for biofuel production. One recent estimation by Börjesson et al. (2013b) suggests the potential for transport biofuel production in Sweden to be in the range of 25 to 35 TWh in the medium term, i.e., somewhat lower than what the present study suggests under some conditions, e.g., if the 80% fossil fuel phase-out to 2030 should be achieved (the domestic biofuel production in main scenario with FFP is 40 TWh in 2030). One reason for this is that the present study allows biomass use to be reduced in one sector if biomass demand (willingness to pay) is higher in another.

In comparison to other model-based studies (for scenarios without sector-specific policies), the resulting road transport biofuel shares of the present study are in the higher range (see, e.g., Martinsen et al., 2010; Börjesson and Ahlgren, 2012a; Jablonski et al., 2010; Schulz et al., 2007). There are several reasons for this. One is that the CO_2 emission reductions applied (-80% to 2050) is more stringent than what many earlier studies assume for a similar timeframe. Another reason is that Sweden has a comparably high per capita biomass supply and the electricity sector, which is based on hydro and nuclear power, is already to large degree carbon-free. Although some studies investigate emission reductions in the same magnitude as the present study, this is often done with a longer time horizon, which often leads to non-biomass based options, e.g., hydrogen-based pathways, being applied in the second half of the century rather than biofuels (see, e.g., Gül et al., 2009; Azar et al., 2003; Grahn et al., 2009a,b). As showed in the sensitivity analysis, lower CO_2 reductions significantly affect the cost-efficient potential for biofuels in transport. As mentioned, some potential future options, such as algae biofuels, hydrogen, electrofuels, fuel cell vehicles and electrified roads, are not included within the scope of the present analysis. An advantageous technological development for any of these options could lead to less demand for the options in focus of the present study. However, many of these alternatives have significant obstacles ahead. Regarding hydrogen, which may be one of the most promising options not included in the study, cost-efficient infrastructure and distribution will be a challenge, not least in a country like Sweden with comparably low population density.

In terms of biofuel choices, the results indicate, in accordance with previous results based on earlier versions of the model (Börjesson and Ahlgren, 2012b), that methanol is a cost-competitive biofuel option under the assumed conditions and technology characteristics. Advantageous features of methanol include low incremental costs for distribution and vehicles combined with comparably high efficiency in the production process. Similarly to other second generation biofuel options, methanol has also the benefit of a biomass feedstock with high availability. Also biomethane (biogas and SNG) accounts for a large share of the transport fuel supply. Regarding biogas, the benefit lies mostly in the possibility of using waste streams with few alternative areas of use. For SNG, one of the advantages is the high conversion efficiency in production, which is also a factor that grows in importance as competition for limited biomass resources increases with more stringent climate targets.

Also other biofuel options are present in the results, but at significantly lower shares than biomethane and methanol. This does not mean there cannot be important roles also for other alternative fuels; due to the formulation of the model, even though differences may be small, the lowest-cost option will take the whole market in a specific demand segment unless other constraints apply (see Börjesson and Ahlgren, 2012b for further analyses of cost differences between different biofuel pathways). Reality is also far more diversified than what could be represented in a model context, and cost-efficient niche markets could not be ruled out. When methanol is further restricted in the sensitivity analyses, DME as well as FT liquids are seen in the results, although at a higher total system cost.

Even though the model only to some part captures inertia and lock-in effects linked to fuel and technology choices, the results indicate that the implementation of targets for an almost fossil-free road transport sector to 2030 also affect choices in the longer term. In this case, early targets favor methanol while disfavor SNG, also in model year 2050, even though the road transport sector is at this point carbon-free whether or not FFP policy is applied.

The study has calculated the system cost increase of CO_2 abatement with and without early fossil fuel phase-out in road transport. For stringent CO_2 constraint (-80%), the increase in system CO_2 abatement cost due to early fossil fuel phase-out is not insignificant but at the same time, perhaps, not too discouraging (between 5–11%, see Fig. 7). For less stringent CO_2 constraints, the cost increase is significantly higher. It should be noted that the model, other than CO_2 emission reductions, does not take potential benefits of a fossil fuel phase-out policy into account. Such benefits could include lowered external costs for local pollution from road transport, less societal sensitivity to oil price shock, or the development of know-how in a growing business area potentially leading to trade possibilities. Remaining questions may not so much be whether early fossil fuel phase-out in road transport is possible, but whether the benefits are worth the costs involved.

Conclusions

The implementation of climate targets aiming at stringent reductions of CO_2 in the 2050 timeframe requires substantial measures starting in the near term and also involving the transport sector. Along with energy-efficient vehicle technologies such as PHEVs and BEVs, biofuels can form an important part of cost-efficient system solutions meeting such targets. In the main scenario, the cost-optimized model results show a biofuel use in the Swedish road transport sector of 15 TWh in 2030 (23% of final energy use) and 42 TWh in 2050 (78% of final energy use), corresponding to an annual growth rate of about 6% per year between 2010 and 2050. Second generation biofuels, in particular methanol and SNG, as well as biogas based on anaerobic digestion, are options showing advantageous cost-performance in the results.

The implementation of a fossil fuel phase-out policy, aiming at an almost fossil-free (-80%) road transport sector already by 2030, requires a doubling of the annual growth rate of biofuels until 2030 (to 12% for the main scenario). The impact on transport fuel choices of a fossil fuel phase-out policy (compared to a situation with only CO_2 restrictions) is considerable around 2030 but decreases towards the end of the studied period. However, due to early market establishment, methanol, the preferred option in the 2030 timeframe, becomes more advantageous also in the longer term, 2050, while markets shares for SNG are affected negatively.

The fossil fuel phase-out policy increases system CO_2 abatement costs by 5–11% for stringent CO_2 reduction scenarios. CO_2 reduction levels are of large significance for cost-competitiveness of transport biofuels and, therefore, the additional CO_2 abatement cost for a fossil fuel phase-out policy under less stringent CO_2 reductions is notably higher. Both in terms of system-wide CO_2 reduction and fossil fuel phase-out in road transport, measures for reduced travel demand growth can, depending on the costs of these measures, imply opportunities for cost-savings.

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