THE BIOFUELS MYTH

WHY 'SUSTAINABLE AVIATION FUELS' WON'T POWER CLIMATE-SAFE AIR TRAVEL

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A Report from the Center for Biological Diversity

Lead Author: John Fleming, Ph.D.

Contributing Team: Liz Jones, Nyshie Perkinson, Kassie Siegel and Shaye Wolf, Ph.D.

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Executive Summary

With flights that depart the United States and its territories responsible for almost one-quarter of global passenger flight carbon dioxide emissions in 2019, [1] the United States has a deep responsibility to cut airplanes' global-heating pollution. Globally, commercial aviation accounts for 2.8% of annual CO_2 emissions from fossil fuel combustion. And those emissions are increasing with growing passenger traffic.[2] With the climate crisis already upending lives and livelihoods, it's crucial that the United States act quickly to decarbonize aviation by mid-century to keep global heating below 1.5 degrees Celsius and avoid devastating and irreversible climate damage.[3]

After failing to set aircraft emissions standards that yield meaningful reductions, the Biden administration has opted to promote "sustainable aviation fuels," or SAFs, instead. Sustainable aviation fuels are defined as alternative jet fuels that achieve at least a 50% reduction in lifecycle greenhouse gas emissions compared to conventional fuel. The Biden administration announced the "Sustainable Aviation Fuel Grand Challenge" in September 2021, with the goal of fully replacing U.S. airline jet fuel demand with SAFs by 2050.[4] Right now SAFs make for just 0.05% of jet fuel globally, so it would take a monumental effort to achieve this goal.[5]

This is especially so given that many currently available feedstocks are either in limited supply or come with significant pollution and environmental harms, further complicating the goal. In this report we assessed the potential for SAFs to meet the goal set in the aviation challenge. We first propose a definition of "sustainable," since there is currently no adequate definition in the aviation fuels context. We next evaluated the feedstocks proposed by the Biden administration based on these criteria. Then, for the feedstocks that met our criteria, we determined the amount of SAF that could be produced with U.S. resources. Finally, we discussed the remaining shortcomings of alternative jet fuels, even those deemed "sustainable," concluding that SAFs are insufficient to solve the aviation emissions problem.

Only municipal solid waste, wastewater sludge and crop residues passed our assessment for sustainability, but the availability of these feedstocks is far from that required to meet the Biden administration's 2050 goal — only 4% to 38% of the predicted 35-billion-gallon demand. Thus, as detailed below, our report finds that to decarbonize aviation, the Biden administration must set strong airplane emissions standards that are not mired in the myth of sustainable aviation fuels. As discussed in the companion Center for Biological Diversity report *Flight Path*,[6] true solutions are available, including fuel efficiency, operational and regulatory improvements, and ambitious advancement toward a fully electrified aviation sector.

The Biden administration must require the adoption of such solutions through standards that apply to both in-service and new aircraft, and that incorporate emissions reductions that can be achieved through aircraft design and operational improvements. They must also apply fleetwide, so that gains from technology applied to individual aircraft are not eclipsed by increased air traffic.[7]

Because sustainable aviation fuels still produce greenhouse gas emissions during combustion, at best they only reduce emissions from the aviation sector — and only if truly sustainable feedstocks are used. However, greenhouse gas emissions must ultimately be eliminated to address the climate emergency. Since their use will not eliminate aviation emissions, SAFs cannot be upheld as the solution to the aviation emissions problem.

Study Metrics

- **Definition of sustainability:** Evaluations of the "sustainability" of alternative aviation fuels either by government or industry have been woefully inadequate. In the absence of such evaluation by either airlines or the Biden administration, we evaluated proposed SAFs using the following definition of "sustainability":[8] (1) the fuel must be produced using feedstock that is readily available and can be replenished; (2) collecting and processing the feedstock must not cause environmental or social harms; (3) procuring the feedstock must not result in significant land-use change or otherwise hinder land's natural ability to store and sequester carbon; and (4) the lifecycle greenhouse gas emissions from the fuel must be near zero relative to conventional jet fuel.

- **Sustainability of feedstocks:** Potential SAF feedstocks designated by the Biden administration include municipal solid waste, wastewater sludge, animal fats, animal manure, used cooking oil and greases, algae, crop and forestry residues, wood biomass, energy crops and food crops.[9] Of these, this report found that only municipal solid waste, wastewater sludge and crop residues showed any potential as sustainable sources. However, because they are waste streams, their supply should remain limited since our goal as a society should be waste reduction. The remainder of proposed feedstocks are not sustainable. Food crop-based feedstocks yield greenhouse gas emissions comparable to fossil fuels, so they do not satisfy our sustainability definition. Used cooking oil is not sustainable because the process to convert it to alternative jet fuel is the same as that for food crop-based feedstocks, so its use would bolster the use of these other problematic feedstocks. Meanwhile, animal fats and animal manure are products of the polluting animal agriculture industry, and their use further incentivizes the industry's expansion and its environmental harms. Relying on wood biomass or forestry residues promotes tree-cutting and removal, degrading forest carbon storage and sequestration. Finally, energy crops and algae are far from commercial readiness and at present also pose an environmental burden.

- **Potential SAF production:** After eliminating feedstocks that failed to meet our sustainability criteria from consideration, we determined the amount of feedstock remaining for SAF production. Then, using fuel yield estimates found in the scientific literature, we determined how much SAF could potentially be produced with available feedstock. Given present-day availability of sustainable feedstocks, only 4% to 38% of a 35-billion-gallon demand would be met in 2050. Since the path for the United States to scale up feedstock production is highly uncertain, SAFs cannot be expected to satisfy all jet fuel demand by 2050 if they are truly sustainable.

- **Remaining concerns with SAFs:** Even if sustainable sources of feedstock are used for SAF production, this still does not eliminate emissions from the sector. Even the most sustainable alternative jet fuel will yield emissions because it is combustion-based. This is not limited to greenhouse gas emissions but includes criteria pollutants such as nitrogen oxides, which are associated with community health harms. We cannot, while trying to reduce carbon emissions, ignore the potential increase in co-pollutants and adverse health effects.

Introduction

Aviation Is a Significant Contributor to Climate Change

Commercial aviation accounts for about 2.8% of annual global CO_2 emissions from fossil fuel combustion — about the same as the whole of Germany.[10] Between 2013 and 2019, passenger flight CO_2 emissions grew by one-third, as growing passenger traffic outpaced fuel-efficiency improvements.[11] With flights departing from airports in the United States and its territories responsible for almost a full quarter of passenger flight CO_2 emissions in 2019,[12] the United States has an outsized responsibility to tackle airplanes' global-heating pollution.

The recent *Climate Change 2022: Mitigation of Climate Change* report from the Intergovernmental Panel on Climate Change makes it clear that global industry sectors, including aviation, must decarbonize by mid-century to keep warming to 1.5°C and avoid devastating climate damages.[13] Yet, according to one U.S. Environmental Protection Agency projection, U.S. aviation emissions in 2040 could exceed those in 2020 by 40%.[14]

The Biden Administration Has Failed to Set Emissions Standards That Cut Airplane Pollution

Rather than setting standards to reduce aviation emissions, in November 2021 the EPA announced that it would keep do-nothing Trump-era standards for U.S. aircraft. With an emphasis on technology-forcing strategies, the U.S. aviation sector could achieve fuel-efficiency improvements of at least 3.5% annually. It could electrify short-haul flights by 2040 and long-haul flights by 2045, thus achieving necessary emissions reductions.[15] But the EPA's final aviation rule does not require any additional technological or operational improvements in aviation beyond those expected if there were no rule at all, meaning it will not result in emissions reductions.[16]

Voluntary 'Sustainable Aviation Fuel' Use Is the Only Airplane Emissions Strategy Promoted by the Biden Administration and Industry

In place of binding emission reduction targets, the Biden administration and airlines are promoting the voluntary use of "sustainable aviation fuels" (SAFs) — alternative jet fuels (AJFs) derived from biomass that supposedly have emissions less than those from conventional jet fuel — as the sole answer to the aviation emissions problem.

