ELECTROFUELS OR HYDROGEN AS MARINE FUEL: A COST COMPARISON

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ABSTRACT

Electrofuels (elsewhere also called e.g., power-to-gas/liquids/fuels), are fuels produced from hydrogen and carbon dioxide (CO_2), using electricity as the major source of energy. Electrofuels is one potential group of fuels that could contribute to reduce the climate impact from shipping depending on type of CO_2 and electricity mix (preferable non-fossil). Hydrogen, if used as a fuel itself and not as feed-stock for an electrofuel, obviously has a lower production cost compared to electrofuels (since electrofuels are produced from hydrogen). Hydrogen is preferably used in fuel cells (FCs), which have a higher conversion efficiency but also a higher cost compared to combustion engines. Electrofuels, in this study electro-diesel, has the advantage that it can be used in conventional combustion engines (ICEs). On annual basis the share “fuel cost” would be higher compared to the share “ship cost” the more the ship is used per year. The aim of this study is to analyze the following two questions (1) would the lower cost for ICEs, compared to FCc compensate for the higher fuel production cost of electrofuels? and (2) is there a breaking point where the total cost would shift between the two concepts electro-diesel in ICE vs hydrogen in FC? The cost comparisons are made for generalized types of vessels (i.e., short sea, deep sea and container). Results show that electro-diesel in ICEs can be competitive, over hydrogen in FCs, when vessels operate less than 150 days per year, whereas hydrogen has advantages when vessels are used more days per year. Container seems to be the category showing the most positive results on electro-diesel.

Keywords: alternative marine fuels, cost, sunfuels, electrofuels, hydrogen, carbon dioxide, fuel cells

NOMENCLATURE

CO_2= carbon dioxide; DME= dimethyl ether, €= Euro, FC= fuel cell; H2= hydrogen; ICE= internal combustion engine; kW= kilo Watt (effect), MWh= Millions of Watt hours (energy); $= US dollars

1. INTRODUCTION

Electrofuels (elsewhere also called e.g. sunfuels or power-to-gas/liquids/fuels), are fuels produced from hydrogen and carbon dioxide (CO_2), using electricity as the major source of energy (Ridjan et al, 2013, 2014, 2016; Nikoleris & Nilsson, 2013; Brynolf et al 2017; Larsson et al, 2015; Connolly et al, 2014; Jansen et al, 2007). Electrofuels is one potential group of fuels that could contribute to reduce the climate impact from transport depending on type of CO_2 and electricity mix (preferable non-fossil). When forming the electrofuels it is possible to choose among a range of different final fuel molecules, such as methane, methanol, dimethyl ether, or longer hydrocarbons such as gasoline or diesel (Brynolf et al, 2017). If a fuel can be blended, in high concentrations, with fossil conventional oil based fuels, within the conventional fuel standards, it is called a drop-in fuel. Drop-in fuels have the potential to, in a short time perspective, substitute fossil transport fuels without changing the fuel infrastructure or drivetrain technologies. That is, drop-in fuels can be used in existing vehicle or vessel fleets and reduce the need for more advanced, and relatively costly, engine technologies as well as avoid implementing a new fuel infrastructure. In Germany, a test facility producing electro-diesel from renewable electricity and CO_2 captured from the air has shown that it is possible to produce high-quality drop-in electrofuels (Sunfire, 2016).

In earlier studies estimating production costs of different types of electrofuels, it is clear that hydrogen has the lowest production cost and electro-diesel among the most expensive ones (see e.g. Brynolf et al, 2017). The reason for that hydrogen has the lowest production cost comes from that hydrogen is used as feed-stock for the production of electrofuels, where investing in a synthesis reactor will add costs to the total fuel production cost. Most electrofuels have the advantage that it can be used in conventional combustion engines (ICE), whereas hydrogen is preferably used in fuel cells, which have a higher conversion efficiency but also a higher cost compared to combustion engines (Grahn et al, 2009; Taljegård et al, 2014). A cost-comparison, where the electrofuel production cost is combined with the propulsion investment cost, to calculate a total annual cost, has to our knowledge never been made before.

