

## WHAT FUTURE FOR ELECTROFUELS?

*Work in progress*

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### *ABSTRACT*

Transport sector is seen as the most difficult sector to decarbonise. In recent years so called electrofuels have been proposed as one option for emissions reduction. Electrofuels – fuels made from electricity and carbon dioxide - can potentially help to manage variations in electricity production and reduce the need for biofuels as well as make use of current infrastructure and can be used in sectors where fuel switch is difficult such as aviation. We investigate the cost-effectiveness of electrofuels under climate mitigation constraint and find that electrofuels are unlikely to become cost-effective unless options for storing carbon are very limited.

**Keywords:** Electrofuels, variable electricity, energy system

### *1. INTRODUCTION*

The UN climate policy aims to keep human induced global warming well below 2°C, aspiring to limit it to 1.5°C. Keeping global warming below 2°C requires halving current greenhouse gas emissions by mid-century, a task that entails radical transformation of energy production and use globally. Transport sector is currently responsible for about 14% of global greenhouse gas emissions and is also thought to be one of the most difficult sectors to decarbonise among other things due to decentralised decision making and limited amount of alternatives on the

market. In recent years electrofuels have been put forward as one possible solution for emissions reductions in transport sector [1-4].

Electrofuels are carbon-based fuels produced from carbon dioxide (CO<sub>2</sub>) and water, with electricity as the primary source of energy [5]. Electrofuels are also known as power-to-gas/liquids/fuels, e-fuels, or synthetic fuels. Electrofuels are produced by mixing hydrogen and CO<sub>2</sub> in a synthesis reactor to form energy carriers. A range of liquid and gaseous fuels, including gasoline and diesel, can be produced. The production process also generates marketable by-products, namely high-purity oxygen and heat. Electrofuels are potentially of interest for all transport modes; some can be used in combustion engines and may not require significant investments in new infrastructure. Thus, if produced from renewable electricity and CO<sub>2</sub> from either sustainable biomass or air capture, electrofuels could be a carbon neutral alternative that enables the use of already made investments.

In addition to representing a possible future option for transport fuels, electrofuels may allow other system related benefits. Recent years have seen large reductions in solar and wind power costs making them in some cases even competitive with conventional technologies. These cost reductions as well as concerns for climate and energy security make a significant share of variable renewables (vRE) rather a standard in future energy system scenarios than an extreme case. However, since the supply from wind and solar technologies is variable on both short- and long-term, it challenges the operation of the current power system.

In the traditional electricity system, different power plants are available most of the time and can be dispatched based on their running cost. The outputs of wind and solar PV, however, are highly dependent on availability of wind and solar radiation which can vary greatly over both short and long time scales (daily and seasonal variations) and are not well predictable over long time periods. Yet wind and solar technologies tend to be employed when available due to near zero running costs. While having some amount of solar power in the system can help balancing higher daytime demand, employing large amounts of intermittent renewables quickly starts to reduce the intermediate and baseload available for other plants and thus also their running times and profitability. The effect on the other plants also depends on the amount of intermittent

sources in the system and their distribution. Electrofuels could help to deal with the variability issue by absorbing excess electricity at windy and/or sunny times when the price of electricity is low or negative at the same time also make room for dispatchable generation that could be run for more hours and thus be more profitable [6].

Another possible alternative for decarbonizing the transport sector is biofuels – fuels produced from biomass. However, how much biomass can sustainably be grown is highly uncertain [7]. Climate change is expected to affect the rain patterns and thus also biomass production. At the same time, the global population is growing, leading to higher food demand. Since most of the arable land is already in use, increasing biomass production for energy purposes is likely to come in expense of food production or lead to deforestation to free more land for agricultural purposes. Thus, it may be desirable to reduce energy system's reliance on biomass. Furthermore, biomass is a very versatile feedstock that can be used in all energy sectors. As a limited resource, it may need to be used for sectors where decarbonation is technically difficult. Since transport sector has also other options such as electricity or hydrogen use, it may not be prioritized. Electrofuels production can help with these difficulties in two ways. First, since biomass contains more carbon than hydrogen, adding extra hydrogen will increase the yield of the fuel produced. Secondly, using biomass in other sectors together with carbon capture and then producing electrofuels from captured carbon would increase the energy obtained from biogenic carbon before it is returned into carbon circulation and allow the use of biomass both in transport and other sectors.