To this end, in September 2021 the Biden administration announced executive actions across the departments of Energy, Transportation, Agriculture, Defense, the National Aeronautics and Space Administration, the General Services Administration, and the EPA to encourage the production of billions of gallons of SAFs and cut aviation emissions by 20% by 2030 compared to business as usual. This includes a goal of producing 3 billion gallons of SAF per year by 2030 and, by 2050, producing enough SAF to meet 100% of aviation fuel demand, currently projected to be around 35 billion gallons.[17] Nothing in the Biden administration's executive actions requires action by airlines.

Many U.S. airlines have set voluntary net-zero emissions goals and advertised them to customers as evidence of a commitment to sustainability: Delta has committed to carbon neutrality from 2020 onward, JetBlue has committed to net zero by 2040, and American,[18] United,[19] and British Airways have committed to net zero by 2050.[20] Previously, most airlines used carbon offsets to meet their emissions-reduction targets. But carbon-offset schemes have been proven flawed and ineffective in providing climate benefits.[21] Now, in line with the Biden administration's executive actions, attention has started to shift to alternative jet fuels.

Major airlines have also announced plans to increasingly incorporate alternative jet fuels into their total jet fuel supplies. Delta, for instance, has a goal to replace 10% of its jet fuel with alternative fuels by the end of 2030.[22] Jet Blue has a goal of replacing

10% of its jet fuel use with blended alternative fuel by 2030.[23] American Airlines has announced plans to buy 10 million gallons of alternative fuel by 2025, while United Airlines has agreed to purchase 1.5 billion gallons of alternative fuel over 20 years.[24] Ultimately, however, the promised goals are negligible compared to expected total fuel usage.[25]

The United States at present produces only 4.5 *million* gallons of alternative jet fuel per year, while commercial jet fuel demand was 21.6 *billion* gallons in 2019.[26] Globally, demand for jet fuel is roughly 53 billion gallons a year, but only 26 to 32 million gallons of alternative fuel were produced in 2021. This means that right now SAFs make for just 0.05% of overall jet fuel.[27]

Voluntary aviation emissions goals have gone unrealized in the past. In 2013 the Federal Aviation Administration set the aspirational goal of 1 billion gallons of alternative jet fuel per year by 2018 — a goal the airlines failed miserably to achieve.[28] Yet the Biden administration is once again relying on voluntary action by airlines rather than mandating real standards to reduce aviation emissions.

Further, many of the fuels currently promoted as sustainable alternatives to conventional jet fuel are not truly sustainable when accounting for associated greenhouse gas emissions and environmental burdens, as discussed in the next section.

Most Biofuels Labeled as 'Sustainable' Are Not

In addition to being voluntary, alternative jet fuels are associated with significant greenhouse gas emissions and other environmental and social harms. Evaluations of the "sustainability" of alternative aviation fuels have so far been woefully inadequate. In the absence of such an analysis by either airlines or the Biden administration, here we define criteria for sustainable aviation fuels and evaluate alternative aviation fuels based on these criteria.

Government and Industry Lack a Clear Definition of "Sustainable"

According to the U.S. Department of Energy, sustainable aviation fuel is "a biofuel used to power aircraft that has similar properties to conventional jet fuel but with a smaller carbon footprint. Depending on the feedstock and technologies used to produce it, SAF can reduce lifecycle GHG emissions dramatically compared to conventional jet fuel."[29] The Biden administration's executive actions explicitly name the feedstocks municipal solid waste, fats (including animal fats), oils, and greases, algae, crop residues and wood biomass as part of its sustainable aviation fuel initiative. The U.S. Department of Energy additionally names energy crops, animal manure, wastewater treatment sludge, wood mill waste, and food crop-based feedstocks as options for sustainable aviation fuel production.[30]

There are seven SAF production pathways that have been internationally certified, with four currently the most common:

- Hydroprocessed Esters and Fatty Acids (HEFA), used to process vegetable oils, waste fats, oils and greases;
- Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) for lignocellulosic crops,* residues and wastes;
- Alcohol to Jet fuels (ATJ) for starchy and sugary crops, lignocellulosic crops, residues, wastes, and industrial flue gases;
- Synthetic Iso-Paraffins (HFS-SIP) for sugar crops.

At present alternative jet fuels are approved only as blends with conventional jet fuel, though efforts are underway to make aircraft that can run on 100% AJFs.[31] The blend level is set at 50% alternative and 50% conventional fuel for all except SIP fuel, which has an approved blend level of only 10% alternative fuel.[32] Boeing is developing commercial airplanes that can fly on 100% AJFs,[33] but they are not predicted to be available until 2035, approximately the same timeline on which Airbus intends to make hydrogen-powered aircraft available[34] and electric aircraft are expected to be in operation for short-haul flights.[35]

Proposed Criteria for Defining Sustainable Aviation Fuel

Despite the definition of SAF by the U.S. Department of Energy as having "a smaller carbon footprint," some feedstocks being considered either do not significantly reduce carbon emissions or cause other environmental harms. Though the Biden administration has said it aims to expand production of alternative jet fuel that achieves at least a 50% reduction in lifecycle GHG emissions compared to conventional fuel, the methodology for establishing such reductions has not been made public or implemented to ensure alternative jet fuels meet this goal.[36] Without a more rigorous definition of SAFs, the selection of feedstocks will become nothing more than greenwashing: Environmentally harmful conventional jet fuels will be replaced by environmentally harmful biofuel. Thus we have established criteria for sustainable aviation fuels to avoid the harms that could result from poorly selected feedstocks.

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* The woody material that gives plants their rigidity and structure, consisting of three carbon compounds — cellulose, hemicellulose and lignin — is called lignocellulose, a key component of lignocellulosic biomass such as grasses and forestry and crop residues. Sanderson, K., Lignocellulose: a chewy problem, 474 Nature (2011).

For a given alternative jet fuel to be deemed a sustainable aviation fuel, it must meet four criteria:[37]

(1) It must be produced using feedstock that is readily available and can be replenished.
(2) Collecting and processing the feedstock must not cause environmental or social harms such as excessive water use or air and water pollution.
(3) Procuring the feedstock must not result in significant land-use change (e.g. deforestation) or otherwise hinder land's natural ability to store and sequester carbon.
(4) In consideration of the full lifecycle of the fuel from feedstock collection to final use, greenhouse gas emissions from the fuel must be near zero relative to conventional jet fuel.

A 50% reduction in the lifecycle greenhouse gas emissions of aviation fuels, even if fully realized as proposed by the Biden administration, isn't enough to get us to near-zero emissions as climate science demands. Nor is cutting emissions in half enough to minimize the environmental harms associated with fuel production. Because our sustainability definition more thoroughly addresses the relevant climate and environmental concerns with aviation fuels, we use it in evaluating potential sustainable aviation fuels in the remainder of this report.

