



Direct Air Capture

An aviation-aligned approach



Contributors

The ACT Strategy for Direct Air Capture was developed under the direction of Dr. Dan Matuszak (Chief Technology Officer of ACT) with input from ACT's Technical Advisory Board members. ACT also acknowledges the contributions from our member organizations.

About ACT

ACT is a nonprofit organization accelerating critical breakthroughs in the invention and scale-up of emerging technologies needed to decarbonize aviation. ACT brings together ten global airlines—including Air Canada, Air France-KLM Group, American Airlines, Cathay Pacific Airways, Delta Air Lines, JetBlue Airways, Lufthansa Group, Southwest Airlines, United Airlines, Virgin Atlantic—together with the Boston Consulting Group.

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1. Background

Direct Air Capture (DAC) is a promising technology for decarbonization and has the potential to serve both as a carbon source for power-to-liquids (PtL) approaches to synthetic fuel production and as a method of carbon dioxide removal (CDR).

As a sustainable carbon supply, DAC has the potential to complement biomass, especially where natural-resource limitations and other constraints prohibit the production of bio-derived aviation fuels. Where both DAC and biomass can serve as carbon sources for aviation fuel, the associated fuel diversity would help to control price escalation due to supply-chain vulnerability to weather and geopolitical dynamics.

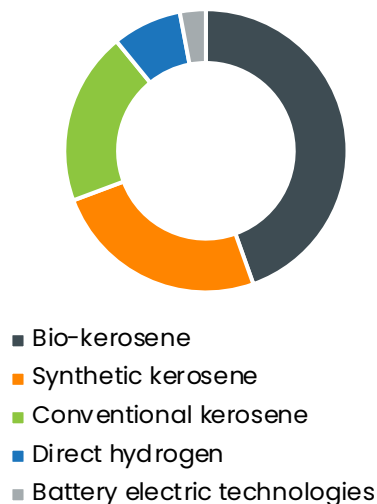
At present, the cost of DAC is prohibitive for aviation-fuel production, rendering the final “DAC-kerosene” fuel uncompetitive. Present DAC-kerosene costs reported in literature range from 202–469 €/MWh_{LHV}, but with increased research and development these costs are projected to be in the range of 112–133 €/MWh_{LHV} by 2030 and 64–75 €/MWh_{LHV} by 2050.¹ For comparison, the present price of jet fuel is 67 €/MWh_{LHV}.² Hence, DAC-kerosene has the potential to become a competitive fuel in the long-term. Until the cost of DAC decreases sufficiently, synthetic kerosene production may take advantage of high-concentration point sources of CO₂ from biomass, for example, from fermentation or biomass gasification.

In a broader context, biofuels, synthetic fuels, and hydrogen are the preeminent candidates for long-distance commercial flight. However, there are significant uncertainties about the deployment schedules of these technologies, including the associated ground-based infrastructure. Ideally, the aviation sector’s energy demand in 2050 would be met using these approaches, but the uncertainty of realizing that vision suggests a prudent course of contingency planning with DAC-kerosene as an option.

The International Energy Agency (IEA)’s Net Zero Emissions by 2050 scenario (NZE) suggests what the sector may need in terms of DAC capabilities and capacity.

Although the aviation sector would continue to be a significant carbon emitter in 2050, emissions would be offset by CDR approaches such as Bioenergy with Carbon Capture and Storage (BECCS) and DAC with Carbon Storage (DACs). Aviation energy demand in 2050 would be met by bio-kerosene (45%), synthetic kerosene (25%), conventional kerosene (20%), direct hydrogen (8%), and battery electric technologies (~3%). The required annual carbon flow provided by DAC in this scenario is unlikely to be less than 320 MtCO₂ –specifically, 180 MtCO₂ to produce synthetic fuels and 140 MtCO₂ for CDR associated with burning conventional kerosene.³

Aviation Energy Demand in 2050
IEA NZE Scenario



The aviation sector is expected to face tremendous competition for DAC capacity. Worldwide DAC operating capacity was 0.01 MtCO₂ in 2022 but would need to grow to 980 MtCO₂ by 2050 to realize the NZE scenario. Hence, the aviation sector would compete for access to at least one-third of the aspired-for DAC capacity (>320 MtCO₂ of the aspirational 980 MtCO₂ DAC capacity).⁴

The aviation sector would also face competition for carbon storage space to accommodate the removal of carbon dioxide from conventional kerosene use. Further, in one scenario, government policies could shift DAC capacity towards carbon removal and storage in lieu of a circular carbon economy, in which the carbon removed is then converted to new fuel. In another scenario, policies encouraging storage could also divert biomass from aviation fuel production and towards BECCS instead.

