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What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation

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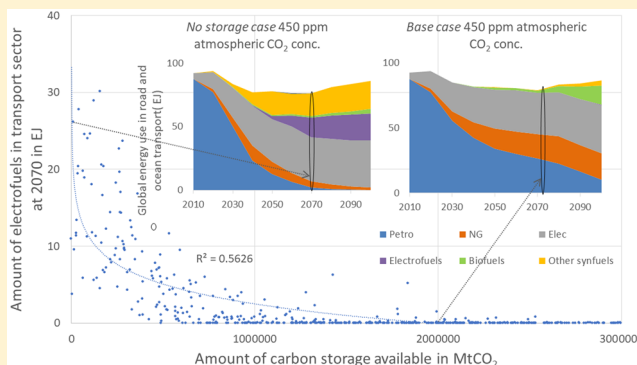
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S Supporting Information

ABSTRACT: The transport sector is often seen as the most difficult sector to decarbonize. In recent years, so-called electrofuels have been proposed as one option for reducing emissions. Electrofuels—here defined as fuels made from electricity, water, and carbon dioxide—can potentially help manage variations in electricity production, reduce the need for biofuels in the transportation sector while utilizing current infrastructure, and be of use in sectors where fuel switching is difficult, such as shipping. We investigate the cost-effectiveness of electrofuels from an energy system perspective under a climate mitigation constraint (either 450 or 550 ppm of CO₂ in 2100), and we find the following: (i) Electrofuels are unlikely to become cost-effective unless options for storing carbon are very limited; in the most favorable case modeled—an energy system without carbon storage and with the more stringent constraint on carbon dioxide emissions—they provide approximately 30 EJ globally in 2070 or approximately 15% of the energy demand from transport. (ii) The cost of the electrolyzer and increased availability of variable renewables appear not to be key factors in whether electrofuels enter the transport system, in contrast to findings in previous studies.



1. INTRODUCTION

The United Nations 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 more than halving current greenhouse gas emissions by 2040,¹ a task that entails radical global transformation of energy conversion and use. The transport sector is currently responsible for about 14% of global greenhouse gas emissions² and is also thought to be one of the most difficult sectors to decarbonize due to, among other things, decentralized decision making and a limited number of alternatives on the market. In recent years, electrofuels have been put forward as one possible option for emission reductions in the transport sector.^{3–9}

Here, we define electrofuels as carbon-based fuels produced from carbon dioxide (CO₂) and water, with electricity as the primary source of energy.¹⁰ Electrofuels are also known as power-to-gas/liquids/fuels, e-fuels, and synthetic fuels. Electrofuels are produced by mixing hydrogen and CO₂ 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 byproducts, namely, high-purity oxygen and heat. Electrofuels are potentially

of interest for all transport modes; they can be used in combustion engines and may not require significant investments in new infrastructure. Thus, if produced from renewable electricity and CO₂ from either sustainable bioenergy (by which we in this article mean primary biomass for bioenergy purposes) or air capture, electrofuels could be a carbon neutral alternative that enables the use of previously made investments in vehicles and fuel infrastructure.

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, to the point of making them competitive with conventional power technologies in some cases.^{11,12} These cost reductions, along with concerns about climate change and energy security, mean that including a significant share of variable renewables (VRE) is the standard in energy system scenarios for the future, not an extreme case. However, since the

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supply from wind and solar technologies is variable in both the short and long term, these technologies challenge the operation of the current power system.^{13,14}

In the traditional electricity system, different power plants are available most of the time and can be dispatched, i.e., brought online, based on their running cost. The outputs of wind and solar PV, however, are highly dependent on the 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 predicted over long time periods. On the other hand, wind and solar technologies tend to be employed when available, due to near-zero running costs. While having some solar power in the energy system can help balance higher daytime demand, employing large amounts of intermittent renewables will quickly start to reduce the intermediate and baseload demand available for other plants and thus their running times and profitability. The effects on the other plants also depend on the amount of intermittent supply in the system and their geographic distribution. Electrofuels could help deal with the variability issue by absorbing excess electricity at windy and/or sunny times, when the price of electricity is low, while possibly also making room for dispatchable generation to run for more hours and thus be more profitable.¹⁵