The Climate Impacts of Alternative Jet Fuels Should Be a Key Consideration in Their Sustainability

Evaluating the climate impacts of different alternative jet fuels requires calculating their carbon intensity — or the amount of carbon dioxide emitted per unit of fuel consumed. The carbon intensity of the fuels can then be compared with that of conventional petroleum-based jet fuel, which ranges from 85 to 95 grams of CO_2-equivalent per megajoule of fuel (g CO_2eq/MJ), with about 73 g CO_2e/MJ attributable to fuel combustion and the rest to fuel extraction, refining, and transportation.[38]

Correctly accounting for the carbon intensity of alternative jet fuels requires calculating the direct and indirect greenhouse gas emissions that come from using specific feedstocks. Direct emissions are those emitted by the feedstock-to-fuel conversion processes and fuel combustion. Indirect emissions include indirect land-use change or displacement emissions.

Taking food crop-based fuels as an example, indirect land-use change can result when, because of existing crops or cropland being diverted to biofuel production, land is cleared and converted elsewhere to replace the diverted crop supply. Depending on the type of land cleared, the indirect emissions can be substantial. [†]

Displacement emissions are similar, except that they extend to the use of oils such as animal fats, corn oil and tall oil. These oils have existing uses in livestock feed, heat and power production, and the chemical industry, so diverting them from those uses to biofuels will lead to their replacement, potentially by oils sourced from newly converted land, once again leading to indirect land-use change emissions. [39]

Because all aviation biofuels, even those labeled sustainable, still produce carbon emissions during combustion, they add to global heating and the climate emergency. Sustainable aviation fuels can, at best, reduce emissions from the aviation sector, but we need them to be eliminated to curb climate change. As discussed below, a limited subset of SAFs can at best be a small interim step toward a completely decarbonized aviation sector. Thus, the claim by industry and the Biden administration that SAFs can decarbonize the aviation industry is a destructive falsehood and must be rejected.

AJF Feedstocks Are Categorized as Either First, Second, or Third Generation, Depending on Their Sustainability Characteristics and Technological Readiness

The sustainability characteristics of different alternative jet fuels are closely tied to the feedstocks that they are made from, where categories of feedstocks are divided into "generations." First-generation biofuels are made from sugar crops such as sugarcane and beets, starch crops such as corn and sorghum, oilseed crops such as soybean and canola, and animal fats. Second-generation biofuels include fuels made from non-food lignocellulosic crops such as grasses, waste biomass such as corn stover, corncobs, straw, wood, and wood byproducts, and solid and oil wastes. Meanwhile, third-generation biofuels use algae as a feedstock. First-generation biofuels are the furthest along in development and use, followed by second-generation and third.

As summarized in Table 1 and discussed in detail below, we assessed the sustainability of first, second, and third-generation feedstocks based on emissions and potential environmental harms.

† Different land types will produce different amounts of carbon emissions when cleared. Forests, for instance, tend to sequester more carbon than grasslands, so will release more carbon when cleared. Thus, if new land for feedstock production is made primarily by clearing forest, then the land-use change emissions are likely to be high.

Table 1: Key Feedstocks Under Consideration for SAF Production

Feedstock	Lifecycle Emissions	Indirect LUC	Displacement Emissions	Water Use	Environmental Harms	Commercially Available?
Municipal Solid Waste	Low (5-12 g CO_2e/MJ)	Low	Low	Low	Risk of disincentivizing waste-reduction efforts	Yes
Wastewater Sludge	Low (5-12 g CO_2e/MJ)	Low	Low	Low		Yes
Crop Residues[a]	Low (15-20 g CO_2e/MJ)	Low	Low	Low	Reduced soil organic carbon (SOC)	Yes
Used Cooking Oil	Low (26 g CO_2e/MJ)	Low	Low	Low	Use incentivizes HEFA pathway and first-gen feedstocks, leading to land-use tradeoffs	Yes
Energy Crops	Low (-17-29 g CO_2e/MJ)	Low	Low	High	Pesticides; fertilizers; tradeoffs with current land use	No
Animal Fats	Moderate (50 g CO_2e/MJ)	Low	High	Low	CAFOs-related pollution; use incentivizes CAFOs expansion	Yes
Forestry Residues[b]	Moderate	Low	Low	Low	Use incentivizes deforestation and forest degradation, air pollution; reduced SOC	Yes
Wood Biomass[b]	High	Low	Low	Low	Deforestation and forest degradation, air pollution; reduced SOC	Yes
Manure	High	Low	High	Low	CAFOs-related pollution	Yes
Algae[c]	High	Low	Low	Low		No
Food Crops/ Virgin Vegetable Oils	High	High	High	High	Pesticides; Fertilizers; Tradeoffs with current land use	Yes

The *Low, Moderate, and High* distinctions are meant to denote differences among the feedstocks relative to each other rather than quantified differences. However, for lifecycle emissions, *High* corresponds to emissions near or above the fossil fuel benchmark (95 g CO_2e/MJ). Those labeled *Low* generally have emissions at least 70% lower than the fossil fuel benchmark. *Green* denotes sustainable feedstocks while *red* denotes unsustainable.

a. Characterization of crop residues assumes removal is at sustainable rates.
b. Wood biomass is assumed to have high lifecycle emissions because logging trees for SAFs releases their stored carbon as well as soil carbon and drastically diminishes the carbon sequestration potential of forests. Forestry residues are considered a subset of wood biomass.
c. Algae as a feedstock currently has high lifecycle emissions because of relatively low algal yield and high energy use in algal cultivation. This could change with further research and development.

First-Generation Feedstocks

First-generation biofuels are the furthest along in development, but also are generally the least sustainable because they have high lifecycle greenhouse gas emissions and bring more land-use environmental harms. Because first-generation feedstocks are food crop-based, using them for fuel can displace existing food crop uses and cause new land clearing and indirect emissions.

For example, in an analysis of 17 potential alternative-fuel pathways looking at different feedstocks, technologies, and regions, it was found that using virgin vegetable oil had the highest indirect land-use change emissions because of links to high deforestation and peat oxidation in southeast Asia, driven by palm expansion.[40] Another study found that using open-pond palm oil, sourced from southeast Asia, in the HEFA pathway leads to emissions that exceed those from petroleum fuels by 11.4%.[41] So high indirect land-use change emissions from virgin vegetable oil HEFA pathways typically undermine any greenhouse gas savings from these fuels.[42]

As a second example, the United States, being the world's largest corn producer,[43] has a lot of potential feedstock for fuel production and already uses corn to produce ethanol.[44] However, using corn is generally energy- and emissions-intensive, resulting in the near-elimination of greenhouse gas savings.[45]

Beyond climate-heating emissions, food-based biofuels have contributed to increased food prices and worsening global food insecurity and water scarcity. A 2017 study found that increased production of first-generation biofuels heavily contributes to global water scarcity and is not the best option for bioenergy.[46] Further, with increased production of first-generation biofuels, there is the potential for increased nutrient and pesticide runoff to surface waters and contamination of groundwater due to crop cultivation.[47]

A 2016 study found that biofuels rely on about 2-3% of the global water and land used for agriculture. Based on the food calories used for biofuel production, that amount could feed about 30% of the malnourished global population.[48] Just in the United States, about 140 million people could be fed with the resources for bioethanol, and about 10 million people could be fed with the resources for biodiesel. This misdirection of much-needed resources would only be worsened by increased production of first-generation biofuels for aviation.

Second-Generation Feedstocks

Since they do not directly displace food crops, second-generation feedstocks, such as perennial grasses (energy crops), plant residues, and wastes, generally yield less indirect land use change and net carbon emissions. However, these second-generation feedstocks also have downsides that limit their feasibility as a sustainable alternative to fossil jet fuel.