2. Changing the game – distinguishing DAC types

DAC has two purposes in relation to aviation: emissions prevention and emissions reduction. Emissions prevention decreases the carbon footprint of goods or services, whereas emissions reduction reverses the carbon that was already emitted (i.e., it is a CDR approach). While a single DAC approach could serve both purposes, it is better to diversify. Ideally, there would be an aviation-aligned DAC approach for emissions prevention, partly to reduce competition for future DAC capacity, and partly to have a more energy- and capital-efficient DAC approach as discussed further herein. For emissions reduction, it would be ideal to broaden the range of available DAC approaches in a way that creates aviation relevance.

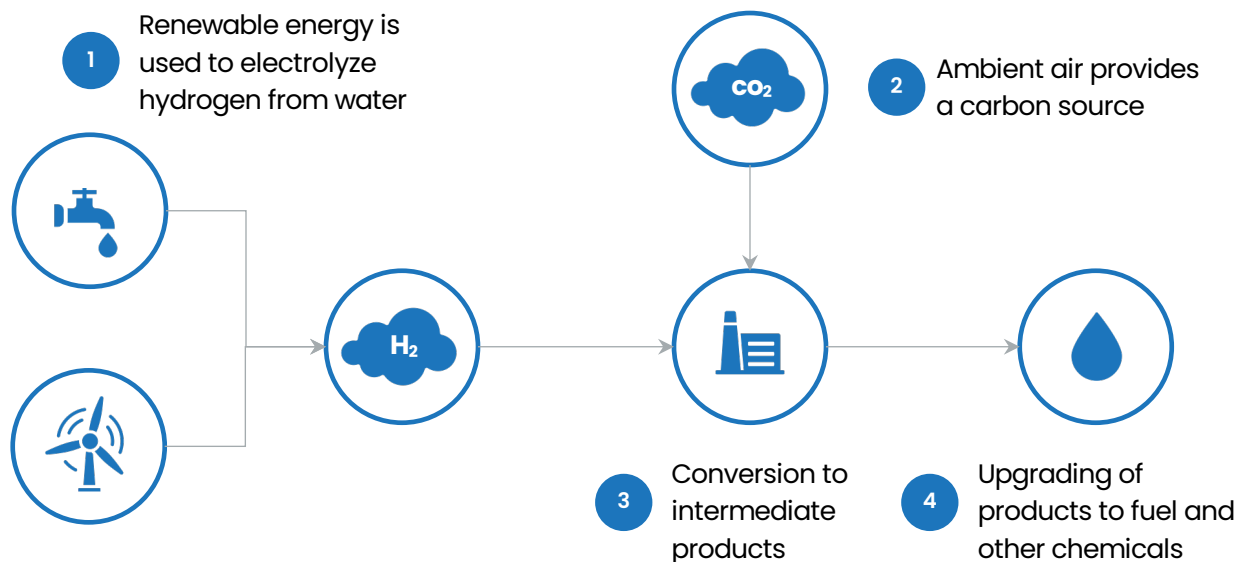
2.1. Emissions prevention through aviation-aligned DAC approaches

The preeminent DAC technologies capture carbon as CO₂ and re-release it as CO₂. A liquid solvent or solid sorbent first absorbs the CO₂ and subsequently releases it as CO₂ upon provision of energy for system regeneration.⁵ This is the most classical DAC system. Carbon Engineering, Climeworks, and Global Thermostat use capture-and-release technologies to move carbon from air to a permanent storage location. Moreover, capture-and-release approaches are relevant to any process that uses CO₂ as an input, as they provide CO₂ as an output. As they are versatile in how they serve CO₂, significant levels of investment have been made by a wide range of entities in this type of DAC approach.

A small set of DAC approaches capture CO₂ and release it as an industrially relevant product. For example, reactions of CO₂ with mineral silicates or mineral oxides can produce mineral carbonates that are suitable aggregates for construction materials.⁶ The first half of Heirloom's capture-and-release DAC technology converts CO₂ to a mineral carbonate, leveraging advantages related to this chemistry and associated thermodynamics.⁷ In these cases of mineral transformation, the reaction is essential to the capture mechanism.

