The Next Generation Policies Project

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Renewable synthetic fuels and their potential for climate change mitigation

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Key Points

- Synthetic fuels from renewable electricity ("e-fuels") are increasingly considered as CO_2 emission reduction option for non-electric energy demands, e.g., in transportation.
- A crucial shortcoming of e-fuels is the low conversion efficiency of their production and utilization in combustion processes. Battery electric vehicles require around five times less electricity input than combustion engine cars powered by e-fuels.
- Due to their low conversion efficiency, e-fuels only yield a meaningful climate benefit if renewable electricity is used for their production. If produced from the current German electricity generation mix, using e-fuels results in around three times higher GHG emissions than conventional petrol.
- E-fuels are also a relatively high-cost climate change mitigation option, with prospective future CO_2 emissions abatement costs of around 400 € per ton CO_2.
- Key benefits of e-fuels lie in their storability and transportability, thus helping to overcome temporal and spatial variability of renewable energy supply.
- Despite their disadvantages compared to direct electrification, e-fuels might become a crucial energy carrier for aviation, freight transport and other end-uses that are difficult to electrify.

1. Limited remaining CO_2 budget within Paris targets

In the Paris Agreement, nations agreed to limit global warming to well below 2°C while pursuing efforts to limit it to 1.5°C. The remaining carbon budget (i.e., the cumulative net global CO_2 emissions from 2018 to the time that CO_2 emissions reach net zero) for limiting global warming to below 1.5°C is estimated to be approximately 320 gigatons (Gt) of CO_2 - or less than 10 years' worth of current emissions [1], [2]. The budget for staying below the 2°C threshold is approximately 1070 Gt of CO_2 - or 26 years of current emissions.

Climate protection strategies derived from detailed energy-economy-climate models show that the Paris climate targets can still be achieved. However, they require systems transformation at unprecedented speed and scale [2]–[4]. These pathways also exhibit a fundamental difference between the decarbonization of electric and non-electric energy. Electric energy can be produced from renewable resources, in particular wind and solar power, at relatively low cost [3]. By contrast, non-electric fuels for the transportation, industry and buildings sectors – currently largely supplied from fossil fuels – are much more difficult to replace. To achieve stringent climate targets, CO_2 emissions from these non-electric energy demands will also have to be reduced drastically.

2. Synthetic e-fuels to overcome decarbonization bottlenecks

In view of the challenges with non-electric energy demands, synthetic hydrocarbon fuels produced from renewable electricity (henceforth: "e-fuels") are increasingly debated as a technology option to overcome decarbonization bottlenecks.

The basic concept is depicted in Fig. 1: Electricity can be converted into hydrogen via electrolysis. The hydrogen can then be reacted with CO_2 – captured from other processes or from the atmosphere – to produce methane or longer-chained liquid hydrocarbon fuels. Using current technologies, these e-fuels can be used to substitute conventional fossil fuels in the transport, building and industry sectors. An additional benefit is the comparative ease of storage (especially long term, i.e., for more than one day) and global transport potential, see Section 7), in contrast to the electricity they were produced from.

E-fuel is, however, not without its drawbacks. Its production and combustion is relatively inefficient (further elaboration in Section 4), which results in comparably high costs and limited climate change mitigation potential, as elaborated in Sections 5 and 6. Note that we here focus much of the quantitative discussion on synthetic e-gas, a technology for which due to its maturity, data is readily available. The results can be expected to apply in similar form to liquid e-fuels.

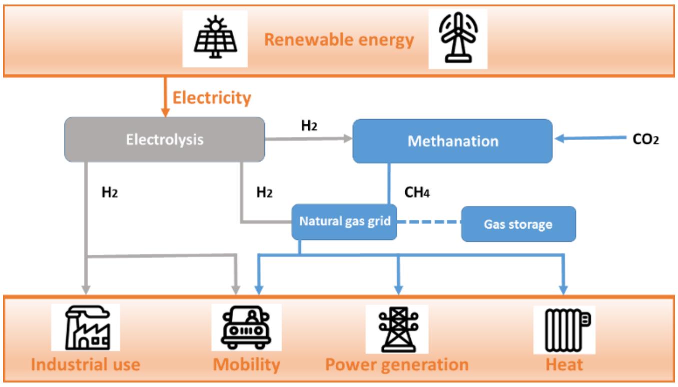

Figure 1: Synthetic renewable fuel generation and use. Electricity is converted into hydrogen and subsequently reacted with CO_2 to produce methane or longer-chained liquid hydrocarbon fuels. These e-fuels can be used to substitute conventional fossil fuels in the transport, buildings and industry sectors using current technologies.