Another possible motivation for electrofuels is that it is more difficult to switch fuels in some transport sectors. Aviation and shipping are usually brought up in this context. Batteries are often considered too heavy for aviation and to have a too low energy capacity for long distance marine transport. Hydrogen, that is another possible option has low energy density per volume, that makes its use problematic both in aviation and shipping and is on top that highly inflammable. Therefore, electrofuels together with biofuels may be the only low carbon alternatives in these sectors. For same reasons, hydrogen may be difficult to use in other transport sectors. Also a new infrastructure needs to be developed for hydrogen making it more difficult to switch.

The aim of this paper is to analyze if and under what conditions electrofuels can be a part of a cost-effective solution for mitigating climate change.

## *2. METHOD*

### *2.1. GET MODEL*

To conduct our analysis we use the Global Energy Transition (GET) model first developed by Azar and Lindgren [8] and further developed in Grahn et al., Hedenus et al., Lehtveer and Hedenus [9-11] and Lehtveer et al. [12]. GET is a cost minimizing “bottom-up” systems engineering model of the global energy system set up as a linear programming problem. The model was developed to study carbon mitigation strategies with an objective of minimising the discounted total energy system cost for the period under study (in general 2000–2100) while meeting both a specified energy demand and a carbon constraint.

The model focuses on the supply side and has five end use sectors: electricity, transport, feedstock, residential–commercial heat and industrial process heat. In each sector, various technologies are available to meet the demand. Technologies are described by the energy carriers they can potentially convert, and are parameterised using e.g. investment and fuel costs, efficiencies, capacity factors and carbon emissions. Demand projections are based on the MESSAGE B2 scenarios with increasing global population, intermediate levels of economic development and a stabilisation level of 450 ppm CO<sub>2</sub> by 2100 [13]. GET has a single demand node for each region and thus the electricity grid is not explicitly modelled. Transportation demand scenarios are based on Azar et al. [8] and assume faster efficiency improvements in the transport sector than in the B2 scenario. The demand for shipping are further elaborated on the Taljegard et al. [14] and updated in this study following the approach in Smith et al. and Sharmina et al. [15, 16]. The model has perfect foresight and thus finds the least cost solution for the entire study period with a discount rate of 5%/year. Consequently, scarce resources such as oil and biomass are allocated endogenously to the sectors in which they are used most cost-effectively.

In the model the world is divided into 10 regions following IIASA region definitions (except that Eastern and Western Europe have been merged into one region): North America (NAM), Europe (EUR), Pacific OECD (PAO), centrally planned Asia (CPA), the former Soviet Union

(FSU), Latin America (LAM), Africa (AFR), the Middle East (MEA), South Asia (SAS) and non-OECD Pacific Asia (PAS).

The current version of GET has several categories of solar and wind power: PV rooftop, PV plant A, PV plant B, concentrated solar power (CSP) with storage A, CSP with storage B, onshore wind A, onshore wind B and offshore wind. The A-versions of each technology have direct access to the electricity grid, whereas the B-versions are available at larger distances from demand and therefore require additional transmission investments; the additional cost is based on [17]. All of these eight types of solar and wind power have five resource classes each.

Three further developments of the model were done for this study. First, to analyse the potential of electrofuels, capturing intermittency and its connection to hydrogen production is important. To capture that connection hydrogen production was sliced in accordance to the variable renewable based slices making the model able to see differences in electricity prices. Secondly, producing electrofuels also requires CO<sub>2</sub>. Therefore, the carbon cycle in the model was modified to separate carbon capture from carbon storage and enable reuse of captured carbon (see figure 1). The possibility to capture CO<sub>2</sub> from air was added to the model. Thirdly, the transport sector in the model were updated increasing the possibility for electric vehicles and improving the representation of the shipping sector based on Taljegard et al. [18].