The aviation sector should invest in DAC approaches that release captured CO₂ as an aviation-relevant molecule (i.e., a molecule that is relevant for aviation fuel synthesis). Electrolysis

approaches such as those of Twelve and Dioxide Materials convert CO₂ directly to syngas, a mixture of carbon monoxide (CO) and hydrogen (H₂). These approaches align with what is needed for aviation because syngas is the input for Fischer-Tropsch (FT) synthesis of kerosene.



However, most low-temperature CO₂ electrolyzers have limitations that preclude their service as standalone DAC technologies.⁸ The electrochemical reactions cannot become an essential part of the capture mechanism; and, hence, these electrolyzers operate best with purified CO₂ as Input⁹ (e.g., CO₂ derived from concentrated point sources, or from a capture-and-release DAC approach at the front-end of an integrated process).

It would be highly impactful if CO₂ conversion to aviation-relevant molecules were sufficiently robust to remove CO₂ from air in one stage, at industrially relevant rates, and without parasitic side reactions. In such a case, the CO₂ conversion chemistry becomes an essential part of the CO₂ capture mechanism, constituting an aviation-relevant DAC technology. In the absence of such CO₂ conversion chemistry, a tandem capture-conversion approach (two-stage) is preferred so that the capture stage is assisted by the conversion stage (via exchanges of mass or energy) in a highly integrated process. The next preferable approach is a capture-release-conversion approach wherein optimization and heat exchange provide benefits that are inaccessible by standalone systems.

Priorities for aviation-aligned DAC technologies:

HIGH

Single-stage processes that capture CO₂ and release it as an aviation-relevant molecule, in such a way that the conversion of CO₂ is an essential part of the capture mechanism. The conversion may provide useful energy for capture or release.

HIGH

Two-stage processes that capture CO₂ and release it as an aviation-relevant molecule, in such a way that the conversion of CO₂ assists the capture mechanism as in a capture-conversion sequence wherein CO₂ is not released after capture. The conversion may provide useful energy for capture or release.

MEDIUM

Processes that capture CO₂ and release it as an aviation-relevant molecule, in such a way that the conversion of CO₂ indirectly assists the capture mechanism as in a capture-release-conversion sequence. The conversion may provide useful energy or mass flows for capture and the conversion may accept lower purity CO₂ from the capture stage.

LOWER

Processes that capture CO₂ and release it as an aviation-relevant molecule, in such a way that the conversion stage is mostly independent of the capture stage. Beneficial heat or mass flows from the conversion stage are not possible. Opportunity exists for the capture operation to deliver CO₂ at lower concentrations than 99.5% because the conversion chemistry remains robust at lower CO₂ concentrations.

DO NOT FUND

Processes that capture CO₂ and release it as an aviation-relevant molecule, in such a way that the capture stage is completely independent of the conversion stage, and wherein the capture stage delivers highly purified CO₂ for conversion.

Techno-economic analysis (TEA) and lifecycle assessment (LCA) should complement experimental cost-performance determination to evaluate merit more accurately and to verify priority order.

There is a unique opportunity to co-optimize or merge the DAC and fuel-synthesis approaches. DAC is often thought to be energy- and capital-inefficient because of requirements for a high purity CO₂ product stream (>99.5% CO₂ for geological storage). However, DAC has lower capital and energy requirements if it produces CO₂ at lower concentrations. Hence, conversion approaches that operate adequately when CO₂ is partially concentrated would create opportunities for DAC systems. Conversion approaches that operate adequately when CO₂ is at ambient concentration would create the highest opportunity—they would constitute a capture mechanism.



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Carbon monoxide and methanol are classical CO₂ intermediates for aviation fuel production.

Most pathways to synthetic aviation fuel pass through CO or methanol intermediates. The CO intermediate passes through the FT synthesis pathway to jet fuel. On the other hand, CO₂ hydrogenation to methanol is a demonstrated pathway that is closer to what is needed for aviation, and it already serves the chemical and transportation sectors. Methanol-to-jet (MTJ) approaches are in late stage of development (TRL 5-6 or higher) and may combine methanol-to-olefins and olefins-to-jet (OtJ) approaches.¹⁰ Given the advanced stages of development of FT and MTJ processes, the best R&D strategy would be to explore synergies of exchanging heat and/or mass flows between a front-end DAC approach and downstream conversion and upgrading processes. For example, partnerships such as Carbon Engineering and Greyrock have emerged to develop Air-to-Fuels processes.¹¹

There is a wider range of aviation-relevant molecules. Other aviation-relevant molecules include, but are not limited to, ethanol, glycol, and olefins.