The aim of this study is to calculate total annual cost (fuel plus propulsion) for the two fuel options hydrogen and electro-diesel. On annual basis the share “fuel cost” would be higher compared to the share “propulsion cost” the more the vehicle or ship is used per year. More specifically this study aims to answer the following two questions (1) would the lower cost for ICEs, compared to FCc, compensate for the higher fuel production cost of electrofuels? and (2) is there a breaking point where the total annual cost (fuel plus propulsion) would shift between the two concepts electro-diesel in ICE vs hydrogen in FC? The cost comparisons are made for generalized types of vessels (i.e., short sea, deep sea and container) for different amount of days per year that the vessel is operated.

2. ELECTROFUELS PRODUCTION ROUTE AND COST

Electrofuels are produced by mixing hydrogen and CO_2 in a reactor to form energy carriers such as for example fuels for transport, see Figure 1. The first step, illustrated in the figure, is the production of hydrogen via electrolysis, where electricity is used as the main source of energy. Water is separated into hydrogen and oxygen by current between two electrodes. The most-discussed types of electrolysers are alkaline, proton exchange membrane (PEM), and solid oxide electrolyse cells (SOEC), read more in e.g. Brynolf et al (2017). 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, read more in e.g. Hansson et al (2017). Different types of synthesis reactors can be used for the formation of the electrofuel, e.g. a Sabatier reactor, for the production of methane, or a Fischer-Tropsch reactor, for the production of hydrocarbons such as jetfuels and diesel, read more in e.g Brynolf et al (2017). A range of liquid and gaseous fuels can be produced at a quality making the electrofuel suitable as a drop-in fuel in conventional transport fuels as well as in advance biofuels. The production process also generates marketable by-products, such as high-purity oxygen and heat.

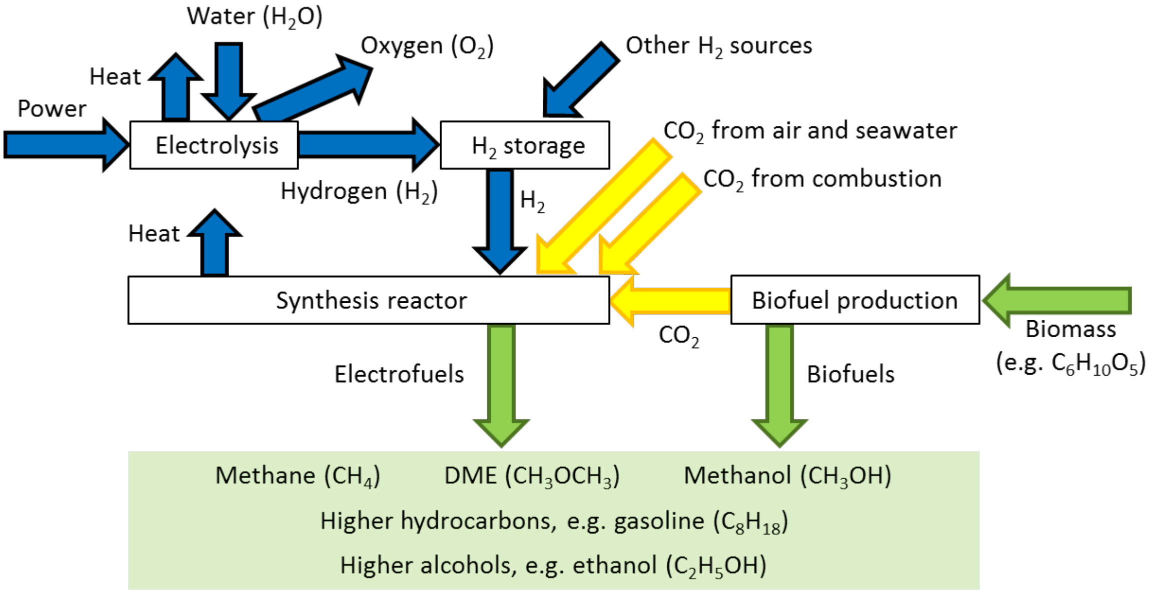

Figure 1: Process steps in the production of electrofuels, modified from Urakawa & Sá (2014), Graves et al (2011), Ganesh (2013), and Grahn et al (2014).