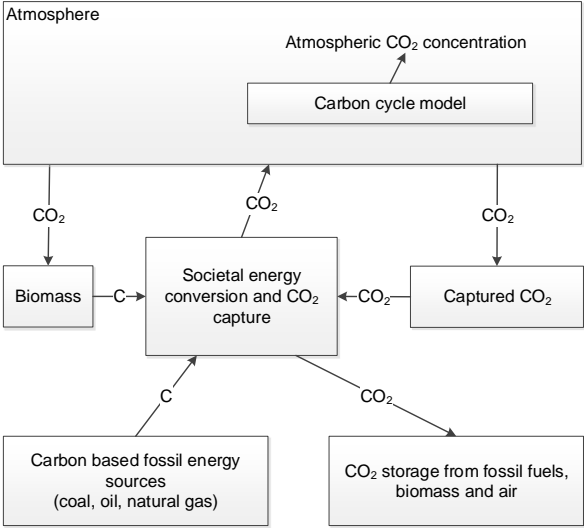


Figure 1. Carbon flows in the GET model

## 2.2. DATA AND SCENARIOS

### Data

Based on previous literature review conducted by Brynolf et al. [1] the cost of the electrolyser and price of electricity are seen as major determinants of the cost of electrofuels. Electricity price and load factors for electrolysers are determined endogenously by the model based on the total system cost minimisation. We introduce variations in the electricity price by analysing different scenarios limiting or advancing certain technology options but do not set the price implicitly. We use costs presented in table 1 as our base costs. In this study we use methanol as a proxy for all electrofuels, since it is the cheapest liquid electrofuel to produce. If methanol proves to be a cost-effective option, more specific analysis can be carried out, otherwise no other electrofuel would enter the system either.

Table 1. Investment costs for relevant technologies in the model

<b>Technology</b>	<b>Starting cost per kW (\$ 2010)</b>	<b>Mature cost per kW (\$ 2010)</b>	<b>Efficiency</b>
Coal PP	1800	1800	45%
Coal with CCS	3000	2500	35%
Gas turbine	800	800	55%
Gas with CCS	2000	1500	45%
Concentrated solar power (CSP) + storage A	7000	4500	N/A
Light water reactor (LWR)	7000	5000	33%
Wind onshore A	2000	1500	N/A
Wind offshore	5000	3000	N/A
Solar PV rooftop	4000	1600	N/A
Solar PV plant A	3700	1250	N/A
Storage 12h	1800	1800	80%
Storage 24h	2900	2900	80%
Storage 48h	5100	5100	80%
Storage 96h	9500	9500	80%
Electrolyser	1300	500	80%
Synthesis reactor	625	375	89%

### *Scenarios*

In this study, we test five different scenarios rooted in the motivations for electrofuels presented in the introduction. First, we run our model with no restrictions or modification, so called base case. Secondly as the low electricity prices introduced by variability of renewables are seen as one of the main drivers for electrofuels, we lower the cost of wind and solar power in our model by 50%. This is expected to lead to higher uptake of wind and solar power in the system and thus increase the amount of hours with low electricity cost as well as increase the deployment in earlier periods (vRE case). Thirdly, we limit the biomass available in the model to capture the risks associated with biomass, such as competition with food that may reduce the amount available for energy purposes or general production uncertainties. This is expected to limit the biofuels production and thus increase the need for alternative fuels. At the same time, there is also less carbon that can be circulated via biomass, so other circulation options may become more attractive (Low bio case). Fourthly, as hydrogen is difficult to transport, it is possible that it will be used only in applications that don't require large distribution networks. We thus assume that hydrogen can be used in heat and electricity production but not in transport, No H2 in transport case. This will reduce the number of carbon free options in transport sector and may thus boost electrofuels. Finally, we analyse a case where public opposition to carbon storage makes it impossible to store carbon but the capture from various sources is still allowed. This is also expected to raise the value of carbon and make it more profitable to recycle it (No storage case).

### *Monte Carlo analysis*

As a sensitivity analysis we perform a Monte Carlo analysis where we vary parameters from previous scenarios together with hydrolyser cost that has been identified as the main key parameter together with electricity cost that is endogenous in our model by Brynolf et al. [1]. The latter will be varied as a result of technology cost (vRE) and resource availability (Low bio).

Currently only relation between carbon storage capacity and electrolyser cost has been analysed, as storage possibility seems to have the creates effect on electrofuels and it is unlikely that in the real world there will be no carbon storage available. We vary the storage space

between 0 and 2000 Gtonne CO<sub>2</sub> and the cost of electrolyser between 300 and 1300 USD2010/kW hydrogen produced. More analysis will be performed in the future.

### *3. RESULTS*

#### *Scenario results*

Since electrofuels production consists of several steps, we look at hydrogen production from electricity, methanol production from hydrogen and finally to estimate the potential use of electrofuels in transport sector we look at methanol in transport while considering also the previous steps. Both methanol and hydrogen are products that can be produced from many different feedstock and used in several applications thus it is not possible to say that hydrogen produced from electricity would be used for methanol production but making that assumption would give us the upper limit for possible electrofuel use.

