Carbon sources for e-fuels

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OIL AND GAS CLIMATE INITIATIVE

OGCI and CRC publish report on carbon sources for e-fuel production

The Oil and Gas Climate Initiative (OGCI) and the Coordinating Research Council (CRC) have jointly produced a comprehensive report on the carbon sources for e-fuel production.

This unique partnership brings together fuel producers and users to build a shared understanding of e-fuels that covers CO_2 sources, production pathways, techno-economics, life-cycle assessment, regulatory and policy landscape in different regions, and potential hubs for e-fuel production.

E-fuels can take various forms, with main examples including e-gasoline, e-kerosene, e-diesel, e-methane, e-methanol and e-ammonia. The focus of this study is on drop-in liquid fuel alternatives for the on-road and aviation sectors, which constitute demand for the most common transport fuels. Accordingly, the e-fuel streams assessed are synthetic versions of gasoline, diesel, and kerosene/jet fuel products.

Effective reduction of transport emissions depends on pursuing a balanced 'all solutions' approach, with e-fuels and biofuels contributing as complementary low-carbon options.

As "drop-in" replacements for petroleum-derived hydrocarbon streams, e-fuels can help lower lifecycle GHG emissions in hard-to-abate transport sectors, such as heavy-duty trucking, shipping and aviation, without the need for significant modifications to existing infrastructure or transport equipment.

Additionally, such fuels can be used to decarbonize existing units in operation without requiring vehicle replacement, including passenger cars and trucks. Biofuels currently have a higher Technology Readiness Level (TRL) and are more commercially available at scalable levels, making them a compelling option for certain nearer-term use cases.

Equally, e-fuels offer the potential to utilize renewable energy surpluses (especially from stranded sources) and captured CO_2, with less dependence on global biomass constraints and land-use change considerations, thus providing another option for reducing carbon intensity for applications in the longer term.

E-fuel production at e-fuel hubs, where CO_2 and hydrogen can be produced in sufficient quantities in close proximity as inputs, could be substantially faster, relatively easier, and cheaper than configurations where either hydrogen or CO_2 needs to be moved long distances.

Industrial sources that have both scale and CO_2 purity to enable CO_2 capture include ethylene oxide, ammonia, bio-ethanol production, as well as the CO_2 separation from oil and gas production. Small sources of CO_2 are well distributed globally, with China, India, the US, and Russia home to large industrial sources of CO_2.

The development of e-fuel hubs with access to relatively pure CO_2 and low-carbon electricity will be crucial for the large-scale production of e-fuels. Three exemplar countries, the US, China, and Germany, are examined in more depth regarding the drivers and barriers to e-fuel production, techno-economics and CO_2 savings.

The e-fuel production pathways assessed in this report are Methanol-to-Gasoline (MTG), Reverse Water Gas Shift + Fischer-Tropsch derived diesel (FTD), and Methanol-to-Kerosene (MTK). Techno-economic analysis of these pathways confirms previous studies showing that e-fuels are expected to be two to seven times more costly per litre than conventional petroleum-based fuels in 2050.

In limited cases, some e-fuel production strategies can be cost-competitive with some biofuels or as much as four times more expensive. A sensitivity analysis shows that hydrogen production dominates the cost of e-fuel production, followed by CO_2 input. E-fuel production process CapEx is important for reaching investment decisions but has less influence on the levelized cost of e-fuel than electricity prices.

Future work should focus on a comprehensive, quantitative assessment of the technical, economic and commercial viability of e-fuels including location-specific analyses and an evaluation of their sustainability and competitiveness relative to alternative approaches.

In particular, a detailed comparison of the wider sustainability impacts of e-fuels and biofuels is warranted, as well as an examination of how this might change in the future. As policies and regulations continue to evolve, it is essential to monitor and adapt to changes in the market and regulatory landscape.

The development of e-fuel production pathways and hubs will require substantial investment and innovation to reduce costs and improve efficiency. Advancements may be achieved with the development and demonstration of new technology and production concepts.

Although e-fuels currently face challenges related to high production costs, scalability, and the need for significant investment and policy support, they offer an alternative solution to decarbonize sectors that cannot be easily electrified and could leverage existing infrastructure.