Energy Crops

Energy crops are a second-generation feedstock and include woody plants such as willow and poplar and grasses such as miscanthus and switchgrass.[49] Energy crops are distinct in that they are grown solely as an energy source rather than for food.

However, like first-generation feedstocks, second-generation energy crops can create harmful tradeoffs with current land use. These include the degradation and loss of wildlife habitats and the disruption of ecosystems. Such crops also compete for agricultural inputs such as farm labor and assets, fuel, irrigation water and fertilizer. According to one study, water use for second-generation biofuels from energy crops is about the same as for first-generation biofuels on a per-unit-energy basis,[50] increasing the likelihood that an expansion in second-generation biofuel production would contribute to global water scarcity. In addition, some energy crops, especially large crop monocultures, contribute to habitat loss and harms to local biodiversity by displacing native plant life.[51] For instance, one study found that the planting of second-generation feedstocks reduced species richness and abundance by 19% and 25%, respectively. The planting of perennial grasses specifically reduced species richness by 29%.[52]

Energy crops are purported to have low or negative indirect land use change emissions due to the potential of energy crops to sequester carbon in the soil as they grow. The International Civil Aviation Organization (ICAO) estimates a range of total lifecycle (from initial feedstock collection and processing to final fuel combustion) greenhouse gas emissions reductions of 70% to 118% for energy crops compared with the fossil fuel baseline.[53] However, energy cropping is not a wide-scale practice, and in the United States it appears virtually nonexistent. The 2016 U.S. Department of Energy report titled *2016 Billion-Ton Report* assumed a base-case scenario where energy crops were planted starting in 2019 and 78 million dry tons of energy crop feedstock would be available by 2022.[54] At present, this is far from reality, with no reported commercial-scale planting of energy crops in the United States.

Municipal Solid Waste

Biogenic solid waste comes from organic components including paper, cardboard, food waste, grass clippings, leaves, wood and leather products found in municipal solid waste. It lacks some of the downsides common with other SAF feedstocks. First, municipal solid waste would be produced regardless of its intended use, so using it for fuel should lead to no additional land-use change or associated emissions. Also, there is less risk of displacement emissions because the current use of municipal solid waste in heat, power, and landfill gas recovery could be replaced by renewable electricity.[55] Finally, if not used for SAFs or other purposes, carbon from the waste would be released as methane or CO_2 during decomposition or combustion. It is important not to use non-biogenic material such as plastic, though, since it stores carbon over a long period of time if it remains in a landfill. Using plastic for biofuel means losing this storage and thus a higher greenhouse gas intensity, in addition to other undesirable pollutants often associated with plastic combustion.[56]

Direct emissions from biogenic solid waste are estimated at less than 12 g CO_2e/MJ using the Fischer-Tropsch process, compared to a fossil fuel baseline of 85 to 95 g CO_2eq/MJ.[57] However, municipal solid waste must remain a limited resource so as not to incentivize an increase in landfill waste, which would exacerbate the environmental impacts of landfills. Impacts of more landfill waste include the mobilization of leachate, a liquid that forms from the percolation of rainwater and moisture through waste, which can contaminate water sources. This can lead to eutrophication, or an overgrowth of algae that creates conditions where animals cannot survive due to a lack of oxygen. Toxic gases from landfills pose a threat to the health of those who work or live nearby. There are also nuisances of odor, smoke, noise and bugs.[58] Finally, low-income and communities of color are more likely to be near landfills, contributing to environmental injustices.[59] This further raises the point that using landfill waste for alternative jet fuels must not be at the expense of continued efforts to reduce waste and reuse, recycle and compost.

Wastewater Sludge

Another feedstock under consideration is wastewater sludge, which is produced when wastewater and stormwater are processed at wastewater treatment facilities. At such facilities, solid wastes are separated from liquid wastes through settling. They're then decomposed by bacteria, resulting in sewage sludge. Also known as biosolids, this material sometimes goes on to landfills, to agricultural cropland as fertilizer, or to other uses in agriculture and landscaping. However, given the heavy metals and pharmaceutical compounds typically present in sewage sludge, there are significant public health concerns about such uses.[60] So diverting wastewater sludge from its current uses might produce some benefit from a public health perspective.

Wastewater sludge falls into the category of wet waste, along with portions of municipal solid waste such as food waste and agricultural residues (grass clippings, leaves, etc.), so similar pathways to those for municipal solid waste exist to convert it to biofuel.[61] Thus, we assume that direct emissions from producing SAFs from wastewater sludge are likewise less than 12 g CO_2e/MJ. Like municipal solid waste, sludge is rich in decomposable organic matter, which means that if not used for alternative fuels or other purposes, it is a significant source of greenhouse gas emissions during decomposition.[62] However, the supply of wastewater sludge is a limited resource that cannot be scaled up in response to increased sustainable aviation fuel demand. This is inherent in its status as a waste product tied to human population.

Used Cooking Oil

Used cooking oil — mostly discarded vegetable oils left over from frying and food preparation — is another waste product that is being tapped as a sustainable aviation fuel feedstock. Direct emissions from used cooking oil as a feedstock are about 13 g CO_2e/MJ.[63] But used cooking oil has applications that compete with its use in alternative jet fuels and other biofuels. According to one study, the supply of yellow grease (often considered synonymous with used cooking oil) is over 900,000 metric tons annually,[64] with about 50,000 tons going to livestock feed and 1,000 tons going to the chemical industry.[65] The result is indirect displacement emissions of as much as 13.2 g CO_2e/MJ if used cooking oil were diverted to biofuel production. Total emissions from used cooking oil are therefore expected to be less than 30 g CO_2e/MJ, compared to a fossil fuel baseline of 85 to 95 g CO_2eq/MJ.

But processing used cooking oil, as is the case with first-generation feedstocks like virgin vegetable oils, is done via the HEFA pathway. The HEFA pathway reacts feedstock with hydrogen at high temperatures and pressures to form fuel and therefore requires substantial inputs of hydrogen.[66] Because petroleum refining uses similar hydrogen infrastructure, efforts are underway to convert existing petroleum refineries to HEFA refining.

Hydro-conversion processes, of which the HEFA pathway is an example, proceed at high temperatures and extremely high pressures, with runaway increases in temperature common. When this happens, refinery flaring will often be employed to bring conditions back under control.[67] Flaring emits toxic and smog-forming air contaminants such as particulate matter, sulfur dioxide and hydrocarbons that worsen air quality.[68] Because HEFA processes require more hydrogen than petroleum refining, it is expected that hydro-conversion-related flaring would be worse with HEFA refining, along with explosion and fire risk.[69] In the United States, refineries are most often sited in low-income communities and communities of color, so there are environmental justice concerns with expanded HEFA refining.[70] An example is in California's Bay Area, where efforts are underway to convert existing oil and gas refineries to HEFA refineries, and where low-income communities and communities of color would bear the brunt of air-pollution exposure.[71]

Promoting used cooking oil for alternative jet fuel production would incentivize further conversions of oil and gas refineries to HEFA refining, as well as prolong the life of fossil fuel infrastructure. This would in turn incentivize the use of problematic first-generation feedstocks in addition to used cooking oil to produce not just jet fuel, but also other HEFA fuels such as renewable diesel for freight and shipping. Given the known harms of using first-generation feedstocks, HEFA combustion fuels can't be locked in for future decades. Since utilizing used cooking oil could contribute to this lock-in, they should not be used for alternative jet fuel production.

