THE POTENTIAL ROLE OF ELECTROFUELS AS MARINE FUEL: A COST-EFFECTIVE OPTION FOR THE FUTURE SHIPPING SECTOR?

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ABSTRACT

In order to reduce the climate impact of shipping the use of alternative marine fuels must increase. There is a range of possible alternative marine fuels and there is a need for more knowledge on the potential for the different options. Besides for example biofuels and hydrogen, electrofuels represent an additional option. Electrofuels (also called power-to-gas/liquids/fuels or synthetic fuels) is an umbrella term for carbon-based fuels, e.g. methane or methanol, which are produced from carbon dioxide (CO_2) and water using electricity as the primary energy source. The CO_2 can be captured from various industrial processes such as exhaust gases, the air or sea water. This study assesses if there are conditions under which electrofuels are cost-effective compared to other fuels for the shipping sector in order to reach ambitious global climate targets. Energy systems analyses are conducted using a well-established energy-economic long-term global model, developed to include also electrofuels as transportation fuels. In this initial assessment, the results indicate that it is not likely that electrofuels can compete with other fuel options, in the near term, in the shipping sector. However, it may become a complement to other alternatives during the end of this century if assuming that neither hydrogen nor fuel cells will be used in the shipping sector as well as that carbon capture and storage technologies will not be available on large scale. The production of electrofuels is still in its infancy, and many challenges need to be overcome before electrofuels can be available in large scale. For example, the production of renewable electrofuels will demand large amount of renewable electricity and non-fossil CO_2. From the literature it is also clear that the competitiveness of electrofuels depend on the electricity price, not assessed in this study.

Keywords: alternative marine fuel, scenarios, CO_2 emissions, global energy systems modelling, cost analysis, renewable energy

1 INTRODUCTION

In order to reduce the environmental and climate impact of shipping, in the short and long term, the introduction of alternative marine fuels is required (Brynolf et al., 2016a). There is a range of possible alternative marine fuels including e.g., liquefied natural gas (LNG), methanol, hydrogen and hydrotreated vegetable oil (HVO). However, there is a need for more knowledge on the potential for different options.

Besides the more well discussed alternative marine fuels, electrofuels represent an additional option. Electrofuels (also called power-to-gas/liquids/fuels or synthetic fuels) is an umbrella term for carbon-based fuels, e.g. methane or methanol, which are produced from carbon dioxide (CO_2) and water using electricity as the primary energy source. The CO_2 can be captured from various sources e.g., different industrial processes such as oil and natural gas processing, flue gases from fossil and biomass combustion plants, iron and steel production, pulp and paper plants. CO_2 can also be captured from the atmosphere or seawater, see Figure 1.

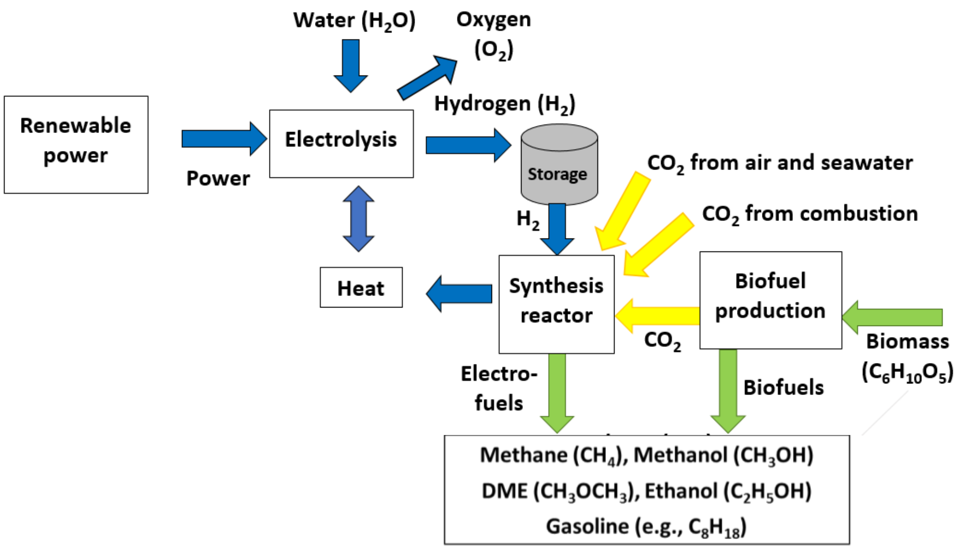

Figure 1: Pathways for electrofuels production, where hydrogen and carbon dioxide form fuels in synthesis reactors.

