THE COST-EFFECTIVENESS OF ELECTROFUELS IN COMPARISON TO OTHER ALTERNATIVE FUELS FOR TRANSPORT IN A LOW CARBON FUTURE

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ABSTRACT: In future, a complement to biofuels, which also can originate from biomass, is electrofuels. Electrofuels are synthetic hydrocarbons, e.g. methane or methanol, produced from carbon dioxide (CO_2) and water with electricity as primary energy source. The CO_2 can be captured from e.g. biofuel production plants and thereby potentially provide an opportunity for biofuel producers to increase the yield from the same amount of biomass. This project assesses if there are conditions under which electrofuels are cost-effective compared to other fuels for transport in order to reach climate targets. Energy systems analysis are conducted using a well-established energy-economic long-term global energy systems model developed to include also electrofuels as transportation fuels. In this initial assessment, the results indicate that electrofuels is not the most cost-efficient option for road transport. It may become a complement to other alternatives if assuming very high cost for fuel cells and batteries. In future studies it would be interesting to analyze the impact from assuming that carbon capture and storage technologies will be large scale available, the effect of fluctuating electricity prices, and the role of electrofuels in the aviation and shipping sectors.

Keywords: alternative fuel vehicle, CO_2 reduction, modelling, cost analysis, decision making, electricity.

1 INTRODUCTION

The carbon dioxide (CO_2) emissions from the transportation sector can be reduced by reducing the number of km travelled, the amount of energy used per km travelled and a transition into less emitting fuels. The three main candidates for less emitting fuels are (i) liquid or gaseous renewable fuels including carbon atoms such as biofuels and electrofuels, (ii) hydrogen from renewables or fossil fuels with carbon sequestration and (iii) electricity from low-emitting power sources [1].

Electrofuels (in literature also determined efuels, sunfuels, power-to-gas, power-to-liquids etc.) are synthetic hydrocarbons, e.g. methane or methanol, produced from CO_2 and water with electricity as primary energy source. The CO_2 can be captured from various industrial processes giving rise to excess CO_2 e.g. biofuel production plants, as well as fossil and biomass combustion plants. CO_2 can also be captured from the atmosphere or seawater, see Figure 1.

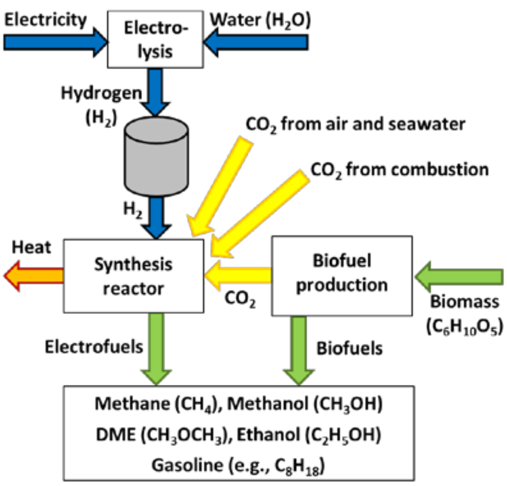

Figure 1: Pathways for electrofuel production.

There is a substantial potential for increased use of biofuels, electricity and hydrogen in the transport sector. However, for both hydrogen and electricity, there are uncertainties to what extent fuel cells and batteries are appropriate solutions in shipping and long-distance road transport. For aircrafts while being in the air electricity is an unlikely solution. There is also a need for a new infrastructure with these energy carriers in the transport sector [2]. A large scale use of biofuels produced from biomass is also facing challenges concerning its impact on sustainability and food production [3-4]. A blendable complement to biofuels, having equally good combustion properties, seems to be attractive in a future sustainable transport system.

Electrofuels are potentially interesting for all transport modes and, depending on the fuel produced, it can be used in combustion engines and may not require significant investments in new infrastructure. Electrofuels potentially provide an opportunity for biofuel producers to increase the yield from the same amount of biomass if the associated excess CO_2 is used in the process [5]. The production of electrofuels may also contribute to balancing intermittent electricity production (e.g. solar and wind power) increasing its attractiveness from a system perspective [6].

Several demonstration scale facilities of electrofuels, have been developed in Europe during the last decade [7]. For example, Carbon Recycling International (CRI) on Iceland, is producing e-methanol by using geothermal energy and CO_2 from the same source [8]. Another example is the company ETOGAS, on behalf of Audi AG, that has invested in a 6 MW plant in Germany, which uses electricity from wind power and CO_2 from a biogas processing plant to produce e-methane [9].

