

ELECTROFUELS – A POSSIBILITY FOR SHIPPING IN A LOW CARBON FUTURE?

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ABSTRACT

Continued growth of carbon dioxide (CO₂) emissions from the shipping industry until 2050 and beyond is expected although of the recent decline. The global share of anthropogenic CO₂ emissions from ships is only about 2 percent, but there is a risk that this share will increase substantially if no action is taken. What are the possibilities for decarbonisation of the shipping industry, then? Some of the measures discussed are energy efficiency, use of biofuels and use of hydrogen. In this paper a fourth option is scrutinised – use of electrofuels. Electrofuels is an umbrella term for carbon-based fuels, e.g. methane or methanol, which are produced using electricity as the primary source of energy. The carbon in the fuel comes from CO₂ which can be captured from various industrial processes such as exhaust gases, the sea or the air. The production of electrofuels is still in its infancy, and many challenges need to be overcome before electrofuels are brought to market on a large scale. First, this paper gives an overview of the current status of electrofuels regarding technologies, efficiencies and costs. Second, as electrofuels production requires significant amounts of CO₂ and electricity, the feasibility to produce enough electrofuels to supply all ships bunkering in Sweden, with regionally produced electricity and regionally emitted CO₂, and the amount of CO₂ that is required to supply all ships globally is evaluated in two case studies assessing supply potential.

Keywords: CO₂ emissions, future marine fuels, Sweden, CO₂ sources, renewable energy, cost efficient

1 INTRODUCTION

Shipping is currently an important part of the global economy and is an essential part of global transportation, carrying approximately 80% of global merchandise trade by volume (UNCTAD, 2013). It is also an efficient mode of transport and consumes less fuel than any other mode per a given mass and distance (Buhaug et al., 2009). Continued growth of carbon dioxide (CO₂) emissions from the shipping industry until 2050 and beyond is expected regardless of the recent decline. Even if the global share of anthropogenic CO₂ emissions from shipping is only about 2 percent (Smith et al., 2014), there is a risk that this share will increase substantially if no action is taken. In 2007, shipping was responsible for the release of approximately 1.0 Gt of CO₂, but these emissions are expected to be in the range of 0.8-3.7 Gt through 2050 in various future development scenarios, indicating a potential increase of up to 270% compared to 2007 (Buhaug et al., 2009; Eyring et al., 2005; ICCT, 2011; Smith et al., 2014; Vergara et al., 2012). This increase stands in contrast to the shipping industry commitment of an equal sharing of the burden of limiting the temperature to a 2°C global increase, which would require the shipping industry to reduce its emissions significantly before 2050 (approximately 80% of 1990 levels) (Anderson and Bows, 2012). Additionally, the goal of the European Union is a 40-50% reduction of greenhouse gases by 2050 compared to 2005 levels from the shipping sector (European Commission, 2011). One important challenge for the shipping sector is to find a fuel that is based on renewable energy, and that do not suffer from supply constraints or negative environmental and social impacts.

What are the possibilities for decarbonisation of the shipping industry, then? The measures mainly discussed in literature are energy efficiency, biofuels, nuclear power and hydrogen (Brynolf et al., 2014; Buhaug et al., 2009; Eide et al., 2012; Vergara et al., 2012). However, energy efficiency is not expected to be enough to reduce the CO₂ emissions (Bazari and Longva, 2011; Smith et al., 2014), and there is a competition for biomass from other sectors potentially limiting the available biomass for the shipping sector (Berndes and Hansson, 2007; Grahn et al., 2007; Taljegard et al., 2014). The use of hydrogen is potentially free from emissions (depending on the production process), but might be unpractical in shipping transportation, e.g. due to the low volumetric energy density, safety issues and the need for a new infrastructure in the distribution chain. Nuclear propulsion are phasing difficulties with, for example, public acceptance. Another possible future marine fuel, so far not much discussed in the literature, is electrofuels or power-to-fuels¹ (see Figure 1). Electrofuels can be seen as an umbrella term for carbon-

¹ Electrofuels/power-to-fuels are sometimes also called for example sun-fuels, power-to-gas, synthetic natural gas (SNG), e-gas, e-fuel, synthetic fuels from carbon dioxide and water and carbon recycling fuels.

based fuels that are produced using electricity as the primary source of energy (Nikoleris and Nilsson, 2013). The possible marine fuels are represented by the routes including electrofuel production in Figure 1.

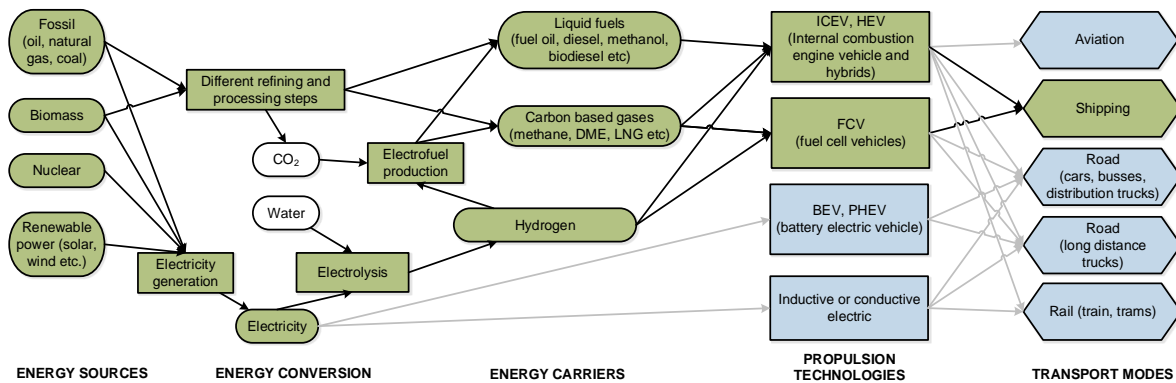


Figure 1: Simplified schematics of primary energy sources, energy conversion technologies and energy carriers for different transport modes with emphasis on potential routes for shipping (indicated by green boxes and black lines). Acronyms used are: DME=dimethyl ether, LNG=Liquefied natural gas, ICEV= internal combustion engines, HEV=hybrid electric propulsion, FCV=fuel cells, BEV=battery electric propulsion, PHEV=plug-in hybrid electric propulsion.

