NATIONAL WILDLIFE FEDERATION

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 (CO_2) 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-CO_2 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 CO_2 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 CO_2, 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.

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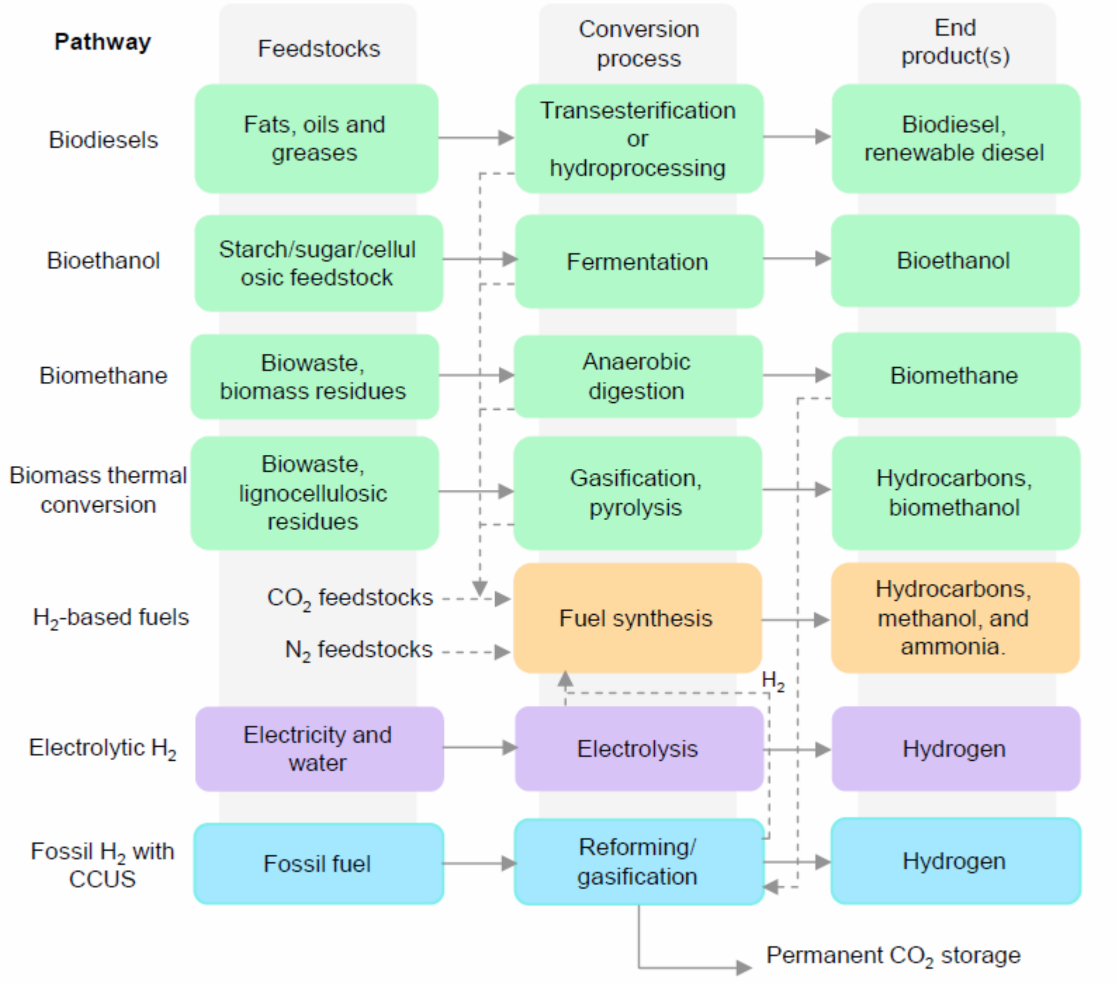
[a] Various definitions for sustainable aviation fuels exist, with certification schemes, regulatory frameworks or incentive programs.

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 CO_2 as inputs.

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



IEA. CC BY 4.0.

Notes: H_2 = 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 (H_2) and carbon dioxide (CO_2) 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 H_2 and non-biogenic sources of CO_2 as inputs – both of which face their own challenges with sourcing and supply chain constraints.