There are, however, many aspects that need to be clarified in order to understand the potential role of electrofuels in a future low-emitting transport sector. One such aspect is the cost-effectiveness of electrofuels in a global long-term energy systems perspective where all energy sectors compete for the same primary energy sources, where the least cost vehicle concept and fuel options can be assessed.

The aim of this study is to assess if there are conditions under which electrofuels are cost-effective compared to other alternative fuels for transport in order to reach ambitious climate targets.

2 METHOD

In order to analyze a possible future transition of the global energy system, Azar and Lindgren have developed the GET (Global Energy Transition) model where cost-effective global fuel choices in the transportation sector can be analyzed [10]. Over the years later versions have been developed to analyze various questions. Grahn et al. have, for example, regionalized a further developed GET model version into ten regions and analyzed the role of biofuels as well as various questions around cost-effective vehicle concepts and fuel choices [11-13].

2.1 Model structure

The regionalized global energy systems model (GET-R 6.4) is a linear optimization model designed to choose primary energy sources, conversion technologies, energy carriers and transportation technologies that meet the energy demands of each region, at the lowest aggregate costs subject to a carbon constraint. It focuses on the transportation sector, while the use of electricity and heat (including low and high temperature heat for the residential, service, agricultural, and industrial sectors) are treated in a more aggregated way.

Energy supply potentials, demand for electricity, heat and transportation fuels, are exogenously given. The model is composed of three different parts: (i) the primary energy supply module, (ii) the energy conversion system with plants that may convert the primary energy sources into secondary energy carriers (e.g., electricity, hydrogen, methanol, gasoline/diesel and electrofuels) and (iii) the final energy demand which includes infrastructure and technologies used in the transportation sector. The basic energy flows in GET-R 6.4 used in this study, i.e. primary energy supply options, trade, and final fuel choices, are presented in Figure 2.

This model version allows for carbon capture and storage (CCS) technologies when applied to fossil fuels for heat, electricity and hydrogen production.

Energy resources can be traded between regions (with the exception of electricity) with costs ascribed to such movement. Regional solutions were aggregated to give global results. The model does not consider greenhouse gases other than CO_2. The pattern of allowed global CO_2 emissions was constrained according to the emission profile leading to an atmospheric CO_2 concentration of 400 ppm, developed by Wigley and co-workers [14]. The model is run for the period 2000–2130 with 10-year time steps, where results from the time period 2020–2120 (i.e., hundred years, with the main purpose of being able to analyze solutions that may appear beyond the fossil fuel era) are presented and discussed.

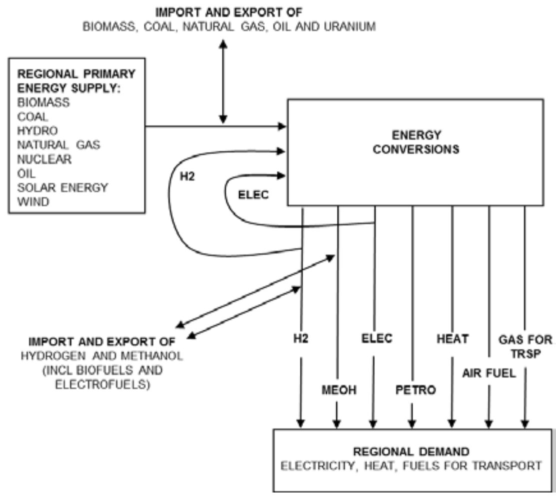

Figure 2: The basic flow chart of primary energy supply and fuel choices in the regionalized energy systems model, GET-R 6.4. Acronyms used are hydrogen (H2), methanol as a proxy for liquid alternative fuels including biofuels and electrofuels (MEOH), electricity (ELEC), low and high temperature heat for the residential, service, agricultural, and industrial sectors (HEAT), diesel and gasoline (PETRO), synthetic fuels for aviation (AIR FUEL) and methane rich gas as transportation fuel (GAS FOR TRSP).

The description of the energy system in the model is a simplification of reality in at least four important respects: (i) consideration of limited number of technologies, (ii) assumption of price inelastic demand, (iii) selections made only on the basis of cost, and (iv) "perfect foresight" with no uncertainty of future costs, climate targets, or energy demand. The model is not designed to forecast the future development of the energy system. The model does however provide a useful tool to understand the system behavior and the interactions and connections between energy technology options in different sectors in a future carbon-constrained world.