1.1 DESCRIPTION OF THE PRODUCTION PROCESS OF ELECTROFUELS

Electrofuels is produced by feeding hydrogen and CO₂ into a synthesis reactor to form different types of energy carriers, see Figure 2. The most common types of energy carriers discussed are methane and methanol. Small molecules, like methanol and methane, seems preferable since more complex molecules, like ethanol, require additional process steps, which lead to efficiency losses (Mohseni, 2012). High purity oxygen and heat are also produced during the production steps from electricity to fuel. High temperature and low temperature heat is produced in electrolysis (see below) and in the fuel synthesis reactor, respectively. The heat can, for example, be feed into a district heating system, and the oxygen can be used in industrial processes or at hospitals.

The most common way to produce hydrogen today is through steam reforming by using natural gas. A less common way is to use a more energy-intensive hydrogen production methods, like the electrolysis of water. In order to produce large quantities of hydrogen, substantial amount of energy is needed, which preferable comes from renewable energy sources in order to produce a renewable fuel. There are three main types of electrolysis: alkaline, proton exchange membrane (PEM) and solid oxide. Current electrolyzers are usually designed to run at steady state with a constant load. However, in order for electrofuels to be power balancing, i.e. be able to follow the non-dispatchable renewable power sources, the production process needs to be flexible, for example short ramp times, and low start-up cost for the electrolyser.

The CO₂ can come from many sources including various industrial processes giving rise to excess CO₂, e.g. biofuel production facilities, natural gas processing, flue gases from fossil and biomass combustion plants, steel plants, oil refineries and other chemical plants, geothermal activity, air and seawater. In biofuel production, e.g. by fermentation of sugar into ethanol, anaerobic digestion of household waste into biogas or gasification of biomass into methane, considerable amounts of CO₂ are produced as a by-product (see section 3 for details). The off-gases from biofuel plants, as well as from ammonia plants, have a very high CO₂ concentrations (some up to 100%). A study by Mohseni (2012) claims that methane production from digestion or gasification of biomass can increase with 44-136% if implementing a synthesis reactor, so that CO₂ released in the process is allowed to react with added hydrogen. In a study by Reiter and Lindorfer (2015), the biggest source of CO₂ emissions in Austria was identified to come from iron and steel industry (about 12 Mton CO₂/yr), cement industry (about 3 Mton CO₂/yr), and power and heat (about 7 Mton CO₂/yr). But to produce a climate neutral fuel, the source of CO₂ has to be a non-fossil source, and in Austria, only a small part (about 0.1 Mton CO₂/yr) of the CO₂ emissions was from biogas upgrading and bioethanol production. On the other hand, a German feasibility study by

Trost et al. (2012) identify a large potential for biogenic CO₂ sources, including such sources as biogas upgrading, bioethanol plants and sewage treatment plants in Germany.

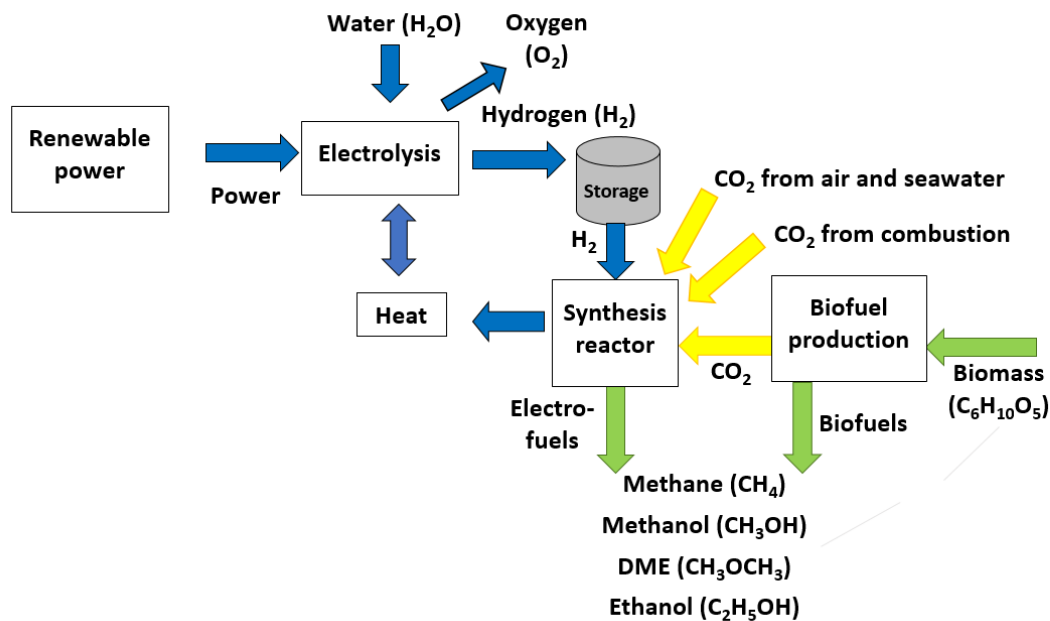


Figure 2: The different process steps in the production of electrofuels.

Producing electrofuels, in relation to conventional biofuel production processes, can increase the use of carbon atoms in the biomass. However, production of electrofuels is still in its infancy, and many challenges need to be overcome before these products are brought to market on a large scale. Several demonstration scale facilities of power-to-gas, or electrofuels, have been developed in Europe during the last decade (Gahleitner, 2013). Most of the projects only consider hydrogen production, but some projects also include capturing of CO₂ and the production of different hydrocarbons, mainly methane. One example is Carbon Recycling International (CRI) at Island, who are producing methanol by using geothermal energy and CO₂ from the same source. A commercial plant has been operated by CRI since the end of 2011 with a capacity to produce 5 million litres of methanol per year (Carbon Recycling International, 2014). Another example is the company ETOGAS, on behalf of Audi AG, that has invested in a 6 MW plant in Germany, which uses renewable electricity from wind power and CO₂ from a nearby biogas processing plant to produce e-methane (ETOGAS). The recent interest in electrofuels, is mainly supported by concerns for finding long-term electricity storage options, but also concerns for finding a climate neutral fuel for the transport sector.

1.2 AIM AND SCOPE

The main aim with this paper is to assess under what circumstances electrofuels may compete with other climate neutral marine fuels. Also included is an overview of current status of electrofuels covering technologies, efficiencies and costs. Since production of electrofuels demand large amounts of electricity and CO₂, it is of interest to elaborate on the amount needed. Therefore, two case studies are carried out, focussing on the supply potential to produce enough electrofuels for (1) all ships bunkering in Sweden with nationally produced electricity and nationally emitted CO₂, and (2) the amount of CO₂ and electricity needed to supply all ships globally. The benefits and drawbacks of electrofuels for shipping from a regional and global perspective are discussed.