Animal Fats and Animal Manure

Animal fats and animal manure are being considered for alternative jet fuel production because they are seen as waste products that can be recycled. However, diverting either to AJF production is linked to displacement effects and indirect emissions because of existing uses. There is existing demand for animal fats in livestock feed, heat and power production, and the oleochemical industry (e.g., production of detergents and soaps). In fact, according to the North American Renderers Association, about 50% of an animal raised for food is considered inedible and goes to renderers, with 99% of that going on to become consumer products, propelling a $10 billion industry.[72] Diverting animal fats to produce AJFs could result in their replacement in these industries, potentially with fossil fuels, virgin vegetable oils, and other sources linked to indirect land-use change.[73] As a result of expected high indirect land-use change emissions, the emissions savings from animal fats relative to fossil fuels are expected to only be 45% when including indirect emissions, instead of 75% when excluding indirect emissions.[74]

Meanwhile, out of an estimated 37 million dry tons of manure that are recoverable,[75] 33% is applied as crop fertilizer and 3% is used to produce biogas that is then combusted in heat and power production. The remainder is managed either in anaerobic lagoons, deep pits, solid storage, or spread on fields and pastures for disposal.[76] As a result of these competing uses, it is estimated that the indirect displacement emissions from manure-derived biofuel is between -35.9 (or negative emissions because of avoided methane emissions) and 118 g CO_2e/MJ. The high estimate assumes manure applied as fertilizer is entirely replaced by synthetic fertilizers, which require fossil gas for production, while the low estimate assumes manure is replaced by an organic source, such as organic material derived from wastewater sludge. Given the uncertainty of whether using manure would yield any emissions benefits over fossil jet fuel, it should not be considered for SAF feedstock.

Animal fats and manure require additional scrutiny because they are sourced from the polluting animal agriculture sector. First, farmed animals and their feed are themselves a significant source of greenhouse gas emissions and consume almost one-

Aerial image of cattle feedlot and manure lagoon from Google Earth

third of all fresh water.[77] Animal agriculture is a leading cause of water pollution and habitat destruction, which in turn is the leading cause of species extinction.[78] Second, in 2012, livestock and poultry grown in the largest Concentrated Animal Feeding Operations (CAFOs) in the United States produced 369 million wet tons of manure — almost 13 times the waste of the entire U.S. population. That waste is often disposed of by spreading it, untreated, on land. This can lead to nutrient-rich runoff to water sources resulting in eutrophication, or an overgrowth of algae that suffocates other animal life.[79] Animal agriculture also produces air pollution and even antibiotic resistance due to the widespread use of antibiotics in meat production. The harms from animal agriculture have an environmental justice component as well, with those affected most often from low-income communities and communities of color.[80]

Further, over 235 million pounds of herbicides and insecticides are used annually across the United States, solely on crops intended for animal feed production.[81] The combination of land clearing for more feed crop production and pesticide use drastically imperils threatened and endangered species, while serving as another source of dangerous runoff to water bodies.

An overarching concern is that committing animal fats to aviation biofuel production would provide an additional financial incentive to meat production and further the proliferation of CAFOs over smaller sustainable farming systems, increasing the harms noted above. Over the past 20 years, many segments of the agriculture industry have seen consolidation. According to the North American Meat Institute, just four meatpacking companies now process 74% of all beef in the United States.[82] Such consolidation, combined with 50% of an animal intended for food already going to non-food purposes, means that large animal agriculture entities could elicit value from expanding their operations. Larger operations would likely be better positioned to transition to biofuel production as they would be able to produce at a larger scale to make profits more likely and have more resources to procure the necessary infrastructure, therefore outcompeting sustainable producers.

Given the pollution and other harms associated with animal agriculture, there must never be an incentive to expand the sector to provide animal fats or manure for alternative jet fuels. Instead, for a sustainable future, the animal agriculture sector should shrink over time through reducing consumption of meat and dairy and switching to more plant-based diets.[83] Since diverting animal fats to biofuel production would likely provide a financial incentive for animal agriculture expansion and considering that manure-derived biofuels have lifecycle emissions potentially greater than conventional jet fuel, neither is a sustainable feedstock for SAF production.

Given the inherent limitations on supply, a long-term plan to reduce emissions from aviation that relies on wastes, including biogenic waste, fats, oils and greases is simply untenable.

Crop Residues, Forestry Residues and Wood Biomass

Crop residues, forestry residues and wood biomass are being considered as SAF feedstocks, but for all three there are climate, health, and ecological benefits from leaving them undisturbed rather than cutting and clearing them. This is most glaring with wood biomass, or whole-tree harvesting. Cutting down trees to produce alternative fuels is counterproductive for the climate given that forests are giant storehouses of carbon.[84] Intact forests are a vital part of the climate solution because they pull enormous amounts of carbon out of the air and provide long-term, natural carbon storage.[85] In contrast, cutting trees for biofuels causes an immediate increase in carbon emissions by releasing the carbon stored in trees and ending their future carbon sequestration, creating a "carbon debt."[86] Proponents of cutting down forests for biofuels claim that biomass is carbon neutral since trees will ultimately regrow, paying back the carbon debt. This is misleading because there is no guarantee that cut forests will be allowed to grow back, and forest regrowth takes time. Once forests are cut, it may take many decades to more than a century, if ever, to pay back the carbon that was lost from cutting and clearing.[87] Meanwhile the increase in CO_2 worsens the climate crisis at a time when global emissions must be halved by 2030 to avoid the irreversible tipping points and climate catastrophes beyond global heating of 1.5 degrees Celsius.[88] Cutting trees for bioenergy also puts forest ecosystems at risk and undermines the benefits that intact forests provide, like wildlife habitat, recreation, flood control, and clean air and water.[89]

"Forestry residue" does not have a set definition and ranges from more conservative definitions (i.e., branches, treetops, and bark left over from other cutting) to expansive definitions that include whole trees. For example, the International Council on Clean Transportation (ICCT) defines forestry residues as the small branches, treetops, and stumps that would typically be left in the forest after logging, but not whole-tree biomass.[90] Meanwhile the U.S. Department of Energy uses an expansive definition of forestry residues: wood materials left after logging, including limbs, tops, and culled trees and tree components that would be otherwise unmerchantable such as dead, diseased or poorly formed trees.[91]

Broad definitions of residues that encompass whole trees mean that these feedstocks can result in similar climate and ecological harms as wood biomass. Even under more conservative definitions, using residues for bioenergy leads to a net increase of carbon emissions in the atmosphere for decades, worsening the climate crisis.[92] Moreover, since forestry residues are a product of logging, expanding the market for forestry residues to feed biofuel production could ultimately promote more deforestation. In the U.S. Southeast, for example, subsidized wood pellet manufacture for bioenergy has been documented to use whole trees rather than only residues as claimed by industry, driving increased deforestation and carbon emissions.[93] In addition, these wood pellet production facilities are concentrated in communities of color and low-income communities. They produce harmful air pollutants such as particulate matter, nitrogen oxides, and sulfur oxides, and degrade local water quality, harming public and environmental health and worsening environmental injustice.[94] The removal of forest residues for bioenergy causes other significant harms to the climate and biodiversity, including decreased soil carbon stocks and degrading habitat for species that rely on downed woody debris and dead trees.[95]

Logging residue photo by Judy Baxter CC BY-NC

Increasingly, the logging and thinning of forests — and using the woody materials for biofuels — is being promoted as a way to reduce wildfire severity in the U.S. West, despite evidence that cutting trees can increase fire severity and decrease the forest carbon sink, lowering the forest's potential to act as a natural climate solution.[96] But research shows that thinning removes more carbon than it prevents from being released in a wildfire, and far more forest is cut than would actually burn.[97] As a result, broad-scale thinning to reduce fire risk or severity leads to more carbon emissions than wildfire and creates a long-term carbon deficit that worsens the climate crisis.[98] Therefore, forestry residues, as a subset of wood biomass, should not be considered for SAF feedstock.

