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SCENARIOS FOR LARGE-SCALE INTEGRATION OF RENEWABLE FUELS IN THE SWEDISH ROAD TRANSPORT SECTOR

Summary report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil-free fuels for transportation. The centre 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).

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The project is also reported through two scientific articles:

Börjessson, M., Athanassiadis, D., Lundmark, R. & Ahlgren, E., 2014. System effects of CO_2 reduction and oil phase-out on bioenergy utilization in Sweden. *Submitted for publication in GCB Bioenergy.*

Börjessson, M., Ahlgren, E., Lundmark, R. & Athanassiadis, D., 2014. Transport biofuel futures – A modeling analysis for Sweden. *Submitted for publication in Transportation Research Part D: Transport and Environment.*

This publication (f3 summary report) shoud be cited as:

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1 INTRODUCTION

Use of bioenergy could contribute to reduction of greenhouse gases (GHGs) and increased energy security, but to what extent strongly depends on the cost and potential availability of biomass resources. While bioenergy today is primarily used in the stationary energy sector for electricity and heat production, there is a strong interest in biofuels for transport and the use has in recent years increased significantly, albeit from very low levels. Declared policy targets on both national and international levels also aim at increasing its future share while also targeting lower GHG emissions.

Biomass can be used for a number of applications, e.g. as raw material in the forest product industry, for biofuel production and/or heat/power production, or in the chemical industry. Changes in biomass demand in any of these sectors will affect the biomass markets and, consequently, imply altered conditions for other biomass application. Thus, a large scale integration of biofuels in the transport sector will have dynamic effects over sector boundaries. A wide systems approach in the analysis of efficient ways of meeting environmental targets for transport and energy systems is therefore imperative.

This study investigates the potential contributions of bioenergy to the future Swedish energy system in general, and to the transport sector in particular, under different policy objectives. Specifically, the study aims to (1) investigate how CO_2 reduction and oil phase-out policies (OP) affect the future supply and price of biomass and its use in the transport sector; (2) what deployment of biofuels in road transport that is required to meet stringent, system-wide CO_2 reduction policy targets cost-effectively to 2050 and; (3) how the attainment of an almost fossil-free road transport sector to 2030 affects cost-effective fuel and technology choices and system costs.

2 METHOD

2.1 MODEL

To address the complex dynamic relationships between different sub-sectors of national energy systems, including a proper representation of biomass markets, a system modeling approach is applied. An already existing model structure of the Swedish energy system, the MARKAL_Sweden model, is developed further and used for the analysis. MARKAL_Sweden is based on the internationally widely applied, bottom-up modeling framework MARKAL. MARKAL_Sweden includes a comprehensive description of the national energy system (Figure 1). The transport sector is represented by a number of fuels and technologies, including first and second generation biofuels and alternative vehicle technologies, such as hybrids, plug-in hybrids and battery-powered electric vehicles. Focus is on options that currently are commercially available or in an early commercialization/demonstration phase, while potential longer term options are excluded (e.g., algae biofuel and hydrogen). Under the given conditions, the model result represents the overall cost-optimal system solution meeting all defined model constraints (e.g., energy service demands and emission restrictions).

MARKAL_Sweden is in the project enhanced in several respects. In particular, the biomass supply representation in the model is updated and improved. Potentially available quantities of biomass from forestry are based on data from the Swedish Forest Inventory (SFI). The forest development was simulated using HUGIN, a calculation system that enables the calculation of potential outcomes of stemwood, logging residues and stumps from harvesting operations. In the simulation, individual growth prognoses for more than 31 000 sample plots from all over Sweden are produced. Supply data from the forest potential modeling are then used to construct detailed biomass supply curves, which are integrated into the MARKAL_Sweden model.