Executive summary

Challenging global climate stabilisation targets can only be met through step changes in carbon management. The rate of growth of CO_2 levels in the atmosphere, today mainly from combustion of fossil fuels, can potentially be limited by using alternative carbon sources. This report synthesises a high-level research and analytical study into carbon sources for e-fuel production. The research illustrates the diversity in feasibility, opportunity, and economics, by comparing different technical approaches, geographies, and sensitivity analysis around costs. Recent policies and regulations in place until the end of 2024 were reviewed, recognising that support levels for specific approaches and projects can change rapidly as policies and markets change.

E-fuels are defined for this project as drop-in replacements for hydrocarbon fuels (gasoline, kerosene and diesel), produced by combining electrolytic hydrogen (H_2) with carbon dioxide (CO_2).[1] There are more than one billion vehicles or vessels in operation and mature supply chains to support them. Heavy Goods Vehicles (HGVs), marine vessels and aircraft are viewed as particularly hard to

1 Other sources of hydrogen and carbon, or other produced fuels, are out of scope for this project.

abate quickly because of the challenges in developing new technologies and infrastructure at the pace required to meet climate targets, E-fuels are regarded as important in enabling rapid decarbonisation for those sectors that cannot be easily electrified and by reducing the need for end-users to change established ways of working.

The OGCI and CRC have created a unique partnership bringing together fuel producers and users to build a shared understanding of e-fuels. In the summer of 2024, following competitive tender, OGCI and CRC commissioned Ricardo, an engineering and environmental consultancy, to produce this overview of e-fuels. This overview considers CO_2 sources, production pathways, techno-economics, life-cycle assessment, regulatory and policy landscape in different regions, and potential hubs for e-fuel production. This report represents the final major deliverable from the project.