The following chemistries are a subset of chemistries relevant to synthetic fuel production:

- CO₂ conversion to ethanol. Ethanol-based Alcohol-to-Jet (ATJ) pathways for synthetic jet fuel production are already approved for civil aviation. Additionally, ethanol is also a precursor of diethyl ether, which has a significant heating value and could be used to support process heating in future jet-fuel refineries.
- Emergent surface-modified electrodes can dramatically shift the CO₂ conversion chemistry from CO to ethylene glycol (with 87% Faradaic efficiency).¹² The imidazolium ion-terminated self-assembled monolayer was able to shift the reaction field of CO₂. In principle, ethylene glycol could be converted to a longer aviation-relevant molecule. Glycols can combine to form a range of ethers, some of which may be amenable to emergent reductive deoxygenation approaches that form carbon-carbon bonds.¹³
- Emergent bifunctional catalysts have been shown to convert CO₂ directly to olefins such as ethylene, propylene, and butylene.¹⁴ These can serve as intermediates for aviation fuel by means of existing OtJ pathways.
- Emergent iron-based catalysts (Fe-Mn-K) show promise for converting CO₂ more directly into jet-fuel relevant hydrocarbons.¹⁵ Relatively high CO₂ hydrogenation activity and high jet fuel range selectivity were observed through this approach: in comparison to a range of other promising catalysts, this catalyst showed the highest yield of C₅+ species (22.3%) as well as the highest CO₂ conversion (38.2%).

2.2. Emissions reduction (Carbon Dioxide Removal) with aviation alignment

The prominent inorganic approach for emissions reduction is DAC combined with carbon storage (DACs). Inherently, the DAC technology is a capture and release approach – the technology captures CO₂ and releases CO₂ for storage. Considering that extensive efforts are directed at

advancing capture-and-release DAC approaches, more impact for the aviation sector is expected in areas other than thermally-regenerated solvents or sorbents. These approaches are expected to become available broadly for the purchase of carbon credits by any sector, and therefore they are not considered to be aligned with aviation.

Unique aviation-aligned emissions-reduction possibilities exist in the design of synthetic fuel refineries, depending on how they are heated in a net-zero carbon future. If renewable electricity supply was limited in the future, refineries could continue the paradigm of consuming internal fluids for heating. DAC-PtL byproducts, including lower-quality fuels, may be consumed internally for process heating. A carbon capture and storage approach would help realize negative carbon flow from air to a carbon storage site, as will be described. However, if renewable electricity was abundant and inexpensive, refineries could rely more on electric resistance heating. In this case, DAC-PtL byproducts, including lower-quality fuels, may be pyrolyzed (heated in the absence of oxygen) to create solid carbon and hydrogen. Thus, negative carbon flow would occur from air to a solid carbon material.

For a DAC-PtL production facility, the consumption of internal process fluids can create opportunities for emissions reduction, including the possibility of a net-negative carbon sustainable aviation fuel (SAF), as embedded in the following priorities that begin with DAC and end with carbon storage:

- Oxycombustion of DAC-PtL byproducts, including lower-quality fuels, for process heat, followed by carbon capture and storage.¹⁶ Oxygen-fed flames attain higher temperatures to support process heating, and their flue gas is very easy to separate because it consists of CO₂ and H₂O. The H₂O would condense upon cooling and would be recycled to water electrolyzers that supply green hydrogen. The CO₂ would emerge as a nearly pure stream, and it would be transported by pipeline to a geological storage site. Overall, the approach begins with DAC and ends with geological carbon storage.
- Pyrolysis of DAC-PtL byproducts, including lower-quality fuels, to produce solid carbon and hydrogen. Process heating is provided by renewable electricity in the most likely scenario. In another scenario, heating is provided by oxycombustion of DAC-PtL chemicals (per above). Hydrogen gas is recycled internally, and solid carbon is transported for permanent storage. Overall, the approach begins with DAC and ends with solid-carbon storage.