2 EFFICIENCY AND COST

Overview of cost estimates and efficiency for different steps in the electrofuel production process and CO₂ capture is presented in Section 2.1-2.3. In Section 2.4, the total production cost is calculated, and in Section 2.5, a comparison is made with hydrogen and methanol produced from natural gas. Methanol is selected as the electrofuel for investigation in this study and will be called e-methanol.

2.1 ELECTROLYSER

There are three main types of electrolysers: alkaline, proton exchange membrane (PEM) and solid oxide. Commercial alkaline electrolyser cells (AECs) have a conversion efficiency of 60-70%. High-temperature solid oxide electrolyser cells (SOECs), which may enter the market in 2020, are expected to reach a conversion efficiency of 80-90%. Due to the high temperatures, the SOECs can also be utilised for co-electrolysis, where the reaction of CO₂ to CO and H₂O to H₂ take place simultaneously, leading to the production of syngas and a higher efficiency. PEM electrolysers have similar conversion efficiency as AEC, but uses more expensive materials. PEM might also have better basic conditions than both AEC and SOEC for short ramp times and possibility for low part load operation due to its impermeability for gases and may thereby be able to follow the non-dispatchable renewable power sources (Mergel et al., 2013).

The electrolyser industry meets today a small, but steadily growing, market. In the literature, assumptions on current prices for complete AEC and PEM systems are in the range 1000-1300 €/kW_{el} and 2000-6000 €/kW_{el}, respectively (Bertuccioli et al., 2014; Grond et al., 2013). The electrolysis stack accounts generally for 50–60% of that costs (Lehner et al., 2014). PEM requires noble catalysts (Pt, Ir, Ru) and uses titanium-based bipolar plates, which makes PEM currently more expensive (about two times) than AEC (Mergel et al., 2013). The reduction potential for PEM are estimated to be in the range of 300-1200 €/kW_{el}, mainly due to economy of scale and improvement of materials (Bertuccioli et al., 2014). Main features for AEC and PEM are summarised in Table 1.

Table 1: Comparison between different electrolyser technologies found in literature (Bertuccioli et al., 2014; Grond et al., 2013; Vandewalle et al., 2014).

	Alkaline		PEM	
	Today	Potential	Today	Potential
System efficiency [%, LHV]	<67%	<70%	<67%	<74%
Minimum part load [% of capacity]	20-40%	10-20%	5-10%	0-5%
Stack lifetime [h]	75 000	95 000	60 000	80 000
Investment cost [€/kW _{el}]	~1000	~400-800	~2000	~300-1200

2.2 CAPTURING OF CO₂

CO₂ can be captured from various sources as described in section 1.2. The cost and capturing efficiency depends on the CO₂ sources and the capture technology (see Table 2). For a bioethanol plant, the exhaust stream has a high concentration of CO₂, and no extra purification step or additional energy is needed in the capture process. This leads to a low capture cost in the range 5-9 €/tCO₂ (Laude et al., 2011). Biogas produced from, for example fermentation of household waste, contains methane, CO₂ (40%) and some trace components. To upgrade the biogas to fuel quality, a cleaning step to remove the CO₂ is needed anyway, and the capture cost of the stream of CO₂ is in the same magnitude as from a bioethanol plant. For other industries and energy technologies such as steel and iron, ammonia, refinery, cement and fossil or biomass combustion plants, where an extra purification step is needed, the capture cost has been estimated to be in the range 20-65 €/tCO₂ depending on the sources, concentration and capture method (see Table 2) (Damen et al., 2007; IEA, 2013; Kuramochi et al., 2012).

The CO₂ concentration in air is approximately 400 ppm and it would require 2-4 times more energy (5.4-9.0 MJ/kg CO₂) to extract the CO₂ from air compared to flue gases. Strong bases such as NaOH, KOH and Ca(OH)₂ can effectively scrub CO₂ out of the atmosphere (Nikoleris and Nilsson, 2013), but the regeneration of the bases is an energy intensive process, and other alternative materials that might be more energy efficient are under development. Different techniques and materials have been proposed and many designs are technically feasible. However, all are still in a very early development phase, and more research and pilot plants are needed to optimise the technology. The cost estimations are uncertain, but fall in the range of 150-1250 €/tCO₂, and are thereby far from competitive compared to other CO₂ sources and separation technologies (Goepfert et al., 2012).

If the captured CO₂ has to be transported to, e.g. a production facility of electrofuels, there will be an additional cost for compression and transportation. The transportation could be done through trucks, ships or pipelines. The transport of compressed CO₂ in pipelines cost approximately 1-10 €/tCO₂ (Damen et al., 2007).

Table 2: Capture cost and efficiency for different CO₂ sources found in literature (Damen et al., 2007; IEA, 2013; Kuramochi et al., 2012).

	Capture efficiency (%)	Capture cost (€/tCO ₂)
Coal power plant	90%	15-50
Natural gas power plant	90%	15-50
Bioethanol plant	100%	5-9
Biogas upgrading	100%	5-9
Pulp and paper industry		21-47
Steel and iron industry	75%	40-65
Ammonia industry	85%	20-55
Cement industry	85%	25-65
Refinery industry	75%	30-60
Ambient air		150-1250

2.3 FUEL SYNTHESIS

Depending on what type of energy carrier that are desirable there are different fuel synthesis processes, for example methane synthesis, methanol synthesis, Fischer-Tropsch synthesis and methanol-to-gasoline. Methane synthesis is usually called methanation and uses the Sabatier reaction ($\text{CO}_{(g)} + 3\text{H}_{2(g)} \leftrightarrow \text{CH}_{4(g)} + \text{H}_2\text{O}_{(g)}$) in combination with the reversed water gas shift reaction ($\text{CO}_{2(g)} + 4\text{H}_{2(g)} \leftrightarrow \text{CO}_{(g)} + 2\text{H}_2\text{O}_{(g)}$). It is possible to convert more than 99.5% of the syngas (mixture of carbon dioxide and hydrogen) to methane (Hannula, 2015; Mohseni, 2012). The synthesis process is exothermic so the highest efficiency is achieved at low temperatures. The process can reach efficiencies of 70-85% depending on temperature and pressure (Grond et al., 2013; Mohseni, 2012; Sterner, 2009). The investment costs of methanation is around 135-275 €/kW_{el} for plants larger than 10 MW_{el}. For smaller plants (<10MW), the cost for chemical methanation will result in 160-280 €/kW_{el} due to standardization of smaller plants (Grond et al., 2013; Sterner, 2009). Methanol synthesis is based on the following exothermic reactions $\text{CO}_2 + 3\text{H}_2 \leftrightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$ and $\text{CO} + 2\text{H}_{2(g)} \leftrightarrow \text{CH}_3\text{OH}$. Hannula (2015) estimated the cost for methanol synthesis to about 200 €/kW_{fuel}.