FIGURE E-1. Overall process diagram for e-fuel production

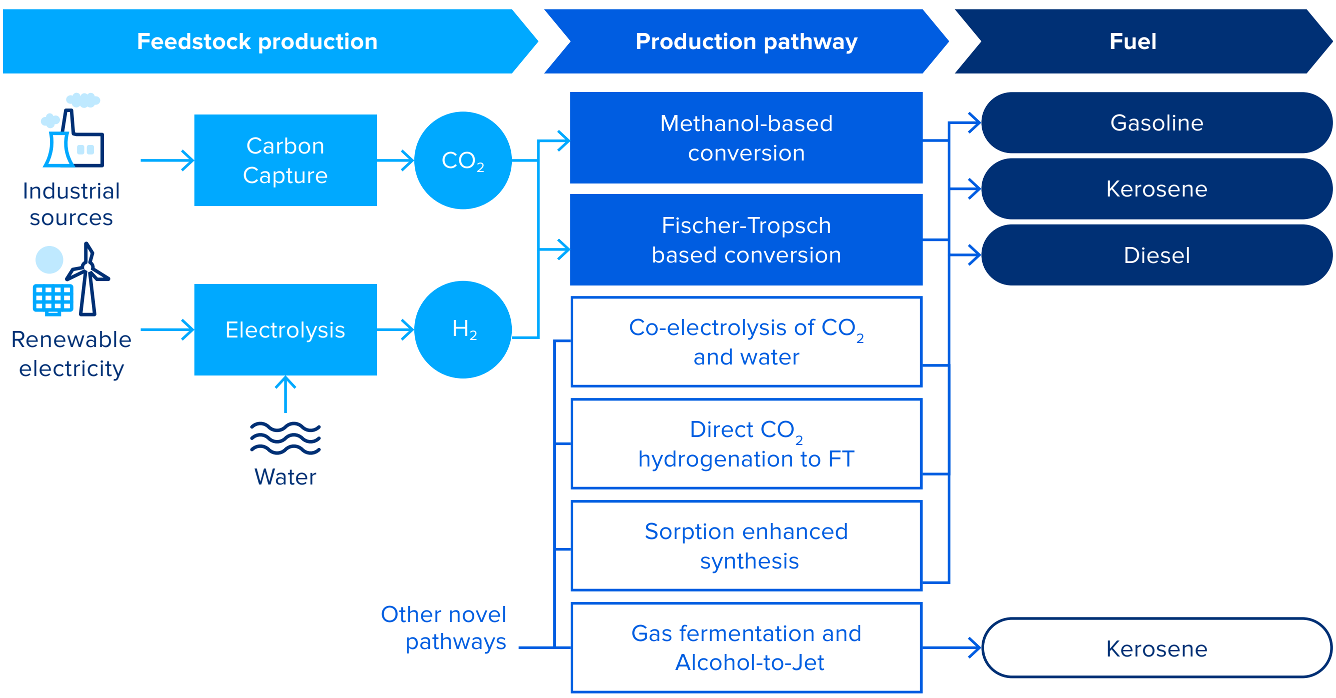


Figure E-1 highlights the main processes for developing e-gasoline, e-kerosene and e-diesel, the fuels that are the focus of this study. Processes involving a reverse Water Gas Shift and Fischer-Tropsch reaction or via e-methanol are currently the most mature, and these are therefore used to estimate costs and CO_2 savings, recognising that innovation could result in improvements to these estimates.

E-fuel production processes require industrial-scale and relatively pure hydrogen and CO_2 as important inputs to achieve e-fuel production scale in line with the scale of refineries (millions of tonnes of CO_2 per year, millions of barrels of oil equivalent per day).

CO_2 streams are a common by-product of many industrial processes (including heat and power generation), and in some cases CO_2 separation is integral offering access to relatively pure CO_2 at low cost (examples are biomethane upgrading and natural gas sweetening), though investment in CO_2 capture would likely be required in most cases. Hydrogen would need investment in electrolyzers – and these would need to be run from low carbon electricity to maximize carbon savings. The feasibility, scale and costs of captured CO_2 and electrolytic hydrogen are highly site dependent, even within countries, depending on specific site characteristics (e.g. purity of CO_2, renewable electricity costs).

E-fuel hubs where CO_2 and hydrogen can be produced in sufficient quantities in very close proximity as inputs will be substantially faster, easier, cheaper, and less risky to develop than configurations where either hydrogen or CO_2 needs to be moved long distances (unless developers can take advantage of pre-existing infrastructure).

Industrial sources that have both scale and CO_2 purity to enable CO_2 capture include ethylene oxide, ammonia, bio-ethanol production, as well as the CO_2 separation from oil and gas production. Small sources of CO_2 are globally well distributed. China, India, the US and Russia are home to large industrial sources of CO_2 that would enable production at the scale of today's oil refineries. Nearly all the largest sources currently are fossil derived, though in the future some may switch to biomass.

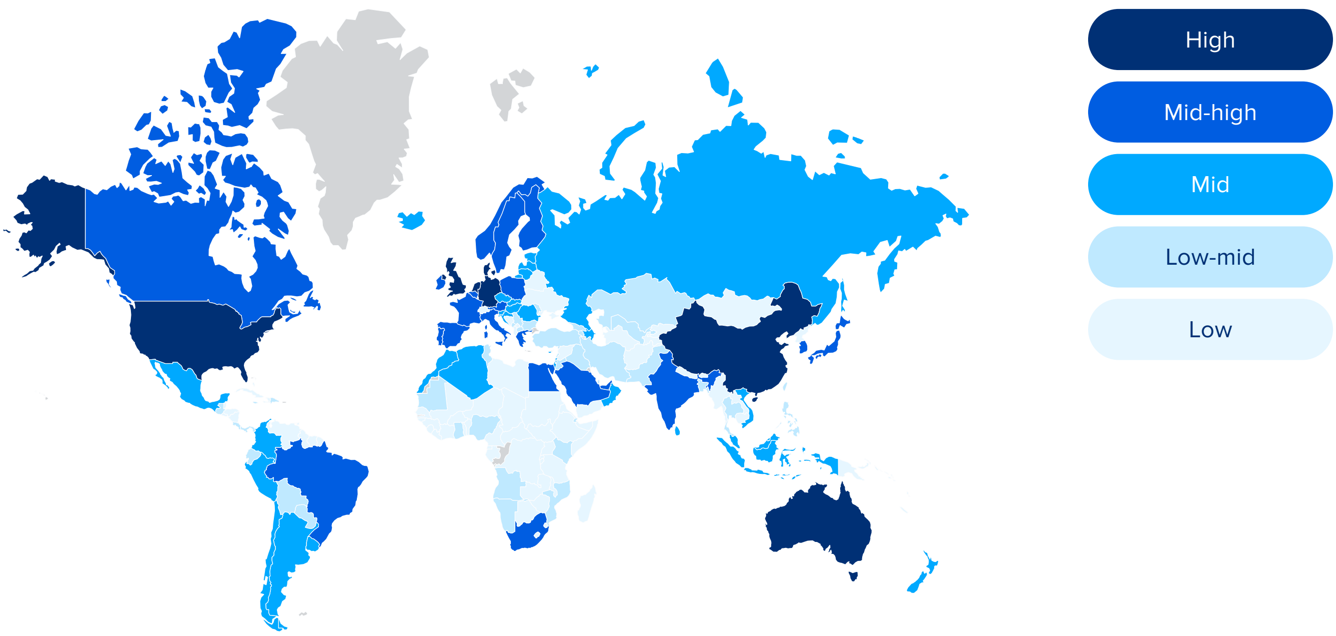
The report identifies political, economic, social, technological, legal and environmental barriers to both CO_2 and hydrogen supply. Policy support for carbon capture, hydrogen and e-fuel production around the world is mixed. The techno-economics shows that hydrogen costs dominate e-fuel production costs, followed by captured CO_2 costs. Hydrogen costs are driven by renewable power costs, implying that e-fuel developers need to focus on regions with very large amounts of low cost, low carbon electricity. In nearly all locations, the latter will require substantial new renewable generation investment, as well as aligned supporting electricity grid and hydrogen infrastructure to ensure that production processes operate continuously. Transport costs for hydrogen or CO_2 further depend on distance mode (e.g. pipeline vs. ship), terrain, capacity and integration within a wider transport network. As an example of an environmental challenge, water availability may further restrict the number of locations able to support e-fuel production.