Clean Hydrogen Inputs

Given that H_2 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 hydrogen[8]:

- **Electrolytic hydrogen.** Often referred to as green hydrogen, this pathway involves using clean electricity and an electrolyzer to isolate H_2 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 H_2, 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.)

CO_2 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 CO_2 for fuel conversion are largely limited to CO_2 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 CO_2 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 CO_2 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 CO_2 directly from the atmosphere in a way similar to plants, instead relying largely on chemical filters that bind the CO_2. While the technology is still nascent or in pilot/demonstration stage, one of the leading pathways, direct air capture (DAC), offers promising opportunities for CO_2 removal and supply.

Box 1: Industrial players are considering the development of e-SAF using captured CO_2

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, CO_2, and renewable energy, but instead of creating hydrogen, Twelve utilizes a CO_2-electrolysis process that directly converts the CO_2 into the hydrocarbon components needed to make fuel (Industrial Photosynthesis, Twelve, 2025). The company also currently gets its CO_2 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 CO_2 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 CO_2 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 CO_2 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.

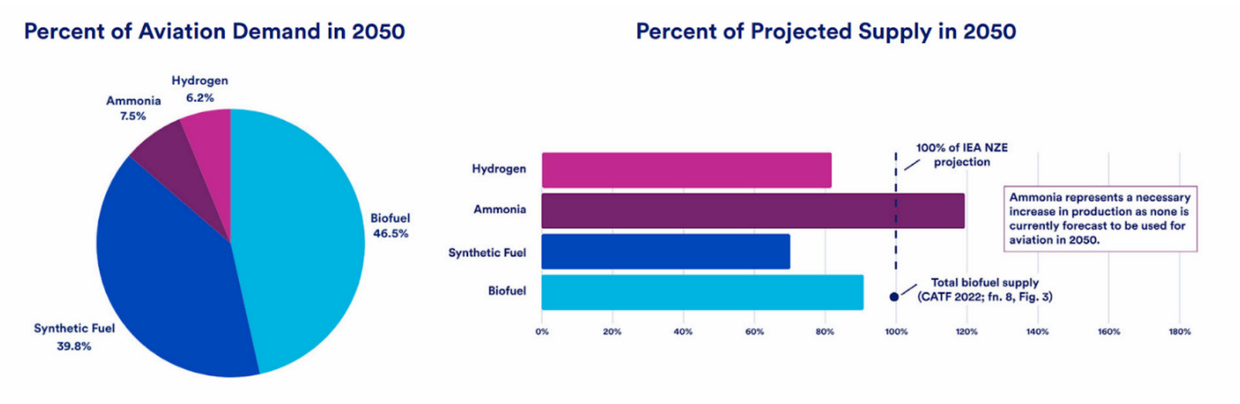


Image used with permission from Clean Air Task Force 2024; Decarbonizing Aviation: Enabling Technologies for a Net-Zero Future. https://www.catf.us/resource/decarbonizing-aviation-enabling-technologies-net-zero-future/

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 H_2.** 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 H_2. 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 CO_2 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 CO_2 geologically, reaching over 100 megatons (Mt) cumulatively in 2023–but to support a growing e-SAF industry, the amount of CO_2 captured and transported for conversion will need to continue increasing.[13]

- **Coming down the cost curve.** Currently, both the H_2 production and CO_2 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 H_2 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 CO_2 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 CO_2 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 H_2, 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 CO_2.

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 (H_2) and carbon dioxide (CO_2), both of which face their own feedstock challenges.

- H_2 and CO_2 production have various levels of sustainability depending on the pathway taken—for example, electrolytic (or green) H_2 relies on renewable energy and water and is considered the "cleanest" pathway for developing hydrogen. CO_2 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 CO_2 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)

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As we will discuss in the following pages, whether SAF repeats the mistakes of first-generation biofuels 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.

How is SAF made?

In general terms, **bio-based SAF** is drop-in liquid hydrocarbon jet fuel made from renewable or waste biomass resources that reduces net life-cycle emissions compared to conventional fuel.