2.4 THE TOTAL PRODUCTION COST AND EFFICIENCY

Table 3 summarizes the main assumptions for the cost calculations of e-methanol in this study. The electricity to e-fuel efficiency is between 50–70% according to literature (Vandewalle et al., 2014; Varone and Ferrari, 2015). In the base case of this study, we assume an efficiency of 70% for the electrolysis and 75% for the methanol synthesis, leading to an electricity-to-methanol efficiency of 53%. An economical life time of 25 years and an interest rate of 5% is assumed. The investment costs of a 5–10 MW_{el} demonstration plant amounts to 2,000 €/kW_{el}, today and are assumed to be reduce to 1,000 €/kW_{el} for greater plants sizes. Vandewalle et al. (2014) further assumes that the total investment cost in the future might go down even lower to 750-800 €/kW_{el}. However, Sterner et al. estimated the costs for a complete system, including electrolyzer, methanation, compression and periphery, as being in the range of 2000/kW_{el} (Sterner, 2009). In order to go from kW_{el} to kW_{fuel}, divide by the efficiency from electricity to fuel. Hannula (2015) estimated the investment cost for a 200MW_{fuel} plant to about 1800€/kW_{fuel} and 1900€/kW_{fuel} for an e-methane and e-methanol, respectively. We assume an investment cost of 1900€/kW_{fuel}. The variable operation and maintenance cost are 2-7% of the capital cost and set to 4% in this study. In this dimensioning analysis, CO₂ is assumed to be available at 10 €/ton CO₂, which includes transportation from the power plants to the electrofuel plant and local buffering. We use 240 €/MWh_{heat} as a selling price for low and high temperature heat to the district heating system (Benjaminsson et al., 2013; Vandewalle et al., 2014). The water needed to produce e-methanol is approximately 0.32 m³/MWh and the cost of water is assumed at 0.7 €/m³.

For the electricity price, we have used spot prices from the Nordic electricity market, Nord Pool, for 2013 and the Swedish price area 3, which is middle of Sweden, including Gothenburg and Stockholm. But the difference in electricity prices between price areas in Sweden were only about 10-20 cent/MWh in 2013. The average electricity price is then 56.12 €/MWh_{el}, including a net tariff, energy tax and electricity certificated of 21, 0.5 and 3.4 €/MWh_{el}, respectively (Statistics Sweden, 2015; Swedish Tax Agency, 2015). In Figure 3, average electricity prices if only running the electrolyser parts of the year is used (meaning that price peaks is avoided and excluded from the electricity price).

Table 3: Assumed parameters for the cost calculations of e-methanol.

Interest rate	5%
Economic lifetime	25 years
Investment cost	1900 €/kW _{fuel}
Electricity price (including tax and net tariff)	47-56 €/MWh _{el}
CO ₂ capture	10 €/tCO ₂
O&M	4%
Water	0.7 €/m ³
Distribution of methanol	1.6 €/MWh
Heat (120°C)	0.04 €/kW _{heat}

E-methanol production cost evolves between 140 and 340 €/MWh_{LHV} depending on the percent of the year in operation (capacity factor), and this cost mostly depend on the cost of electricity and cost of electrolysis stacks and pressure vessels. As seen in Figure 3, it seems to be most profitable to run the process at least 60-90% of the year, assuming today's investment costs, efficiency and electricity prices, which will result in an e-methanol price of 140-150 €/MWh_{HHV}. In the literature, an e-fuel cost in the range 120-241 €/MWh_{HHV} is found, and the main difference is due to different assumptions about investment cost, interest rate and revenues from heat. If instead assuming that the CO₂ is captured from an industry, and then a higher cost for capturing CO₂, at 30 €/tCO₂ (i.e., increase by a factor 3), the e-methanol cost will increase with 5.2 €/MWh_{HHV}, which is still small compared to the cost for electricity. A change of the investment cost or the efficiency of the process will, however, have an impact on the cost of e-methanol (see Figure 4). In this scenario, selling excess heat is not included as a revenue. If including selling heat to the district heating system, the cost of e-methanol will decrease with 13 €/MWh_{LHV}.

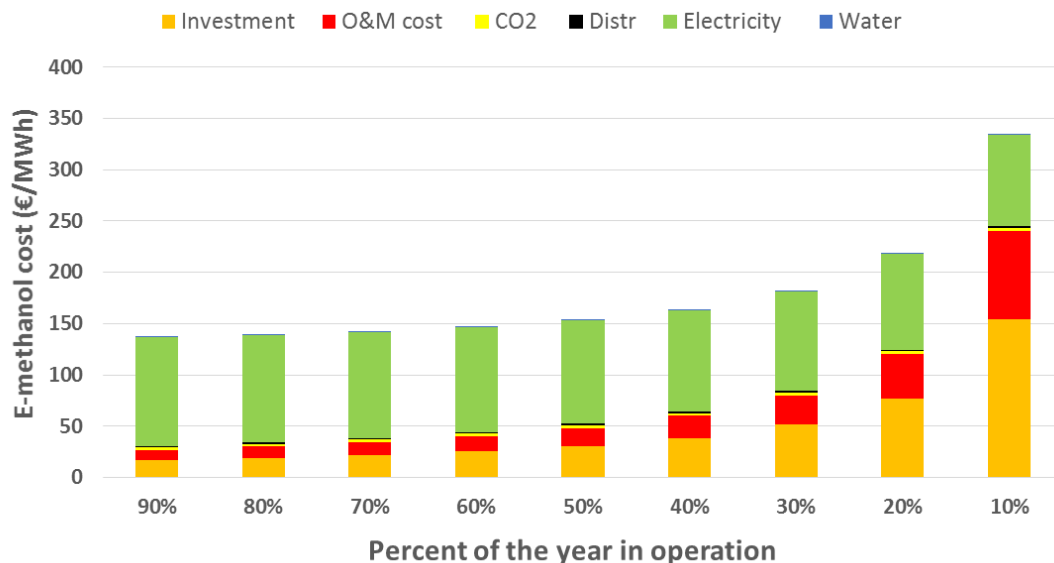


Figure 3: The production cost of e-methanol, assuming production cost and efficiency as of today, for different capacity factors without the potential income for selling heat.