Today oil refineries rely on economies of scale and fuel production is typically focussed at hubs that process many millions of barrels of oil each year, often from nearby oil and gas fields. Whilst these are likely to remain important for other reasons, future e-fuel production hubs may instead be driven as much by availability of electrolytic hydrogen and captured CO_2, which could be independent of the locations of oil and gas reserves.

This report considers the factors above to provide a high-level global assessment of relative ease of e-fuel production as shown below.

Country-level analysis is a reasonable starting point but limited by the heterogeneity within countries. Future work could explore specific locations in more detail, considering costs and competition for resources (such as renewable electricity or water), and understand individual CO_2 sources (timing, capture feasibility and costs, fossil/ biogenic CO_2 supply). Together with plausible scenarios for infrastructure and production configurations, this could be used to quantify the technical potential (i.e. amounts) for supply of e-fuels from locations with sufficient local resources to support production.

FIGURE E-2. High level assessment of ease of e-fuel production in countries



Direct air capture is currently a very early-stage technology being piloted. A theoretical advantage is geographical flexibility, not tied to an existing industrial source. Considerable technology development would be required to scale up to meet the scales associated with e-fuel production. Equally challenging is that most concepts for localised direct air capture are energy intensive, compounding the challenge of needing additional renewable generation beyond the already steep requirements for energy needed to produce hydrogen. Direct air capture of CO_2 through mineralisation does not generate a concentrated CO_2 source that can be combined with hydrogen at a particular location.

Moving beyond the high-level global analysis, examination of a few exemplar countries helps to highlight the interplay of these factors. In agreement with OGCI and CRC, the report examines current drivers and barriers to e-fuel production, techno-economics and CO_2 savings in three different countries, the US, China, and Germany, in more depth.

Costs

The techno-economic analysis in this report confirms previous studies showing that e-fuels are expected to be two to seven times more costly per litre than conventional petroleum-based fuels. In limited cases, some e-fuel production strategies can be cost competitive with some biofuels. The range of e-fuel prices shown in Figure E-3 includes possible production costs across different countries and CO_2 sources. The lower bound corresponding to the lowest cost scenarios, namely lowest hydrogen cost in China coupled with high concentration CO_2 sources. The upper bound corresponding to the highest hydrogen cost in Germany coupled with the highest estimate of captured CO_2 (from direct air capture). The underlying data can be found in Section 9.5. As recommended by OGCI and CRC, fossil fuel and biofuel costs are based on the recent OGCI report: *Energy Demand Dynamics Across the Transportation Sector,* published in November 2024.