Several demonstration-scale facilities have been developed in Europe in the last decade (Gahleitner, 2013). For example, Carbon Recycling International (CRI) on Iceland produces methanol by using geothermal energy and CO_2 from the same source. CRI has operated a commercial plant since 2011, with the capacity to produce 5 million liters of methanol per year (CRI, 2016). Audi AG’s ETOGAS has invested in a 6 MW plant in Germany that uses renewable electricity from wind power and CO_2 from a biogas processing plant to produce methane (ETOGAS, 2016). In Germany, a test facility producing diesel from renewable electricity and CO_2 captured from the air has shown that it is possible to produce high-quality drop-in electrofuels (Sunfire, 2016).

In addition to the new pilot and demonstration plants, a range of papers assessing different aspects of electrofuels have been published in recent years: electrofuels as a way to balance the increasing share of intermittent renewable electricity in the energy system (e.g., Zhang et al, 2015; Zakeri & Syri, 2015), as a transport fuel (e.g., Grahn et al, 2014; Larsson et al, 2015; Ridjan et al, 2013, 2014; Connolly et al, 2014;

Jensen et al, 2007), and as a way to increase carbon utilization in biofuel production (e.g., Mignard & Pritchard, 2008; Hannula, 2015, 2016; Mohseni et al, 2012). However, many aspects need to be clarified in order to understand the potential role of electrofuels in a future transport sector with low CO_2 emissions, including the costs of producing electrofuels compared to other energy carriers.

3. ASSUMPTIONS MADE FOR THE COMPARISON

Brynolf et al (2017) have carried out a comprehensive literature review of costs and efficiencies for the steps when producing electrofuels followed by calculations to compare the production costs of the different fuel options in a harmonized way. Results from their base case scenario, assuming values representing year 2030, have been used for this study comparing electro-diesel (via a Fischer-Tropsch synthesis) with hydrogen (produced via alkaline electrolyzers). The production cost for hydrogen and electro-diesel sum up to 116 and 180 €/MWh, respectively, in their base case, as well as 84 and 112 €/MWh in their case "low", see Table 1.

To be able to compare costs for the three different generalized categories of vessels, run on either electro-diesel or hydrogen, the fuel production costs are combined with propulsion and storage costs taken from Taljegård et al (2014). Cost-calculations are made depending on how much each vessel category is operated per year expressed in days per year for the vessels. For vessels run on hydrogen, the fuel stack need to be replaced if the fuel cell life time ends before the vessel's life time. Stack replacements are assumed to cost half of the fuel cell investment. Tables 1-2 present assumptions made in this study and Table 3 lists the calculated amount of stack replacements needed depending on how frequent the vessel is used.

Table 1: Assumptions on currency, fuel production costs, life time and engine efficiency.

	Base Case	Case Low fuel cost
Interest rate [%]	5	5
Currency $/€ (Forex, 2017)	0.89	0.89
Production cost electro-diesel [€/MWh] (Brynolf et al, 2017)	180	112
Production cost H_2 (Alkaline electrolyzer) [€/MWh] (Brynolf et al, 2017)	116	116
Additional cost H_2 liquefaction [€/MWh] (Brynolf et al, 2017)	3	3
Tot production cost H_2 (liquid) [€/MWh] (Brynolf et al, 2017)	116	84
Life time fuel cell stack [hours] (Brynolf et al, 2017)	65000	65000
Average vessel engine load (factor of max capacity) (Taljegård et al, 2014)	0.75	0.75
Engine efficiency Diesel-IC (Taljegård et al, 2014)	0.40	0.40
Engine (fuel cell) efficiency H_2-FC (Taljegård et al, 2014)	0.45	0.45

Table 2: Assumptions made for vessels using either electro-diesel in diesel combustion engines or liquefied hydrogen used in fuel cells (Taljegård et al, 2014).

	Electro-diesel in Diesel combustion engines			Liquefied hydrogen in fuel cells		
	Short sea	Deep sea	Container	Short sea	Deep sea	Container
Engine power [kW]	2400	11000	23000	2400	11000	23000
Investment cost [1000 € per vessel]	15638	69163	113574	23769	118309	201948
Annuitized investment cost [1000 € per vessel per yr]	1017	4499	7388	1546	7696	13137
Life time [years per vessel]	30	30	30	30	30	30
Cost fuel cell stack replacement [1000 € per replacement]	n.a.	n.a.	n.a.	264	1599	2874

Table 3: No of stack replacement during vessel life time depending on how frequent the vessel is operated, calculation utilizing data in Table 1-2.