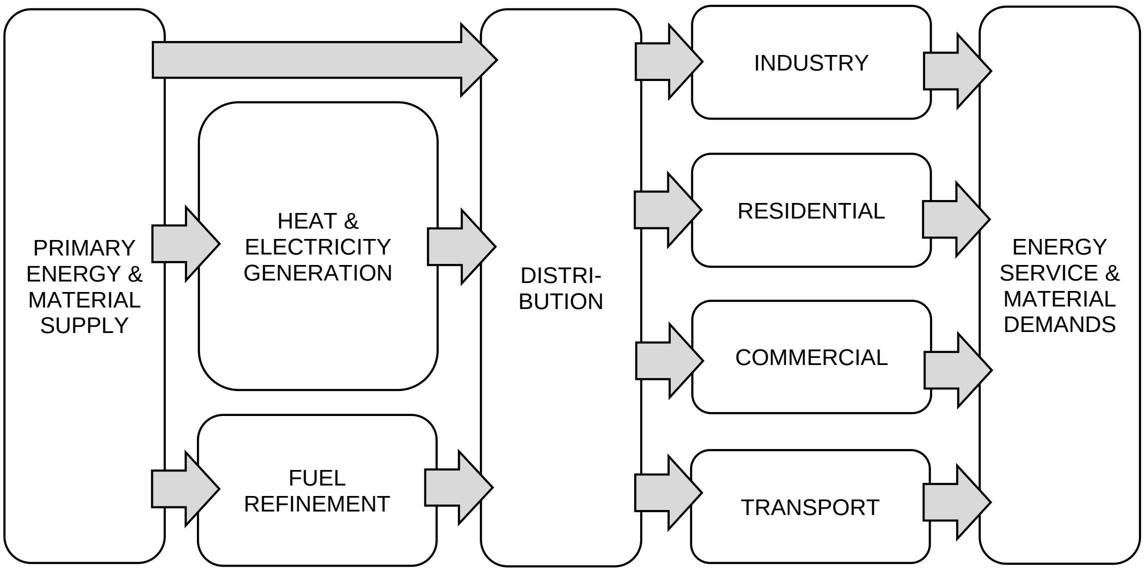


Figure 1. Aggregated overview of sectors, processes and energy and material flows in MARKAL_Sweden.

2.2 MODEL SCENARIOS AND OIL-PHASE OUT (OP) CASE

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 alternative scenarios simulate different developments of the stationary energy system as well as in the transport sector. In the scenarios, a stylized energy policy situation compared to reality is applied, and policies are represented as quantitative constraints regarding CO2 emissions and fossil fuel use. Table 1 shows an overview of the scenarios.

To investigate the system effects of aiming for a “fossil-independent”, i.e. an almost fossil free, road transport sector to 2030, an additional fossil fuel phase-out constraint is introduced. For each of the scenarios (the main scenario as well the alternative scenarios), two model cases are carried out: one case without and one case with an additional constraint on road transport fossil fuel use. The additional constraint, denoted the oil phase-out (OP) policy, is defined as an 80% reduction of fossil fuel use in the road transport sector to 2030 and a 100% reduction to 2050.

Table 1. Overview of model scenarios. For the "alternative scenrios", 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. Import fossil fuel prices are based on the "450 scenario" of IEA's World Energy Outlook, 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 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 for CO_2: 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 second 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 environmental 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).
TRAF_SG	Slow traffic growth: An alternative development with lower traffic levels than with base assumptions is assumed: the traffic 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 paper and pulp 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.

3 RESULTS

3.1 OVERALL SYSTEM DEVELOPMENT

To meet the increasingly stringent CO_2 reductions, several different measures are required across all sectors of the energy system. The development of the energy system as a whole as well as of the electricity generation system is presented in Figure 2 for the main scenario GLOB_CA.

To enable a reduction of fossil fuel use, the scenario presents an increased use of biomass and other renewables and a significant deployment of energy efficiency measures. Expressed as share of total energy supply, biomass, waste and peat increase from 17% in 2000 to 32% in 2030 and 36% in 2050. In 2050, wind power (included in "other renewables" in Figure 2) accounts for a production of 26 TWh of electricity, i.e. considerable higher than the production of 3.5 TWh as of 2010 (Reference: Swedish Energy Agency, Energy in Sweden 2011). Bio-based electricity generation peaks in 2025 at a production level of 23 TWh and then decreases to 13 TWh to 2050. 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 (e.g., aviation).