Biofuels—fuels produced from biomass—are another option for decarbonizing the transport sector. However, the amount of bioenergy that can be produced sustainably is highly uncertain.^{16,17} Climate change is expected to affect the rainfall patterns and thus also bioenergy 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 bioenergy production for energy purposes can come at the expense of food production or lead to deforestation to clear more land for agriculture.¹⁷ Thus, it may be desirable to reduce reliance on bioenergy. Furthermore, bioenergy is a very versatile feedstock that can be used in all energy sectors. As a limited resource, bioenergy may need to be used for sectors where defossilization is technically difficult. Alternatively, bioenergy may be dedicated to applications that allow for carbon capture in order to create negative emissions. Electrofuels production can address these difficulties in two ways. First, since bioenergy contains more carbon than hydrogen, adding extra hydrogen in gasification-based biofuel production would increase the fuel yield. Second, using bioenergy in other sectors, capturing the carbon, and using that carbon to produce electrofuels would increase the energy obtained from biogenic carbon before it re-enters the carbon cycle and also allow for the use of bioenergy in several sectors.

Another possible motivation for electrofuels is the limited number of alternatives for reducing carbon emissions in some transport sectors. Aviation and shipping are usually brought up in this context.^{7,8} Batteries are often considered too heavy for aviation and to have too low energy density for long distance marine transport. Hydrogen faces similar problems, making its use challenging in both aviation and long-distance shipping. Also, new infrastructure needs to be developed for hydrogen, adding another barrier to large-scale adoption. Therefore, carbon-based fuels such as electrofuels and biofuels may be the only feasible alternatives for climate mitigation in these sectors.

Rooted in the possible system benefits discussed above, the aim of this paper is to analyze if and under what conditions electrofuels in transport can be part of a cost-effective solution for mitigating climate change.

2. METHOD

To conduct our analysis, we use the Global Energy Transition (GET) model first developed by Azar and Lindgren¹⁸ and further developed in Grahn et al., Hedenus et al., Lehtveer and Hedenus,^{19–22} and Lehtveer et al.¹³ GET is a cost-minimizing “bottom-up” systems-engineering model of the global energy system set up as a linear programming problem in time steps of 10 years. The model was developed to study carbon mitigation strategies with an objective of minimizing 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 main features in GET 10.0 are shown in Figure S.A.1, with carbon-flow details in Figure S.A.2, in the Supporting Information (SI). The carbon cycle in the model was modified for this study to separate carbon capture from carbon storage and enable reuse of captured carbon. The possibility of capturing CO₂ from the air was also added to the model. The most important aspects and assumptions for assessing the role of electrofuels in transport are described below. More information is available in the SI.

2.1. Model Structure and Assumptions. 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 can meet the demand. Technologies are described by the energy carriers they can potentially convert and are parametrized using, e.g., costs, efficiencies, load factors, and carbon emissions. All prices and costs are in real terms as future inflation is not considered. A global discount rate of 5% per year is used for the net present value calculations. The model has perfect foresight and thus finds the least-cost solution for the entire study period. Consequently, scarce resources such as oil and bioenergy are allocated endogenously to the sectors in which they are used most cost-effectively. We further assume that all technologies are available in all regions as global dissemination of technology is not seen as a limiting factor. In the model, the world is divided into 10 regions. Regional solutions are aggregated to give global results. Demand projections for all sectors except transport are based on the B2 scenarios from the IIASA GGI Scenario Database^{23–25} and further described in the SI.

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 (set, in general, so that it takes 50 years to change the entire energy system), as well as annual or total extraction limits on the respective available energy sources.

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

Variable Renewable Energy Production and Storage. The GET 10.0 version has several categories of solar and wind power: PV rooftop, PV plant, concentrated solar power (CSP) with

Table 1. Data on Cost (USD₂₀₁₀) and Efficiency (%) for Relevant Technologies in the Model for the Base Case and for the Monte Carlo Analysis

