



ISSUE BRIEF

Sustainable Aviation Fuels: *e-Fuels*

DECEMBER 2025

Introduction

Today, the aviation sector is responsible for roughly 2 to 3 percent of global carbon dioxide (CO₂) emissions. Although technological advancements continue to increase fuel efficiency, total emissions continue to grow as a result of robust demand and rising air traffic. Aviation emissions are projected to more than double by 2050 without ambitious efforts to decarbonize.¹

The sector's contributions to climate warming may be far higher when non-CO₂ warming effects are included. Condensation trails, or **contrails**, formed when ice condenses around soot particles, trap thermal energy in the atmosphere, and their total warming impact may be even greater than warming from direct CO₂ emissions.^a

In addition to carbon pollution, the aviation sector is also responsible for significant emissions of other greenhouse gases (GHGs) and health-harming pollutants, including soot (or fine particulate matter), nitrogen oxides (NO_x), and other ozone precursors. Communities adjacent to airports and military personnel are both disproportionately exposed to these pollutants.

To address the significant and growing impacts of the sector on human health and the climate, policymakers and industry players alike have set ambitious decarbonization goals. The challenge is formidable: electrification holds promise for the ground transportation sector, but aviation

must grapple with gravity's pull. Though rapid advancements in battery technologies could enable electrification of short-haul flights, the energy density of jet fuel remains many times higher than that of today's batteries.²

As a result, interest in alternatives to petroleum-based jet fuels has exploded in recent years. **Sustainable aviation fuels (SAF)** or **alternative fuels** are drop-in renewable jet fuels made from non-conventional feedstock such as biomass or hydrogen and captured carbon dioxide, compatible with existing aircraft engines.¹ When made from biomass, truly sustainable fuels should emit fewer lifecycle GHGs compared to petroleum, and also be made from feedstocks with minimal requirements for fresh water that do not compete with food production or drive deforestation or habitat conversion. When created via industrial processes like power-to-liquid (PtL) conversion, hydrogen and carbon dioxide must be sourced through sustainable means, such as electrolysis with renewable energy and industrial point-source carbon capture.

Although SAF currently comprises less than 0.5 percent of aviation fuels used annually, in recent years, major economies have committed to SAF blending targets for 2030 and beyond to advance their progress toward climate goals.³⁻⁴ Responsibly sourced and efficiently produced SAF could contribute a substantial portion of total climate mitigation by the aviation sector in the coming decades, though it is by no means the only option available in the mid- to long-term.

Because SAF generally burns cleaner than conventional jet fuel, emitting less soot and other pollutants, adoption of SAF could also help to reduce contrail formation and pollutant emissions. At the same time, even if emissions are substantially reduced, the impacts of CO₂, NO_x, and soot on health and the climate in future decades could remain unacceptably high amid rising global demand for air travel. Moreover, if SAF feedstock production competes with food and feed crops for prime agricultural land and encourages conversion of natural ecosystems, the impacts on food security, ecosystem service delivery, and biodiversity conservation could be significant.