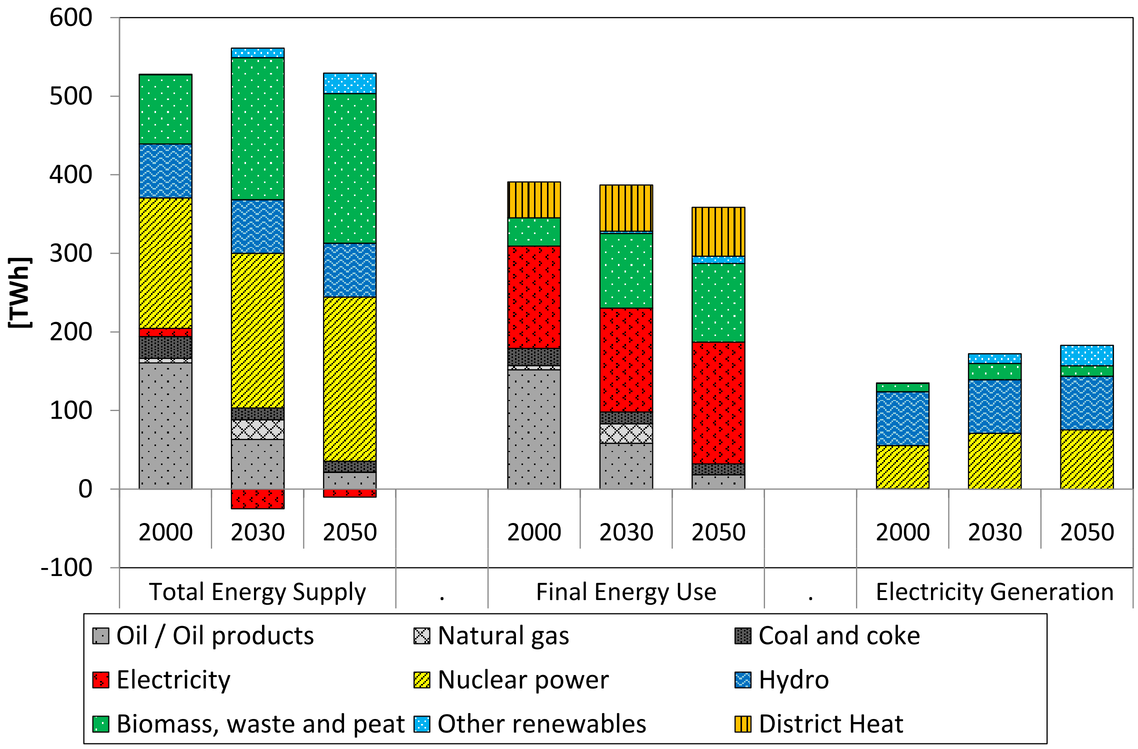


Figure 2. Total energy supply, final energy use and electricity generation for the main analysis scenario GLOB_CA . Nuclear power is for "total energy supply" represented in gross values (input energy).

3.2 BIOMASS UTILIZATION AND PRICE DEVELOPMENT

The results indicate a potential for significantly increased use of bioenergy in the energy system. For GLOB_CA, in which a system-wide CO_2 reduction of 80% to 2050 is imposed, total bioenergy utilization increases by 63% to 2050 compared to 2010 (Figure 3). A future high demand for biomass resources leads to the utilization of higher-cost biomass sources, such as stumps and cultivated energy forest, in the model results. To some extent, also pulpwood is used for energy purposes.

While bioenergy supply to the energy system as a whole increases steadily throughout the studied time horizon, the use of biomass in individual sectors of the energy system develops differently. Utilization of domestic biomass resources for heat and power, on the one hand, and for transport biofuel production, on the other hand, is presented in Figure 4. Results are presented for all scenarios as well as with and without the OP policy applied. Generally, the largest increase in biomass use occurs in transport biofuel production, which by 2050 accounts for 41% of total primary biomass use for GLOB_CA.