Parameter	Starting data for 2010	Mature data for 2050	Min	Max	Distribution
CSP + storage investment cost (USD ₂₀₁₀ /kW)	7000	4500	0.5 × base	1.5 × base	Uniform
Wind onshore investment cost (USD ₂₀₁₀ /kW)	2000	1500	0.5 × base	1.5 × base	Uniform
Wind offshore investment cost (USD ₂₀₁₀ /kW)	5000	3000	0.5 × base	1.5 × base	Uniform
Solar PV rooftop investment cost (USD ₂₀₁₀ /kW)	4000	1600	0.5 × base	1.5 × base	Uniform
Solar PV plant investment cost (USD ₂₀₁₀ /kW)	3700	1250	0.5 × base	1.5 × base	Uniform
Solar H ₂ investment cost (USD ₂₀₁₀ /kW)	4200	2500	0.5 × base	1.5 × base	Uniform
Electrolyser investment cost (USD ₂₀₁₀ /kW)	1300	500	0.6 × base	1.4 × base	Uniform
Electrolyser efficiency (%)	80	80	65	85	Uniform
Synthesis reactor investment cost (USD ₂₀₁₀ /kW)	625	375	0.66 × base	1.33 × base	Uniform
Synthesis reactor efficiency (%)	89	89	69	95	Uniform
Bioenergy availability (EJ/year)	134	134	0.5 × base	1.5 × base	Uniform
Global carbon storage capacity (Gtonne CO ₂)	2000	2000	0	3000	Uniform
CO ₂ storage cost (USD ₂₀₁₀ /tonne)	10	10	0.5 × base	1.5 × base	Uniform
Direct air capture cost (USD ₂₀₁₀ /tonne)	500	500	0.06 × base	1.8 × base	Uniform
Fuel cell investment cost (cars, trucks, buses) (USD ₂₀₁₀ /kW)	97.5	65	0.69 × base	1.31 × base	Uniform
Fuel cell investment cost (shipping) (USD ₂₀₁₀ /kW)	1335	890	0.56 × base	1.44 × base	Uniform
Fuel cell investment cost (stationary sector) (USD ₂₀₁₀ /kW)	1200	800	0.5 × base	1.5 × base	Uniform
H ₂ in transport (USD ₂₀₁₀ /kW)	Possible	Possible	Not possible	Possible	Binary
Infrastructure cost for road transport with synfuels (USD ₂₀₁₀ /kW)	1200	1200	800	1600	Uniform
Infrastructure cost for road transport with H ₂ (USD ₂₀₁₀ /kW)	2700	2700	2500	3100	Uniform
Infrastructure cost for ocean transport with synfuels (USD ₂₀₁₀ /kW)	200	200	100	300	Uniform
Infrastructure cost for ocean transport with H ₂ (USD ₂₀₁₀ /kW)	2100	2100	1800	2400	Uniform

storage, onshore wind, and offshore wind. These five categories each have five resource classes. GET has a single demand node for each region; i.e., the electricity grid is not explicitly modeled.

The model uses resource-based time slices, meaning that instead of selecting time slices primarily based on the time of day and season, we select slices based on the level of wind and solar generation. For example, a slice called “high solar, medium wind” would aggregate together all hours that are described by this label, irrespective of when during the year they occur. The slicing is performed individually for each model region. The data for resource potentials and slicing is provided by GIS analysis described in detail in Lehtveer et al.¹³ The model includes direct electricity storage options for 12, 24, 48, and 96 h. For long-term electricity storage, hydrogen is used. Hydrogen produced from electricity can also be used in other sectors or be converted to electrofuels, thus absorbing electricity when the production cost is low. Along with hydropower and flexible thermal generation (gas, bio), these options balance the variations in wind and solar power. For more information, see the PDF version of the SI.

Hydrogen and Electrofuel Production. 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 analyses can be performed, but if methanol is not cost-effective, no other electrofuel will be either. For biofuels, coal-to-liquids, and natural-gas-to-liquids, we also use data for methanol production as a proxy.

A literature review study conducted by Brynolf et al.³ shows that the cost of the electrolyzer and the price of electricity are the major determinants of the cost of electrofuels. In the GET model, the cost of the electrolyzer is set exogenously (Table 1), while the electricity price and load factors for electrolyzers are endogenous variables, determined by the model in the course of minimizing the total system cost.

Being able to capture intermittency and its connection to hydrogen production is important in analyzing the potential for electrofuels. For this purpose, hydrogen production was sliced in

accordance with the variable renewable based slices, allowing the model to see differences in electricity prices while producing hydrogen.

Transport Sector. The transport sector includes personal transportation and freight. Cars and buses, trucks, short sea, deep sea, and container ships are represented by energy demand along with technology cost and efficiency data, while rail and air are only represented by energy demand. The model does not distinguish between gasoline, diesel, and jet fuels, which are lumped together as petroleum-based fuels (petro). In the model, a generic synfuel technology is used as a proxy for any liquid fuel other than petroleum-based liquid fuels such as methanol and Fischer–Tropsch diesel. The synfuel may be generated from bioenergy, coal, natural gas, and hydrogen combined with CO₂ (electrofuels), and CCS may be applied to the emissions generated in the production process. The other energy carriers available for transport are natural gas, hydrogen, and electricity. Cars, trucks, and buses can choose between internal combustion engines, hybrid electric, plug-in hybrid electric, battery electric, and fuel cells, while ships can only choose between combustion engines and fuel cells. For technology performances and costs, see the SI.