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

The Biden-Harris Administration's 2023 SAF Grand Challenge defined SAF as fuels that reduce emissions by 50 percent compared to the baseline.[5]

SAF production pathways must be approved by ASTM International, and feedstocks vary in their compatibility with approved SAF production pathways. Alongside **power-to-liquid fuels** (discussed in Part 2), there are three main fuel synthesis routes: **Fischer-Tropsch (FT), hydroprocessed esters and fatty acids (HEFA),** and **alcohol-to-jet (ATJ)**. HEFA is currently the main SAF pathway globally. In Table 1, we provide a summary of these pathways.

Table 1. Summary of Pathways

Pathway	Examples of Feedstocks	Process	Technological Maturity & Costs	Potential Emissions Reductions Compared to Conventional Jet Fuel
Hydroprocessed Esters and Fatty Acids (HEFA)	Used cooking oil, animal fats, oils from alternative oilseeds	Requires gaseous hydrogen (H_2), which replaces oxygen molecules from fats via hydrogenation	Currently produced at commercial scale – costs unlikely to decrease	Up to 70-85 percent, but potentially much lower if demand for feedstocks drives ecosystem conversion, directly or indirectly
Gasification with Fischer-Tropsch	Crops, woody residues, municipal solid wastes (MSW), lignocellulosic biomass	Requires gasification of biomass to create syngas (H_2 and CO) for FT reactors	Piloting, with commercial scale production projected for mid-2030s– costs may lower as technology scales	Roughly up to 80 to 95 percent, depending on feedstock (e.g., very high for MSW, but potentially high for woody biomass with superior alternative fates)
Alcohol-to-Jet (AtJ)	Crops, including corn, sugarcane, other grains; lignocellulosic biomass	Alcohols from fermentation of biomass feedstocks are converted to SAF via dehydration, oligomerization, hydrogenation, and fractionation	Piloting, with commercial scale production projected for later this decade – potential for cost reduction unclear	Roughly up to 80 to 95 percent, depending on feedstock, but potentially much lower if demand for feedstocks drive ecosystem conversion
Power-to-Liquid (PtL)	Hydrogen (H_2) and gaseous CO_2 (requires substantial supply of renewable electricity as well)	H_2 is combined with CO_2 (from industrial carbon capture or direct air capture) in a process powered by renewable electricity	Varies by technology, but generally in development, commercial-scale production projected for late 2030s – high costs remain a barrier	Up to 85 to nearly 100 percent, depending on energy and feedstock sources

Sources: *NREL, 2024*; *WEF, 2024*; *Zahid et al., 2024*; *WEF, 2022*.

All ASTM-approved SAF must be blended with commercial Jet A fuel. Presently, all pathways are approved for maximum blending of 50 percent or less, although 100 percent SAF-powered flights have been tested successfully and commercial aircraft using SAF exclusively are currently in development for delivery by 2030.[6]

Is there enough biomass available to meet ambitious goals for e-SAF production? Estimates of total biomass available for SAF and other biofuel production in the U.S. vary, but the U.S. Department of Energy's 2023 *Billion-Ton Report* projected that around 1.1 to 1.5 billion tons of biomass could be potentially available for use in bioenergy.[7] Achieving the SAF Grand Challenge goal of satisfying 100 percent of demand for aviation fuel in the U.S. in 2050 (projected to be around 35 billion gallons) with bio-based SAF would require around 1 billion tons of biomass feedstock.[5] Even the more conservative scenarios explored in the 2023 *Billion-Ton Report* assume significant expansions in the collection of agricultural residues and in the cultivation of perennial feedstocks, which both contribute negligible amounts to U.S. energy production today.

See Table 2 for more information on feedstocks and supply constraints.