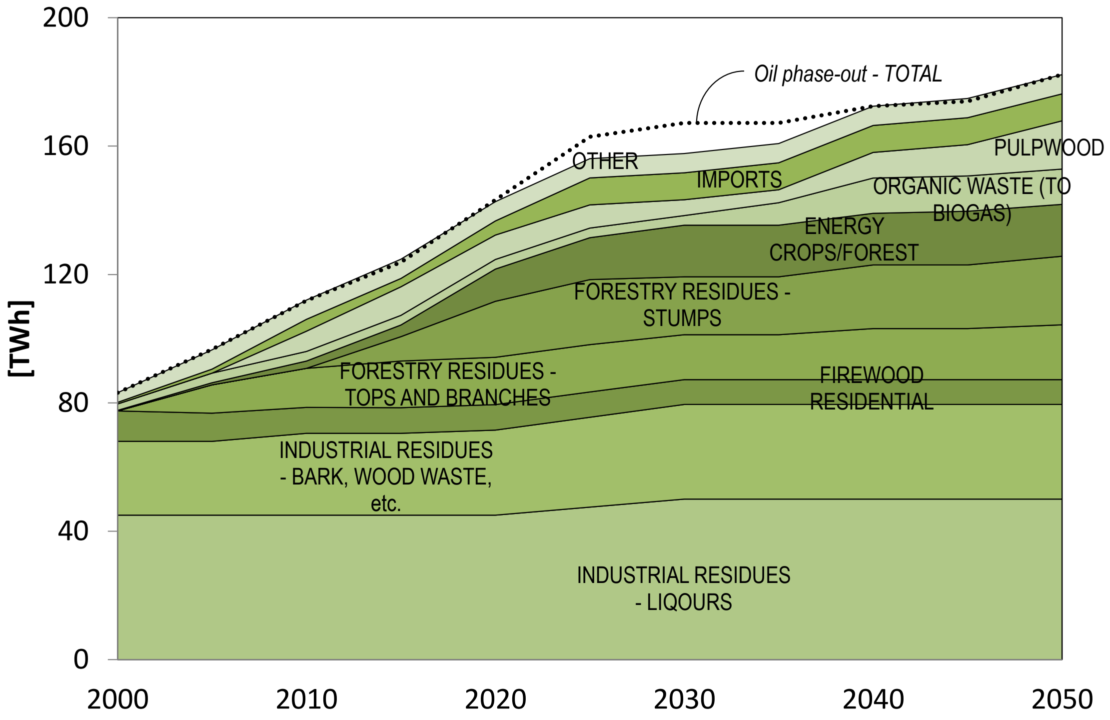
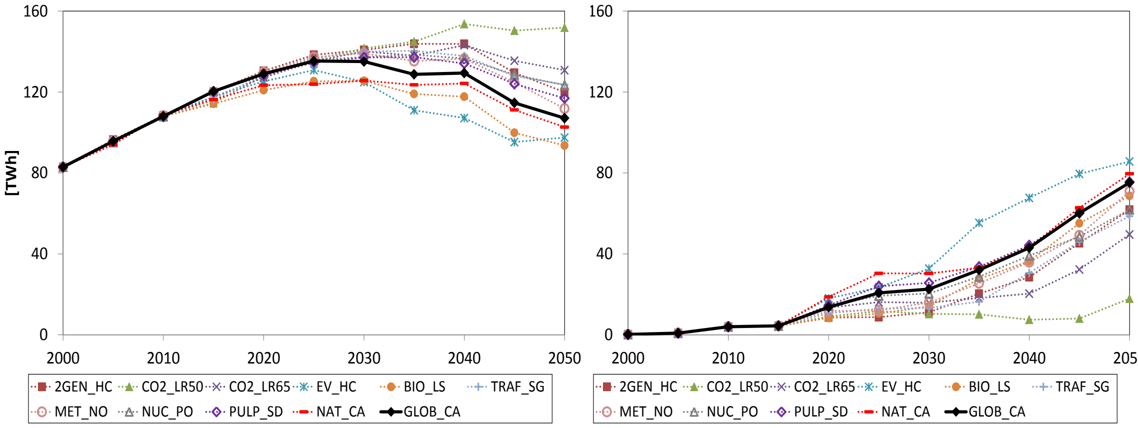
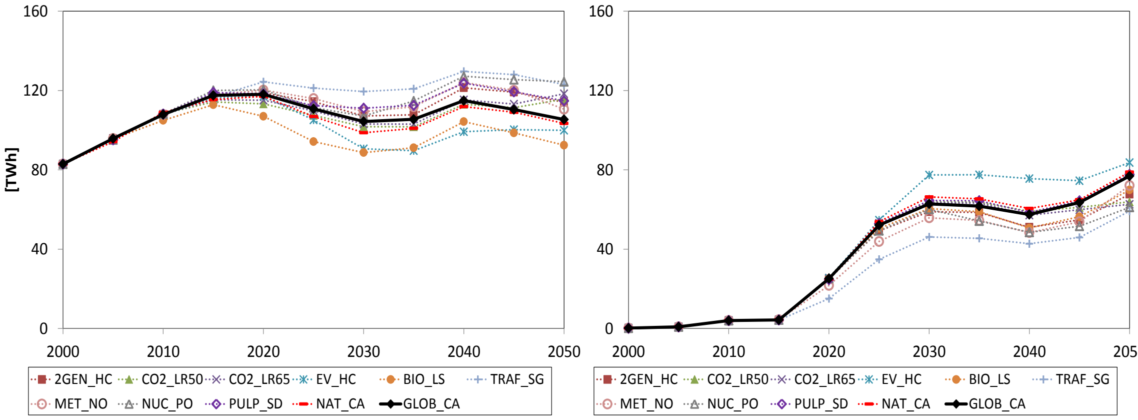