FIGURE E-3. Comparison of e-fuel production costs with fossil- and bio-based fuels

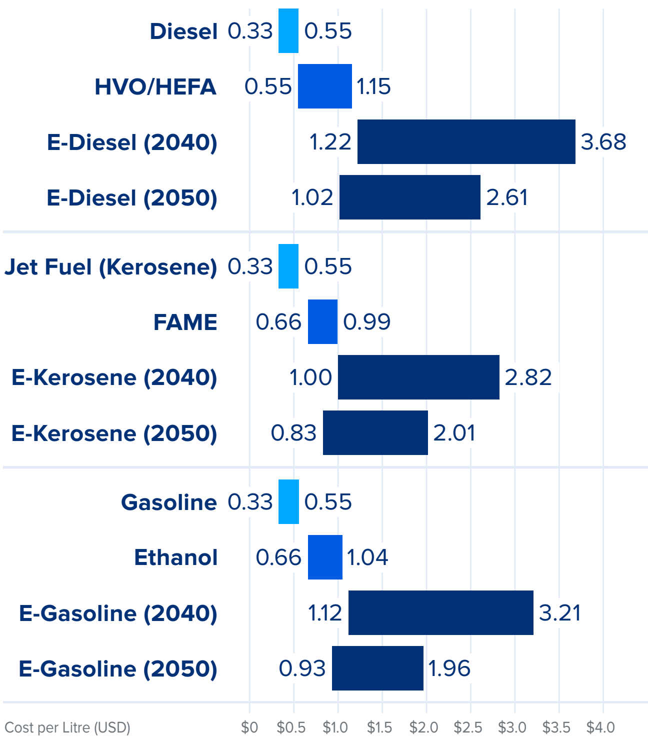
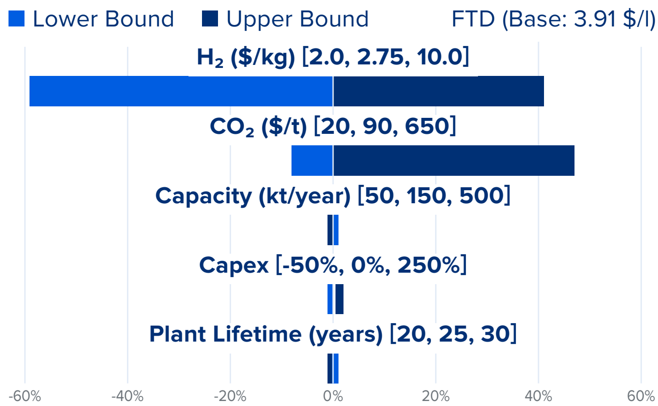


FIGURE E-4. Sensitivity analysis for FTD (Diesel via Fischer-Tropsch)



There are considerable uncertainties on costs and future availability of fossil fuels and sustainable biofuels today and in the future. Changes in feedstock supply, government policies, and market dynamics might influence conventional and biofuel production costs and selling price. For example, if SAF were available at $2.80/litre (as per one ICCT report[2]), the ratio of e-fuel / biofuel cost would be close to 1.

A sensitivity analysis shows that hydrogen costs dominate the cost of e-fuel production, followed by CO_2 input cost. E-fuel production process capital expenditure, though important for reaching investment decisions has less influence on levelized e-fuel production cost.

Carbon impacts

A high-level literature review of lifecycle analysis considerations reveals that key considerations for carbon impacts associated with e-fuel production are:

- Low-carbon electricity used to produce hydrogen
- Use of high purity and biogenic CO_2 sources where available
- Heat optimisation between hydrogen, CO_2 capture and e-fuel production processes
- Legislation that may restrict the use of fossil sources of CO_2
- Proximity of CO_2 capture, hydrogen supply and e-fuel production
- Proximity of CO_2 capture, hydrogen supply and e-fuel production