From our preliminary results, we see that very little hydrogen is produced from electricity before 2060, except in no storage and vRE case where production picks up a decade earlier. This is due to other balancing options that are available in the system such as flexible gas generation, hydro power plants and short-term storage. Some electricity is curtailed but the time period of this happening is too short to make it worthwhile to invest into electrolyser. However, at the end of the century when emissions trajectory is more stringent and the share of vRE increases in the system, gas can no longer be used for balancing the system. Also, the amount of hours with over production will increase, making it profitable to produce hydrogen instead of curtailing. All scenarios see some production by 2070 but the level is significantly higher if no carbon storage is allowed (figure 2).



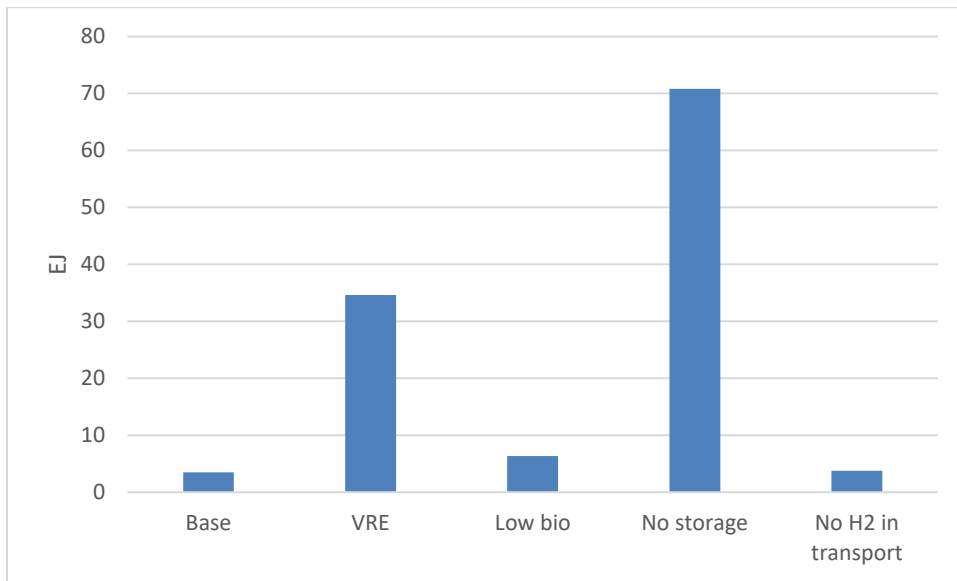


Figure 2. Hydrogen production from electricity by 2070 in different scenarios.

A similar pattern can be seen in methanol production from hydrogen, but cheap vRE has a much more limited effect in this case, as it is cheaper to use hydrogen directly instead of converting it to methanol and thus some of the hydrogen gets absorbed (figure 3).

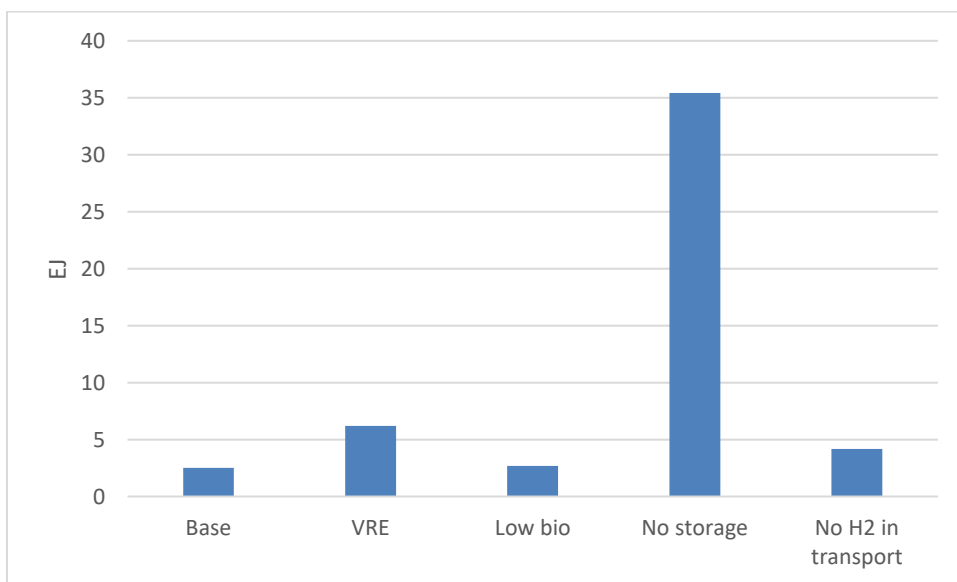


Figure 3. Methanol production from hydrogen by 2070 in different scenarios.