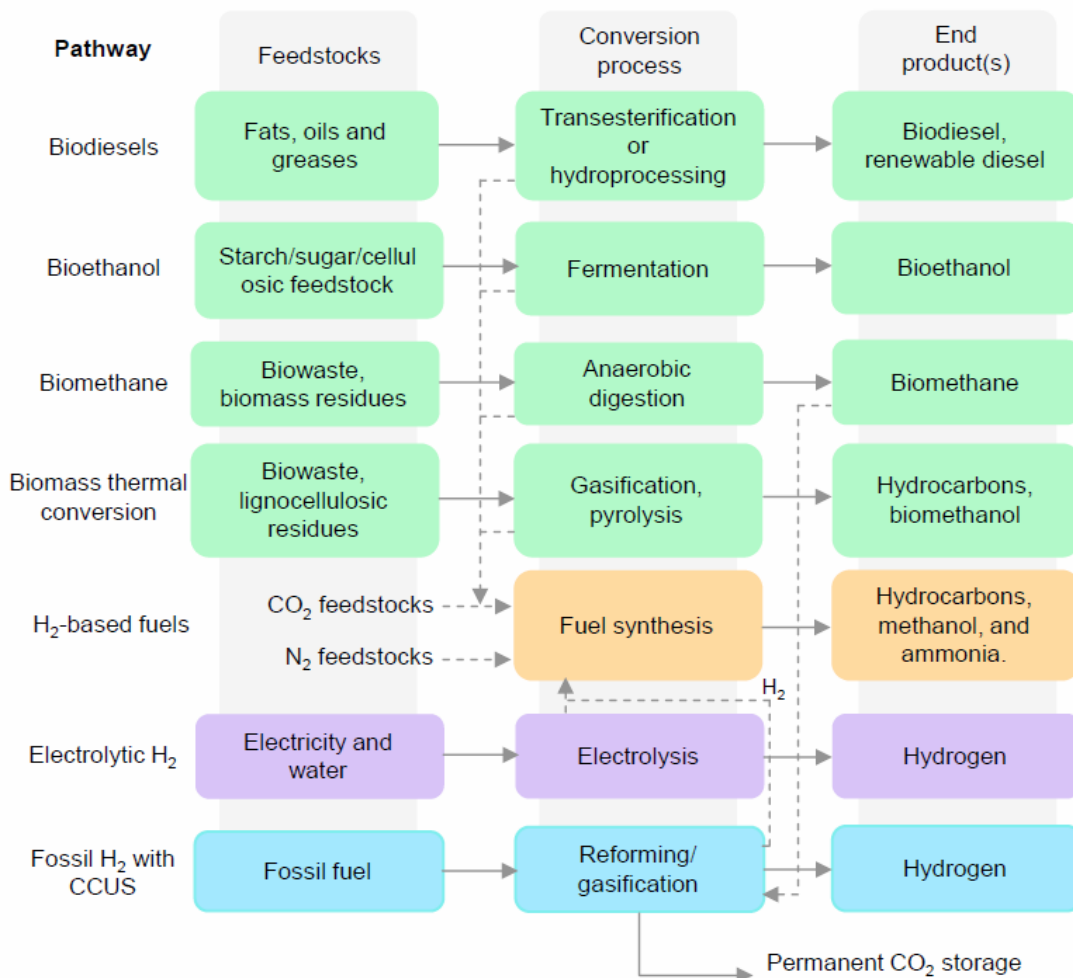
As we will discuss in the following pages, whether SAF repeats the mistakes of first-generation biofuels or continues to innovate in synthetic alternatives and delivers net-positive benefits to the environment depends upon many factors, including (but not limited to) feedstock production and processing, conversion technology, and global market dynamics. As global demand for SAF rises – stimulated by blending mandates in the European Union, Japan, and beyond – the U.S. could seize the opportunity to lead in the production of fuels that yield social, economic, and environmental benefits.

^a Various definitions for sustainable aviation fuels exist, with certification schemes, regulatory frameworks or incentive programs.

How is e-SAF made?

The term e-SAF here refers to alternative forms of sustainable aviation fuel that are primarily made using non-biomass feedstocks and clean energy and are also often referred to as synthetic fuels (see Figure 1).⁵ Some definitions of synthetic fuels include alcohol-to-jet (AtJ) pathways, as explored in the companion biofuels brief, but due to the reliance of this pathway on biomass-based ethanol feedstocks, it will not be the focus of our e-SAF review here. Instead, this section will focus on hydrogen-based fuel pathways for e-SAF, which can also entail the use of captured CO₂ as inputs.

Figure 1: Pathways of SAF production detailing feedstocks, conversion processes, and end products.



IEA. CC BY 4.0.

Notes: H₂ = hydrogen; CCUS = carbon capture, utilisation and storage.

Image used with permission from IEA 2025; *Delivering Sustainable Fuels: Pathways to 2035*, www.iea.org/reports/delivering-sustainable-fuels, License: CC BY 4.0.

E-SAF primarily relies on power-to-liquid (PtL) conversion processes where hydrogen (H₂) and carbon dioxide (CO₂) are combined via a Fischer-Tropsch (FT) synthesis or a methanol-to-jet fuel process to form liquid hydrocarbon fuel.⁶ This method of e-SAF development is considered especially viable as it can be blended with up to 50 percent of kerosene (conventional jet fuel) by volume to create fuel that is still compatible with current jet engines.⁶⁻⁷ In order for this form of SAF to be sustainable, it requires both clean H₂ and non-biogenic sources of CO₂ as inputs – both of which face their own challenges with sourcing and supply chain constraints.