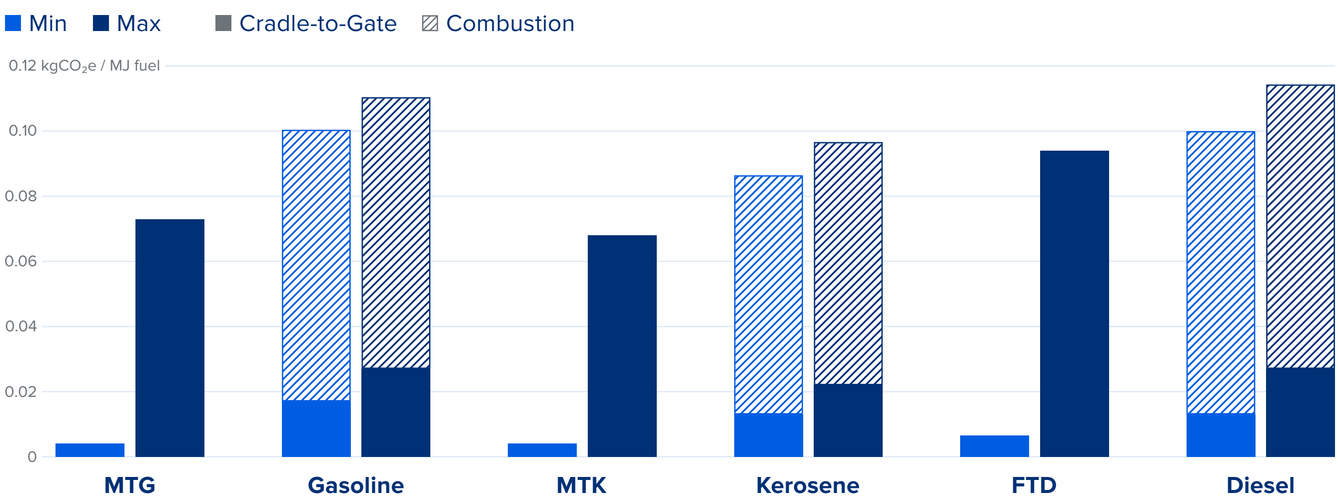
2 Nikita Pavlenko, Stephanie Searle, and Adam Christensen, The Cost of Supporting Alternative Jet Fuels in the European Union (Washington, DC: International Council on Clean Transportation, 2019), https://theicct.org/wp-content/uploads/2021/06/Alternative_jet_fuels_cost_EU_2020_06_v3.pdf

Compared to fossil fuels, the e-fuel production pathways have a wider range of carbon impacts. They can result in lower cradle-to-gate emissions than conventional fossil fuels under optimum conditions. However, in the worst case, cradle to gate emissions of e-fuels can exceed those of fossil fuels.

When considering the impact of the tailpipe emissions associated with combustion, the impact associated with the carbon released by the fossil fuels in use dwarfs the cradle-to-gate impact. These results are shown below. This is because the CO_2 which is released on combustion for the fossil fuels needs to be accounted for in calculation of the total cradle-to-grave impact, whereas for e-fuels, the CO_2 released on combustion is not included in the Global Warming Potential (GWP). For the e-fuels, the CO_2 emitted at combustion is considered to be the release of the carbon captured (in the case of DAC and biogenic CO_2) or avoided (in the case of fossil CO_2) for the production of the e-fuel and is therefore considered to have a net zero impact.

Note that a full review of wider environmental and sustainability challenges associated with fossil fuels, biofuels and e-fuels are out of scope of this project but would benefit decision makers beyond lifecycle carbon impacts.

FIGURE E-5. Comparison of ranges of GWP impact of e-fuel production (renewable electricity consumption only) against fossil fuel equivalent, using system expansion approach



Carbon abatement cost effectiveness

The carbon abatement cost can be estimated by combining US$/energy and CO_2 emissions data from the techno-economic analysis with the CO_2/energy data from the lifecycle analysis.

The US$/t$CO_2$ saved varies across a wide range, depending on the CO_2 source, the e-fuel synthesis pathway employed, and the country under consideration.