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 (Ball and Wietschel, 2009). A large scale use of biofuels produced from biomass is also facing challenges concerning its impact on sustainability and food production (Mendes et al, 2015; Azar, 2011). A blendable complement to biofuels, having equally good combustion properties, seems to be attractive in a future sustainable transport system.

Electrofuels are interesting for the shipping sector since they depending on the fuel produced, can be used in combustion engines and may not require significant investments in new infrastructure. In addition, the production of electrofuels may also contribute to balancing intermittent electricity production (e.g. solar and wind power) increasing its attractiveness from a systems perspective (Vandewalle et al, 2015).

The production of electrofuels is still in its infancy. However, there are several demonstration scale facilities of electrofuels, in Europe (Gahleitner, 2013). Carbon Recycling International (CRI) on Iceland that produces e-methanol by using geothermal energy and CO_2 from the same source is a well-known example (CRI, 2016). Brynolf et al (2016b) presents a review of the production costs of electrofuels.

There are, however, many aspects that need to be clarified in order to understand the potential role of electrofuels in a future low-emitting shipping 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 vessel and vehicle concepts as well as 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 the shipping sector in order to reach ambitious climate targets.

2 METHOD

In order to analyze a possible future transition of the global energy system, the GET (Global Energy Transition) model, where cost-effective global fuel choices in the transportation sector can be analyzed, was developed (Azar et al, 2003). Over the years later versions have been developed to analyze various questions. For example, Grahn and co-workers have 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 (Grahn et al, 2009a; 2009b; 2013a; 2013b).

2.1 MODEL STRUCTURE AND CO_2 REDUCTION SCENARIO

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.

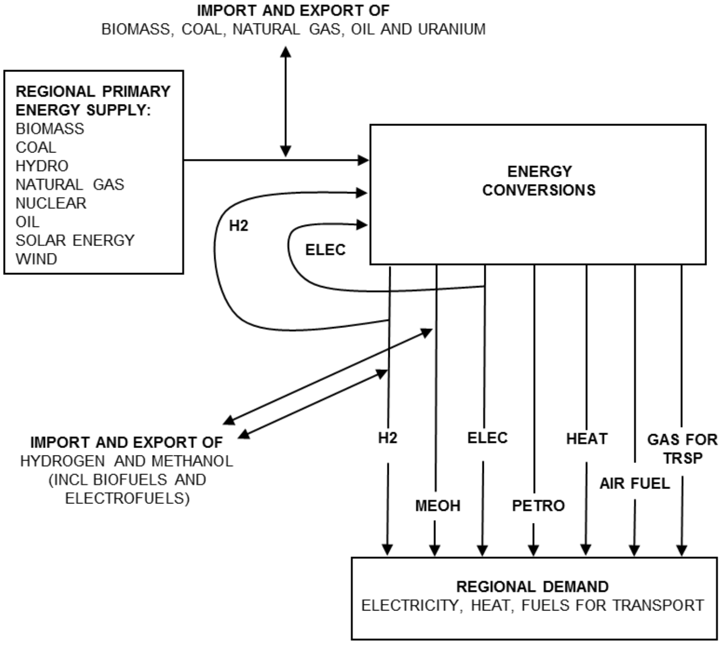

Figure 2: The basic flow chart of primary energy supply and fuel choices in the regionalized energy systems model, GET-R 6.4. Acronyms used are hydrogen (H2), methanol as a proxy for liquid alternative fuels including biofuels and electrofuels (MEOH), electricity (ELEC), low and high temperature heat 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).

This model allows for carbon capture and storage (CCS) technologies when applied to fossil fuels and biomass for heat, electricity and hydrogen production. Energy resources can be traded between regions (with the exception of electricity) with associated costs. Regional solutions were aggregated to give global results. The model is run for the period 1990–2140 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.

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 a stabilized atmospheric CO_2 concentration of 400 ppm, developed by Wigley (2015). All energy sectors are assumed to follow the same CO_2 reduction curve, i.e. the shipping sector have to phase out fossil fuels in the same pace as all other sectors.

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 systems 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 splitting 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 new electrofuels production facilities. Possible pathways for the electrofuel production, in the model GET-R 6.4, can be seen in Figure 3.