Clean Hydrogen Inputs

Given that H₂ is a required ingredient for e-SAF production – as well as a fuel itself – decarbonizing the hydrogen industry is pivotal, but it is not without its own trade-offs. There are two primary pathways for creating clean hydrogen⁸:

- **Electrolytic hydrogen.** Often referred to as green hydrogen, this pathway involves using clean electricity and an electrolyzer to isolate H₂ molecules in water. This form of hydrogen relies on readily available and low-cost renewable energy and water availability.
- **Methane reforming/gasification with carbon capture.** A low-carbon alternative form of H₂, blue hydrogen, utilizes natural gas in a reformation process with added carbon capture equipment to capture and sequester CO₂ emissions, preventing their release during production. This type of hydrogen builds on existing natural gas infrastructure but requires additional carbon capture, transport, and sequestration infrastructure. (NWF's views on clean hydrogen can be found [here](#).)

CO₂ Inputs

Carbon dioxide is a critical input in the PtL conversion process, and while naturally occurring, it is required in substantial amounts and at a certain level of purification for the creation of e-SAF. The pathways for obtaining CO₂ for fuel conversion are largely limited to CO₂ capture and newer methods relying on technological carbon dioxide removal (CDR) pathways, including:

- **Biogenic or industrial carbon capture.** Point-source carbon capture equipment can be retrofitted onto existing facilities that emit CO₂ to capture the emissions before they enter the atmosphere. Industries that manufacture cement, steel, aluminum, and many other materials emit high amounts of non-biogenic carbon that can be captured.⁹ Carbon capture on ethanol facilities is a low-cost method of capturing biogenic CO₂ that is also high-

purity.¹⁰ However, as explained in our companion paper on biogenic SAF, there are many complex considerations for rendering these methods sustainable or even carbon-neutral.

- **Technological carbon removal.** These technological pathways mirror similar processes to photosynthesis, removing CO₂ directly from the atmosphere in a way similar to plants, instead relying largely on chemical filters that bind the CO₂. While the technology is still nascent or in pilot/demonstration stage, one of the leading pathways, direct air capture (DAC), offers promising opportunities for CO₂ removal and supply.

Box 1: Industrial players are considering the development of e-SAF using captured CO₂

The Washington-state-based corporation [Twelve](#) is an e-SAF supplier that uses a slightly different version of PtL conversion discussed above to create its fuel. The process similarly requires water, CO₂, and renewable energy, but instead of creating hydrogen, Twelve utilizes a CO₂-electrolysis process that directly converts the CO₂ into the hydrocarbon components needed to make fuel ([Industrial Photosynthesis, Twelve, 2025](#)). The company also currently gets its CO₂ supply from ethanol facilities due to their focus on sources that are: high purity, located in or near areas with low-cost renewable energy, and from biogenic capture or directly removed from the atmosphere ([Carbon Transformation, Twelve, 2025](#)). Twelve asserts that using CO₂ captured from ethanol facilities could result in the production of 5 billion gallons of their e-Jet fuel per year. Capturing the emissions from ethanol facilities not only provides companies like Twelve with a high-quality stream of CO₂ for their e-SAF production, but the low-carbon ethanol produced at the facility can also be utilized in AtJ processes.

Ongoing research into the development of e-SAF pathways, including the CO₂ electrolysis used by Twelve and alternative methods of producing the necessary components of these fuels, will continue to advance the sector and close the gap between current biofuel production and the future of more sustainable fuels.

Why e-SAF: Challenges and Opportunities

As stated in the Introduction, decarbonization of the aviation industry is a necessary part of meeting net-zero goals as a society, and e-SAF presents a variety of pathways to decarbonize while avoiding some of the challenges presented by biogenic SAF. Various modeling scenarios of the potential fuel mix (Figure 2) show that e-SAF has the potential to represent almost 40 percent, if not almost 56 percent, in the most advanced scenario, of the overall demand for aviation fuel by 2050.¹¹

Figure 2: The base case modeling scenario, meant to represent the net-zero aviation future that is attainable with available technologies and the assumption that biofuels will be used to meet a large part of total demand. The figure shows the fuel that would be needed for aviation as a percentage of the projected total supply.