Crop residues are the stalks and leaves of food crops and include corn stover (stalks, leaves, husks and cobs), wheat straw, oat straw, barley straw, sorghum stubble and rice straw. The lifecycle emissions of crop residues are estimated at less than 20 g CO_2e/MJ,[99] or nearly 80% less than a fossil fuel baseline. This estimate relies on the assumption of residues being sustainably harvested. Because residues provide important environmental benefits, such as protection from wind and water erosion, maintenance, and sequestration of soil organic carbon (SOC), and soil nutrient recycling, all residues cannot be sustainably harvested.[100] According to a review by the U.S. Department of Agriculture, in general, 70% of residues need to be left on the soil surface to prevent erosion and losses of soil organic carbon and nutrients. This is based on findings that erosion levels off with residue retention of higher than 70%.[101] However, other studies have found that any crop residue removal results in a loss of soil carbon.[102] Generously assuming that only 70% retention is necessary means that only 30% of crop residues could be sustainably harvested for alternative jet fuels.

Third-Generation Feedstocks

Algae is a third-generation biofuel feedstock that is actively being researched, as noted in the Biden administration's executive actions. Algae, which are photosynthetic plants such as seaweed, capture high quantities of carbon dioxide and produce oxygen along with oil.[103] Algal biofuels have the advantage of no food competition and no land use because algae can be grown on non-arable land and in wastewater, saline, or brackish water, and they grow extremely rapidly. However, using algae at commercial scale is currently cost-prohibitive, and there is no reported commercial-scale cultivation of algae in the United States.[104] Most importantly, at its present state of development, algal biodiesel has higher lifecycle GHG emissions than fossil diesel. That's because of relatively low algal yield and high energy use in algal cultivation.[105] This is likewise expected to be the case with algal aviation fuels.

Non-Biomass Feedstocks Being Considered for SAFs May Not Reduce Emissions

Electrofuels

Some potential sustainable aviation fuels are unique in that they do not require a biomass feedstock. One category of such fuels is electrofuels, also known as power-to-liquids. These are fuels that are produced using CO_2 and water, with renewable electricity ideally as the primary energy source.[106] The CO_2 for electrofuels production can be sourced in two ways: point sources such as flue gases from industrial processes, power plants, or other chemical processing facilities;[107] and direct air capture, which takes CO_2 from ambient air, either chemically or physically.[108] These fuels are often too quickly labeled carbon neutral with the assumption that the CO_2 released during their combustion is balanced by that removed during production.

One place where this assumption can be incorrect is the source of electricity used to produce electrofuels. If produced using clean, renewable electricity like solar or wind, the electricity used for their production would add negligible greenhouse gases to the atmosphere. But if produced using grid-average electricity, electrofuels may have higher greenhouse gas emissions than petroleum fuels.[109] There is currently no mechanism for ensuring that electrofuels are produced entirely from clean, renewable energy. Further, a greater benefit could come from putting solar and wind-generated energy directly into the grid to displace fossil fuels rather than diverting energy to electrofuel production.

The other place where the carbon-neutral assumption can be incorrect is in the source of CO_2. Diverting CO_2 from the smokestacks of industrial processes, power plants, or other fossil fuel facilities via carbon capture equipment to make electrofuels still results in a net addition of CO_2 into the atmosphere. Promoting carbon capture from fossil fuel facilities for electrofuel production can perpetuate fossil fuel use, rather than promoting the needed rapid transition to clean, renewable energy.

Further, carbon capture and storage, or CCS, poses significant health, safety, and environmental risks including toxic air pollution, pipeline ruptures, and leaks from underground compressed carbon storage that can sicken and even kill people.[110] Perpetuating fossil fuel use would continue both carbon emissions and the production of co-air pollutants that are harmful to human health.

Alternately, sourcing CO_2 from direct air capture, or DAC, is currently very energy inefficient, expensive, and unproven at scale. As with CCS, DAC poses health and safety risks including pipeline ruptures and underground storage leaks. The solar or wind energy that might go to DAC could, once again, be put to better use as a direct replacement for fossil fuels in the energy grid.[111] Electrofuels thus could result in net harms rather than net benefits to the climate and environment.

Hydrogen

Hydrogen fuels are also considered a potential replacement for aviation jet fuel because of the relative cleanness of the fuel as it burns. In the aviation sector, hydrogen fuels could be either used directly in large aircraft as a combustion source or in fuel cells substituted for jet engines in smaller planes.[112] Hydrogen fuels represent a near-elimination of greenhouse gas emissions from the jet engine, including carbon, soot and sulfur oxides.[113] However, 95% of hydrogen produced in the United States is currently made from fossil gas, emitting substantial climate and air pollution.[114] As with electrofuels, in the absence of any mechanism for ensuring that hydrogen is "green" — that is, electrolytic hydrogen produced by splitting water solely using clean, renewable solar and wind energy — hydrogen cannot be considered as a fuel that mitigates carbon emissions.

Also, the benefits of producing hydrogen for aviation must be weighed against the benefits of directing solar and wind energy directly to the grid. However, future renewable energy systems are expected to experience times when solar and wind energy exceed demand,[115] so these future energy surpluses could be diverted to hydrogen production, perhaps making hydrogen more sustainable.

Even if hydrogen is produced using clean, renewable energy, hydrogen as a fuel still yields emissions—water vapor in the case of hydrogen fuel cells, and both water vapor and nitrogen oxides in the case of hydrogen combustion.[116] Water vapor from conventional jet fuel combustion leads to contrails, which form when water vapor condenses on aerosols. Contrails are responsible for over half of the radiative forcing (trapping of solar radiation reaching the Earth's surface, leading to warming) associated with aviation, followed by CO_2.[117] Depending on the balance of competing effects, hydrogen as jet fuel could either reduce or increase the effect of contrails. Because hydrogen produces fewer aerosols, using hydrogen can lead to contrail reductions. However, the higher water vapor emission levels with hydrogen could increase the lifetime of contrails in the atmosphere.[118] Nitrogen oxides meanwhile can contribute to the formation of ozone, a greenhouse gas and air pollutant that threatens public health at the local and regional level.[119] Thus, for hydrogen to be seriously considered as a sustainable alternative to conventional jet fuel, the effects of hydrogen-associated emissions on global warming and public health will have to be thoroughly understood.

Only a Subset of Proposed SAF Feedstocks Should Be Considered Sustainable

Producing sustainable aviation fuels would require sustainable feedstock, which is a limited resource. Of the feedstocks named by the Biden administration's executive actions, the only feedstocks that are potentially sustainable in the short term are municipal solid waste, crop residues and wastewater sludge. As discussed above, food-based feedstocks, wood biomass and forestry residues, used cooking oil, animal fats and manure are not sustainable because of associated emissions or other environmental harms. Meanwhile, energy crops and algae seem nowhere near commercial viability.

How Much Sustainable Aviation Fuel Can the United States Produce?