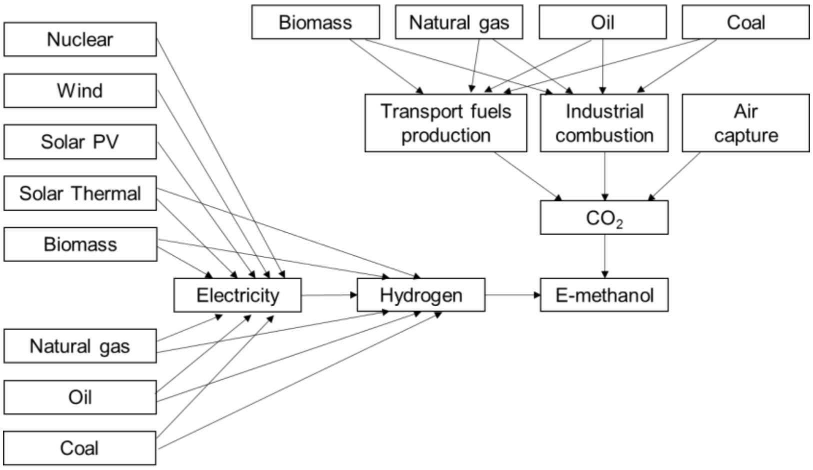

Figure 3: Possible pathways for the production of electrofuels, represented by e-methanol, in GET-R 6.4.

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). 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 (IIASA/WEC, 2015). 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, as well as the demand for freight, is proportional to GDP_{PPP} growth and the regional demand further depend on regional population growth. Transportation scenarios are developed separately for passenger and freight transportation and disaggregated into trains, cars, buses, trucks, container ships, ocean ships, coastal ships and aviation. Full details are given in Azar et al (2003), Grahn et al (2009b; 2013b) and Taljegård (2014).

2.4 PRIMARY ENERGY SOURCES AND EMISSION FACTORS

We have chosen to follow the regional biomass supply potentials described in Johansson et al. (1993) 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 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 the authors find extremely difficult to produce in a sustainable way (Heyne et al, 2015).

For global supply potential of oil and natural gas (NG), we have chosen 12,000 and 10,000 EJ, respectively (WEA, 2000; BP, 2009), and assumed a regional distribution following Johansson et al. (1993). For coal we have chosen a global supply potential of approximately 260,000 EJ following the total resource estimates in Rogner et al (2012). 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 ambitious CO_2 reduction targets). 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 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 (Swedish EPA, 2014). When using LNG in the shipping sector a 3% methane slip is assumed (unburned methane molecules in the exhaust gases). Future use of nuclear, hydro, wind, biomass, and solar energy is assumed to contribute with negligible CO_2 emissions.

2.5 FUEL AND PROPULSION TECHNOLOGY OPTIONS AS WELL AS 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 technologies 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, the following assumptions are made. The model does not distinguish between gasoline, diesel, jet-fuel and bunker fuels, which are lumped together as petroleum (Petro). Nine fuel options: Petro, compressed natural gas (NG), liquefied natural gas (LNG), synthetic fuels (coal to liquid, CTL; gas to liquid, GTL; biomass to liquid, BTL), electricity, hydrogen (H2), and electrofuels (E-methanol) 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 FCVs 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 (Santini and Wang, 2008). 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. Grahn et al, 2009b, 2013b; Taljegård, 2014).

For the shipping sector, engine concepts considered are combustion engines (IC) and fuel cells (FC) combined with Petro, LNG, CTL, GTL, BTL, H2 and E-methanol. Hydrogen is, in the literature, seen as a possible future fuel option for the shipping sector, whereas it among the shipping actors currently is treated with some suspiciousness mainly due to that hydrogen, which has a low volumetric density, requires large storage space, also when stored as liquid, and thereby reduce the amount of goods that can be transported by the ship. It is currently very uncertain if hydrogen will be large scale available as a fuel option in the shipping sector.

A recent study has reviewed scientific papers and 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 (Brynolf et al, 2016b). From that study, the results on e-methanol production costs (electrolysis, synthesis reactor etc), for 2030, have been used as assumptions in the GET model for the electrofuel production, where key data for the electrofuel production is presented in Table 1.

Table 1: Key data chosen for the production of electrofuels in the GET-R 6.4 model.

	Investment cost ($\$/kW_{fuel}$)	Conversion efficiency (%)	Capacity factor (%)	Life time (yr)
Electrolyser (electricity to H2)*	700	90	70	25
Synthesis reactor, 50 MW (H2 to e-methanol)	500	80	80	25

*) Note that hydrogen production from an electrolyser is only one option for hydrogen production in the GET-model. For the production of e-methanol the model can choose any kind of H2 production to form electrofuels.