Oxycombustion of PtL mixtures with subsequent capture and storage can be a net negative carbon approach that provides essential heat for aviation fuels production. PtL byproducts, including lower-quality fuel mixtures, are expected in fuel production in part because conversion technologies typically produce a distribution of products.¹⁷ In the present context of process heating, a wider distribution of PtL products is not a problem—it can even become an advantage as it has the potential to reduce the level of effort required in the upstream integrated DAC-conversion (DACX) approach.

Electrolysis produces pure oxygen that otherwise is vented to the atmosphere. By combusting PtL

byproducts, including lower-quality fuel mixtures, in pure oxygen, the resultant products are CO₂ and H₂O, which are very easily separated to yield a purified CO₂ product suitable for carbon storage. Preliminary analysis suggests that there is sufficient oxygen generated within the PtL process to enable oxycombustion of at least a minor fraction of PtL species.¹⁸

If geological storage capacity becomes intermittent, the purified CO₂ product emerging from oxycombustion may be recycled to the front-end DACX operation, potentially enhancing CO₂ conversion kinetics and alleviating the DAC sub-operation.

Pyrolysis of PtL byproducts, including lower-quality fuels, to produce solid carbon and hydrogen can be a net negative carbon approach when geological sequestration is not available or is intermittent. Pyrolysis of hydrocarbons can produce solid carbon and hydrogen gas. The solid carbon can be stored while the H₂ can be recycled for PtL fuel synthesis. For example, consider methane pyrolysis: $\text{CH}_4 \rightarrow \text{C(s)} + 2\text{H}_2$. Pyrolysis temperatures tend to be high, and their energetics tend to be endothermic, but under some conditions pyrolysis pathways could be a good option for future aviation-fuel refineries, for instance when carbon storage capacity is intermittent and the refinery needs to operate continuously. Currently, the high temperatures required for commercial pyrolysis are attained by combustion of fuels such as natural gas. Future pyrolysis systems suitable for converting PtL byproducts as discussed would need to be heated with renewable electricity or another form of carbon-free heat. One scenario that supports the pyrolysis pathway occurs when renewable electricity is abundant and inexpensive due to natural fluctuations. In another scenario, pyrolysis may be combined with oxycombustion (with CO₂ recycling upstream to the DACX operation).

Recycling of DAC-PtL byproducts, including lower-quality fuels, for re-processing could improve SAF yield, but it does not provide a negative carbon flow and it has many techno-economic uncertainties. A competing alternative to oxycombustion or pyrolysis is to recycle the PtL byproducts back into the PtL process, for example, by means of full or partial oxidation or another conversion. The economic benefits of all considered approaches are yet to be determined and are expected to vary based on energy prices and policy factors. Cost-performance determination by means of judicious research and development would enable better understanding.

Consumption of DAC-PtL byproducts is a surrogate to direct DAC with storage, but techno-economic insights are needed to decide which is better for given sets of conditions. Capturing CO₂ with a conventional DAC approach and relaying it to

Oxycombustion re-introduces a technical path toward carbon storage, allowing leverage of internal process flows and retention of a simplified DAC sub-operation.

geological storage directly is an alternative to oxycombustion or pyrolysis of DAC-PtL species. However, the conventional DAC approach must be able to generate on the order of 99.5% pure CO₂ at high pressures to qualify for storage. The simplification of DAC in a DACX technology would reduce its cost and energy intensity but, in return, it would almost certainly preclude its use as a conventional DAC approach for carbon storage. Oxycombustion re-introduces a technical path toward carbon storage, allowing leverage of internal process flows and retention of a simplified DAC sub-operation. Cost-performance determination by means of judicious research and development would enable better understanding.

3. Summary

The aviation sector's DAC strategy should match the unique needs of the sector: emissions prevention and emissions reduction. While a single capture-and-release DAC approach could serve both needs, approaches that offer a synergy and alignment with aviation should be prioritized because of the efficiencies and associated cost reductions that are possible through integration.

For emissions prevention, it would be impactful to have integrated DAC-and-conversion processes (DACX) that capture CO₂ and release it as an intermediate that is suitable for aviation fuel synthesis. Intermediates may include, but are not limited to, alcohols, glycols, olefins, and other multi-carbon species.