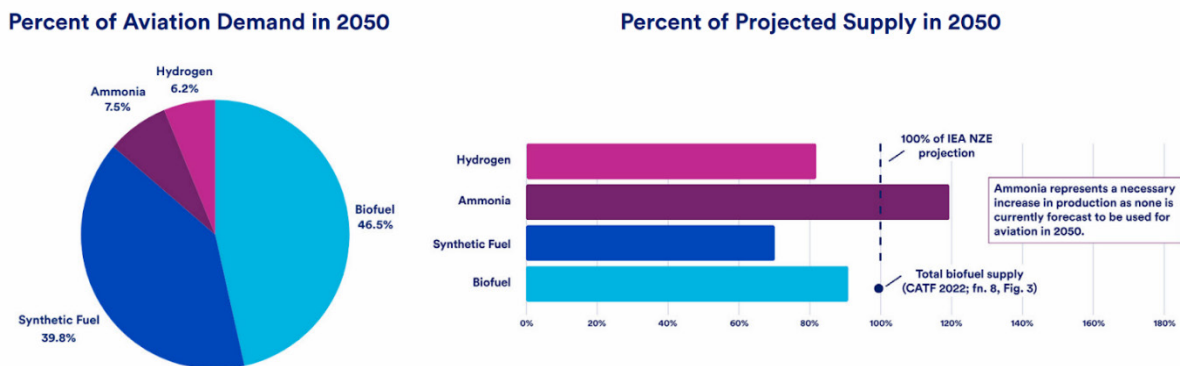


Image used with permission from Clean Air Task Force 2024; *Decarbonizing Aviation: Enabling Technologies for a Net-Zero Future*. <https://www.catf.us/resource/decarbonizing-aviation-enabling-technologies-net-zero-future/>

Predictions going forward show that, of global fuel demand by sector, the transportation sector will continue to be the main driver, with e-fuels playing a substantial part in meeting those needs.⁵ That said, the sector is not without its own unique constraints. Major challenges facing the e-SAF sector include, but are not limited to:

- **Energy intensity, availability, and cost for creating clean H₂.** Creating e-SAF is an energy-intensive process relying on not only abundant and affordable renewable energy, but a steady and consistent supply of electrolyzers to create H₂. While the U.S. is trending towards renewable energy—with 30 percent of the country’s large-scale power generation in 2024 coming from clean tech like solar, wind, geothermal, and battery storage—there is still substantial work to be done in decarbonizing the American grid.¹² The deployment of clean energy faces its own issues with high project interest rates that raise costs and supply chain constraints that have the potential to become added barriers for the development of e-SAF. Onshoring clean manufacturing and creating dedicated renewable energy capacity for e-SAF production will be necessary if the sector is to be successful.
- **Deployment of carbon management infrastructure.** Carbon management refers to a range of technologies and their supporting infrastructure, including both point-source carbon capture, like that which occurs on ethanol plants, as well as carbon removal strategies like DAC. These technologies can provide e-SAF producers with the CO₂ needed for their processes, but the availability of these projects and their proximity to e-SAF facilities can result in bottlenecks for the industry. Currently, out of the Americas, the U.S. stores the most CO₂ geologically, reaching over 100 megatons (Mt) cumulatively in 2023—but to support a growing e-SAF industry, the amount of CO₂ captured and transported for conversion will need to continue increasing.¹³
- **Coming down the cost curve.** Currently, both the H₂ production and CO₂ capture processes (whether point-source or DAC) are costly compared to fossil-based methods of fuel production, which, alongside the capital needed to develop e-SAF, result in fuel costs that are two- to five-times higher than traditional jet fuel.¹¹ So even if developing e-SAF is possible, it is not currently cost-competitive for the aviation industry to deploy. It is likely that with the ongoing and widespread deployment of clean energy technology and carbon management infrastructure, costs for e-SAF could come down, but due to the energy-intensive nature of processing and a growing demand for H₂ for other clean fuel needs, closing the gap between e-SAF and traditional jet fuel will require supportive policy mechanisms.⁵

While the challenges of scaling e-SAF are not insubstantial, the decarbonization benefits of research and development (R&D) and deployment of e-SAF—beyond avoiding biomass pitfalls—far outweigh them.