Analysis of Potential Sustainable Aviation Fuel Production

The Biden administration has set a national goal of producing 3 billion gallons of SAF per year by 2030. By 2050, it aims for enough SAF to meet 100% of aviation fuel demand, currently projected to be around 35 billion gallons.[120] Meanwhile, an estimated 4.5 million gallons of aviation biofuel were consumed in the United States in 2019.[121] With more than 20 billion gallons of jet fuel consumed in total in the same year, only 0.02% of demand was met with aviation biofuel. Alternative jet fuels are currently far from the scale where they can fully meet commercial aviation energy needs.

Below, we determine the amount of SAFs that could be produced from feedstocks that potentially fit our previously established definition of "sustainable": (1) It must be produced using feedstock that is readily available and can be replenished; (2) collecting and processing the feedstock must not cause environmental or social harms such as excessive water use or air and water pollution; (3) procuring the feedstock must not result in significant land-use change (e.g. deforestation) or otherwise hinder land's natural ability to store and sequester carbon; and (4) in consideration of the full lifecycle of the fuel from feedstock collection to final use, greenhouse gas emissions from the fuel must be near zero relative to conventional jet fuel.

Methods

To determine the amount of SAF that could be produced from current feedstocks, we first excluded feedstocks with high emissions and/or environmental burdens and then used existing literature to approximate the amount of remaining feedstock available. Using yield estimates (gallons of SAF/ton of feedstock) from existing literature, we then determined the amount of SAF that could currently be produced.

As discussed above, we concluded that the feedstocks warranting further consideration were municipal solid waste, crop residues and wastewater sludge. These feedstocks are currently available in the United States in the amounts shown in Table 2. The amounts in Table 2 assume an ideal scenario where the feedstock available can be feasibly and economically collected and processed, so they serve as an upper limit on availability.

Table 2: Potential SAF Feedstock in 2022

Feedstock	Potential Availability (million dry tons)
Municipal Solid Waste[122]	97.6
Crop Residues[123]	26.3
Wastewater Sludge[124]	12.6
Total	**136.5**

Note: Municipal solid waste represents the biogenic fraction only, so it excludes plastic, glass, and metals. Crop residues are reported assuming that only 30% of available material can be sustainably collected.

Based on a comprehensive summary of the potential production pathways of SAFs from different feedstocks, we found that the Fischer Tropsch process best represented the range of potential yield (gal/ton) from using municipal solid waste, crop residues and wastewater sludge. Using the potential availability of the given feedstocks and the fuel yield, we determined potential SAF production from a given feedstock (Table 3).

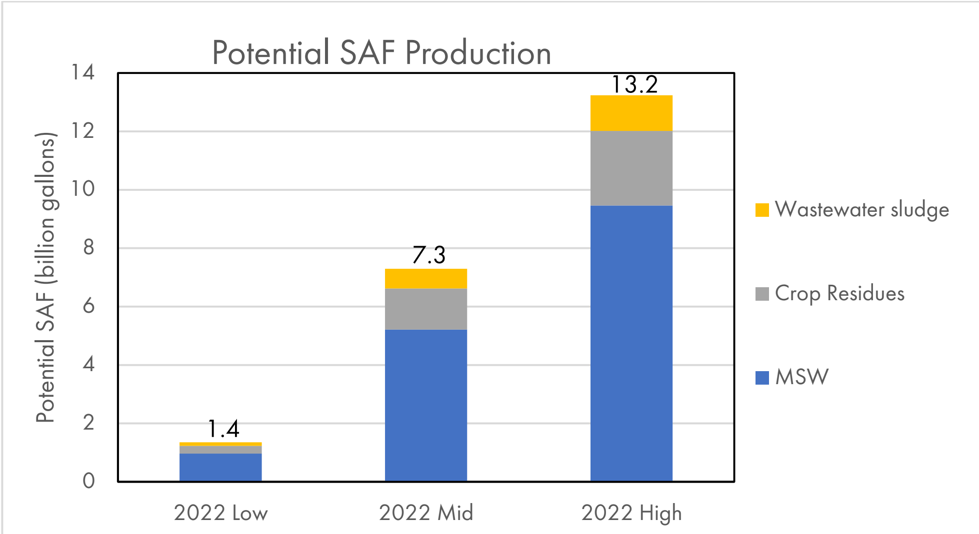
Results

Table 3: SAF That Could Be Produced in 2022 Given Estimates of Current Feedstock Availability

Feedstock	Availability (mil. tons/yr.)	Conversion Yield (gal/metric ton)[125]			SAF Produced (bil. gal/yr.)		
		Low	Mid-	High	Low	Mid-	High
Municipal Solid Waste	97.6	10	53	97	1.0	5.2	9.5
Crop Residues	26.3	10	53	97	0.3	1.4	2.6
Wastewater Sludge	12.6	10	53	97	0.1	0.7	1.2
Total	**136.5**	--	--	--	**1.4**	**7.3**	**13.2**

The low and high conversion yield values represent the lowest and highest possible yields (gal/metric ton) from the Fischer Tropsch production pathway. The "mid-" conversion yield is the value at the midpoint of the low and high conversion yields. Conversion yields were converted from gallons per U.S. ton in the original source.

Figure 1: Potential SAF Production From Feedstock Categories Under Conditions of Low, Mid-, and High Conversion Yields



Labels on columns display total SAF production potential at either low, mid-, or high conversion yield.

Potential SAF production given present amounts of feedstock ranges from 1.4 billion gallons to 13.2 billion gallons, with 7.3 billion gallons as a mid-range value. At all potential SAF yields, municipal solid waste constitutes about 72% of potential SAF production, followed by residues at about 19% and wastewater sludge at about 9% (Figure 1).

Sustainable Aviation Fuels Cannot Satisfy Aviation Fuel Demand

Feedstock Availability Does Not Guarantee Sustainable Aviation Fuel Production

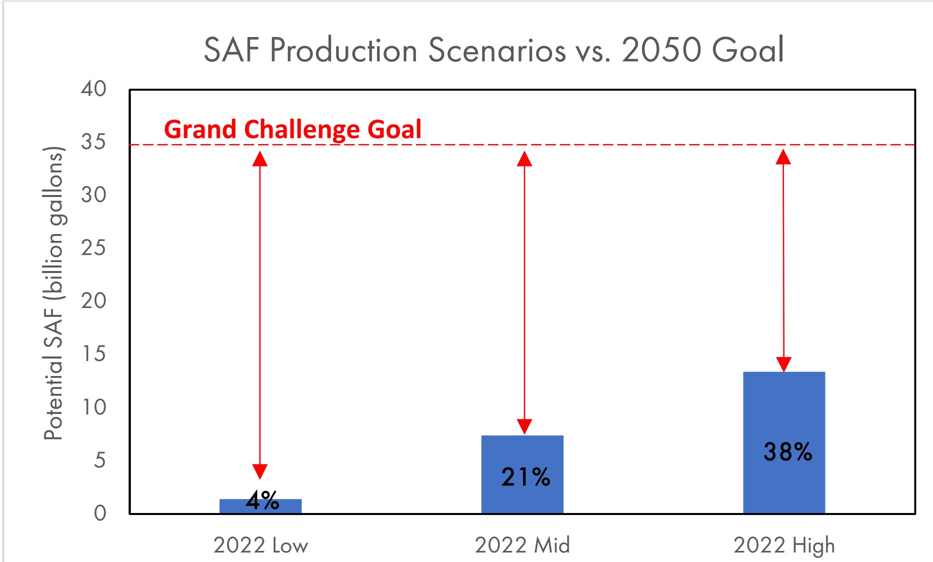
According to the U.S. Department of Energy's *2016 Billion-Ton Report*, nearly 450 million dry tons of additional feedstock could be made available in 2022 from a combination of forestry, agricultural and waste resources.[126] Given that the present analysis shows that at most 136.5 million dry tons of additional feedstock may be available, this is a large overestimate. That's largely because the Billion-Ton Report assumes amounts of energy crops and algal cultivation that have not been realized and relies on unsustainable feedstocks such as whole-tree biomass — highlighting the fact that aspirational projections of future resource availability are often unreliable. In 2013 the Federal Aviation Administration set the goal of 1 billion gallons of alternative jet fuel per year by 2018, but this is far from reality in 2022.[127] Right now the United States produces only 4.5 million gallons of SAF per year, or 0.5% of the 2018 goal.[128]