2.2 Added module on electrofuels

In earlier versions of the GET model there are multiple ways to produce hydrogen, i.e. from steam reforming of natural gas, gasification of biomass, oil and coal, as well as from slitting water either through electrolysis or from high temperature solar thermal. Earlier versions of the GET model also keep track of all CO_2 emissions from both fossil and biogenic sources. In this model version we have combined the multiple ways of hydrogen production with the different CO_2 sources in a new electrofuel production facility. The possible pathways for the electrofuel production, in the model GET-R 6.4, can be seen in Figure 3.

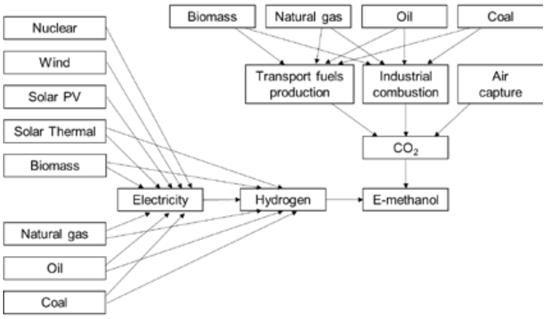

Figure 3: Possible pathways for the production of electrofuels, in the form of e-methanol, in GET-R 6.4.

2.3 Energy demand scenarios

Regional population, GDP_{PPP} per capita (GDP measured in purchasing power parities), heat and electricity demand are based on scenarios developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. Their ecologically driven demand scenario, titled "C1", where it is assumed that technological development leads to energy efficiency improvements, so that per capita heat and electricity demands in industrialized countries are reduced, has been chosen [16]. The IIASA demand scenarios are, however, not sufficiently detailed for the GET analysis of the transportation sector. We have, therefore, developed our own transportation scenario by assuming that the increase in the amount of person kilometers traveled is proportional to GDP_{PPP} growth. Transportation scenarios are developed separately for passenger and freight transportation and disaggregated into trains, cars, buses, trucks, ships and aviation. Full details are given in e.g. refs [10, 13, 17].

2.4 Primary energy sources and emission factors

We have chosen to follow the regional biomass supply potentials described in Johansson et al. [18] adding up to a global potential of 205 EJ/yr. This potential fits very well into the range that has been concluded in a study reviewing more than 20 scientific publications analyzing the global biomass supply potential. The authors conclude that the literature review show that up to 100 EJ/yr of bioenergy can be produced in a sustainable way and that 300–500 EJ/yr may be technically possible but that such expansion might challenge sustainability criteria. Bioenergy over 500 EJ/yr they find extremely difficult to produce in a sustainable way [19].

For global supply potential of oil and natural gas (NG), we have chosen 12,000 and 10,000 EJ, respectively [20, 21], and assumed a regional distribution following Johansson et al. [18]. For coal we have chosen a global supply potential of approximately 260,000 EJ following the total resource estimates in Rogner [22]. In the model, CO_2 emission constraints limit the use of fossil fuels (generally less than 10% of the coal supply potential is used within this century when meeting 450 ppm). The potential for wind and solar energy is huge and have therefore not been assigned an upper limit but are limited by expansion rate constraints.

The CO_2 emission factors we have used are NG (15.4 kgC/GJ), oil (20.5 kgC/GJ), coal (24.7 kgC/GJ), and biomass (32 kgC/GJ) of delivered fuel [23]. Future use of nuclear, hydro, wind, biomass, and solar energy is assumed to contribute with negligible CO_2 emissions.

2.5 Cost data

Technological change is exogenous in the GET model, that is, the cost and performance of the technologies are independent of how much they are used. We assume mature technology costs throughout the time period considered. We further assume that all technologies are available in all regions. Global dissemination of technology is not seen as a limiting factor and thus is not included. All prices and costs are in real terms as future inflation is not considered. A global discount rate of 5% per year was used for the net present value calculations.

Data for vehicle technology as well as conversion plants and infrastructure (e.g., investment costs, conversion efficiencies, lifetimes, and capacity factors) are held constant at their “mature levels”. Vehicle costs are based on costs for main components, where the mature level for batteries, fuel cells and hydrogen storage are among the most uncertain cost-parameters.