Total production costs, for all fuel options, including annualized investment cost (assuming 5% interest rate), O&M cost, primary energy extraction cost, and distribution cost to fuel stations, are summarized in Table 2.

Table 2: Production costs for 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 (between 12-31 $\$/GJ_{H2}$) 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 from both biogenic and fossil energy conversion 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, unless converted into hydrogen or electrofuels. 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 (IPCC, 2005), a maximum rate of increase of CCS of 100 MtC/year and negligible leakage of stored CO_2. CO_2 storage underground has been questioned and many test facilities have closed down their activities. In this study it is therefore assumed that CCS will not be a large scale available technology.

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. In this study it is assumed that the contribution of nuclear power does not exceed current levels in absolute terms.

3 RESULTS

The model is first run under a business as usual scenario without any CO_2 reduction constraints. Thereafter, it is run with two CO_2 reduction scenarios, both meeting an atmospheric CO_2 concentration level stabilized at 400 ppm in the end of this century. The difference between the two CO_2 reduction scenarios is that hydrogen and fuel cells are assumed available as fuel option and propulsion technology for the shipping sector in one scenaio and not available in the other scenario. Key assumptions for the three scenarios are presented in Table 3. For a list of all parameter values used in the model, see Grahn et al (2013b) and Taljegård (2014).

Table 3: Key assumptions made in the three included scenarios using the GET-R 6.4 model version.

	Business as usual scenario	CO_2 reduction scenario 1	CO_2 reduction scenario 2
H2 and FC assumed large scale available for the shipping sector	Yes	Yes	No
Carbon capture and storage technology assumed available on large-scale*	No	No	No
CO_2 concentration target (400 ppm)	No	Yes	Yes

*) It can be noted that electrofuels do not enter the scenarios, in this model version, if CCS is assumed available on large scale.

Results for the three scenarios are presented in Figures 4-6.

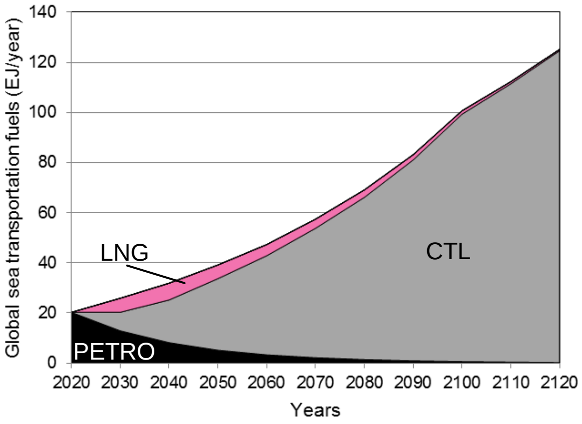

Figure 4: Cost-effective fuel choices for the shipping sector in the business as usual scenario without any CO_2 reduction constraints. Acronyms used are liquefied natural gas (LNG), coal to liquid (CTL), oil-based fuels (Petro).

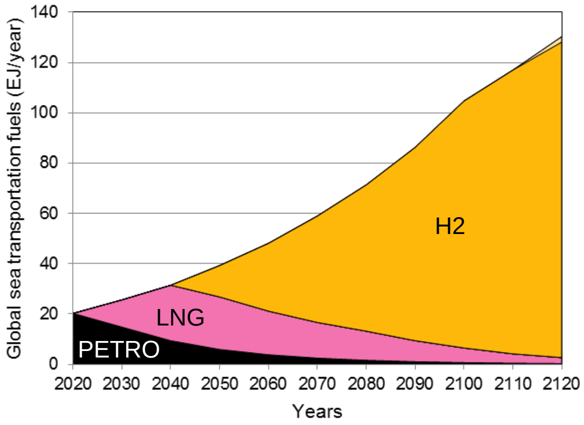

Figure 5: Cost-effective fuel choices for the shipping sector in a policy scenario meeting a stabilized CO_2 concentration of 400 ppm, assuming that hydrogen and fuel cells are large scale available for the shipping sector. Acronyms used are liquefied natural gas (LNG), hydrogen (H2), oil-based fuels (Petro).