Figure 3. Biomass utilization (excluding peat and combustible minucipal waste) in scenario GLOB_CA. Dotter line shows total biomass utilization with OP policy applied.



a) Bio4HePo **b) Bio4Tran**

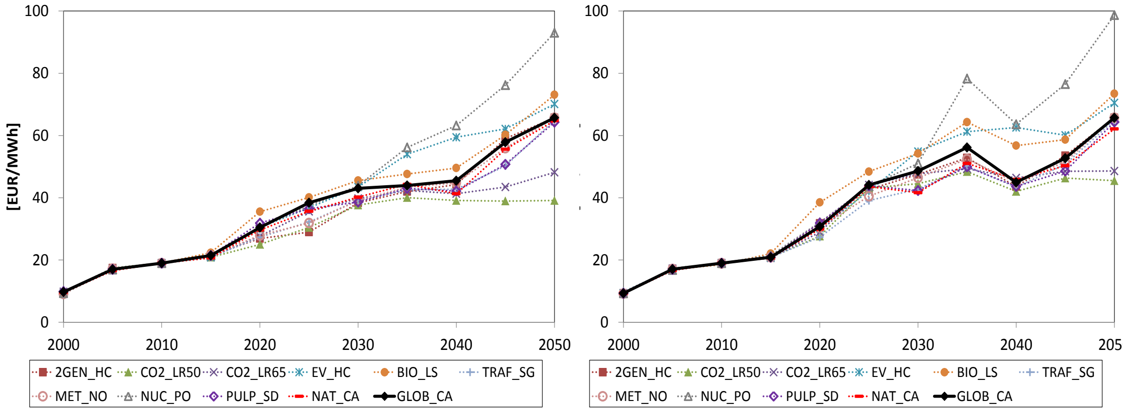


c) Bio4HePo, with OP **d) Bio4Tran, with OP**

Figure 4. Biomass use divided in sectors (all scenarios); for heat and power production (Bio4HePo) in (a) and (c), for transport biofuel production (Bio4Tran) (b) and (d). In (a) and (b) *without* OP policy and in (c) and (d) *with* OP policy.

The sector-specific OP policy leads to a large part of the biomass resources being allocated to transport biofuel production in the middle of the studied period. Compared to the case without the OP policy, the total system-wide use of bioenergy is 5% higher (Figure 3) but the bioenergy use for heat and power is 20% lower during the period from 2025 to 2035 (Figure 4). In 2050, the difference between the two cases is small.

In all scenarios, the high demand and strong competition for biomass significantly increases biomass marginal costs (Figure 5). For the GLOB_CA, marginal biomass cost more than triples from 2010 to 2050. Increased stress on the system in the form of additional policy measures such as early oil-phase out in road transport or a nuclear power phase-out, or other factors such as a slower development and cost reduction of electric vehicles than anticipated furthermore pushes up marginal costs.