Table 2. Feedstock categories and supply constraints

Category	Feedstock	Pros	Cons
Wastes & Residues	**Waste fats and oils** (used cooking oil, animal fats, and grease)	Relatively easy to convert to drop-in fuel, lower cost, potential for reduced land-conversion	Limited supply with decentralized supply chains; requires processing to remove impurities and prevent corrosion during refinement; the use of animal fats potentially offsets production costs for animal agriculture, which is also emissions-intensive, resulting in leakage; relies upon robust certification schemes to ensure sustainable sourcing and prevent fraud by suppliers; often imported from countries such as China.
	Municipal solid waste (MSW) and **wet waste** (food waste, manure, sewage sludge)	Very low cost; diverts waste from landfills and avoids methane emissions; high total emissions reduction potential	MSW can be highly heterogenous, requiring more pre-treatment, potential for pollution and contamination
	Agricultural residues (corn stover, rice husks, nutshells, etc.)	No additional land conversion, widely available, sometimes pile-burned (which makes finding alternative economic uses appealing)	Challenging to determine appropriate removal rates for a given cropping system and climate; in some contexts, harvesting increases erosion, depletes soil nutrients, reduces fertility; logistically challenging and costly to collect and aggregate at scale
	Forestry residues and **wood waste** (logging residues, bark, small-diameter thinnings, sawdust)	Utilization could reduce pile burning, which is a source of health-harming pollutants, can be part of evidence-based forest stewardship (e.g., preparing for prescribed burn)	Limited availability, as forestry wastes and residues are already utilized for energy generation; superior alternatives for valorization exist; challenging to determine optimal removal and retention rates for forestry residues; excessive removals cause erosion, reduce soil fertility, and reduce wildlife habitat; communities in areas where biomass is sourced and processed have been harmed by local increases in pollution and lost ecosystem services; challenging to aggregate and transport long distances
Purpose-grown biomass crops	**Algae and aquatic biomass**	High lipid production and high-yield, can utilize wastewater/brackish water and captured industrial CO_2 as inputs, can be sited on non-arable or contaminated lands	Water requirements, high cost and energy-intensive harvest
	Food and feed crops (including corn, soy, and sugarcane)	Conversion technologies are mature, could provide an offramp for biofuels for land transportation as electrification of vehicles continues	Contributions to land-use change and conversion (direct and indirect, domestic and international), potential for conflict between food vs. fuel production, water-intensive, input-intensive (with fertilizer application leading to greater nitrate pollution and N_2O emissions), often requires pesticide application, and yields limited GHG benefits, if any, when full life-cycle emissions are included
	Dedicated perennial energy crops (miscanthus, switchgrass, native prairie mixes, short-rotation willow coppice)	Can be grown on degraded and contaminated lands, require fewer inputs and less (or no) irrigation, can provide wildlife habitat and other valuable ecosystem services.	If grown on productive agricultural lands, could contribute to direct or indirect land-use conversion; proposals often include fast-growing species with potential to escape and invade other ecosystems

Sources: *BETO, 2024; Zahid et al., 2024; DOE, 2022; Doliente et al., 2020*

Logistical challenges and costs associated with feedstocks may create significant challenges. Biomass has a low energy density. For some feedstocks, such as corn stover or forestry residues, biomass must be collected with specialized equipment from many locations before being transported to processing facilities. Feedstock availability may be mediated by weather, global demand, pests and diseases, and other factors.[6] It may also need to be pre-processed or homogenized before being converted into fuels ready for blending. For these reasons, in addition to other impacts on ecosystems discussed below, the total volume of low-cost, sustainable biomass available may be far lower than what is estimated to be theoretically available.

Impacts of feedstocks from agricultural areas and natural and managed ecosystems

Increased demand for bio-based SAF may drive direct or indirect land-use change, with consequences for conservation and carbon storage. Habitat loss and degradation remains the single greatest threat to biodiversity conservation.[8] Though grasslands once covered huge swaths of the U.S., today, only a tiny fraction of the original extent remains.[9] Expansion of biofuel feedstock production for the RFS and other alternative fuel policies has been linked to substantial grassland loss and conversion,[10-11] with net cropland expansion of around 1 to 7 million acres estimated to have been associated with the RFS.[12]