2.5 COST OF ALTERNATIVE FUELS

The cost of producing e-methanol are high when comparing to the fuels used in shipping today. The price of heavy fuel oil (IFO380) and marine gas oil (DMA, DMX) in Rotterdam in September 2015 was about 225 and 440 \$/tonne, respectively (Bunkerworld, 2015). This corresponds to about 17 and 32 €/MWh for heavy fuel oil and marine gas oil, respectively. E-methanol is one of the most costly fuels, as seen in Table 4. However, potentially in the same range as some of the biofuels.

Table 4: Historical and expected price ranges (€/MWh) for some potential marine fuels (adapted from Bengtsson et al. (2014) and Brynolf et al. (2014)).

Heavy fuel oil	17-43
Marine gas oil	32-68
Rapeseed methyl ester	90-140
Fischer-Tropsch biodiesel ^a	50-97
Liquefied natural gas	11-43
Liquefied biogas	40-180
Methanol (from natural gas)	18-54
E-methanol ^{a,b}	80-140
Hydrogen gas (from electrolysis) ^{a,b}	75-90

^aThe figure represent expected production cost range and not price

^bThe low range is for a future (optimistic) scenario of investment cost and electricity-to-methanol efficiency (see 2.4) and high range represents estimates from the base case scenario assuming an investment cost and efficiency of the production process as of today. In both calculations, a capacity factor of 70% is assumed.

Compared to gaseous fuels, methanol can use existing infrastructure with only small modifications. Figure 4 shows a comparison between the cost of e-methanol and hydrogen, two potentially carbon neutral fuels, when also including the cost for engines, fuel cells and storage on a vessel. Four different scenarios are presented in Figure 4 and the assumptions made in these scenarios are presented in Table 5. In our base case, assuming the cost and efficiency of the e-methanol production process as of today, hydrogen is more cost-competitive than e-methanol if the ship is running more than 100 days per year (Figure 4A). If instead assuming an investment costs and efficiency for the production process according to future estimations, instead around 150 days of operation or less is needed to make e-methanol profitable compared to hydrogen. In Figure 4B, when increasing the process efficiency to 64% per year and halving the electricity cost (from 56 €/MWh to 28 €/MWh), which can be seen as extremely low electricity prices for a capacity factor of 70%, e-methanol is competitive with hydrogen up to 170 days of operation per year. E-methanol might also be competitive with hydrogen if significantly increasing the cost for fuel cell from 3000 to 4500 €/kW (Figure 4C and 4D). In the literature, a cost range from 1500 to 6700 \$/kW has been found for high temperature fuel cells. A parameter not varied in Figure 4, but with an impact on the relative competitiveness of e-methanol versus hydrogen, is the depreciation time, here set to 30 years. With a depreciation time of 15 years instead, e-methanol is associated with lower costs up to 250 days of operation per year also in the base case scenario.

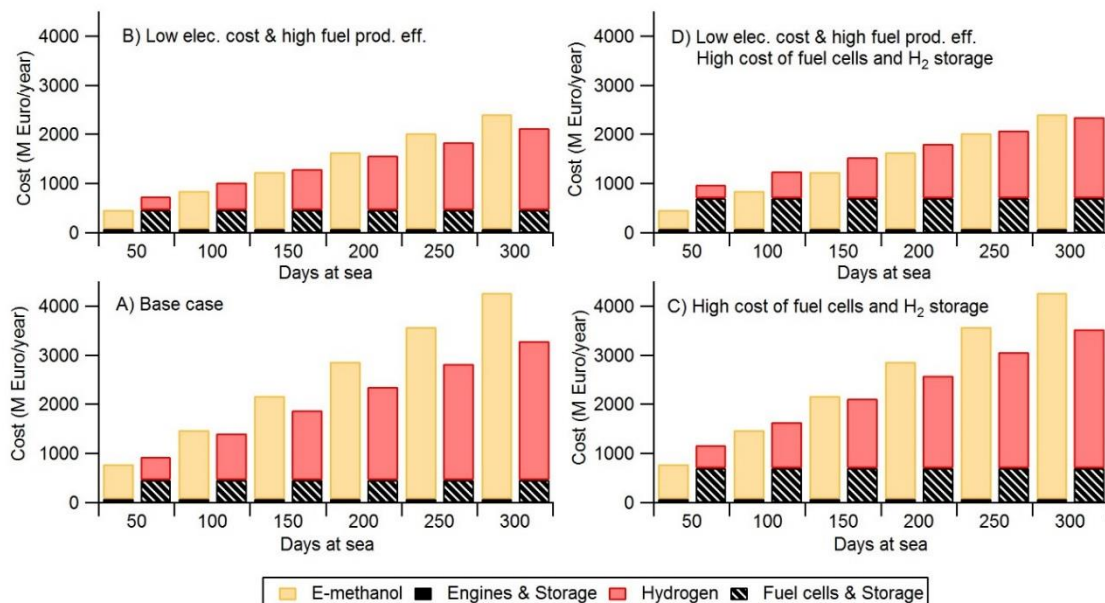


Figure 4: An assessment of the costs associated with using e-methanol and hydrogen on a short sea vessel with 2400kW engine power and a tank capacity of 3500 GJ. A) In the base case, the cost for e-methanol is from Figure 3 with a capacity factor of 70%. B) Halve of the electricity price of that in A (28 €/MWh instead of 56 €/MWh) and a higher electricity-to-methanol efficiency of 64% instead of 53%. C) Fuel cell cost of 4500 €/kW and hydrogen storage cost of 450 €/GJ. D) Combining B and C assumptions.

Table 5: Assumed parameters for comparing the cost of using e-methanol and hydrogen on board a short sea vessel based on data from Taljegard et al. (2014).

	A	B	C	D
Engine power (kW)	2400	2400	2400	2400
Tank capacity	3500 GJ	3500 GJ	3500 GJ	3500 GJ
Lifetime	30 years	30 years	30 years	30 years
Interest rate	5%	5%	5%	5%
Methanol engines cost (€/kW)	540	540	540	540
Hydrogen fuel cell cost (€/kW)	3000	3000	4500	4500
Methanol storage cost (€/GJ)	30	30	30	30
Hydrogen storage cost (€/GJ)	225	225	450	450
Investment cost for hydrogen liquefaction (€/kW) ^a	880	880	880	880
Distribution of hydrogen (€/MWh)	12	12	12	12
Methanol engine efficiency	40%	40%	40%	40%
Hydrogen fuel cell efficiency	45%	45%	45%	45%

^aFrom Schwartz (2011).