Electrofuels do not enter the solution in significant amount in any other scenario but in no carbon storage case where they reach 19EJ by 2070 making up about 10% of the global transport energy demand (figure 4).

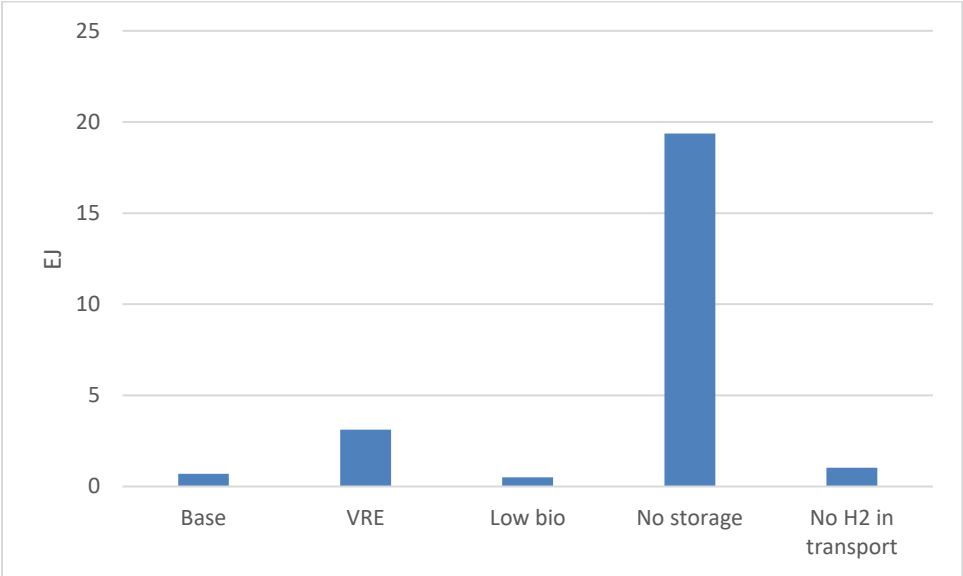


Figure 4. Potential electrofuels production by 2070 in different scenarios.

We also compare the marginal cost of carbon in different scenarios. Again, the scenario with no carbon storage stands out with much higher marginal cost but vRE case has reduced carbon cost compared to base case (figure 5). We can conclude that much high carbon prices are needed to make electrofuels cost-effective.

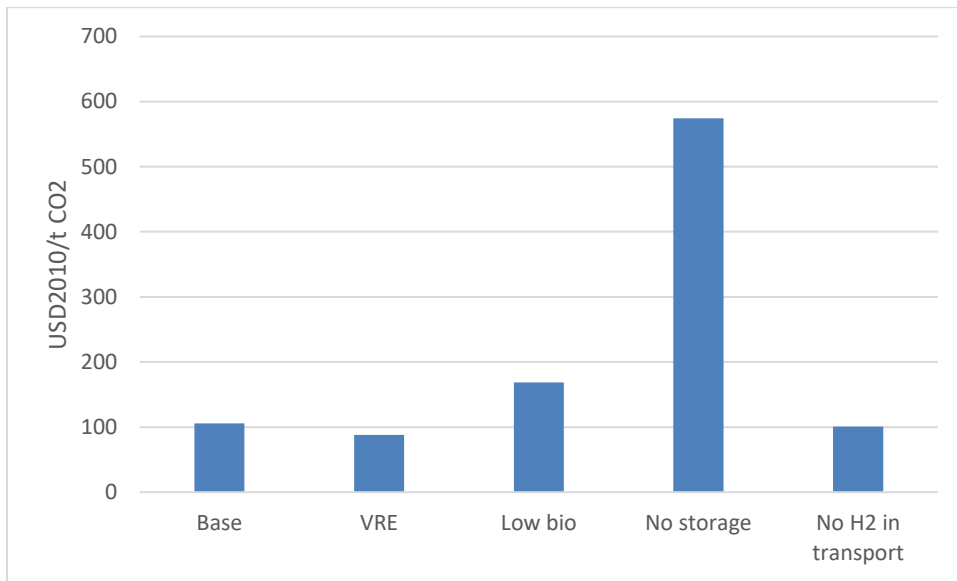


Figure 5. Marginal cost of carbon by 2070 in different scenarios.