As a result, the direct and indirect land-use change related to dedicated production of biofuel feedstocks are also significant threats to biodiversity conservation, both in the U.S. and in some of the world's global biodiversity hotspots. For example, a global synthesis linked biofuel crop production to declines in local species richness and abundance, with greater impacts from first-generation biofuels.[13] Monoculture cropland cannot support sensitive species, such as grassland-nesting birds, and may increase their direct or indirect exposure to harmful pesticides and herbicides. An analysis exploring impacts in North Dakota found that grassland birds responded more negatively to the expansion of biofuel feedstock production (i.e., corn and soy) than to oil and gas development.[14]

There may be some opportunities to increase the supply of non-food SAF feedstocks on lands that provide little value to people or wildlife due to their management history. When cultivated on degraded or contaminated lands that provide few ecosystem services to people or wildlife, some non-food feedstocks such as switchgrass, miscanthus, or algae may present opportunities to considerably expand feedstock supply without increasing nutrient input and irrigation requirements or exacerbating land-use pressures. (Unlike most dedicated biofuels feedstocks, perennial grasses have been found to increase species abundance of migratory birds and pollinators in some contexts.[13]) Invasive species should *never* be cultivated as feedstocks.

Biofuel feedstock production in marginal agricultural lands is sometimes proposed as a better option. Often, marginal agricultural lands are described as worthless. It is important, however, to note that economically marginal lands (i.e., those with very little potential for returns for producers, if converted to cropland) may still provide a variety of valuable ecosystem services and public goods. When restored to grasslands, wetlands, and riparian buffers, these areas can provide important habitat to pollinators and other wildlife, reduce nutrient runoff into waterways (protecting drinking water from contamination by synthetic agricultural inputs), and increase soil carbon storage.[15] Some researchers are exploring the potential for cultivating a diverse mixture of species (approximating the variety of natural grasslands) as biofuel feedstocks.[16] However, potential climate benefits of cultivating perennial grasses and other biofuel feedstocks in these areas would likely be counterbalanced by impacts on soil health and wildlife habitat during feedstock harvest.

Cultivating food and feed crops as dedicated SAF feedstock can have other unintended negative consequences. The negative externalities of biofuel feedstock production are borne by communities across the country – and very often, by rural and economically disadvantaged communities.[17-18] Conventional production of food and feed crops requires synthetic inputs, including fertilizers, pesticides, and herbicides. Reliance on fertilizers can emit GHGs in the form of nitrous oxide (N_2O) and increase water pollution for rural communities and downstream cities, as nitrates enter waterways through soil leaching and runoff. Corn and soy production also often requires irrigation, and though water requirements can vary substantially from region to region, this demand could place additional stress on aquifers across the country.

Still, there may be opportunities to increase feedstock production without driving further direct or indirect land-use conversion. When included in rotational cropping systems, oilseeds such as camelina, canola, and pennycress could provide yet another source of feedstock for SAF, while also providing environmental benefits to farmers and ecosystems such as reduced soil erosion – without increasing land-use pressures. When grown as a winter "cash cover crop," for example, camelina (*Camelina sativa*) could provide benefits to producers by reducing soil erosion and water run-off, interrupting pest cycles, and improving nutrient retention while helping farmers to diversify their operations and income streams.[19]

Challenges with wastes and residues as feedstocks

For HEFA, bottlenecks related to feedstock availability and traceability could prevent scaling. The HEFA pathway uses fats, oils, and greases, with used cooking oil (UCO) as the dominant feedstock. In the U.S., a significant volume of UCO is imported from China and other countries. Fraudulent sale of virgin oils, including palm oil, labeled as "used" cooking oil has led to heightened scrutiny of imports and led to calls for improved traceability systems in the European Union and the U.S.[20-21] While palm oil is one of the least land-intensive oil crops, palm oil production is still a significant driver of deforestation in the tropics, and demand for vegetable oils is projected to increase by nearly 50 percent by 2050.[22] The limited availability of feedstocks and the potential for induced indirect land-use change in response to demand for SAF – particularly in biodiversity hotspots such as Southeast Asia – are already prompting some jurisdictions, including the United Kingdom, to restrict use of the HEFA pathway in SAF targets.[23]