2.2. Cases. In this study, we test five different cases rooted in the motivations for electrofuels presented above. In *Base*, we run our model with no additional modification. In *VRE*, we lower the mature 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 energy system and thus increase the number of hours with low electricity cost as well as increase the deployment of these technologies in the first part of the century, possibly creating beneficial conditions for electrofuels. In *LowBio*, we reduce the bioenergy available in the model by half to capture the risks associated with bioenergy, such as competition with food that may reduce the amount of biomass available for energy purposes. This is expected to limit biofuels production and thus increase the need for alternative transport fuels. In *No H2 in*

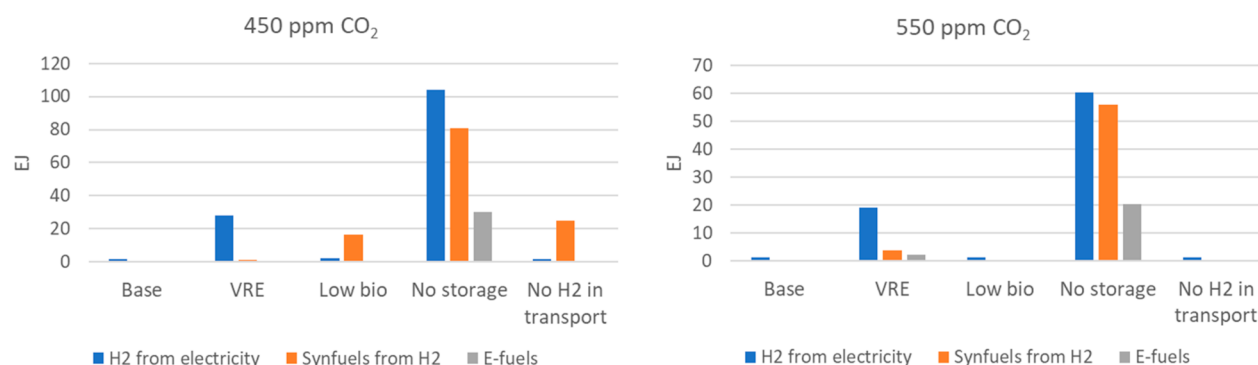


Figure 1. Total amount of hydrogen produced from electricity, total amount of synfuels produced from hydrogen, and maximum amount of electrofuels in the transport sector in 2070 for the five cases, in the 450 ppm scenario (left) and 550 ppm scenario (right). Note that the scales on the axes differ.

transport, we take into account that hydrogen is difficult to transport (and might therefore only be used in applications that do not require large distribution networks) and assume that hydrogen can be used in heat and electricity production but not in the transport sector. This will reduce the number of climate-friendly options in the transport sector and could boost electrofuels. Finally, in *No storage*, we analyze a case where public opposition to carbon storage makes it impossible to store carbon, but the capture of it from various sources is still allowed. This is expected to raise the price of carbon and make it more profitable to recycle carbon. Each case is run with two different cumulative carbon emission constraints, corresponding to atmospheric CO₂ concentrations in 2100 of 450 and 550 ppm of CO₂, respectively.

2.3. Monte Carlo Analysis. To examine the sensitivity of our results to the parameter values, we performed Monte Carlo (MC) analyses varying the electrolyzer cost, which along with the electricity price was identified as the key parameter in Brynolf et al.³, and parameters from the five different cases. In addition, we vary the cost of synfuel production from hydrogen, investment cost of fuel cells, infrastructure cost for synfuels and hydrogen, and direct air capture cost. Cost variations are summarized in Table 1. Most variables were varied uniformly, except for the possibility of using hydrogen in transport, which was treated as a binary variable. The climate target was set to 450 ppm of CO₂ for the MC analysis. In total, we performed 500 model runs with carbon storage available and 500 without that option.

3. RESULTS

To estimate the maximum potential for cost-effective use of electrofuels in the transport sector, we analyze results for hydrogen production from electricity, synfuel production from hydrogen, and synfuel use in transportation. Hydrogen produced from electricity will not necessarily be used for synfuel production nor will synfuels produced from hydrogen necessarily be used in transport. However, assuming the contrary gives an upper limit for potential electrofuel use in the model. The potential for electrofuels is calculated as the amount of synfuels in the transport sector that can be provided from hydrogen subject to the limit of hydrogen from electricity, assessed on the regional level. All analyzed results refer to the year 2070 if not stated otherwise.