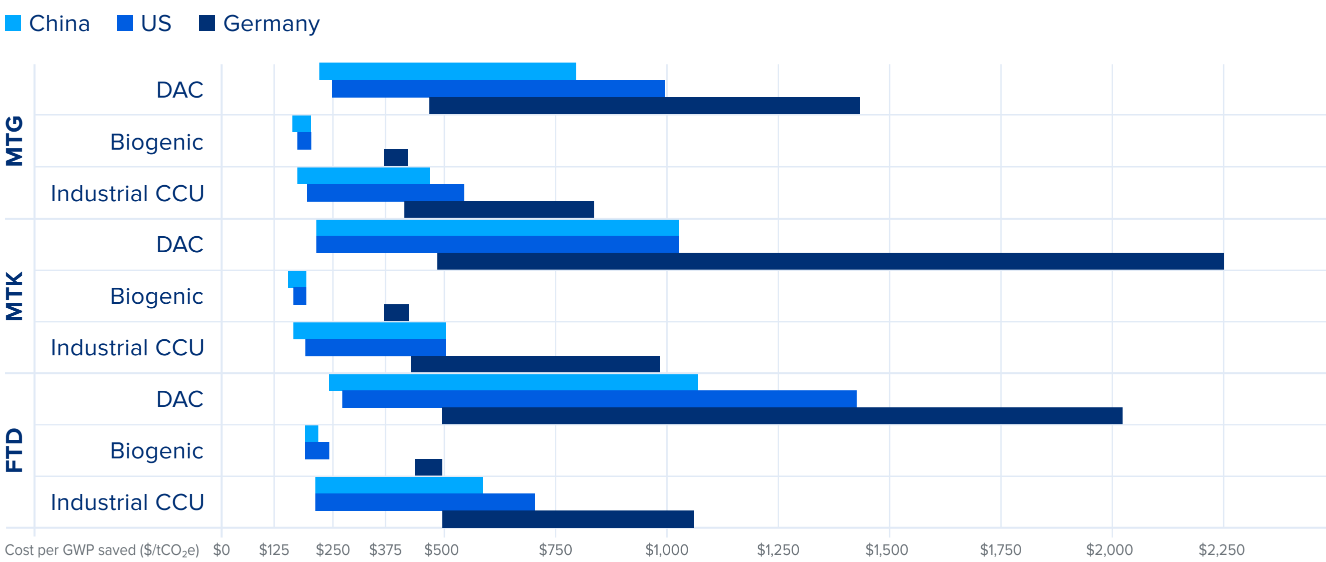
Across the three countries analyzed (China, the US, and Germany), Germany has the highest e-fuel production costs, mainly due to higher hydrogen price (in large part due to higher energy prices).

Three distinct CO_2 sources are considered: DAC, biogenic CO_2 (from biomethane upgrading), and industrial CCU. Biogenic CO_2 from biomethane upgrading appears more cost effective than industrial CCU or DAC and could be considered a best case. CO_2 feedstocks vary significantly in amounts, concentration (and nature of impurities), which in turn affects the cost of capture. While some biogenic sources, such as biomethane upgrading, provide relatively pure CO_2 streams, others may be more dilute and costly to upgrade. Certain fossil-based sources such as natural gas processing or glycol plants can also offer high-concentration CO_2 streams requiring minimal clean-up.

The primary motivation for considering replacing fossil hydrocarbon fuels with e-fuels is the lower life cycle carbon impact of e-fuels. However, for e-fuels to be an economically viable carbon abatement strategy, their costs must be competitive with other carbon reduction measures. Careful focus on e-fuels production strategy is important to minimize carbon abatement costs. E-fuels with the lowest carbon abatement cost (<US$200/$tCO_2$) can only be produced in the future from production sites in locations with access to large amounts of very low cost and low carbon electrolytic hydrogen (<$1.5/kg), and captured CO_2 that are co-located with e-fuel production to minimize hydrogen and CO_2 transportation costs.

Future work could develop supply marginal cost curves (unit cost vs. cumulative quantity) for e-fuel production quantifying location- specific amounts and costs across a wide range of locations, reflecting plausible infrastructure development at different times, to quantify the economic potential for e-fuels. This could also be overlaid with marginal cost curves for sustainable biofuels (and other alternative fuels). Excessively high e-fuel carbon abatement costs (around or above US$1,000/$tCO_2$) risk limiting the ultimate market for e-fuels: If e-fuel carbon abatement costs are too high, industry may instead focus on alternative decarbonisation strategies, including greater use of alternative low carbon fuels, or even combinations of fossil fuel combustion with direct air CO_2 capture and storage (DACCS) elsewhere, if DACCS technologies mature.

FIGURE E-6. Cost per GWP saved based upon region, pathway and CO_2 source for 2050



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