3 CASE STUDIES FOR THE SUPPLY POTENTIAL OF ELECTROFUELS FOR SHIPPING

In this section the prerequisites for the production of electrofuels needed to supply the domestic and international shipping in Sweden, as well as, globally are assessed from a CO₂ and electricity perspective. Also in these case studies, e-methanol is selected as an example of an electrofuel.

3.1 SWEDEN

The total Swedish use of bunker fuels in 2014 was about 22 TWh (or about 1.9 million tonnes) of which 96% was used for international transport (Swedish Energy Agency, 2015). To supply all domestic and international shipping currently bunkering in Sweden with e-methanol, it requires about 6 Mton of CO₂ (assuming a conversion factor from CO₂ to e-methanol of 0.26 tCO₂/MWh_{CH₃OH}) and 42 TWh of electricity (see Table 6).

The total current availability of CO₂ in Sweden is based on a mapping of major sources of CO₂ emissions in Sweden and associated assessment of the technical possibility of carbon capture. In Sweden, about 50 Mton of CO₂ is emitted per year from point sources in the form of industries and combined heat and power plants, etc. (transports and households are not included). About 60% of this CO₂ potential has a biological origin (about 29 Mton). The main biogenic CO₂ source is the paper and pulp industry with 23 Mton per year. About 45 Mton per year of the produced CO₂ is assumed technically possible to recover and about 0.4 Mton originates from the production of biofuels for transport representing streams with relatively high CO₂ concentrations (usually 100%). From currently available and recoverable domestic CO₂ emissions, it would be possible to produce more than 180 TWh of e-methanol. Thus, this case study indicate that supply of CO₂ in Sweden does not have to be a limiting factor for the potential future production of electrofuels for the shipping sector. However, the potential streams of relatively pure CO₂ that probably will be the most interesting to recover from an economical point of view seem limited. Although the excess CO₂ from the production of biofuels for transport in Sweden is currently relatively low, the domestic biofuel production is expected to increase substantially in near future, potentially corresponding to CO₂ streams at roughly 2 Mton of CO₂ in 2030. This would lead to that today's 0.4 Mton CO₂, corresponding to around 1.5 TWh e-methanol per year, can be increased to a potential production of e-methanol at about 8 TWh/yr, as seen in Figure 5 (based on Grahn and Hansson, 2015).

The amount of electricity needed to produce enough e-methanol to supply the current Swedish use of bunker fuels corresponds to about 42 TWh (assuming a conversion efficiency from electricity to e-methanol at 53%). The total production of electricity in Sweden in 2013 amounted to about 150 TWh (Swedish Energy Agency, 2015), implying that the electricity supply have to increase substantially (by 22%) to meet the new electricity demand from electrofuels production. This number can also be compared with the goal within the Swedish-Norwegian electricity certificate market, suggested by the Swedish Energy Agency, of 30 TWh of renewable energy by 2020, compared to 2002.

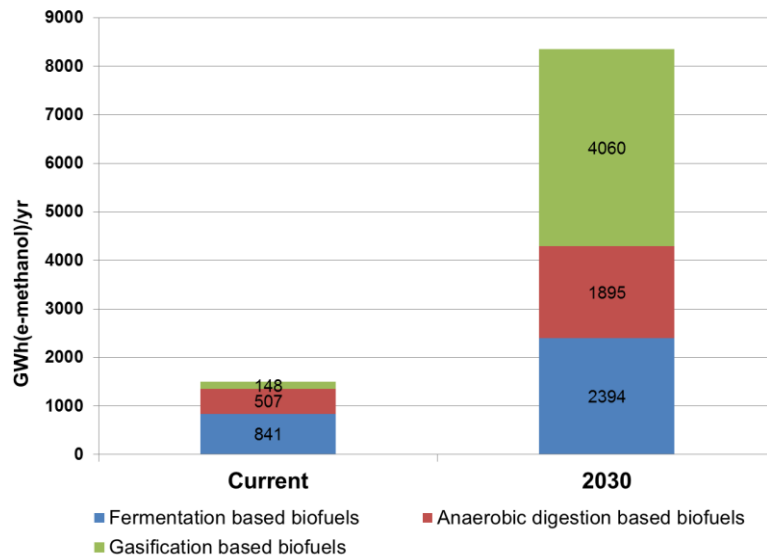


Figure 5: E-methanol production potential if utilizing excess CO₂ potentially available from different kinds of biofuels production plants in Sweden, today and 2030 (based on Grahn and Hansson, 2015).

3.2 GLOBALLY

All ships globally is roughly using 300 million tonnes of fuel per year, which roughly correspond to about 3400 TWh/yr (Smith et al., 2014). If 50% of the global shipping fuel should be replaced with e-methanol this would require about 3240 TWh of electricity, which corresponds to a global increase in electricity production of about 15%, or almost 70% increase of renewable electricity production (IEA, 2015). Additionally, 450 Mton CO₂ will be used in the production of 1700 TWh_{LHV} e-methanol.

The estimated amount of CO₂ needed to supply half of the current fuel demand from global shipping with electrofuels (450 Mton) will be high compared to biogenic CO₂ emissions from the current and potential use of bioenergy. There are however other global sources for biogenic CO₂ emissions (i.e., pulp and paper industry), as well as other fossil CO₂ sources potentially available. The current total global use of biomass for energy purposes amounts to approximately 50 EJ/year, in biomass terms (IPCC, 2011). The technical primary biomass potential for bioenergy in 2050 is in the literature estimated to be in the range 100-300 EJ (in biomass terms) with medium agreement (Creutzig et al., 2015). As a rough estimation the current global bioenergy use may generate excess recoverable CO₂ in the order of about 1000 Mton CO₂/year, assuming a mean average of 20% recoverable CO₂ of total carbon content in bioenergy (22 MtCO₂/EJ), and the estimated future bioenergy supply potential corresponds to recoverable CO₂ potential of about 2000-7000 Mton CO₂/year. This, indicates that the global supply of CO₂ does not have to be a limiting factor for the potential future production of electrofuels for the shipping sector.

Table 6: Required inputs and outputs to produce electrofuels in the two case studies.