The regional distribution of electrofuel potential in no storage case is presented in figure 6. As can be seen, electrofuels have a potential in almost all regions except Pacific OECD but on very different levels with the main potential in Asia (CPA, SAS, PAS) with ca 14 EJ combined by 2070 out of global 19EJ.

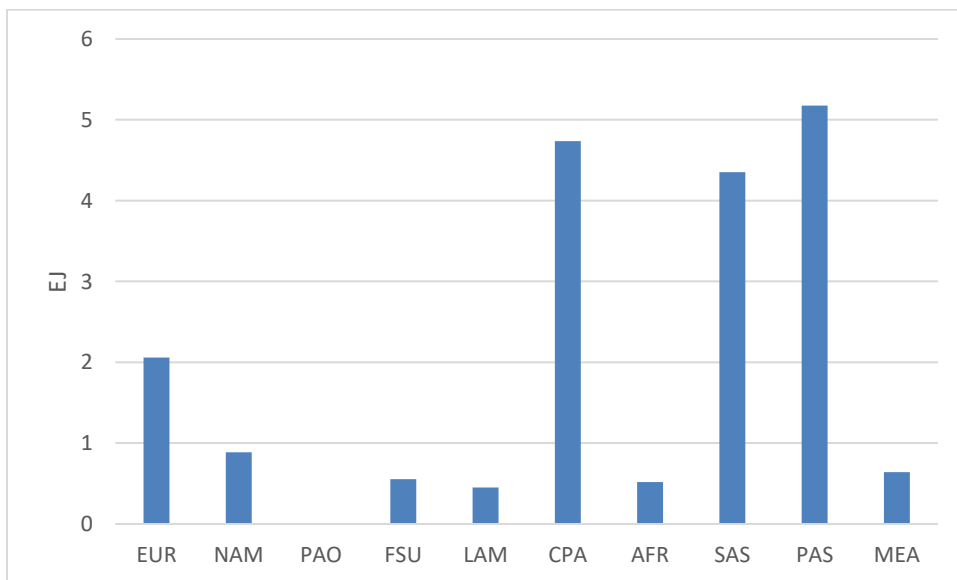


Figure 6. Regional distribution of electro-fuels in no carbon storage scenario at 2070.

We also find that without specific target shipping and aviation will continue to use petrol based fuels and mitigation will take place in other sectors compensating for the emissions created in shipping and aviation.

*Monte Carlo analysis results*

Our results show that there is no correlation between the cost of electrolyser and the potential amount of electrofuels in the system but a very strong correlation between carbon storage availability and electrofuels potential (Figure 7 and 8).

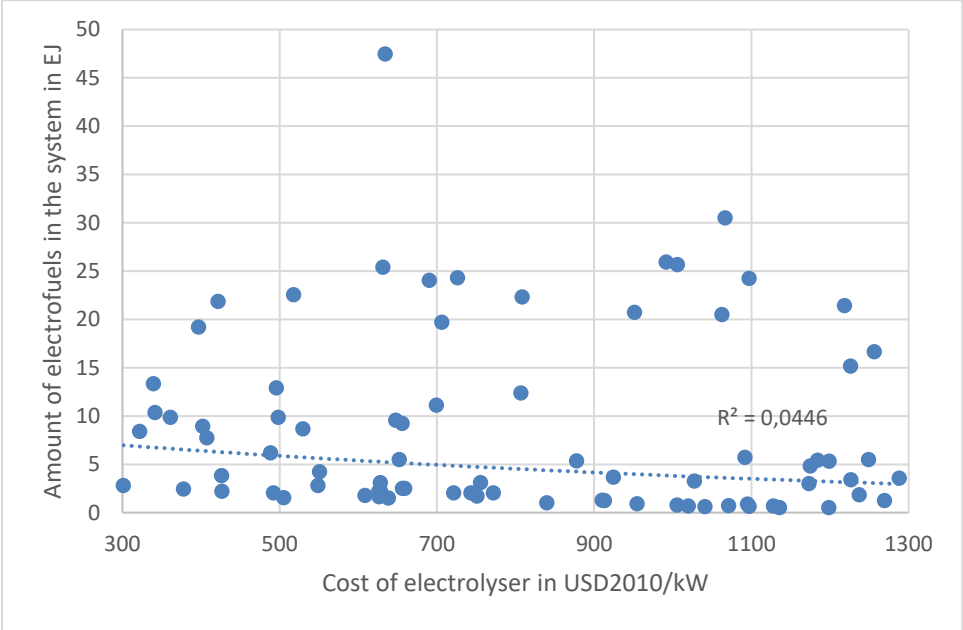


Figure 7. Regional distribution of electro-fuels in no carbon storage scenario at 2070.