3. The CO_2 source matters!

As the production of e-fuels utilizes zero-emission hydrogen produced from renewable electricity in combination with CO_2, they exist as a climate friendly alternative to conventional fuels. However, the source of CO_2 is an important determinant of their climate mitigation potential.

Re-utilization of CO_2 of fossil origin (Fig. 2, left), e.g., CO_2 from a traditional coke-based steel plant, for the production of e-fuels still results in a net flow of CO_2 from geological reservoirs to the atmosphere. On the system level, such double-utilization of CO_2 can at best yield a halving of emissions, if efficiency losses and leakage are ignored. It is thus not compatible with the long-term carbon neutrality requirement prescribed by the Paris climate targets. Combusting e-fuels that contain fossil carbon still results in CO_2 emissions and drive climate change.

Assuming renewable based energy inputs, if CO_2 from biomass or air capture is used instead (Fig. 2, right), e-fuels can become carbon neutral. When combusting e-fuels, CO_2 of atmospheric origin is emitted back into the atmosphere, giving rise to a closed carbon cycle. This full recycling of CO_2 can lead to starker emission reductions, even though this process requires more land (mainly biomass) or energy (air capture).

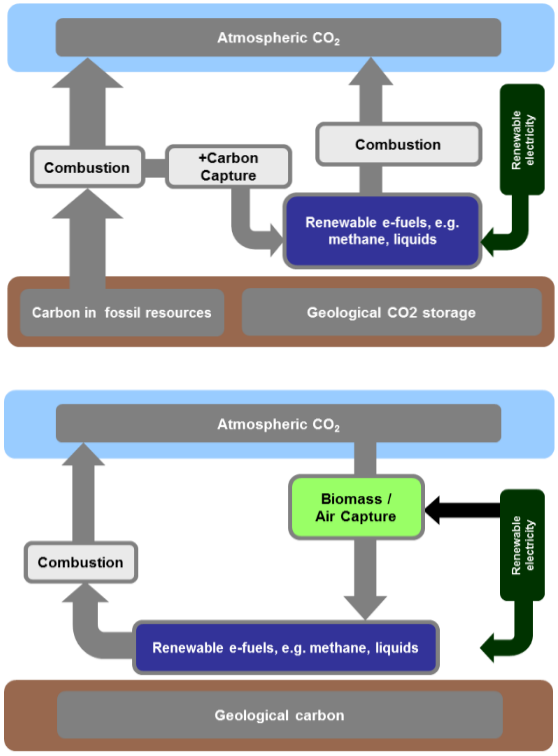

Figure 2: Carbon flows associated with using CO_2 in e-fuels when using CO_2 from fossil (above) and non-fossil sources, i.e., biomass and air capture (below). Using CO_2 of non-fossil origin creates a carbon cycle which is compatible with global emission neutrality requirements.

4. Energy conversion efficiency

E-fuels are an *indirect* form of electrification. For many end uses they compete with *direct* electrification alternatives, which are substantially more energy efficient. Using e-fuels in an internal combustion engine (ICE) vehicle requires about five times more renewable electricity than directly using electricity in an equivalent battery electric vehicle traveling the same distance.

The e-fuel route is less efficient for two reasons: Firstly, generating a hydrocarbon fuel from electricity currently requires at least two conversion steps with compounding efficiency losses, in addition to energy inputs when capturing CO_2 from the air [5], [6]. Secondly, converting chemical energy of a fuel into mechanical energy in a combustion engine is an inefficient process, especially compared with an electric engine. The values shown in Fig. 3 are indicative of relevant orders of magnitude – exact values can vary for specific types of electrolysis, synthesis or fuel (e.g., gaseous or liquid). Additional losses from energy transport and storage are neglected.