	Sweden	Global shipping
Bunker fuel demand 2014 (TWh)	22	3400
Electrofuel replacement (%)	100	50
Electrofuel demand (TWh)	22	1700
Inputs to electrofuel production		
Electricity (TWh)	42	3240
Carbon dioxide (Mton)	6	450
Water (Mm ³)	7	550
Outputs from the electrofuel production		
E-methanol (TWh)	22	1700
Oxygen (Mton)	6	490
Heat (TWh)	20	1400
Required infrastructure		
Production capacity (GW) assuming 70% capacity factor	4	550

4 DISCUSSION AND CONCLUSIONS

Electrofuels, or power-to-fuels, connects the power sector with other energy sectors, such as the shipping sector and the heating sector. Electrofuels produced from non-fossil CO₂, with the help of renewable electricity, could potentially be a supplement to other alternative marine fuels in a world with ambitious climate targets. The aim of the study was to investigate under what circumstances electrofuels may compete with other climate neutral marine fuels, and possible resource limitations in a Swedish and global perspective.

4.1 MAIN FINDINGS

If comparing e-methanol with biofuels or methanol produced from natural gas, e-methanol will be a more costly alternative. Also hydrogen is less costly to produce per energy unit compared to e-methanol, but has both a higher infrastructure cost and a higher cost for fuel cells compared to a conventional combustion engine. If a carbon neutral shipping sector is to be reached, and there is a competition for biofuels, hydrogen and electrofuels might be the only options. This study shows that from an economical point, and with the limitations to only one ship type (short sea), hydrogen seems to be more cost-competitive than e-methanol. But that depends both on the development of fuel cells for ships and on process efficiency for producing e-methanol, as well as, the electricity price in the future. Additionally, we have not considered safety issues or practical problems of introducing a new fuel, or the fact that combustion of hydrocarbons releases other emissions than CO₂, e.g. particles, NO_x and CO, which contributes to air pollution.

In the supply potential case study, we showed that the amount of biogenic and recoverable CO₂ emitted in Sweden today (at about 29 Mton), is more than enough to supply the total current fuel demand for national and international shipping in Sweden with e-methanol, which corresponds to a demand of about 6 Mton CO₂. Even if only a small part of the CO₂ comes from high emission sources like bioethanol plants, the cost for recovering CO₂ from the paper and pulp industry will still make e-methanol cost competitive with hydrogen as a marine fuel. But due to the low efficiency from electricity to e-methanol, a substantially amount of electricity, 42 TWh, would be needed to supply the Swedish shipping demand with e-methanol. This is three times the amount of electricity needed if the whole Swedish road transport sector would be electrified and include only electric vehicles. There is, thus, a tradeoff between using renewable electricity as electricity (which is an energy efficient choice) or as converted into an energy carrier with ≈40% energy losses and thereafter use the fuel in combustion engines with much lower efficiency than an electric engine. In the global supply potential case study it was shown that renewable electricity production need to increase substantially if supplying the Swedish vessels or if half of the global demand for shipping fuels should be met with e-methanol. The potential availability of CO₂ was not limiting. However, there may be practical limits not investigated in this study.

Apart from the economic and resource aspects, one may discuss if it is preferable from a climate change perspective to store captured CO₂ underground or recycle the CO₂ into electrofuels. From one perspective it might be preferable to capture and store CO₂ underground, using Carbon Capture and Storage (CCS) technology, and not convert CO₂ into a fuel that after combustion will be released to the atmosphere again. If the CO₂ has been captured from burning fossil fuels, CCS will avoid increased CO₂ concentration, and if the CO₂ is captured from burning biomass (or from air), CCS will decrease the atmospheric CO₂ concentration. Today, however, there are several obstacles that have to be overcome before CCS could be available at a large scale, including public acceptance. But even if CCS would be available, should CO₂ always be pumped underground? An argument for converting CO₂ into electrofuels, instead of using CCS, has to do with the lack of other long-term fuel options in the transportation sector. If no other major long-term alternative fuels are available or technically possible, e.g. if bioenergy has been expanded to its maximum and batteries as well as fuel cells face difficulties with up-scaling, maybe only tailor-made carbon based fuels, electrofuels, remain as an alternative to fossil fuels.

Finally, assuming the cost and efficiency of the e-methanol production process as of today, hydrogen seems to be more cost-competitive than e-methanol. But there are several uncertainties and further research is needed to better understand the technical and economic potential. For example, uncertainties about future (i) investment cost for producing electrofuels and cost for fuel cells, (ii) electricity prices, and (iii) role of CCS.

4.2 FUTURE WORK

In future work, we plan a more detailed literature review of the production cost of e-methanol, and the different CO₂ sources. We will also use the global energy system model GET, to further analyze under which circumstances electrofuels can be cost-effective compared to other alternative marine fuels in order to reach stringent climate targets. An energy system model, like GET, captures the mechanisms where energy sectors compete for the same primary energy sources and produced fuels, and the tradeoff between using captured CO₂ for the production of carbon based fuels, where it will be emitted again or be stored underground for a more rapid decrease in global atmospheric CO₂ concentration.

We will also use data derived from an investment model and dispatch model of the European electricity system, and look at future electricity prices in Europe when meeting ambitious climate targets (more renewable energy sources which creates fluctuating electricity prices). As seen in Figure 3, the electricity price has an important impact on the fuel price of e-methanol. Another important area of future work is environmental assessment of electrofuels using methods such as life cycle assessment. It is important to understand under what circumstances electrofuels can reduce environmental and climate impact of transport.