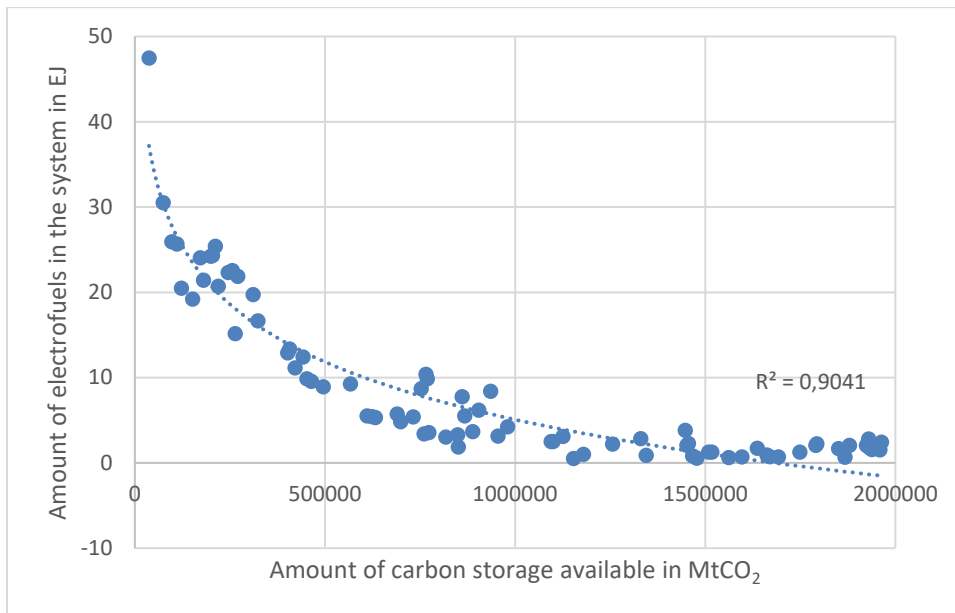


Figure 8. Regional distribution of electro-fuels in no carbon storage scenario at 2070.

#### 4. DISCUSSION

Our analysis finds that electrofuels are not a cost-effective option in most cases. This can be explained by two major factors. First, electrofuels are expensive and energy intensive to produce. Thus, they are out competed by other options when there is room for carbon emissions. Secondly, when carbon budget becomes limited, it becomes also expensive to emit carbon. Therefore, if there is an option to store carbon, it becomes more economical to remove the carbon from circulation and store it rather than reuse it like is the case in making electrofuels. If carbon storage is limited due to technical reasons or public opinion, electrofuels can become cost-effective as complementary fuels that enable to get more energy out per carbon atom before emitting it again.

We also see, that without specific targets aviation and shipping will continue to use petrol based fuels and mitigation of these emissions will take place in other sectors. Whereas this may indeed be the cost-effective solution, it is not clear if it is politically desirable or fair as it violates the “polluter pays” principle.

## 5. CONCLUSIONS

Transport sector is seen as the most difficult sector to decarbonise. In recent years so called electrofuels have been proposed as one option for emissions reduction. Electrofuels – fuels made from electricity and carbon dioxide - can potentially help to manage variations in electricity production and reduce the need for biofuels as well as make use of current infrastructure and can be used in sectors where fuel switch is difficult such as aviation. We investigate the cost-effectiveness of electrofuels under climate mitigation constraint. We draw following conclusions from our analysis:

- The potential for electrofuels is very limited or non-existent in most cases.
- There is a strong correlation between availability of carbon storage and the potential for electrofuels in the system but not between the cost of electrolyser and amount of electrofuels.
- In case of no carbon storage available, electrofuels have a potential of ca 19 EJ globally by 2070, making up ca 10% of transport energy.

## FURTHER WORK

The results presented here are preliminary. More sensitivity analysis will be performed before the conference. Literature review and discussion will also be developed further.

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