Municipal solid waste (MSW) from biological sources (e.g., food waste or unrecyclable paper) could provide a desirable feedstock. When biogenic MSW is used as a feedstock in the FT pathway, it may have a carbon intensity of only 5.2 g CO_2 equivalent (CO_2e) per megajoule (MJ).[24] For comparison, the intensity of corn ethanol-to-jet fuel is around 65 gCO_2e/MJ, and the jet fuel baseline is 89 gCO_2e/MJ.[24] (However, when non-biogenic MSW is used as a SAF feedstock, the carbon intensity increases significantly.) MSW also generally has a comparatively higher fuel yield per ton but significantly lower price per ton of feedstock than agricultural or forestry residues.[25] (As noted above, however, gasification with FT remains costly.) Management of MSW is a costly problem for communities, and landfilling and incineration may lead to groundwater and air pollution, respectively – with the effects disproportionately borne by low-income communities and communities of color in the U.S.[26] With continued advancements in pretreatment, gasification, and FT synthesis, SAF from MSW could reduce emissions by up to 80 to 90 percent compared to conventional jet fuel.[27] Recent analysis suggests that the European Union could meet its blending mandates with MSW feedstocks while complying with regulations prohibiting the use of food and feed feedstocks.[27]

Other biomass wastes and residues originating in agricultural systems and natural and managed ecosystems are generally considered to be ideal feedstocks for SAF, but the type and source of these materials matters. *Wastes* are materials that are discarded, with no intended use. *Residues* are by-products that may have uses in other contexts or applications. The difference is subtle but worth noting, as evaluating the carbon intensity of SAF may require consideration of alternative fates. If the use of residues for SAF displaces alternative uses that provide greater emissions reductions, causing *leakage*, the net benefits could be reduced or even negated.

Moreover, fuels are not the only potential application for biomass. Indeed, as global economies attempt to reduce fossil fuel reliance and reach net-zero in all sectors, biofuels may not prove to be the best use of biomass wastes and residues.

Given finite supplies, biomass wastes and residues may be instead diverted to alternative applications with higher return on investment, fewer logistical challenges, or greater net benefits to rural communities. For example, this could include biomass-based carbon dioxide removal, production of durable wood products from woody residues, or cellulose-based alternatives to fossil-derived plastics or chemicals. Often overlooked in assessments of potential SAF production is the ecological and environmental value of so-called "wastes" or "residues" when left on site in managed ecosystems or agricultural systems. Plant stems and leaves, woody debris, and even charcoal from burned biomass replenish soil nutrients; conversely, excessive removal of woody or herbaceous biomass from fields and forests can increase soil erosion and nutrient leaching or reduce soil organic carbon.[28-29] Yet in other contexts, including some conventional cropping systems with synthetic inputs, increased residue removal may have minimal or positive effects on yield, or may even reduce N_2O emissions.[30-31] Determining the appropriate retention level to optimize climate and ecosystem benefits isn't straightforward, as it may vary with local climate, soil type, water availability, and plant type, as well as silviculture or cropping system and management practices.[32]

In summary, wastes and residues should only be considered "sustainable" fuel feedstocks if they:

1. Can deliver net emissions reductions (i.e., minimal leakage or displacement of superior alternative uses);
2. Are responsibly sourced, without imperiling human health, food security, biodiversity, or wildlife habitat, and are traceable; and
3. Are harvested within ecological limits, in the case of agricultural and forestry residues.

Understanding carbon intensity and net impact

Climate benefits are not guaranteed, and even estimating the net climate impact of biofuel remains challenging. There are a few key reasons for this:

- **The use of life-cycle assessment (LCA), sometimes called cradle-to-grave analysis, to understand the net carbon intensity of biofuel production and use on greenhouse gas emissions has created controversy and ongoing debate.** Although LCA is an essential tool for decisionmakers, the results of LCA can change dramatically depending on the underlying assumptions and decisions made by modelers related to system boundaries.[33-34] Fundamentally different approaches to model design (including where system boundaries are drawn) and in key assumptions create uncertainty and variability; moreover, this uncertainty and variability is not always transparently communicated to policymakers.[35]