3.1. Case Results. Here, in the main article, we focus on presenting the results related to electrofuel production. Results related to general energy system composition such as primary

energy use, electricity mix, biomass use, and fuel use in the transport sector, are presented in the SI. In the model, hydrogen is used directly as a transportation fuel and to produce synfuels, store electricity, and, in some cases, generate industrial heat. The total amount of hydrogen cost-effectively produced in the model varies from 40–221 EJ in the 450 ppm scenario and from 6–162 EJ in the 550 ppm scenario, with the highest production in *Low bio* and *No storage* (Tables S.A.12 and S.A.13). In the 450 ppm scenario, in all cases, hydrogen is deployed from 2020 on but at a very low level, with production increasing gradually over the century. As an energy carrier, hydrogen is costly to produce and use, and the model finds other options to satisfy energy demand at the beginning of the century. Prior to 2060, there is only little hydrogen produced from electricity, except in *No storage* and *VRE*, in which hydrogen production is significant already by 2050. In the former, *No storage*, hydrogen production from electricity starts by 2040 already. From the perspective of the electricity system, there are less expensive options for balancing supply available, such as flexible gas generation, hydropower plants, and short-term storage. Some electricity is curtailed but too briefly to make investments in electrolyzers worthwhile. However, at the end of the century when emissions need to be close to zero, natural gas can no longer be used to balance the system. Further, the share of VRE increases at the end of the century, increasing the number of overproduction hours. Thus, investing in electrolyzers to produce hydrogen becomes profitable. In both climate scenarios, all cases show some hydrogen production from electricity by 2070, but the level is significantly higher when no carbon storage is allowed (*No storage*) and when variable renewables are cheap (*VRE*) (Figure 1). The effect is also much stronger in the 450 ppm scenario, compared to 550 ppm.

The total amount of synfuels that can be produced cost-effectively is greatest in *No storage* (84 EJ for 450 ppm and 62 EJ for 550 ppm), approximately twice as high as in *Base*, *VRE*, and *No H2 in transport*, and four times as high as in *Low bio* (Tables S.A.14 and S.A.15). Regarding synfuels specifically produced from hydrogen, production is the greatest when carbon storage capacity is assumed to not exist (Figure 1). In the 450 ppm scenario, there is also a significant amount of synfuels in *Low bio* and *No H2 in transport*. Inexpensive VRE has a limited effect on synfuel production from hydrogen, as it is cheaper to use hydrogen directly instead of converting it into synfuels, so most of the hydrogen gets used directly.

Electrofuels are not present in significant amounts in the transport sector in any case other than *No storage*, in which they