REFERENCES

- Anderson, K., Bows, A., 2012. Executing a Scharnow turn: reconciling shipping emissions with international commitments on climate change. *Carbon Management* 3, 615-628.
- Bazari, Z., Longva, T., 2011. Assessment of IMO mandated energy efficiency measures for international shipping, International Maritime Organization,
- Bengtsson, S.K., Fridell, E., Andersson, K.E., 2014. Fuels for short sea shipping: A comparative assessment with focus on environmental impact. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 228, 42-52.
- Benjaminsson, G., Benjaminsson, J., Rudberg, R.B., 2013. Power to Gas - A technical review (El till gas - system, ekonomi och teknik), Svenskt Gastekniskt Center AB, Malmö.
- Berndes, G., Hansson, J., 2007. Bioenergy expansion in the EU: cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. *Energy Policy* 35, 5965-5979.
- Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., Standen, E., 2014. Development of water electrolysis in the European Union. Lausanne, Switzerland: Fuel Cells and Hydrogen Joint Undertaking.
- Brynnolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. *Journal of Cleaner Production* 74, 86-95.
- Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K., 2009. Second IMO GHG Study 2009, International Maritime Organization, London.
- Bunkerworld, 2015. Rotterdam, Platts, McGraw Hill Financial, <http://www.bunkerworld.com/prices/port/nl/rtm/> (2015-10-20).
- Carbon Recycling International, 2014. Plants, <http://www.carbonrecycling.is/> (2014-02-18).
- Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., Maserà, O., 2015. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* 7, 916-944.
- Damen, K., van Troost, M., Faaij, A., Turkenburg, W., 2007. A comparison of electricity and hydrogen production systems with CO₂ capture and storage—Part B: Chain analysis of promising CCS options. *Progress in Energy and Combustion Science* 33, 580-609.
- Eide, M., Chryssakis, C., Alvik, S., Endresen, Ø., 2012. Pathways to Low Carbon Shipping - Abatement Potential Towards 2050, Det Norske Veritas, Høvik, Norway.
- ETOGAS, Industrial 6.3 MW PtG plant (Audi e-gas plant), (2015-07-08).
- European Commission, 2011. WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system, Brussels.
- Eyring, V., Köhler, H.W., Lauer, A., Lemper, B., 2005. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *Journal of Geophysical Research D: Atmospheres* 110, 183-200.
- Gahleitner, G., 2013. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *International Journal of Hydrogen Energy* 38, 2039-2061.
- Goeppert, A., Czaun, M., Surya Prakash, G.K., Olah, G.A., 2012. Air as the renewable carbon source of the future: an overview of CO₂ capture from the atmosphere. *Energy & Environmental Science* 5, 7833-7853.
- Grahn, M., Azar, C., Lindgren, K., Berndes, G., Gielen, D., 2007. Biomass for heat or as transportation fuel? A comparison between two model-based studies. *Biomass and Bioenergy* 31, 747-758.
- Grond, L., Schulze, P., Holstein, S., 2013. Systems analyses power to gas: deliverable 1: technology review. DNV KEMA energy & sustainability, Groningen.

- Hannula, I., 2015. Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: Performance and cost analysis. *Biomass & Bioenergy* 74, 26-46.
- ICCT, 2011. Reducing Greenhouse Gas Emissions from Ships - Cost Effectiveness of Available Options, White Paper Number 11, July 2011, International Council on Clean Transportation,
- IEA, 2013. Technology Roadmap - Carbon Capture and Storage, International Energy Agency, Paris.
- IEA, 2015. International Energy Statistics U.S. Energy Information Administration (EIA) Washington, US. <http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12> (2015-10-26).
- IPCC, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York, NY, USA.
- Kuramochi, T., Ramírez, A., Turkenburg, W., Faaij, A., 2012. Comparative assessment of CO₂ capture technologies for carbon-intensive industrial processes. *Progress in energy and combustion science* 38, 87-112.
- Laude, A., Ricci, O., Bureau, G., Royer-Adnot, J., Fabbri, A., 2011. CO₂ capture and storage from a bioethanol plant: carbon and energy footprint and economic assessment. *international journal of Greenhouse Gas Control* 5, 1220-1231.
- Lehner, M., Tichler, R., Steinmüller, H., Koppe, M., 2014. *Power-to-Gas: Technology and Business Models*. Springer.
- Mergel, J., Carmo, M., Fritz, D., 2013. Status on technologies for hydrogen production by water electrolysis. *Transition to renewable energy systems*, 423-450.
- Mohseni, F., 2012. Power to Gas- Bridging Renewable Electricity to the Transport Sector. KTH Royal Institute of Technology, Stockholm, Sweden.
- Nikoleris, A., Nilsson, L., 2013. *Elektrobränslen en kunskapsöversikt [Electrofuels an overview]*, Lund, Sweden.
- Reiter, G., Lindorfer, J., 2015. Evaluating CO₂ sources for power-to-gas applications—A case study for Austria. *Journal of CO₂ Utilization* 10, 40-49.
- Schwartz, J., 2011. Advanced Hydrogen Liquefaction Process, Praxair Technology, Inc, Tonawanda, NY. http://www.hydrogen.energy.gov/pdfs/review11/pd018_schwartz_2011_p.pdf
- Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., Chesworth, S., Pandey, A., 2014. Third IMO GHG Study 2014, International Maritime Organization (IMO), London, UK.
- Statistics Sweden, 2015. Elpriser för olika typkunder, tidsserie [Electricity prices for different types of customers, timeseries], Statistics Sweden, Stockholm, Sweden. <http://www.scb.se/sv/Hitta-statistik/Statistik-efter-amne/Energi/Prisutvecklingen-inom-energiomradet/Priser-pa-elenergi-och-pa-overforing-av-el-nattariffer/Aktuell-Pong/6429/Tabeller-over-arsvarden/85467/> (2015-10-26).
- Sterner, M., 2009. Bioenergy and renewable power methane in integrated 100% renewable energy systems: Limiting global warming by transforming energy systems. *kassel university press GmbH*.
- Swedish Tax Agency, 2015. Lägre skatt för industriell verksamhet [Lower taxes for industry] Swedish Tax Agency, <http://www.skatteverket.se/foretagorganisationer/skatter/punktskatter/energiskatter/verksamhetermedlagreskatt/industriellverksamhet.4.18e1b10334ebe8bc80002009.html#> (2015-10-26).
- Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., Johnson, H., 2014. Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environmental Science & Technology* 48, 12986-12993.
- Trost, D.-W.-I.T., Horn, S., Jentsch, M., Sterner, M., 2012. Erneuerbares Methan: Analyse der CO₂-Potenziale für Power-to-Gas Anlagen in Deutschland. *Zeitschrift für Energiewirtschaft* 36, 173-190.
- UNCTAD, 2013. Review of Maritime Transport 2013, United Nations Conference on Trade and Development (UNCTAD), Geneva, Switzerland.
- Vandewalle, J., Bruninx, K., D'haeseleer, W., 2014. The interaction of a high renewable energy/low carbon power system with the gas system through power to gas, 14th IAEE European Conference, October, pp. 28-31.
- Varone, A., Ferrari, M., 2015. Power to liquid and power to gas: An option for the German Energiewende. *Renewable and Sustainable Energy Reviews* 45, 207-218.
- Vergara, J., McKesson, C., Walczak, M., 2012. Sustainable energy for the marine sector. *Energy Policy* 49, 333-345.