According to the Billion-Ton Report, 134 million tons of municipal solid waste were landfilled in 2013, but only 41% of it were likely to be available at a predicted market price.[129] Taking this example, our finding that, at mid- or high-production yield, there is enough feedstock to produce 3 billion gallons of SAF per year by 2030 is based on an idealized assumption that the feedstock available can be feasibly and economically collected and processed, which is unlikely. Assuming price and collection constraints on our municipal solid waste estimate would reduce SAF production in our analysis by one-third across the range of production yields. The likelihood of such economic factors affecting potential feedstocks detracts from the feasibility of the idealized mid- and high-production yield scenarios being truly representative of real-world SAF production.

The Most Sustainable Feedstocks Are Inherently Limited in Supply and Cannot Be Scaled Up

Even under a high-yield scenario, there isn't enough sustainable feedstock available to meet the goal of fulfilling 100% of aviation fuel demand, around 35 billion gallons, by 2050 (Figure 2).

Figure 2: Potential SAF Production Under Low, Mid-, and High Production Yield Scenarios



Depicted is the SAF Grand Challenge Goal of 35 billion gallons of SAF by 2050 and the potential production at present. Within the bars is the percent of the Grand Challenge Goal that could be met with current feedstocks.

Given current feedstock, and an idealized scenario regarding its availability, only 4% to 38% of a 35-billion-gallon demand would be met in 2050. Thus, between 2022 and 2050, the amount of feedstock available would have to increase by 3 to 25 times the current potential to meet the 2050 goal. This is daunting for numerous reasons. First, the feedstocks that are currently available and potentially sustainable are difficult to scale up. Further, many feedstocks should not be scaled up given their nature as wastes. For instance, municipal solid waste and wastewater sludge are unwanted products of human population centers. There are numerous mechanisms in place to deal with waste, such as recycling to minimize landfill waste and wastewater treatment to reuse or repurpose water. Incentives to promote alternative jet fuel production must not disincentivize such waste-reduction endeavors. For waste resources to be sustainable, any waste put toward AJFs must be sourced only after applying every other effort to reduce the waste stream. Removing mechanisms that minimize landfill waste or wastewater to have feedstock for AJFs would negate the benefits.

Second, we are highly skeptical that other feedstocks that are not currently at commercial scale will reach such scale in time to meet the SAF production goal. At present energy crops represent one of the few potentially low-carbon feedstocks of which supply can increase. In the *2016 Billion-Ton Report*, a projection of future feedstock availability assumed that 411 million tons of energy crop material, dominated by switchgrass and miscanthus grasses, would be available by 2040.[130] This was predicated on there being 78 million tons of energy crop material in 2022. However, it failed to account for the barriers to energy cropping that persist, namely supply chain logistics, profitability, and natural resource constraints.[131] Since there is currently no commercial production of either switchgrass or miscanthus, it is clear how off the mark the United States often is in goal setting.

Third, current efforts to convert existing oil and gas refineries to alternative jet fuel refineries indicate no desire to select feedstock based on the need to diversify or choose that which is most sustainable. There are currently two such efforts underway in California's Bay Area, and in both cases the use of virgin vegetable oils such as corn oil, soybean oil, and rapeseed oil are mentioned as likely feedstocks,[132] despite the associated indirect land-use change emissions. The conversion of fossil fuel infrastructure to food-based-feedstock refining points to an unfortunate likelihood where, to meet the 2050 SAF goal, the United States comes to rely on feedstocks that are no more sustainable than fossil fuels.

Even Truly Sustainable Aviation Fuels Still Produce Greenhouse Gases and Other Pollutants

In pathways consistent with limiting warming to 1.5 degrees Celsius, global CO_2 emissions must reach near zero around 2050,[133] the same time that the Biden administration wants 100% of U.S. jet fuel demand to be replaced by sustainable aviation fuels. But sustainable aviation fuels still produce emissions during combustion, both direct and indirect, so relying on them does not bring the aviation sector to near-zero emissions. Sustainable aviation fuels can, at best, *reduce* emissions from the aviation sector. We need the emissions to be eliminated.

Also, sustainable aviation fuels, being combustion-based, still produce pollutants such as nitrogen oxides that are associated with community-level health harms. A recent study found that sustainable aviation fuels can result in increased nitrogen oxide, or

NOx, emissions relative to conventional jet fuel.[134] Nitrogen oxide, an ozone precursor, is associated with the development and aggravation of respiratory diseases, especially asthma. Communities are already struggling with the burden of NOx pollution from aircraft. We cannot, while trying to reduce carbon emissions, ignore the potential increase in co-pollutants and adverse health impacts.

Because SAFs fail to eliminate greenhouse gas emissions and still produce pollutants, they simply don't provide an emissions-free future. At best, SAFs — limited to those derived from municipal solid waste, wastewater sludge, and crop residues — should be an interim measure on the path to a fully decarbonized aviation sector through innovations such as electric aircraft.

Conclusions

Of the feedstocks put forth for use in sustainable aviation fuels, only a subset of them keep greenhouse gas emissions and environmental harms to a minimum. Of these potentially sustainable feedstocks, virtually all are limited in supply and, as waste materials, must remain so. Therefore, these feedstocks cannot be expected to satisfy all jet fuel demand by 2050. As a result, current conversions of refineries to alternative fuel production point to future reliance on problematic feedstocks that are not sustainable to satisfy demand, such as food-based feedstocks that contribute to indirect land-use change and deforestation. The focus on SAFs in this context becomes a greenwashed diversion from the real emissions reductions we need in order to decarbonize.

The Effective, Reliable Method of Reducing Emissions: Strong standards for New and In-Service Aircraft

To truly decarbonize aviation, the Biden administration must set strong airplane emissions standards that are not mired in the myth of sustainable aviation fuels. The Clean Air Act gives the EPA the power to set a stringent, technology-forcing, declining emissions standard that:

(1) Applies to aircraft in operation as well as new aircraft.
(2) Allows for reducing emissions through airframe and engine design and operational improvements.
(3) Includes a ratchet mechanism to reduce emissions over time and achieve zero emissions by 2045 or sooner.[135]

As outlined in the 2020 companion report *Flight Path*, such a standard can and should include a multipronged strategy of improving fuel efficiency by at least 3.5% annually, electrifying all regional flights by 2040, and replacing fossil fuel jets with zero emission aircraft by 2045.[136] Doing so is possible and necessary to achieve near-zero emissions levels and keep global heating below the dangerous threshold of 1.5 degrees Celsius. The United States' outsized airplane pollution gives it not only a heavy responsibility, but also a tremendous opportunity to advance climate protections by setting strong aviation standards. For Biden to waste that opportunity on so-called sustainable aviation fuels that are unsustainable, unavailable and, in many cases, unsafe, would be a dangerous mistake.

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