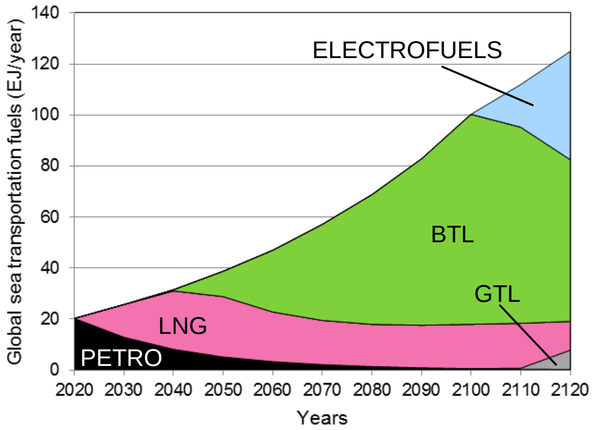

Figure 6: Cost-effective fuel choices for the shipping sector in a policy scenario meeting a stabilized CO_2 concentration of 400 ppm, assuming that hydrogen and fuel cells will not become available on large scale for the shipping sector. Acronyms used are liquefied natural gas (LNG), biomass to liquid (BTL), gas to liquid (GTL), oil-based fuels (Petro).

In the case of no CO_2 reduction policies it is indicated that the least cost solution for the shipping sector is to remain using fossil fuels. When oil-based fuels are phased out they are substituted by coal-based fuels, e.g. coal-methanol and a small share of LNG, see Figure 4. As can be seen when comparing Figure 5 and 6 the cost-effective fuel choices differ significantly between these two scenarios. Figure 5 shows that in the case of a CO_2 reduction target, LNG, and later in the century hydrogen, tend to dominate as fuels in the shipping sector if H2 and FC are assumed available. However if these options are not assumed available on large scale in the shipping sector the dominating cost-effective fuel choice is biofuels, e.g. biomethanol, combined with LNG in the initial part of the century and electrofuels in the latter part of the century, see Figure 6.

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 other alternative marine fuels in a future carbon constrained world. Main findings from the model runs can be summarized as:

Cost-competitiveness

- It is not likely that electrofuels in the near term can compete with other fuel options in the shipping sector.
- Cost-competitiveness depends on, e.g. the availability of advanced CO_2 reduction technologies such as CCS, and costs for the competing technologies. With assumptions chosen in this study, electrofuel production seems to be a too costly solution for the shipping sector.
- 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 solutions and hydrogen used in fuel cells.
- If scaling up the production of electrofuels the demand for renewable electricity may face major expansion challenges.

Climate perspective

- The development for CCS, which seem to be a more effective way to lower the atmospheric CO_2 concentration, will impact the prerequisites for electrofuels.
- To be determined as a sustainable solution, a large scale use of electrofuels can only exist in an energy system with abundant renewable electricity.

It should be stressed that the topic of electrofuels is relatively new and steps of the production chain are 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 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 different types of molecules, chosen to be able to be blended with e.g. biofuels. Molecules that can be blended in conventional fuel options are generally attractive from both the automotive industry and the actors building the fuel infrastructure.
- 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 challenges connected to local emissions (NOx, soot etc), which would be lower if choosing 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 (Wismans et al, 2016).
- All fuels that can be blended in conventional gasoline, diesel and bunker oil 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 and sensitivity analyses will be performed. One important aspect that has not been taken into account so far is the possibility that there might be times where the supply of electricity is larger than the demand, which may lead to low electricity prices. 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. Brynolf et al, 2016b). 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, further, 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. In future work the model will be developed with daily time slices to be able to capture these features of an eventual grid balancing income as well as the effect from having possible excess electricity available at a low electricity price.

Another aspect is the location issue. 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. This is another feature that would be interesting to assess in future work.

In this study hydrogen is found more cost-effective than e-methanol in the shipping sector at chosen assumptions and pre-requisites. Since actors have indicated that hydrogen has disadvantages that can be connected to reduced profit, e.g. since hydrogen storage in ocean going ships need space that otherwise could have been used for transporting goods it would be interesting, in future work, to analyze the effect of including a possible cost penalty for fuel options that will reduce profit.

6 ACKNOWLEDGEMENTS

We thank the fuel team at Chalmers University of Technology Selma Brynolf, Maria Taljegård, and Karin Andersson for their feedback on early versions of the manuscript as well as for model developments. Financial support from the Swedish Research Council for Environment, Agricultural and Spatial Planning, Formas and Nordic Energy Research through the Nordic flagship project Shift (Sustainable Horizons for Transport) is gratefully acknowledged. In addition, this publication is partly the result of a project within the Renewable Fuels and Systems Programme (Samverkansprogrammet Förnybara drivmedel och system), funded by the Swedish Energy Agency and the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre contributes, through knowledge based on science, to the development of environmentally, economically and socially sustainable and renewable transportation fuels, as part of a future sustainable society (see www.f3centre.se/samverkansprogram).

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