Days per year in operation	50	100	150	200	250	300
No of replacements	0	1	1	2	2	3

4. RESULTS BASE CASE

Annual cost per vessel is calculated depending on how much they are operated per y, and results are presented for the three vessel types in Figs 2-4.

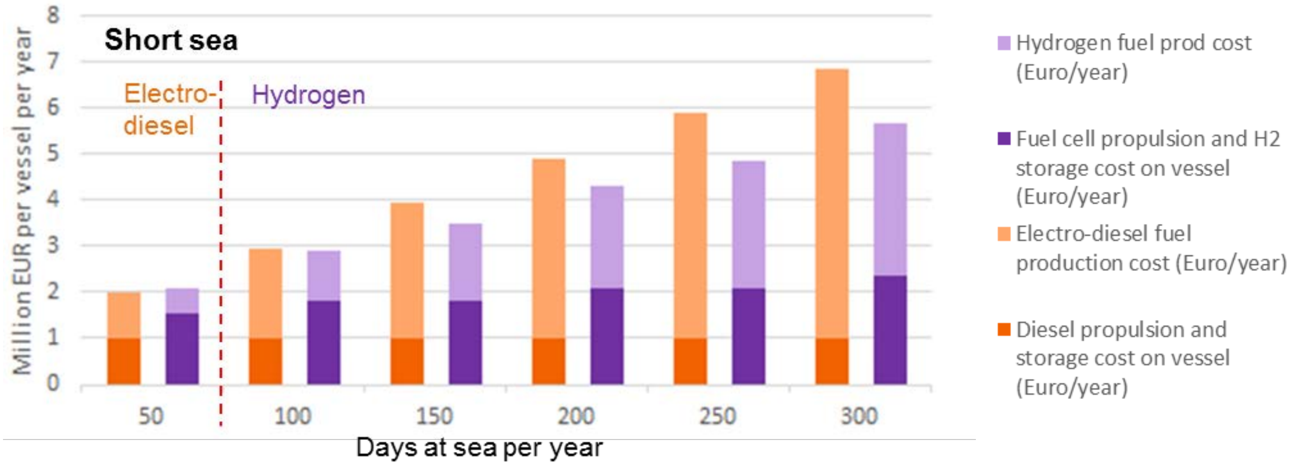

Figure 2: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *short sea* vessels, depending on how many days they are operated per year.

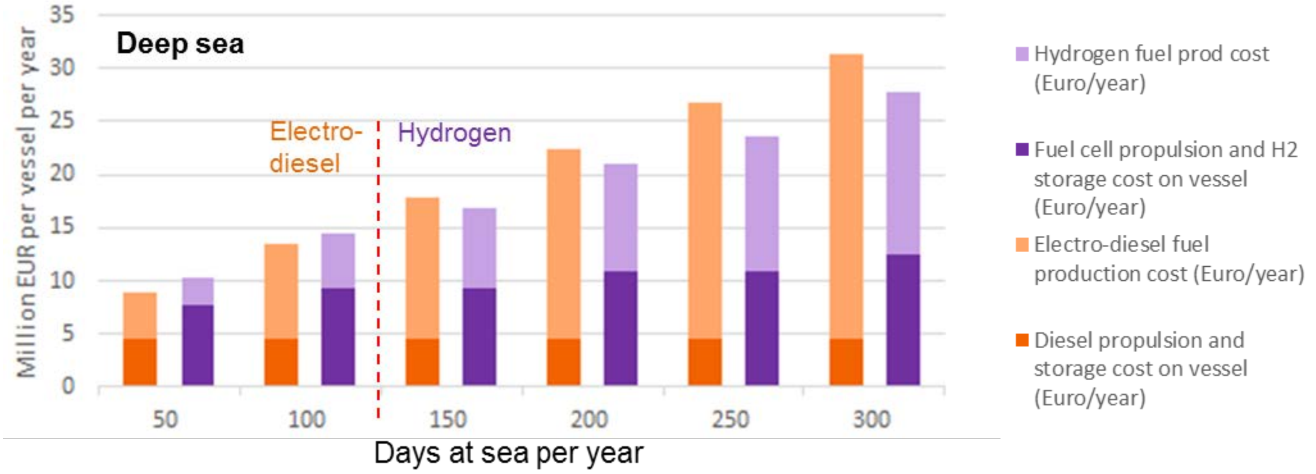

Figure 3: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *deep sea* vessels, depending on how many days they are operated per year.