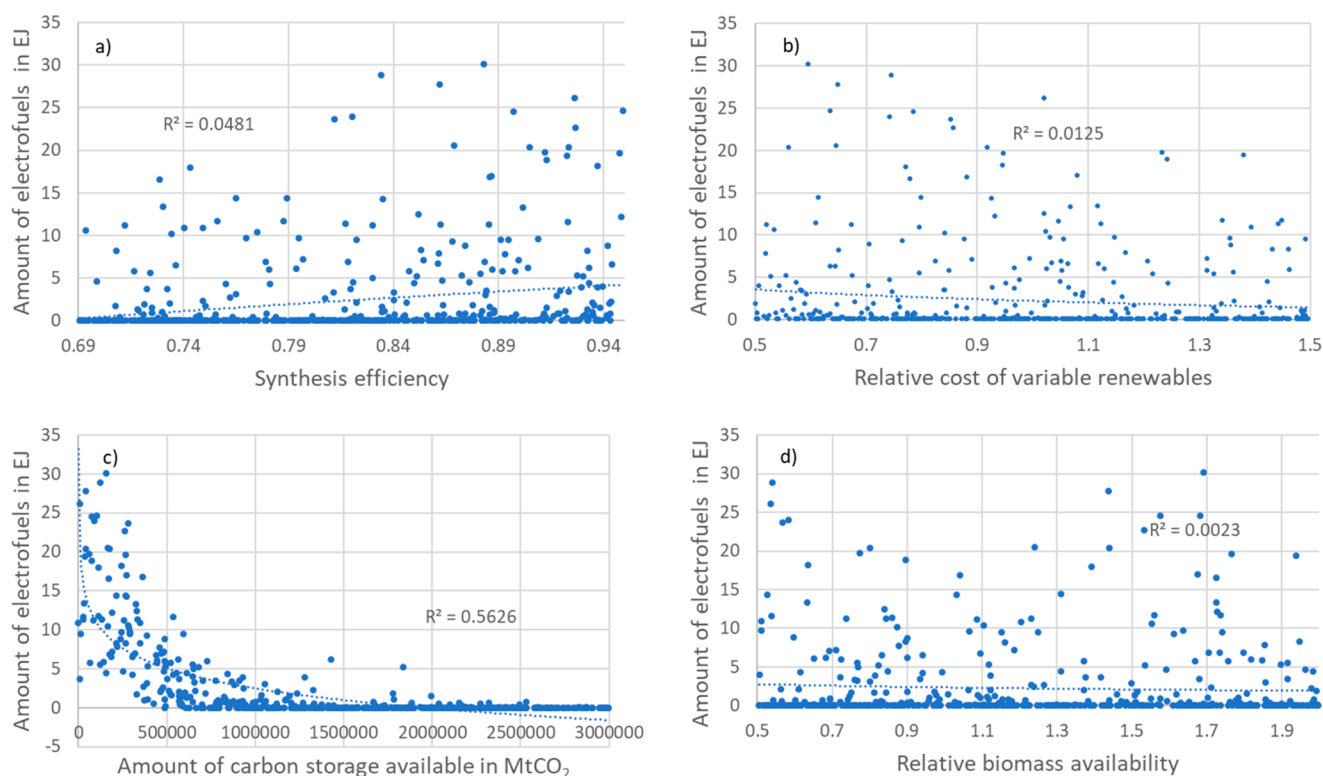


Figure 2. Monte Carlo analysis showing the potential for cost-effective use of electrofuels in the global transport sector in 2070 for 500 runs plotted against (a) the synthesis efficiency, (b) the relative cost of variable renewables, (c) the availability of carbon storage, and (d) the relative biomass availability.

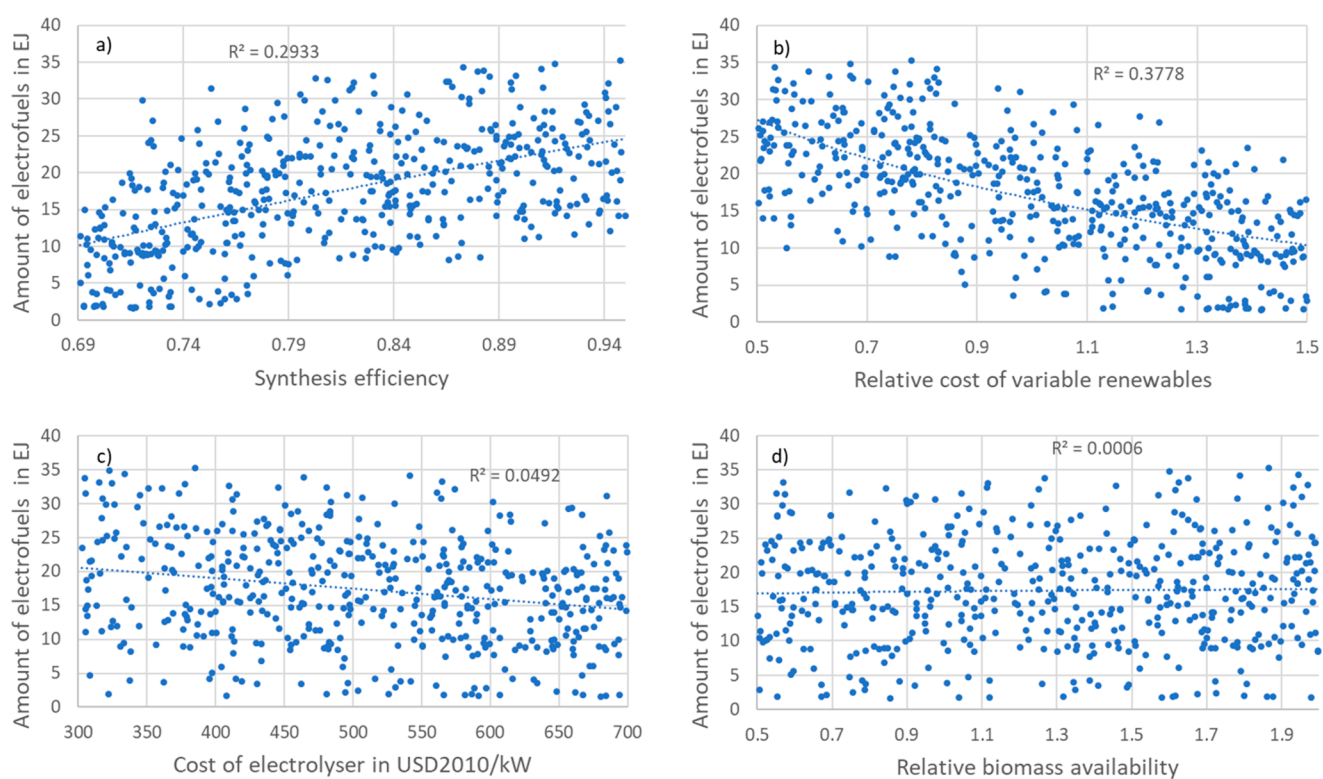


Figure 3. Monte Carlo analysis showing the potential for cost-effective use of electrofuels in the global transport sector in 2070 in *No storage* (no carbon storage) for 500 runs plotted against (a) the synthesis efficiency, (b) the relative cost of variable renewables, (c) the electrolyzer cost, and (d) the relative biomass availability.