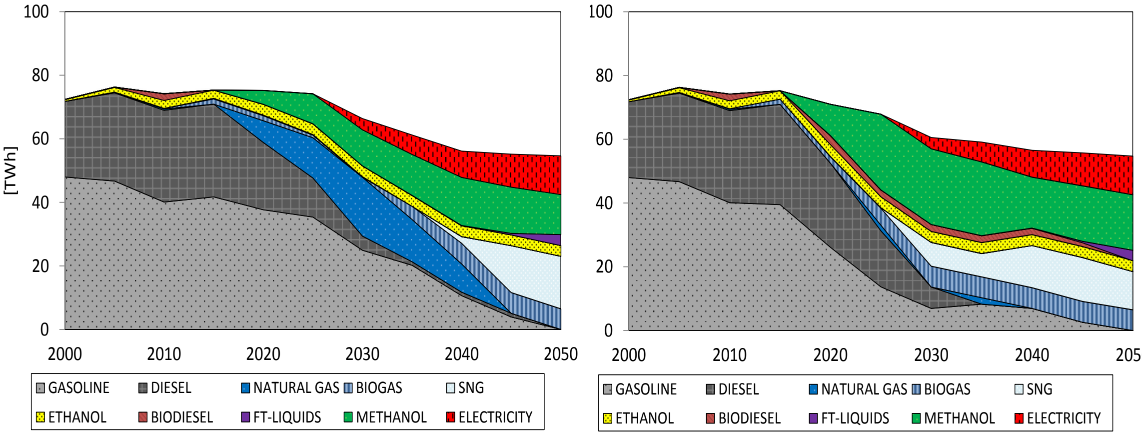
a) **b)**

Figure 5. Biomass marginal cost in different scenarios, without (a) and with (b) OP policy.

3.3 FUEL CHOICES IN THE ROAD TRANSPORT SECTOR

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 form an integral part of cost-efficient system solutions meeting such targets (Figure 6). In GLOB_CA, the cost-optimized model results show a biofuel use in the 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 the OP policy, giving 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 GLOB_CA). The impact on transport fuel choices of the OP 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 market shares for SNG are affected negatively.



a) **b)**

Figure 6. Fuel use in road transport for scenario GLOB_CA, without (a) and with (b) OP Policy.

3.4 SYSTEM CO_2 ABATEMENT COST

By definition, further restraining of the system implies higher system costs. Thus, an early phase-out of fossil fuel in road transport in addition to system-wide CO2 reductions increases system costs (Figure 7). For GLOB_CA without OP policy, the implemented CO_2 reduction increases the total energy system cost by 3.2% (compared to a situation without CO_2 restrictions). The introduction of the OP policy adds 0.2% giving a total system cost increase for both CO_2 and OP policy of 3.4%. Put differently, the OP policy increases total system-wide CO_2 abatement costs by about 7%. For the alternative scenarios with stringent CO_2 reduction (-80%), the corresponding increase is 5-12%. CO_2 reduction levels are of large significance for cost-competitiveness of transport biofuels and, therefore, the additional CO_2 abatement cost for the OP policy under less stringent CO_2 reductions (-50 to -65%) is higher, 17-36%.

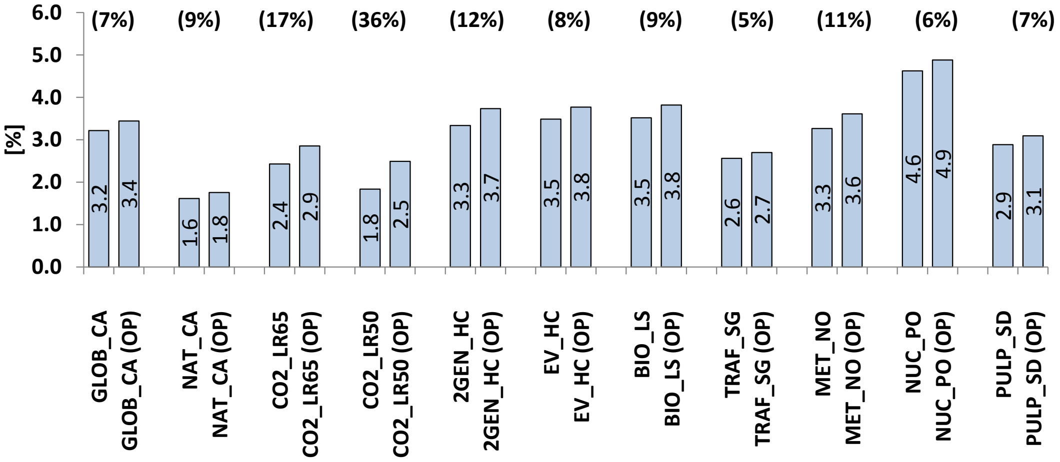


Figure 7. Incremental system cost for CO_2 reduction, as well as for CO_2 reduction and OP policy jointly, expressed in relation to corresponding situation without these actions taken. Within brackets, the percentage increase in incremental system cost for adding OP.