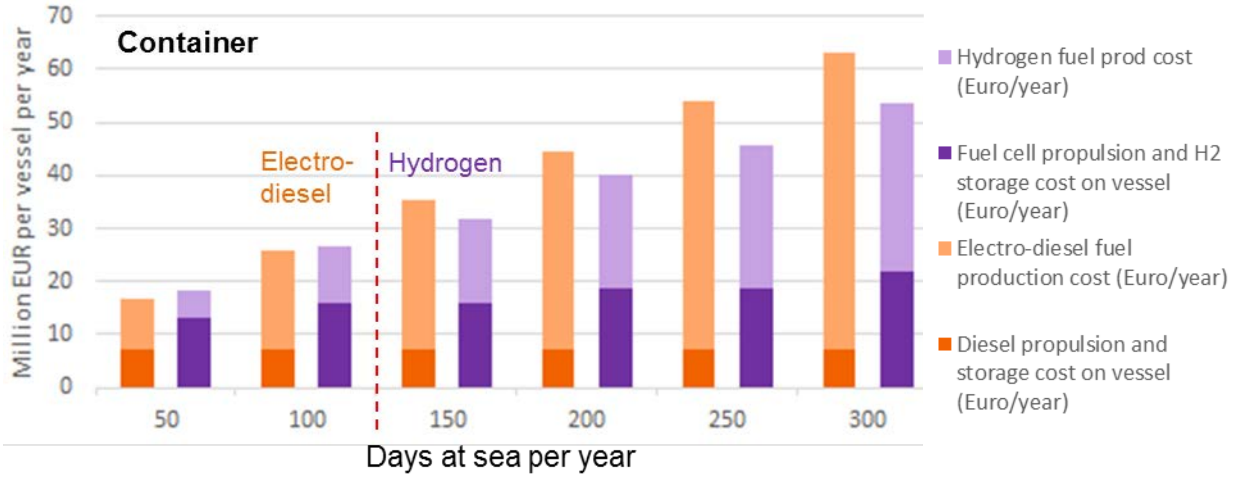

Figure 4: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *container* vessels, depending on how many days they are operated per year.

In Figure 2-4 it can be seen that the annuitized cost for the combustion technologies (the vessels with an ICE) is constant regardless of how many days the vessel is operated per year, whereas the annuitized cost for the fuel cell technologies is increasing with each stack replacement needed over the vessel's 30 years life time. The annual cost for fuel increases significant the more days per year the vessel is operated.

Results show that the total electro-diesel option (fuel +propulsion) is slightly less costly than the hydrogen option for vessels that operate less than 100-150 days per year, for all three ship categories. Expensive investments dominate the total cost at low use, whereas expensive fuel costs dominate at large use. Stack replacements is shown to be only a minor post. The hydrogen option becomes more and more cost-competitive the more days per year the ship is operated, i.e., if the vessels are operated more than 150 days per year it seems to be more beneficial from a total cost perspective to install the relatively costly fuel cell technologies onboard, in base case.

Container seems to be the category showing the most positive results on electro-diesel.

5. RESULTS CASE LOW FUEL COST

As shown in Brynolf et al (2017) there are uncertainties connected to production cost of fuels. In this alternative case values from lower end of range are assumed, i.e. H2=84 €/MWh (base=116 €/MWh) and Electro-diesel=112 €/MWh (base=180 €/MWh). All other parameter values are kept the same as in the base case. Again total cost (fuel plus propulsion) per vessel is calculated depending on how much they are operate per year, and results are presented for the three vessel types in Figs 5-7.