reach approximately 30 EJ in the 450 ppm scenario, supplying about 15% of the global transport energy demand. In *Low bio*,

synfuels produced from hydrogen are used in industry instead of in the transport sector.

3.2. Monte Carlo Analysis Results. The results from the MC analysis are plotted as the potential amount of electrofuels in the transport system in 2070 depending on the sensitivity ranges of various assumptions, e.g., the carbon storage availability. The amount of electrofuels ranges from 0 to 30 EJ in the MC runs, with a median value of 0 EJ when all chosen parameters are varied. Our results show that there is a significant correlation between the availability of carbon storage and the potential amount of electrofuels ($R^2 = 0.56$) (Figure 2c). When storage availability is low, electrofuels can be a cost-effective climate mitigation solution for transport; they are present in all cases when global carbon storage availability is less than 500 GtCO₂ (compared to 2000 GtCO₂ in *Base*). The synthesis efficiency for electrofuels, relative cost of VRE, and biomass availability explains almost no variability in the amount of electrofuels in the system (Figure 2a,b,d). All other studied parameters show no correlation (more results are shown in Figure S.A.8).

To further investigate the factors that influence the introduction of electrofuels in *No storage*, we ran the MC analysis of the model for that case, too. However, it should be kept in mind that this represents an extreme case. The amount of electrofuels ranges from 2 to 35 EJ with a median value of 17 EJ. There is a correlation between the amount of electrofuels in the system and the cost of VRE and ($R^2 = 0.38$) and the efficiency of the synthesis plant ($R^2 = 0.29$) (Figure 3), as well as with whether hydrogen is allowed in transport sector ($R^2 = 0.12$) (Figure S.A.9). However, bioenergy availability has no explanatory power for the amount of electrofuels employed. With low availability of bioenergy, the amount of CO₂ that can be recirculated in the energy system is limited. With high availability, cheaper biomass-based fuels can satisfy the transport demand. Further, the production cost of electrofuels is dominated by the cost of electricity, of which the cost of CO₂ is a minor share. Therefore, the availability of other options for transport and low-cost electricity production determines whether electrofuels enter the system.

CO₂ from direct air capture (DAC) in combination with electrolytic hydrogen can form a closed loop with no net CO₂ emissions to the atmosphere. This makes it interesting to investigate how the cost of DAC affects the cost-effectiveness of electrofuels production. However, the MC analysis did not show any significant correlation between the cost for DAC and the cost-effective potential for electrofuels in the transport sector (Figures S.A.8 and S.A.9).

4. DISCUSSION

We find that electrofuels are not a cost-effective option in the global transportation sector, in most cases, for two major reasons. First, electrofuels are more expensive than the other fuel options, and production is energy intensive. Thus, other options out-compete electrofuels when there is room for carbon emissions. Second, with a limited carbon budget, emitting becomes expensive. Therefore, if there is an option to store carbon, it becomes more economical to remove the carbon from the system and store it, rather than to reuse it to produce, for instance, electrofuels, that reemit the carbon when used. However, if carbon storage is severely limited for technical reasons, or due to public opinion, electrofuels can become cost-effective as complementary fuels. Although not analyzed here, the same dynamics would hold for even more ambitious targets, such as limiting average global warming to 1.5 °C.

Synfuels are used as both feedstock and transportation fuel in the model, with the former use greater than the latter in all cases. The synfuel fraction used in transportation (0%–24%) can be biofuels, electrofuels, or other synthetic carbon-based fuels. The cost-effective potential for biofuels can fulfill almost all synfuel use in the transport sector in the model in all cases except *Low bio* in the 450 ppm scenario and *No storage* in both. In these three cases, the cost-effective potential for electrofuels is greater than for biofuels. There is no case in which electrofuels can meet the total synfuel demand from the transport sector cost-effectively.