Key benefits to producing e-SAF include, but are not limited to:

- **Drop-in ready fuel.** Unlike hydrogen or ammonia as potential fuel sources, most e-SAF is considered “drop-in” fuel, which means that it can be deployed today when blended with traditional jet fuel and does not require that new planes or engines be built.¹⁴ This not only allows e-SAF developers to tap into the existing aviation base but also means immediate emissions reduction potential.
- **Opportunities to support the carbon removal sector.** The Intergovernmental Panel on Climate Change (IPCC) recognizes that CDR is integral to meeting net-negative scenarios and preventing the worst impacts of the climate crisis.¹⁵ In response, the CDR industry has continued to develop both biotic and abiotic pathways to remove CO₂ from the atmosphere, including direct air capture. With the additional incentive of providing sustainable CO₂ sources for the e-SAF supply chain, there are opportunities for collaboration between the technological CDR sector and e-SAF developers. Some DAC companies, such as Carbon Engineering, are already looking into “air-to-fuels” PtL models to develop their own e-SAF using the CO₂ their DAC technology has pulled from the atmosphere.¹⁶ CDR is a steadily growing field that is seeing global investment, but the demand certainty that guaranteed off-takers like e-SAF producers could provide might help create the added assurance needed for the industry to reach scale.
- **Economic development across the supply chain.** For the e-SAF industry to overcome its challenges and provide fuel to the aviation industry at scale, an entire supply chain of H₂, carbon management technologies and infrastructure, and renewable energy will need to be built out alongside continuing research and development (R&D) to discover and evolve new pathways. Capital investments in clean energy projects, new e-SAF construction projects, and re-skilling of laborers in the traditional jet fuel economy all present opportunities for regional and national economic development.⁵⁻¹⁴

- **Improvements in public health.** Given that e-SAF burns cleaner than traditional jet fuel, there are potential benefits to public health as well as the climate from scaling the industry. Traditional jet fuel combustion releases ultrafine particulate matter and sulfur dioxide, which present negative impacts to human health, especially for populations that reside near airports.¹⁴⁻¹⁷ Traditional jet fuel refinement and production processes also release various air pollutants that are avoided by e-SAF production, which largely relies on clean energy and captured CO₂.

The Outlook: e-SAF as a Long-term Strategy

While innovation in aviation is continuing to evolve alongside the clean energy transition, there are still significant hurdles to overcome to help the industry reach scale, especially given the need for deploying supportive infrastructure. This infrastructure, including what is needed for clean hydrogen and carbon capture, is often in early deployment and will require its own investment and continued innovation to come down the cost curve and therefore contribute to reducing the cost of e-SAF in the long term.

Given the challenges that e-SAF faces currently, it makes sense to lean into the use of truly sustainable biofuels in the near-term as a transition strategy—should these fuels meet strict environmental and socio-economic requirements across the entire life cycle of feedstock-sourcing to guarantee true climate benefit.

To close the gap between the ongoing R&D and small-scale deployment of e-SAF and the need for fuel at scale, as well as to ensure that biofuels remain a transition fuel and to avoid negative impacts, supportive policy mechanisms are going to be necessary across the value chain. The potential for e-SAF as a viable technology and industry is worth the financial and political investment that it will take to grow the sector to diminish the aviation sector's contribution to climate change.

Key Points:

- The creation of e-SAF primarily relies on processes combining hydrogen (H₂) and carbon dioxide (CO₂), both of which face their own feedstock challenges.
- H₂ and CO₂ production have various levels of sustainability depending on the pathway taken—for example, electrolytic (or green) H₂ relies on renewable energy and water and is considered the “cleanest” pathway for developing hydrogen. CO₂ can be produced biogenically or through carbon capture or carbon removal processes.
- For e-SAF to reach scale and meet aviation demand, there are a variety of challenges that need to be overcome, including sourcing clean, affordable energy; the deployment of carbon management infrastructure to provide non-biogenic CO₂ for production; and reducing the cost of development across the value chain.
- One of the biggest benefits of e-SAF is that it is a “drop-in” fuel, meaning it can be deployed today when blended with traditional fuel using existing infrastructure. Other benefits of e-SAF development include economic development, improvements in public health, and opportunities for a growing carbon removal sector.
- In short, developing e-SAF and scaling the sector to meet commercial demand is not without its challenges, but investment in synthetic fuels as a long-term strategy will be beneficial for meeting climate goals.