As an example of how the technologies included in the transport sector are modelled, following assumptions are made for light-duty passenger vehicles. The model does not distinguish between gasoline and diesel fuels, which are lumped together as petroleum (petro). Five fuel options: petro, natural gas (NG), synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), electricity, and hydrogen (H2) and five vehicle technologies: internal combustion engines (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs) were considered. The efficiency is modelled as tank-to-wheels energy (HHV) and improves over the time period with 0.7% per year for ICEVs, HEVs, PHEVs and FCV while BEVs improve with 0.12% per year. An electric battery range of 65 km was adopted for PHEVs which enables approximately two-thirds of their daily driving distance to be powered by electricity from the grid on a single overnight charge [24]. HEVs have a relatively short all-electric range (we assume 2 km). The all-electric range was set to 200 km for BEVs, while all other vehicle types are assumed to have fuel storage enough for 500 km. For a complete list of cost assumptions used in the GET model, see e.g. [13,17,25].

A recent study has reviewed scientific papers and extensive reports to analyze the production costs of different electrofuels. Data found in the literature has been used to calculate a base case as well as a best and a worst case of total production costs for a range of electrofuel options, today and for 2030 [26]. In this study we have used their 2030 base case cost on e-methanol as production costs for electrofuels. In an alternative scenario we also apply the authours’ best case data on methanol synthesis. Production costs, used in the model, including annualized investment cost (assuming in general 25 years lifetime and 5% interest rate), O&M cost, primary energy extraction cost, and distribution cost to fuel stations, are summarized in Table I.

Table I: Production costs for alternative fuel options included in the GET-R 6.4 model version, where e-methanol can be produced from any hydrogen pathway.

Primary energy and energy carriers to be further converted	Energy carrier	Production cost* ($/GJ$_{fuel}$)
Oil	Petro	9.73
Natural gas	Natural gas	8.90
Biomass	Methanol	11.69
Natural gas	Methanol	9.97
Coal	Methanol	10.02
Biomass	Hydrogen	15.92
Natural gas	Hydrogen	12.76
Coal	Hydrogen	13.53
Oil	Hydrogen	14.22
Solar-thermal	Hydrogen	31.04
Biomass-CCS	Hydrogen	21.73
Natural gas-CCS	Hydrogen	14.22
Coal-CCS	Hydrogen	15.00
Oil-CCS	Hydrogen	15.80
Electricity**	Hydrogen	7.19
Hydrogen***	E-methanol	5.91

*) These production costs include distribution cost to fuel station but do not include scarcity rents neither carbon taxes (which both are generated endogenously in the model adding costs to first and foremost natural gas, oil, coal and biomass based energy carriers).
**) The electricity production cost should be added to this option to be able to compare with the other hydrogen production options. In the model electricity can be produced from a range of different pathways at production costs between 5-23 $/GJ$_{elec}$ where the cheapest option is hydropower.
***) The hydrogen production cost should be added to this option to be able to compare e-methanol with other fuel options. Note also that a cost for CO_2 capture will be added. In the model CO_2 can be captured in CCS-facilities as well as from the air.

2.6 Constraints

Constraints on how rapidly changes can be made in the energy system have been added to the model to avoid solutions that are obviously unrealistic. This includes constraints on the maximum expansion rates of new technologies (in general, set so that it takes 50 years to change the entire energy system) as well as annual or total extraction limits on the different available energy sources.

The contribution of intermittent electricity sources, i.e., wind and solar photovoltaic (PV), is limited to a maximum of 30% of the electricity use, but solar energy supplies are abundant and can in the model become useful for the entire energy sector if converted into hydrogen. To simulate the actual situation in developing countries, a minimum of 30 EJ/year of the heat demand needs to be produced from biomass during the first decades. For CCS, we assumed a storage capacity of 600 GtC [27], a maximum rate of increase of CCS of 100 MtC/year and negligible leakage of stored CO_2.

The future role of nuclear energy is primarily a political decision and will depend on several issues such as nuclear safety, waste disposal, questions of nuclear weapons pro-liferation and public acceptance. We assume that the contribution of nuclear power does not exceed current levels in absolute terms.

3 RESULTS

The model is first run under base case assumptions and then with an alternative scenario assuming lower costs and higher conversion efficiency for e-methanol synthesis as well as higher costs for batteries and fuel cells assuming that only current high cost alternatives will be available in future and thus mature level remain at current costs or even higher. Key assumptions for the two scenarios are presented in Table II. For a list of all parameter values used in the base case, see [13,17,25]. Results from the two model runs are presented in Figure 4.

Table II: Key assumptions made in the two scenarios run using the GET-R 6.4 model version.

