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MEETING THE SAF GRAND CHALLENGE: CURRENT AND FUTURE MEASURES TO INCREASE U.S. SUSTAINABLE AVIATION FUEL PRODUCTION CAPACITY

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EXECUTIVE SUMMARY

The U.S. Sustainable Aviation Fuel (SAF) Grand Challenge, announced by the Biden Administration in Fall 2021, is an ambitious proposal aimed at increasing domestic production of SAF. It set targets for producing 3 billion gallons of SAF in the United States by 2030 and 35 billion gallons by 2050, enough to meet long-term aviation fuel demand. Following this announcement, the U.S. government enacted tax credits for SAF production of up to $1.75 per gallon through 2027.

This study assesses the feasibility of meeting the targets in the SAF Grand Challenge based on resource availability, production costs, technology readiness level, and policy support. In total, we find that the United States has approximately 21.7 billion gallons of theoretical SAF production potential from available biomass, but only 12.2 billion gallons of that is from sustainably available biomass (i.e., biomass without adverse market and environmental consequences). This is sufficient to meet the 2030 SAF production target, but not the 2050 target. Further, the current SAF tax credit system has fluctuating, unstable values and expire by the end of 2027. Without a long-term price signal, SAF developers will lack sufficient incentive to invest in projects from less-tested, advanced fuel pathways. Even with strong policy support, many SAF projects will continue to operate on thin profit margins due to the fuel's high production costs relative to fossil jet kerosene.

To illustrate the potential production volumes of cost-viable SAF, we developed four scenarios which reflect a combination of policy incentives, technology delays, and feedstock eligibility requirements. Figure ES1 displays the estimated volume of SAF production in 2030 under each scenario, organized by feedstock type and technology pathway.

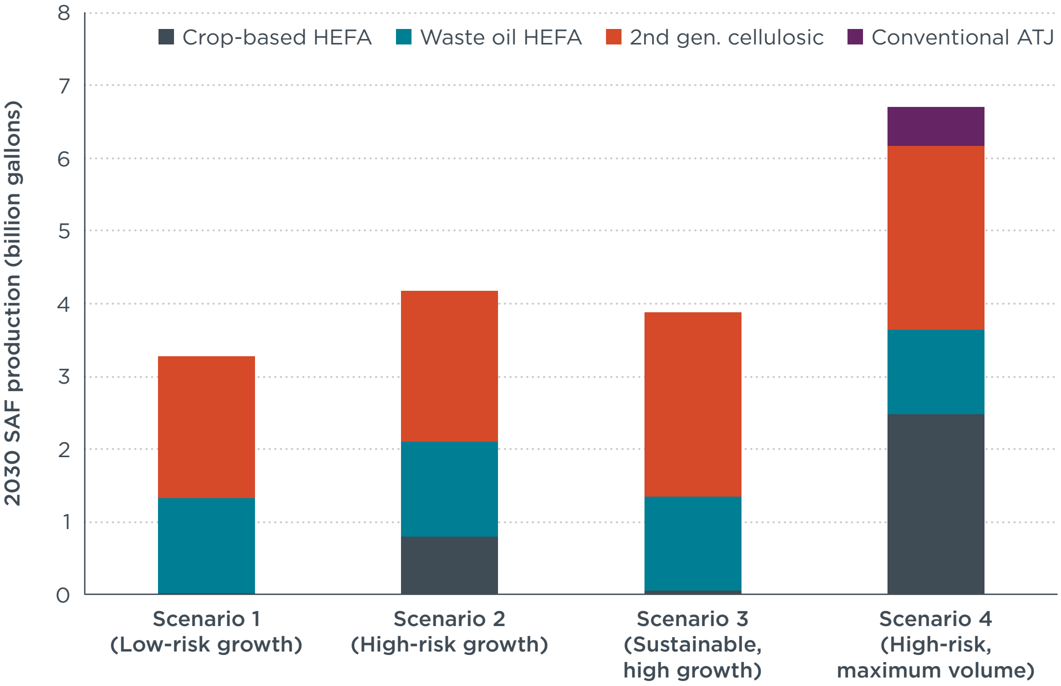

Figure ES1. Estimated 2030 SAF production across four deployment scenarios.