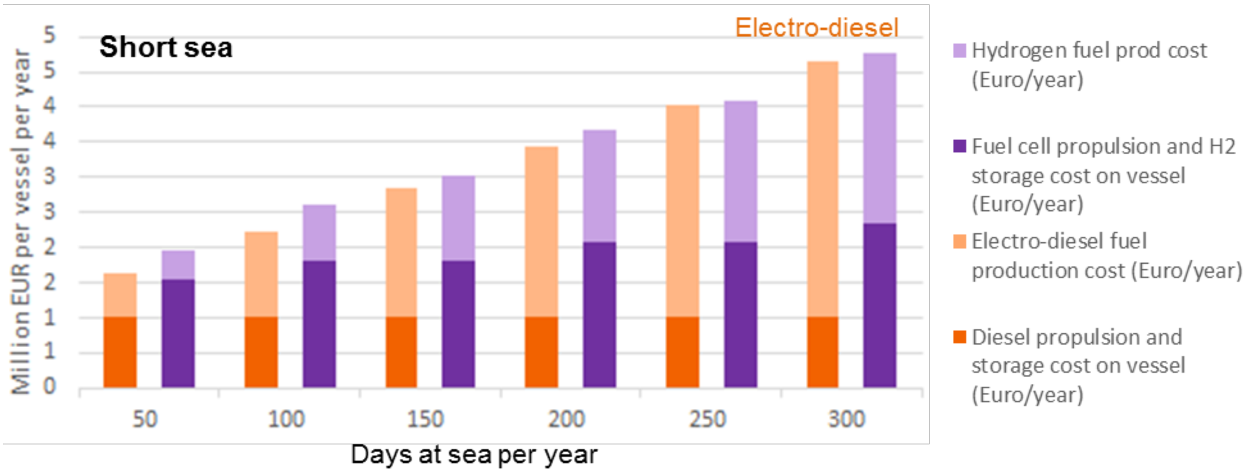

Figure 5: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *short sea* vessels, depending on how many days they are operated per year, assuming lower production cost on both hydrogen and electro-diesel.

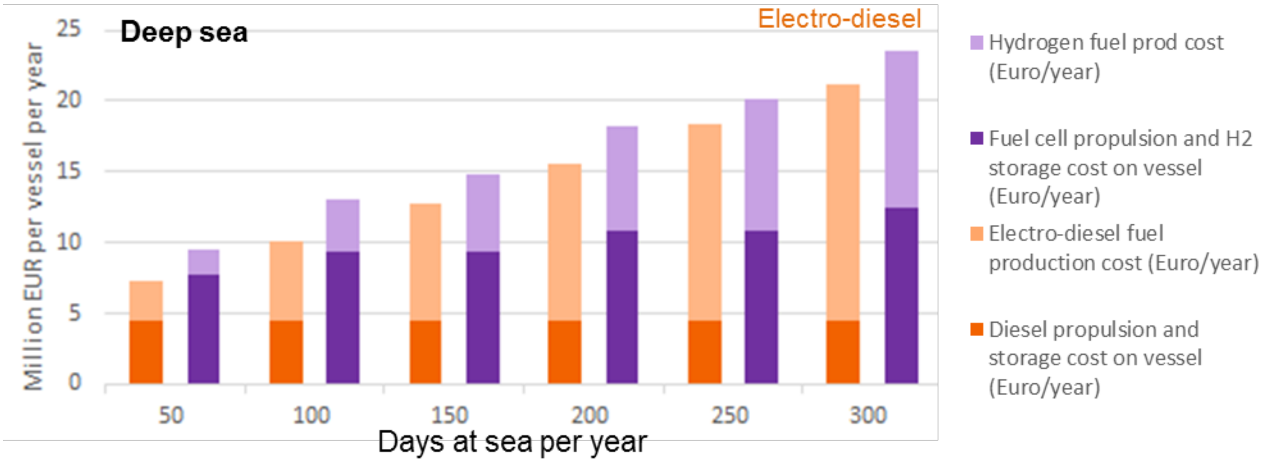

Figure 6: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *deep sea* vessels, depending on how many days they are operated per year, assuming lower production cost on both hydrogen and electro-diesel.