4 DISCUSSION AND CONCLUSIONS

In this study, the potential utilization of bioenergy in the future Swedish energy and transport system is studied under different policy objectives. 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 captures important linkages between the sectors. 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. However, due to its partial equilibrium approach, macroeconomic effects are essentially not captured by the model. The model calculations are based on direct technological costs and with full knowledge of future developments (perfect foresight), and represents technological learning in an exogenous manner.

The results show that stringent CO_2 reduction targets make biomass a highly cost-competitive source for energy. However, without sector-specific polices, significant (above 50%) CO_2 reductions are required for transport biofuel production to take off. With higher reduction levels, transport biofuel production increases, and with stringent CO_2 constraints (e.g., reduction of 80% to

2050), the largest increase in bioenergy use occurs in transport biofuel production. Further, the results of the study show that achieving stringent CO_2 emission reductions and road transport fossil fuel phase-out is feasible without considerable cost increases, excessive biofuel imports or dramatic future technological advances and, further, that biofuels in the road transport sector are an important contributor to the meeting of such targets in cost-optimized systems solutions.

With increasing CO_2 restrictions, biomass availability constraints lead to an upward pressure on price. As a consequence, in sectors with better possibilities for substitution to other energy sources or feed-stocks, such substitution will occur (within the constraints of the model and scenarios). Since there are more economically viable ways to generate electricity and heat based on non-bioenergy sources than transport fuels, we see a decreasing utilization of bioenergy for electricity and heat as the price increases and, e.g., wind power becomes more cost-efficient in the stationary energy system.

Due to the national approach applied, this study has represented bioenergy trade over national borders in a simplified manner, and basically only allowed a small increase in bioenergy imports compared to current levels. In reality, higher imports could dampen some of the biomass marginal cost peaks seen in the model results; however, effects of possible imports are highly uncertain in a climate conscious world since a sharp global biomass demand increase is then expected. Only in the NAT_CA scenario the climate ambitions in the surrounding world, and thus the demand for low carbon fuels, are 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.

The increasing marginal cost for biomass might affect the profitability and, ultimately, the survivability of the pulp and paper industry. The results indicate that the bulk of the increasing utilization of bioenergy is using harvesting residues, stumps and other biomass fractions not competing as a feed-stock with the pulp and paper industry but in a competitive policy driven situation even slight changes needs 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 with new technologies can be re-constructed to energy combines with multiple outputs in addition to the conventional products. The full potential benefits of this kind of industry-integrated polygeneration opportunities are not captured in the current model version.

While there are previous estimates on transport biofuel potentials for Sweden, 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. Some of these present somewhat lower estimates than what the present study suggests for certain scenario conditions. 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. Also in comparison to other similar type of comprehensive and dynamic model-based studies for other countries or regions, the resulting road transport biofuel shares of this study are in the higher range. There are several reasons for this. One is that the CO_2 emission reductions applied (-80% to 2050) is more stringent than what many studies have assumed for a similar time-frame. Another reason is that Sweden has a comparably high per capita biomass supply and the electricity sector is already to large degree carbon-free being based on hydro and nuclear power. Although some studies investigate emission reductions of the same magnitude as the present study, this is often done with a longer time horizon applied, 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.

In terms of biofuel choices, the results indicate 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 production process. Similarly to other second generation biofuel options, methanol has also the benefit of a biomass feedstock with high potential. 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 that there cannot be important roles also for other alternative fuels; due to the linear formulation of the model, even though differences may be small, the lowest-cost option will take the whole market in a specific demand segment if no other constraints apply. 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.

Even though the model only to some part captures inertia and lock-in effects linked to fuel and technology choices (the perfect foresight feature is one reason for the low level of inertia in the model), 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 OP 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 abatement cost due to early fossil fuel phase-out is not insignificant but at the same time, perhaps, not too discouraging. For less stringent CO_2 constraints, the cost increase is significantly higher. It should be noted that the model does not take potential benefits, other than CO_2 emission reductions, 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 potential development of know-how in a growing business area 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.