Brief by Simone H. Stewart, Ph.D., Senior Industrial Policy Specialist (stewarts@nwf.org) (2025)

References

- ¹ Climate Action Tracker. (2025). "International Aviation." <https://climateactiontracker.org/sectors/aviation/>
- ² Pattanayak, T., & Mavris, D. (2025). Battery technology for sustainable aviation: a review of current trends and future prospects. *Applied Energy*, 397, 126356. <https://doi.org/10.1016/j.apenergy.2025.126356>
- ³ IATA. (2024). "Disappointingly Slow Growth in SAF Production." <https://www.iata.org/en/pressroom/2024-releases/2024-12-10-03/>
- ⁴ World Economic Forum. (2024). *Scaling Up Sustainable Aviation Fuel Supply*. <https://www.weforum.org/publications/scaling-sustainable-aviation-fuel-supply-overcoming-barriers-in-europe-north-america-and-the-middle-east/>
- ⁵ IEA. (2025). "Delivering Sustainable Fuels." <https://www.iea.org/reports/delivering-sustainable-fuels>, License: CC BY 4.0
- ⁶ Rojas-Michaga, M., Michailos, S., Cardozo, E., Akram, M., Hughes, K. J., Ingham, D., & Pourkashanian, M. (2023). Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. *Energy Conversion and Management*, 292(117427). <https://doi.org/10.1016/j.enconman.2023.117427>
- ⁷ Vaquerizo, L., Rego-Fernandez, D. (2025). Net-zero sustainable aviation fuel (SAF) production via CO₂ hydrogenation in low-temperature Fischer-Tropsch synthesis: Process design and alternatives. *Journal of CO₂ Utilization*, 102, 103235. <https://doi.org/10.1016/j.jcou.2025.103225>
- ⁸ National Wildlife Federation. (2025). "National Wildlife Federation Fact Sheet: Hydrogen as a Clean Energy Option." <https://www.nwf.org/-/media/Documents/PDFs/Environmental-Threats/NWF-Hydrogen-Fact-Sheet.pdf>
- ⁹ National Wildlife Federation. (2021). "Carbon Capture and Removal: State of the Science for Responsible Deployment." https://www.nwf.org/-/media/Documents/PDFs/Environmental-Justice/NWF_CCUS-CDR_Issue-Brief_2021.ashx?la=en&hash=E36EA3F67C52AA8E1F40FB64507B2F41A37C1709&hash=E36EA3F67C52AA8E1F40FB64507B2F41A37C1709
- ¹⁰ Battelle Insider. (2021). "Why Ethanol Producers Should Look at CCS Now." <https://inside.battelle.org/blog-details/why-ethanol-producers-should-be-looking-at-ccus-now#:~:text=By%20selling%20CO2%20directly,reducing%20carbon%20emissions%20through%20CCS>
- ¹¹ Walker III, T.K., Tatsutani, M., Lewis, J. (2024). "Decarbonizing Aviation: Enabling Technologies for a Net-Zero Future." <https://www.caf.us/resource/decarbonizing-aviation-enabling-technologies-net-zero-future/>
- ¹² Bird, L., Light, A., Goldsmith I. (2025). "US Clean Power Development Sees Record Progress, As Well As Stronger Headwinds." <https://www.wri.org/insights/clean-energy-progress-united-states>
- ¹³ Global CCS Institute. (2025). "Global Status of CCS 2025: Staying the Course." <https://www.globalccsinstitute.com/wp-content/uploads/2025/10/Global-Status-of-CCS-2025-report-9-October.pdf>
- ¹⁴ Hebert, J., Laska, A., Price, J., Ehrnschwender, D., Haley, B.; Kwok, G., Farbes, J. (2024). "Soaring to New Heights: The Economic Impacts of Building an American SAF Industry." <https://www.thirdway.org/report/soaring-to-new-heights-the-economic-impacts-of-building-an-american-saf-industry>
- ¹⁵ IPCC. (2023). Summary for Policymakers. In: *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, <https://doi:10.59327/IPCC/AR6-9789291691647.001>
- ¹⁶ Carbon Engineering. (2025). Air to Fuels. <https://carbonengineering.com/air-to-fuels/>
- ¹⁷ Blanco, M., Louie, M.S., Liu, N., Mishra, S.K., Austin, E. (2025). "Quantifying health benefits of sustainable aviation fuels: Modeling decreased ultrafine particle emissions and associated impacts on communities near the Seattle-Tacoma International Airport." *Atmospheric Environment*, 355, 121280. <https://doi.org/10.1016/j.atmosenv.2025.121280>