The analysis reveals that **technology delays will limit SAF production increases in the near term, while meeting 2050 targets will require additional resource supply.** Mature technologies, such as hydrotreated vegetable and waste oils, will make up the greatest share of SAF in the near term but will quickly be surpassed by SAF produced from cellulosic feedstocks such as municipal solid waste. Hydroprocessed esters and fatty acids (HEFA) fuels are highly resource constrained, while alcohol-to-jet pathways are likely to be cost-prohibitive in the near-term.

Although federal guidance requires that SAF meet a 50% lifecycle greenhouse gas (GHG) reduction relative to fossil jet fuel, **there remains risk that tax credits could be used to support SAF pathways with high sustainability risks.** These feedstocks include purpose-grown biomass such as corn and soybean that are linked with land use expansion and associated upstream emissions impacts, and are in competition with food and feed markets. Implementing policy safeguards consistent with international regulations would ensure that financial support is directed toward sustainable feedstocks and conversion technologies.

Current policy incentives are insufficient for SAF to attract long-term investment and remain cost-competitive with fossil jet. Without additional policy support, we find that 3.3 billion gallons of low-risk SAF reaches a breakeven point with conventional jet fuel in 2030, falling far short of targets in later years. Due to the expiration of tax credits beginning in 2028, future production volumes and investment risks are more uncertain. On their own, the voluntary production targets identified in the SAF Grand Challenge are unlikely to motivate substantial volumes beyond current industry commitments.

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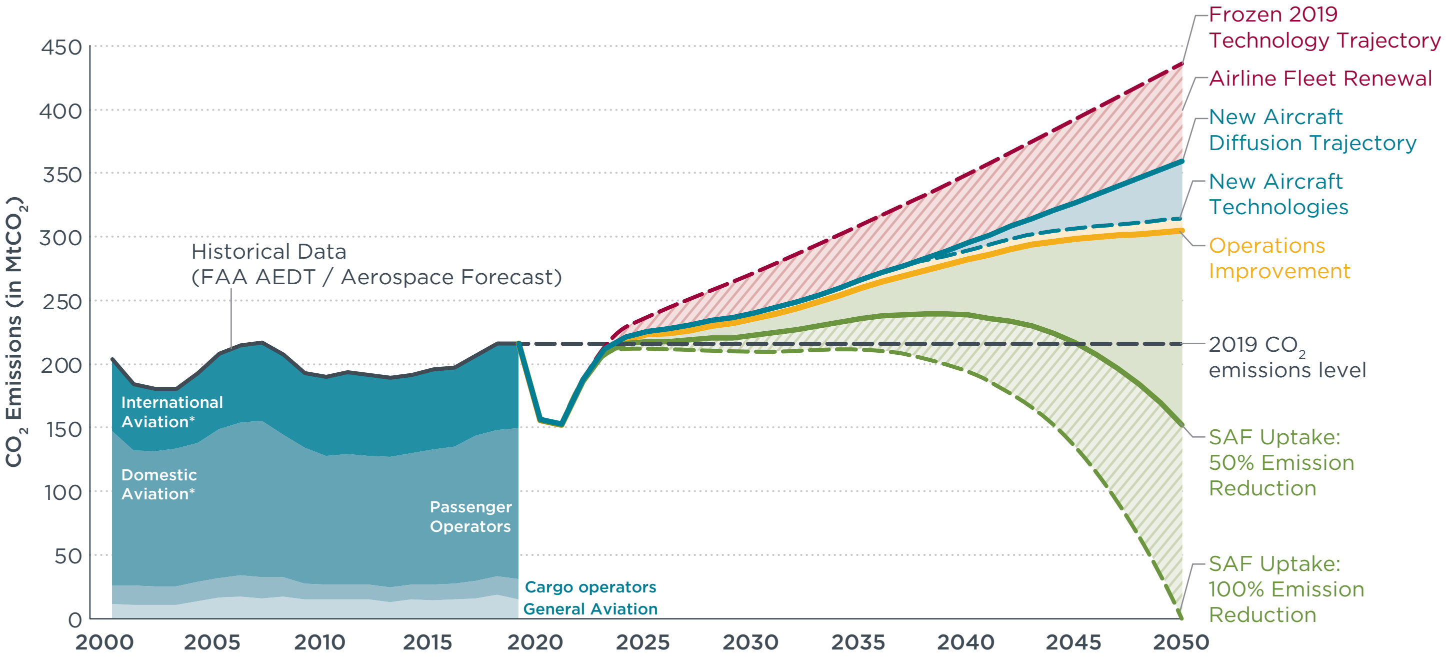
INTRODUCTION