The low overall energy conversion efficiency of e-fuel in combination with ICEs restricts its full domestic implementation in countries with limited renewable energy resource potential, for instance in Europe. It further has important implications for the effectiveness of e-fuels as a climate change mitigation option, and makes e-fuels a rather expensive climate change mitigation option, as the calculations in the following two sections demonstrate.

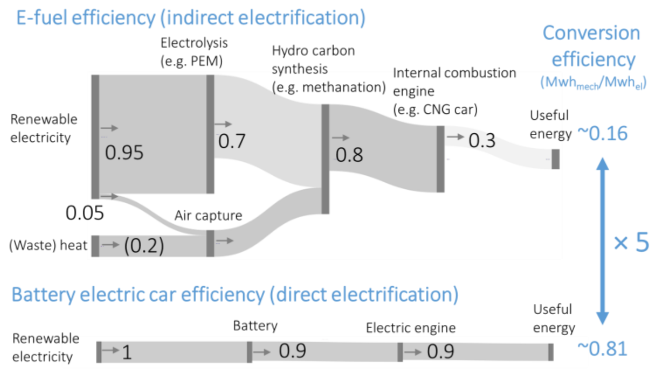

Figure 3: Energy efficiencies for major conversion steps from electricity input to kinetic output for e-fuel vehicles (top) and battery electric vehicles (bottom). The e-fuel route consumes five times more renewable electricity than the battery electric vehicle.

5. Effectiveness as climate change mitigation option

With the current German electricity mix, e-fuels produce around 3 times more greenhouse gases than the equivalent amount of conventional diesel, see Fig. 4 on the left (turquoise bar) [7]. E-Fuels only match diesel vehicle CO_2 emissions at a carbon intensity of 100 gCO_2 equivalents per kWh – corresponding to an electricity supply system with at least 80% low-carbon generation. Only for truly renewable-based power supplies do e-fuels become an effective mitigation option.

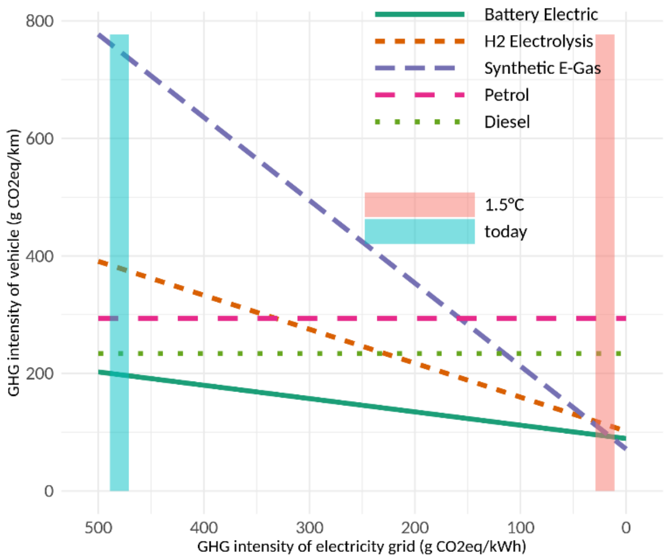

Figure 4: Greenhouse gas intensity of LDVs from a life-cycle perspective as a function of the CO_2 intensity of electricity generation. Turquoise bar on the left indicates CO_2 intensity of German electricity generation, red bar indicates 2050 CO_2 intensity compatible with the 1.5°C target.

Battery electric vehicles, by contrast, have GHG emissions that are comparable to or lower than those of diesel cars already at today's German electricity mix. The further decarbonization of power supply mandated by the *European Union's Emissions Trading System* and the *Renewable Energy Directive* will increase the mitigation effectiveness of electric vehicles over the course of the coming decade.

6. Economic performance

E-Fuels' generation costs are comparatively high, both due to high energy input costs and high capital costs, especially for electrolysis. This results in present day generation costs for synthetic natural gas of around 240 € per MWh, compared to fossil natural gas costs of around 30 € per MWh. It is often argued that e-fuel production can benefit from cheap or even zero-cost renewable over-production in times of high solar and wind generation and low load. However, if only such excess renewable electricity were used, electrolyzers could only be operated at 1000-2000 full load hours per year (compared to the 8760 hours that there are in a year), making the capital-intensive equipment uneconomical. Detailed techno-economic analysis suggests that cost-optimal operation requires at least around 4000 annual full load hours.