- **Understanding the impacts of direct and indirect land-use change – which can drive substantial GHG emissions – remains particularly challenging.** Understanding induced land use change requires both economic models that can assess land use change and emissions factors to understand the impacts of such changes, and there are substantial uncertainties in key elements of these economic models.[35] (Notably, in the summer of 2025, Congress removed the need to consider indirect land-use change emissions from LCA for biofuels producers seeking 45Z credits.[36])

- **Achieving net-zero in the aviation sector requires fuels that can reduce emissions by nearly 100 percent – and that's something SAF can't deliver.** Harvesting, transporting, pretreatment, and conversion create emissions across the lifecycle. Even the most favorable LCAs generally estimate maximum reductions of 80 to 94 percent (though some assume net-negative emissions related to positive changes in land use stimulated by biomass demand, even if those changes happen over decades).[24,37] Again, however, key methodological decisions and assumptions in LCA can change results dramatically, and all LCA is subject to considerable uncertainty. Moreover, the aviation sector also produces significant non-CO_2 climate impacts related to contrails, which are also associated with large uncertainties.[38]

Scaling SAF in a changing world

As noted above, expansion of SAF production will be constrained by the supply of affordable feedstocks. Many of these feedstocks are also used to produce biodiesel for ground transportation. Simultaneously, growing demand from the maritime industry could also increase competition for wastes and residues.[39]

Even as technologies for bio-based SAF production advance, these conversion technologies remain capital intensive – and the challenges related to sustainable biomass sourcing remain. For this reason, in the medium- to long-term, innovations in synthetic SAF, also known as **e-SAF** – including power-to-liquid fuels, made from hydrogen and CO_2 with renewable energy – will offer greater potential for decarbonization, without the trade-offs related to land use, food production, and biodiversity conservation. New analysis suggests that corn ethanol, a SAF feedstock, has a land footprint up to 30 times greater than solar PV.[40]

The outlook: Bio-based SAF as a stepping stone

Producing purpose-grown crops for biofuel production presents serious trade-offs for both food security and biodiversity conservation, particularly as climate change continues to intensify and undercuts gains in crop yield or makes some areas inhospitable to agriculture altogether. The world has only a finite amount of arable land, water for irrigation, and synthetic inputs for cropping systems. Growing populations will continue to require more food, and increased urbanization and extreme weather events intensified by elevated atmospheric CO_2 concentrations will continue to shrink the total area available for conservation of carbon- and biodiversity-rich ecosystems free of industrial activity.

Key Points:

- As a drop-in fuel compatible with today's aircraft, bio-based SAF is an important tool to reduce emissions, but it should be seen as a *transition fuel.*
- There are many potential feedstocks and pathways for bio-based SAF. Different feedstocks present different challenges and opportunities, in terms of cost, availability, and pre-treatment requirements. Pathways vary in terms of cost and technological maturity.
- Using food and feed crops for fuel contributes to direct and indirect land-use change, which has serious consequences for climate change and biodiversity conservation.
- Wastes and residues should only be considered "sustainable" fuel feedstocks if they deliver net emissions reductions (i.e., minimal leakage or displacement of superior alternative uses), are responsibly sourced (and traceable), and, when applicable, harvested within ecological limits.
- Due to constraints on the supply of sustainable biomass feedstocks, costs, and logistical challenges, synthetic SAF holds greater long-term promise for decarbonization.
- In short, bio-based SAF may not be the best use of limited biomass feedstocks, and indiscriminately increasing the use of biomass for SAF could have serious unintended consequences on the climate and on ecosystem services.

Although bio-based sustainable aviation fuels have the potential to reduce emissions of pollutants such as soot and NO_X, they do not eliminate these health-harming emissions.[33] Stemming harm to the climate and human health while meeting growing global demand for air travel will also require improvements in aircraft efficiency, investments in affordable and efficient alternatives such as high-speed rail, battery- and hydrogen-powered short haul flights, and other technological advancements.

Brief by Edie Juno, Climate & Land Use Policy Manager (junoe@nwf.org) (2025)

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