	Base case scenario	Alternative scenario
Electrolyser ($/kW$_{elec}$)*	700	700
Methanol synthesis reactor 50 MW ($/kW$_{fuel}$)	500	300
Conversion efficiency synthesis reactor (%)	80	90
Fuel cell stack cost ($/kW$_{elec}$)	100	700
Batteries ($/kWh)	300	700
H2 storage ($/GJ$_{fuel}$)	2500	6500
NG storage ($/GJ$_{fuel}$)	1100	1500
Carbon capture and storage technology**	No	No

*) When assuming optimistic values for electrofuel production, a reduced cost for electrolyzers is a natural assumption. However, in the alternative scenario the investment cost for electrolyzer are assumed to be equally high as the investment costs for fuel cells.
**) In this model version, electrofuels do not enter the scenarios if assuming that CCS will be a large scale available technology for CO_2 reduction.

From comparing results presented in Figure 4a and 4b it can be seen that both the cost-effective fuel choices and the total energy demand differ between the scenarios. The energy demand depend on vehicle technology choices where the energy demand is reduced when more energy efficient vehicle technologies, e.g., hybrid electric vehicles and plug-in electric vehicles, are included in the scenarios, compared to internal combustion engines. When assuming more optimistic values on the methanol synthesis reactor for the electrofuel production as well as higher costs for batteries, fuel cells, and gaseous onboard storage, the scenario include less hydrogen and battery electric solutions and instead biomethanol as well as some e-methanol are shown in the scenarios. The amount of natural gas is also higher in the alternative scenario. This is a global study, assuming that the emissions are reduced in the region and sector where it is cheapest. Figure 4 shows the aggregated emissions from all regions, but some regions, such as Europe, might need to reach almost zero emissions much earlier than what can be seen in the figure whereas it may be cost-effective to keep other regions in the fossil fuel era during a longer time period.

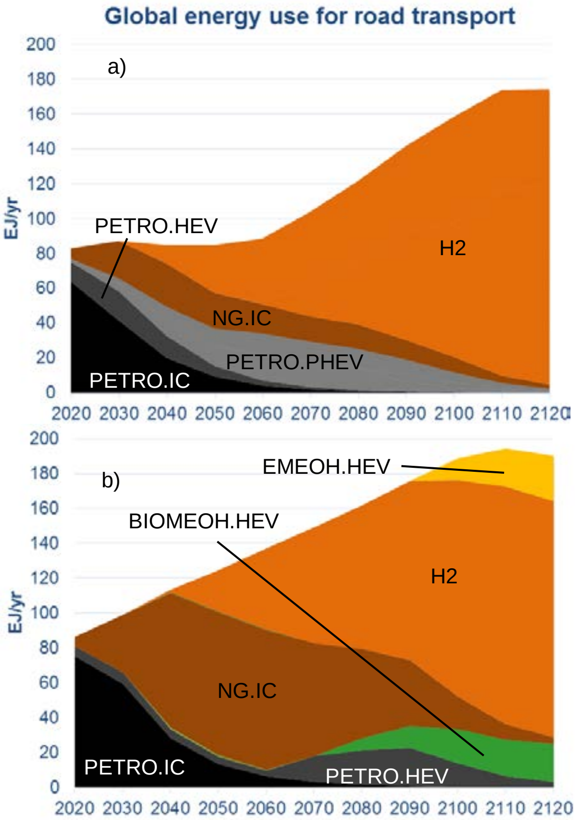

Figure 4: Cost-effective fuel choices for global road transport when CO_2-concentration is stabilized on 400 ppm for the (a) base case scenario and (b) an alternative scenario assuming lower costs and higher conversion efficiency for e-methanol synthesis as well as higher costs for batteries and fuel cells. Acronyms used are: PETRO= petroleum-based fuels e.g. gasoline and diesel, NG= natural gas, H2= hydrogen, BIOMEOH= biomass-based methanol, EMEOH= electrofuels as e-methanol, FC= fuel cell, IC= internal combustion engine, HEV= hybrid electric vehicle, PHEV= plug-in hybrid electric vehicle (assumed to run 65% of the distances in electric mode).