During the second half of the century in the 450 ppm scenario, and toward the end of the century in the 550 ppm scenario, petroleum- and natural-gas-based fuels are replaced by electricity and synfuels and in some cases hydrogen in the transport sector (Figure S.A.4). Neither electrofuels nor biofuels are shown to dominate the fuel mix in transport during this century in any of the investigated cases. However, the cost-effective potential for biofuels is higher than for electrofuels in most cases. All synfuels have one problem in common, though: they all contain carbon atoms, so burning them releases carbon to the atmosphere. Our results are in line with previous results that have shown that it is more cost effective to use the bioenergy in the heat sector, where carbon can be captured and stored more efficiently than in the transport sector.²⁶

Interestingly, the model chooses to introduce electrolyzers at very low load factors in the energy system. In many cases, the load factor is between 10%–30% of the maximum production capacity for the year. Earlier studies have shown that the production cost per MWh of electrofuels increases dramatically at load factors less than 40%–50%.³ The current results are due to the model optimizing over both balancing electricity production and producing useful energy products as well as due to the perfect foresight assumption that allows model to assess the cost of investing in a technology over the whole model horizon with no uncertainty. This, however, is not representative of the situation real investors are facing.

The costs for hydrogen distribution infrastructure and hydrogen storage in vehicles are uncertain and may be under- or overestimated in the model. However, even in *No H2 in transport*, the cost-effective potential for electrofuels is very low, for either climate constraint. In *Low bio*, hydrogen is only cost-effective in road and ocean transport during the second half of the century.

Direct hydrogen production from concentrated solar power competes with electrolytic hydrogen production. The greatest share of hydrogen produced from electricity is found in *VRE* and *No storage*. We also see a large amount of hydrogen produced from concentrated solar power in these cases as the whole energy sector moves toward a hydrogen economy.

Electrofuels mainly enter the model when storage capacity is low. Several studies, e.g., Fridahl and Lehtveer,²⁷ have shown that current acceptance of carbon capture and storage (CCS) technologies is low. However, if climate targets are prioritized, the cost of providing energy will increase and will do so more steeply without CCS availability.²⁸ Faced with a choice between CCS and steep rises in energy prices, the public may be more inclined to accept CCS.

Model Limitations. Our model comes with important caveats that should be kept in mind while interpreting results. The GET transport sector does not include any representation of consumer choice. Instead, vehicles are chosen based on cost. However, all vehicles in the model are normalized to provide the

same utility in terms of kilometers traveled. Therefore, the solution provided here is optimal from a social planner's view but may not materialize without other policies in addition to a carbon tax. Similarly structured models have taken steps to improve consumer representation;²⁹ future versions of this model could consider this.

Furthermore, there is no representation of demand response in our model. Some of the demand reduction and efficiency improvements resulting from higher prices related to climate change mitigation have been taken into account in the IIASA demand data that we use in our model, but there is no variation in demand among our cases. Since the model has to satisfy the exogenously given demand, it can result in more expensive technologies employed than would be the case in the real world where reducing demand is an option. That may reduce the cost-effective amount of electrofuels.

Another limitation is that our model represents intermittency and energy demand variations in a stylized and aggregated manner. Thus, the results presented here should be seen as qualitative not quantitative. More detailed models will provide more in-depth insights on the operation of electrolyzers and storage. However, our model captures the general system dynamics of the effect of intermittency.

Our results show that cost-effective use of electrofuels in the transport sector is relatively limited in a world where large-scale storage of carbon is available. In this article, we have only assessed the use of electrofuels in road and ocean transportation. Air transportation constitutes a large fraction of the energy demand in the model, and electrofuels could prove of interest in decreasing the climate impact from aviation.⁸ However, the model does not currently represent air transportation with sufficient detail to assess the role of electro-jet fuels. This version only includes fuel costs, not technology costs, for aviation. With no investment cost for the aircraft, the fuel with the lowest cost, taking into account scarcity of resources and cost of emitting CO₂, will be chosen for this sector. Results for air transportation show petroleum-based jet fuel at the beginning of the century and hydrogen at the end. However, electrofuels do not enter aviation sector in *No H2 in transport*, suggesting a limited potential.

The model only includes a limited number of technologies and energy carriers; including more options could change the results. Ammonia, for example, is a carbon-free fuel that can be produced from electrolytic hydrogen and help balance the energy system while avoiding the cost of emitting or capturing carbon. However, ammonia faces many other challenges, and its potential role needs further investigation.

■ ASSOCIATED CONTENT

■ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b05243.

Detailed model description; tables with results for hydrogen production, synfuel production, and electrofuel potential; figures with fuel use in the transport sector, composition of electricity generation, composition of primary energy use, and use of biomass, marginal cost of carbon by 2070; additional results from Monte Carlo simulations. (PDF)

Investment costs used in the model. (XLSX)

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Notes

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