There is substantial potential for cost regression in e-fuel production. On the one hand, innovation in energy conversion technologies, in particular electrolyzers, will reduce capital costs for future installations. Further cost decreases can be realized by generating the e-fuels at locations with high quality and low-cost wind and solar resources [8], [9]. In combination, these could reduce e-fuel generation costs to around 130 € per MWh. This level implies that a CO_2-price of around 400 €/t CO_2 would be required to make e-fuels competitive, even under optimistic assumptions regarding cost regression potentials. The exact CO_2 abatement cost of e-fuels depends on future cost development assumptions of the e-fuels production and the fossil resource price development [10], [11].

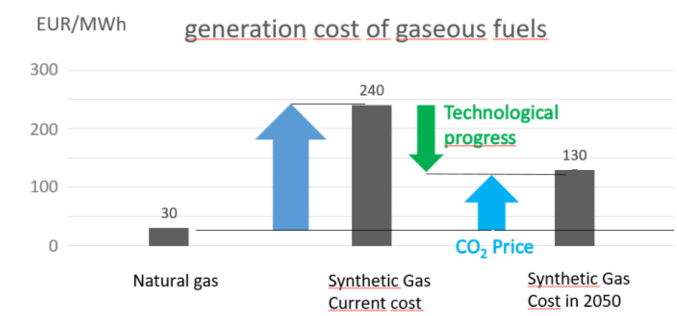

Figure 5: Future cost competitiveness of synthetic fuels and fossil fuels.

7. E-fuels allow transport and storage of renewable energy

Renewable energy potentials vary substantially across regions, and also have a distinct seasonal pattern in most world regions. The discrepancies between supply and demand are among the greatest barriers hindering a large-scale switch to a fully renewable-based energy system. For instance, the high demand seen in winter months coincides with low sunlight availability. Also, heavily populated and industrialized demand centers have only modest wind and solar potential, while the Subtropics and especially the MENA region, Latin America, and Australia have considerable, inexpensive resource potentials and could become renewable fuel exporters [8], [10].

Renewable e-fuels are a potential remedy to this problem as they are easily transportable and can function as a renewable energy storage medium decoupled from seasonality and locality.

8. Policy implications and conclusions

Engineers, businesses and policymakers put high hopes in the generation of e-fuels, chiefly since they would avoid a transformative change on the demand side. They enable storage and long-range transportation to overcome variability of renewable power supply and harness the wind and solar potential of the Global South.

A crucial shortcoming of e-fuels is, however, the low conversion efficiency of their production and utilization as a combustion fuel. The high energy intensity of e-fuels has important implication for environmental effectiveness and economic efficiency. E-fuels only deliver substantial climate benefits compared to conventional fuels, if produced with renewable electricity. If produced from predominantly fossil-fuel electricity, e-fuels contribute exceptionally higher lifecycle GHG emissions than conventional petrol. E-fuels are also a relatively high-cost climate change mitigation option, with prospective future CO_2 emissions abatement costs of around 400 € per ton CO_2. Moreover, possible impacts on other environmental, social or political dimensions are still to be investigated. For example, water and mineral resource requirements for e-fuel production could be a significant barrier.

In view of the limited renewable energy potential in Germany and Europe in combination with the low system-level efficiency of e-fuels, large scale and self-sufficient domestic e-fuel production is unlikely. A much more likely scenario is the large scale generation of e-fuels in world regions with favorable resources, such as the Middle East, North Africa, Australia or Patagonia (5).

The characteristics of e-fuels vis-à-vis other decarbonization technologies suggest that direct electrification outperforms e-fuels in most sectors where electrification technology options exist. E-fuels imported from resource-rich world regions, by contrast, remain a plausible energy carrier for aviation, freight and other end-uses that are difficult to electrify, as well as backup electricity generation.

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For more information

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