4 DISCUSSION AND CONCLUSIONS

In this study, we have used the GET-R 6.4 model to assess if there are conditions under which electrofuels are cost-effective compared to biofuels and other alternative fuels for transport in a future carbon constrained world. Main findings from the model runs can be summarized as:

Cost-competitiveness

- It is not likely that electrofuels can compete with current conventional fuels in road transportation (unless higher taxes on fossil CO_2-emissions).
- Under some circumstances, electrofuels may be able to complement battery electric vehicles and hydrogen used in fuel cells in a scenario reaching almost zero CO_2 emissions in the global road transport sector.
- Cost-competitiveness depends on, e.g. the availability of advanced CO_2 reduction technologies such as CCS, and costs for the competing technologies, but also on the costs and efficiencies of synthesis reactors for the electrofuel production.
- From the literature it is also clear that the competitiveness of electrofuels depend on the electricity price, not assessed in this study.

Resource perspective

- Electrofuels used in combustion engines demand significantly more energy compared to battery electric vehicles and hydrogen used in fuel cells.
- If scaling up the production of electrofuels the demand for renewable electricity might be challenging.

Climate perspective

- The results indicate that a more effective way to lower the atmospheric CO_2 concentration would be to store captured CO_2 underground (CCS). However, the CCS technology is currently struggling with public acceptance and it is not obvious that CCS will be a large scale available technology.
- To be determined as a sustainable solution, a large scale use of electrofuels can only exist in an energy system with abundant renewable electricity produced in a sustainable way.

In the literature it is shown that the electricity price is one of the most critical parameters when assessing the total electrofuel production costs, see e.g., [26]. The model is, however, not designed to distinguish between fluctuating electricity prices over the year, over the day or over even shorter time periods. The production of electrofuels is sometimes discussed as a possible service to the power generation sector (e.g. electricity storage and frequency balancing), especially in a future carbon constrained world where the share of renewable intermittent electricity may be much larger than today. The cost-competitiveness of electrofuels might be affected by fluctuating electricity prices, as well as an eventual income from the service of balancing the electricity grid, however not included in this model version.

The facility producing electrofuels can either be built close to the CO_2 source or close to the power generating source. The e-methanol production costs in this study do not consider possible distribution costs if hydrogen, CO_2 or electricity have to be transported to the electrofuels production site.

It should be stressed that the topic of electrofuels is relatively new and steps of the production chain are often still immature. Data found in the literature, on future production costs, is therefore very uncertain. This argument also applies to the competing technologies, where mature costs on batteries, advanced biofuels, fuels cells and hydrogen storage technologies still are very uncertain, making it challenging to compare production costs.

The reason for that BEVs are not shown to be cost-effective in this model version is that PHEV is shown to be a more cost-competitive option when utlilizing electricity in the road transport sector. Also at very low battery costs, PHEVs are a lower cost solution compared to BEVs. In sensitivity analyses made in Grahn et al [28] it is shown that when reducing the BEV driving range to 100 km, BEVs may enter the scenario. Read more about the cost-competitiveness of BEVs in Grahn et al [28].

The attractiveness of electrofuels will to a large extent depend on the cost-competitiveness but also on other aspects not included in the model. Some of the main benefits and challenges with an increasing production of electrofuels that are not captured by the model are listed below.

- Electrofuels can be tailor-made into useful molecules and thereafter blended with e.g. biofuels.
- That electrofuels can be blended into conventional fuels, may however also lead to some drawbacks of the concept, such as that fuels used in internal combustion engines do not solve the challenges with local emissions (NOx, soot etc), which would be much lower if choosing the concepts of hydrogen in fuel cells or electricity in battery vehicles. The local emissions may, however, be slightly lower if choosing, e.g., DME, methanol or methane as electrofuel option, instead of gasoline or diesel.
- All fuels that can be used as a drop-in fuel to conventional gasoline and diesel, always come with the risk that these fuels may contribute to a prolonged era of fossil fuels.

5 FUTURE WORK

This study is still in progress and complementary analyses will be performed shortly. To be able to analyze the cost-effectiveness of electrofuels it would be beneficial to further analyze the impact from CCS, and the availability of resources such as biomass and natural gas. We will also further develop the model with a more detailed time representation in order to better capture the fluctuating costs of electricity production in the model. It would also be interesting to study the role of electrofuels in the aviation and shipping sectors that face challenges to use hydrogen and battery electric options.

6 ACKNOWLEDGEMENTS

Financial support from the Swedish Energy Agency, the Swedish Knowledge Centre for Renewable Transportation Fuels (f3), and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning, Formas, is gratefully acknowledged. We also thank Magnus Fröberg, senior engineer, Scania CV AB as well as dr Mariliis Lehtveer and prof Karin Andersson, Chalmers University of Technology, for valuable input and fruitful discussions.

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