For emissions reduction (Carbon Dioxide Removal), it would be impactful to have approaches for net-negative carbon flow that are supportive of aviation fuel production: (a) oxycombustion of PtL byproducts, including lower-quality fuels, for refinery heat followed by capture and storage, (b) pyrolysis of PtL byproducts including low-quality fuels for production of solid carbon and hydrogen.

Questions about technical feasibility and economic viability of these approaches could be answered through judicious research and development guided by the priorities in this strategic document. The range of technologies mentioned herein need to be examined in the context of aviation needs to form definitive conclusions.

7. APPENDIX

¹ Cost ranges reflect first and third quartiles noted within the study by Deutsche Energie-Agentur GmbH (dena), “E-Kerosene for Commercial Aviation: From Green Hydrogen and CO₂ from Direct Air Capture—Volumes, Cost, Area Demand and Renewable Energy Competition in the United States and Europe from 2030 to 2050”, Table 13 and Figure 36; URL (accessed 22-FEB-2023): <https://www.dena.de/en/newsroom/publication-detail/pub/study-e-kerosene-for-commercial-aviation/>

² IATA Jet Fuel Price Monitor, averaged by world share, jet fuel price ended 107.03 \$/bbl the week of 18-FEB-2023. For conversions 158.987 L/bbl; 31.16876 MJ_{LHV}/L; 0.94 EUR/USD. URL (accessed 22-FEB-2023): <https://www.iata.org/en/publications/economics/fuel-monitor/>

³ Y2021 direct CO₂ emissions from the aviation sector were 712.39 Mt CO₂ and attributed to convention kerosene use. These emissions are directly proportional to aviation energy demand. Twenty percent of energy demand is associated with 142.48 Mt CO₂. Hypothetically, if energy demand growth remains constant until 2050, the aviation sector would need at least 142.48 Mt CO₂ removal via DACCS or other CDR approaches. It is likely that energy demand growth will increase between now and 2050, so the aviation sector would need a minimum of 140 Mt CO₂ (rounded down) of CDR capacity by 2050 to support the continued use of conventional kerosene. URL for emissions data (IEA, accessed 21-JAN-2023): <https://www.iea.org/reports/aviation>

Further, in the NZE scenario, 25% of energy demand is met by synthetic fuels. Assuming that this fuel is synthetic kerosene with an equivalent direct carbon intensity as conventional kerosene, there would be a minimum of 178 Mt of direct CO₂ flow associated with the combustion of said synthetic kerosene in the hypothetical constant-demand case. If sector energy demand growth increases, 25% of energy demand would be associated with a greater amount of direct CO₂ flow. Hence, the aviation sector would need a minimum of 180 Mt of CO₂ flow (rounded, from DAC or biomass) to supply carbon for synthetic fuels. Indirect CO₂ contributions from fuel production and transportation are not considered in this reference calculation.

⁴ Competition among suppliers can be helpful to reducing DAC costs, leading technologies down a learning curve toward a low-cost and scalable solution. On the other hand, competition on the demand side is likely to increase prices of CO₂ from DAC. Deployment challenges due to DAC’s technical maturity or resource limitations are additional risks of price escalation.

⁵ The regeneration energy typically is thermal, a mixture of thermal and mechanical (vacuum swing), chemical (moisture swing), or electrochemical.

⁶ One should note that there are lifecycle assessment concerns pertaining to some mineralization approaches due to mining, milling, chemical use, transportation, and related activities.

⁷ Heirloom’s technology reverses the chemistry after capture, recreating the mineral oxide and releasing the captured CO₂. Overall, it is a capture-and-release DAC process.

⁸ In general, CO₂ electrolyzers have competing reactions for CO₂ that divert it from the intended CO product. Most notably, the presence of hydroxide ions (HO⁻) diverts CO₂ towards the bicarbonate ion

(HCO_3^-). Another common side reaction in systems that employ water (H_2O) is electrolysis to H_2 and O_2 . For example, if the aim was to increase the reaction's driving force (voltage difference) to enable reasonable conversion of CO_2 at lower concentrations, the system is likely to become inefficient due to electrolysis or other side reactions.

⁹ In general, purified CO_2 is better for these reactions in part because the driving force for reaction is maximized and in part because side reactions are minimized.