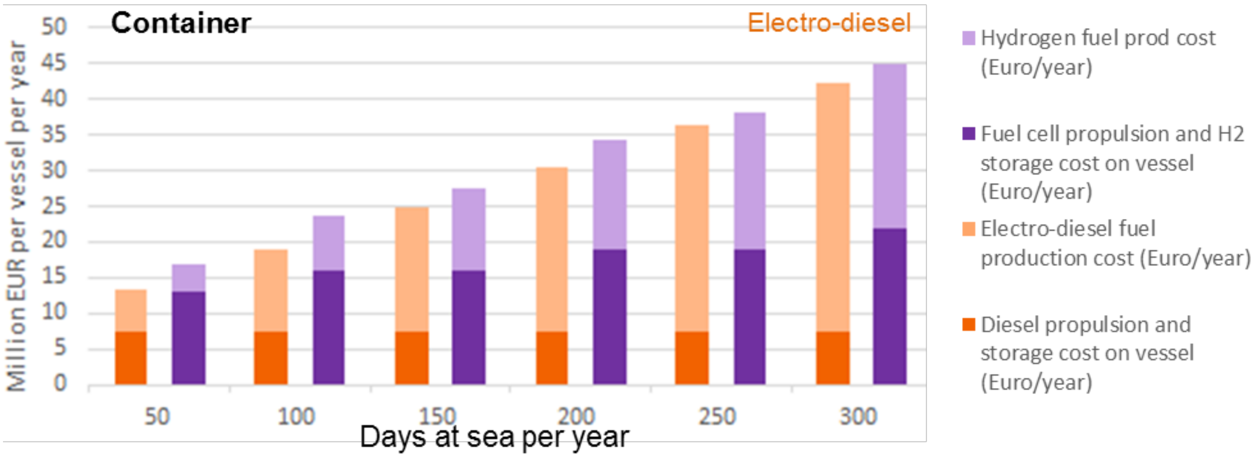

Figure 7: Cost-comparison electro-diesel in combustion engines versus hydrogen in fuel cells for *container* vessels, depending on how many days they are operated per year, assuming lower production cost on both hydrogen and electro-diesel.

As in base case Figure 5-7 show that the annuitized cost for the ICE propulsion is constant regardless of how many days the vessel is operated per year, whereas the annuitized cost for the fuel cell technologies is increasing with each stack replacement needed over the vessel's 30 years life time. The annual cost for fuel increases significant the more days per year the vessel is operated. Stack replacements is shown to be only a minor post.

Results in this alternative case show that the total electro-diesel option (fuel +propulsion) is slightly less costly than the hydrogen option for vessels regardless of how many days per year the vessel is operated, for all three ship categories. That is, when assuming lower fuel production costs the results show that it would be more beneficial from a total cost perspective to operate the vessels on the electrofuel concept instead of hydrogen.

The reason for the opposite result is that the two concepts lies rather close to each other when total cost is compared and that the change in fuels production cost is slightly more beneficial for electro-diesel than for hydrogen. The percentual reduction in production cost for electro-diesel is 112/180=0.62, compared to hydrogen 84/116=0.72.

Container is again the vessel category showing the most positive results on electro-diesel.

6. DISCUSSION AND CONCLUSIONS

Results show that there may be circumstances where electrofuels in combustion engines are cost-competitive to hydrogen in fuel cells. This study especially points out that the option electro-diesel in diesel engines seems to be beneficial for vessels only used part time of the year, whereas the option of hydrogen in fuels cells seems beneficial for vessels that is used for more days during the year. This can be understood from that if costs from relatively expensive investments, such as fuel cells, can be spread out over a large amount of operating hours, the cost is less dominated by the investment, but more of the cost of fuel. When it is the fuel cost that dominates the total cost, hydrogen has a great advantage compared to the more expensive electro-diesel fuel.

All cost assumptions made in this study are chosen to reflect mature technology around 2030 or beyond, and are of course associated with uncertainties. Alternative assumptions has been tested using values taken from Brynolf et al (2017), where it was shown that values in the lower end of the range gave advantages for the concept of electrofuels, but other uncertain parameter values has not been tested in this study. Further sensitivity analyses, e.g. using Monte Carlo simulations for testing combinations of uncertain data would improve the analysis. This is planned as the next step for this study.

Important to note is that if electrofuels are used as drop-in fuels, although they may offer a solution for a fast transition away from fossil fuels, there is a risk that they may contribute to a prolonged era of fossil fuels. Policy measures that continuously encourage increased shares of low-emitting drop-in fuels would reduce this risk.

Regarding effects on human health, such as the local emissions NOx and soot, from combustion engines would also remain in the case where electrofuels are used in conventional internal combustion engines These local emissions would be slightly lower with electrofuels in the form of, e.g., dimethyl ether, methanol or methane, than with gasoline or diesel, however, never as low as with hydrogen in fuel cells. The majority of these local emissions can, on the other hand, be reduced with exhaust after treatment technologies.

For traffic outside cities, local emissions are of less concern for human health, simplifying the use of electrofuels in ships, and long-distance road transport.

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