¹⁰ For example, consider the following:

CAC Synfuels (<https://www.cac-synfuel.com/en/kerosene#:~:text=CO%202%2C%20water%20and%20electricity%20are%20used%20to,The%20kerosene%20technology%20New%2C%20unique%20method%20of%20manufacture>),

MissionGreenFuels (<https://missiongreenfuels.dk/methanol-to-jet/>),

ExxonMobil (https://www.exxonmobilchemical.com/en/resources/library/library-detail/101116/exxonmobil_sustainable_aviation_fuel_production_en)

Masdar, TotalEnergies, Siemens Energy and Marubeni (<https://news.masdar.ae/en/News/2023/01/25/11/17/Novel-pathway-to-make-SAF-from-methanol>)

¹¹ Greyrock press release, "Carbon Engineering And Greyrock Energy Partner To Deliver Commercial Air-to-Fuels Systems", URL: <https://www.greyrock.com/news/carbon-engineering-and-greyrock-energy-partner-to-deliver-commercial-air-to-fuels-systems/>

¹² J. Tamura, A. Ono, Y. Sugano, *et al.* "Electrochemical reduction of CO_2 to ethylene glycol on imidazolium ion-terminated self-assembly monolayer-modified Au electrodes in an aqueous solution", *Phys. Chem. Chem. Phys.*, 17 (2015) 26072–26078; URL: DOI: <https://doi.org/10.1039/C5CP03028E>

¹³ Z Cao and Z Shi, "Deoxygenation of Ethers To Form Carbon–Carbon Bonds via Nickel Catalysis", *JACS* 2017, 139, 19, 6546–6549; URL: <https://doi.org/10.1021/jacs.7b02326>

¹⁴ P Gao, S Dang, S Li, *et al.* "Direct Production of Lower Olefins from CO_2 Conversion via Bifunctional Catalysis", *ACS Catal.* 2018, 8, 1, 571–578; URL: <https://doi.org/10.1021/acscatal.7b02649>

¹⁵ Yao, B., Xiao, T., Makgae, O.A. *et al.* "Transforming carbon dioxide into jet fuel using an organic combustion-synthesized Fe–Mn–K catalyst", *Nat Commun* 11, 6395 (2020). <https://doi.org/10.1038/s41467-020-20214-z>

¹⁶ Suitable low-quality PtL species/mixtures include hydrocarbons that do not have sufficient properties to qualify as an aviation fuel. With effort, these species/mixtures could be enhanced and recycled. Other suitable PtL byproducts may include species that are not suitable for rework and recycling.

¹⁷ For example, this is evident in copper-based catalysis of CO_2 to fuels, which has received significant

focus for converting CO₂ to fuel-relevant mixtures. The widely perceived disadvantage is that product distributions of the mixtures are not well controlled, rendering the mixtures inadequate for use as a fuel.

¹⁸ Preliminary analysis suggests that there is sufficient oxygen generated within the PtL process to enable oxycombustion of at least a minor fraction of PtL species. Consider an alcohol C_nH_{2n+2}O that was synthesized from CO₂ and H₂O. The stoichiometric requirement for hydrogen is (n+1)H₂ and this comes from (n+1)H₂O, which produces 0.5(n+1)O₂ through electrolysis. The stoichiometric requirement for carbon is (n)CO₂, which produces (n)O₂. Altogether, the oxygen available is (1.5n+0.5)O₂. For n=1, the alcohol is methanol, CH₃OH; and there are 2O₂ molecules available; in the gas phase, this represents a 66.7% O₂ concentration (for comparison, the stoichiometric requirement is 60% O₂). Further, if one methanol molecule proceeded to make SAF while one was retained for process heating, there would be an 80% O₂ concentration. In practice, even more oxygen would be available because additional hydrogen is required to upgrade the methanol molecule that proceeded towards SAF. For n=2, the alcohol is ethanol, C₂H₅OH; and there are 3.5O₂ molecules available; in the gas phase, this represents a 77.8% O₂ concentration (for comparison, the stoichiometric requirement is 75% O₂). Further, if one ethanol molecule proceeded to make SAF while one was retained for process heating, there would be an 87.5% O₂ concentration. In practice, even more oxygen would be available because additional hydrogen is required to upgrade the ethanol molecule that proceeded towards SAF. Hence, it is not impossible to operate in an enriched oxygen environment using the oxygen derived from H₂O and CO₂, in order to allow oxycombustion of PtL species that do not yield SAF. While these examples oversimplify the problem, they illustrate the effect of carbon number and of product yield.