In 2019, U.S. airlines used 23 billion gallons of jet fuel, one third of which was consumed on international flights (Federal Aviation Administration, 2021). Demand for jet fuel has been steadily growing over time, except for a temporary decrease in travel early during the COVID-19 pandemic. Aviation fuel demand is further expected to increase over the coming decades. The Federal Aviation Administration (FAA) estimates that greenhouse gas (GHG) emissions from aviation could double from 2019 levels by 2050 absent technology and behavioral interventions. When taking into account operational and efficiency improvements of aircraft, the FAA estimates a 40% emissions increase over the same period (FAA, 2021).



* Note: Domestic aviation from U.S. and Foreign Carriers. International aviation from U.S. Carriers.

Figure 1. Analysis of future U.S. domestic and international aviation CO$_2$ emissions. Reproduced from FAA (2021).

The FAA has emphasized the role of sustainable aviation fuel (SAF) in mitigating the projected rise in emissions over the long term. SAF typically refers to alternative aviation fuels that reduce lifecycle GHG emissions by at least 50 percent relative to fossil-based jet kerosene. SAF can be produced from a variety of different feedstocks and through multiple pathways. As of 2022, the most common and cheapest SAF production method is via hydrotreating vegetable oil and fat-based compounds (i.e., lipids) in the hydroprocessed esters and fatty acids (HEFA) pathway, which is a similar process to producing drop-in renewable diesel for the road sector. Another likely pathway in the near-term involves upgrading ethanol intermediates produced from food and feed crops such as corn starch and sugarcane. More challenging SAF pathways involve the conversion of cellulosic materials, such as woody and agricultural biomass, upgraded via Fischer-Tropsch (FT) gasification or the alcohol-to-jet (ATJ) conversion process. SAF can also be produced from recycled carbon, whether captured and combined with renewable electricity to generate e-fuels (i.e., power-to-liquids or e-kerosene), or from energy-rich flue gases from industrial processes.

Because SAF can reduce emissions using existing aircraft and fueling infrastructure, it has generated strong interest from government leaders as a method to decouple growth in demand from rising emissions. The corporate sector has also embraced SAF as a potential tool to meet green portfolio targets (Freed, 2022). Still, SAF's share of U.S. aviation fuel production remains small (approximately 0.1%) due to supply limitations, high costs, and sustainability concerns.

Various assessments have estimated that SAF costs are between two and five times that of conventional jet kerosene (Bann et al., 2017; M. Pearlson et al., 2013; Staples et al., 2014; Suresh et al., 2018). SAF's high production costs stem from a combination of factors that can vary from pathway to pathway, including high feedstock or upfront capital costs, complex feedstock pre-treatment processes, supply chain development, and the costs of chemical inputs. There is substantial potential for cost reductions as understanding of conversion technologies improves and economies of scale are achieved. However, these technology and operational improvements alone are unlikely to be enough for SAF to achieve cost parity with conventional jet kerosene (Pavlenko et al., 2019).

To encourage increased domestic production of SAF, the Biden Administration announced the U.S. Sustainable Aviation Fuel Grand Challenge (SGC) in Fall 2021. The proposal sets targets for producing 3 billion gallons of SAF in the United States by 2030 and 35 billion gallons by 2050, which is enough to meet long-term aviation fuel demand. Following this announcement, the U.S. government enacted tax credits for SAF production of up to $1.75 per gallon through 2027. Notably, the SGC does not establish binding targets for SAF deployment. Instead, it relies entirely on voluntary SAF purchases and complementary incentives at the federal and state levels. Furthermore, the SGC does not establish detailed sustainability criteria to determine which SAFs should contribute to targets, creating uncertainty about the policy's overall climate impact.

This paper assesses the feasibility of the SGC targets, evaluating the potential for the United States to expand domestic SAF production and meet 2030 and 2050 production goals. First, we evaluate existing, overlapping policies and incentives for SAF production in the United States. We then assess the supply and sustainability of available bio-resources, fuel production costs, and technology readiness of different SAF pathways. After assessing resource availability, we review the contribution of existing policy incentives to reduce the cost gap between conventional fossil jet fuel and SAFs across several deployment scenarios. For each scenario, we project the volumes of SAF produced and GHG emissions mitigated to evaluate the risks associated with the range of potential feedstocks and conversion pathways.

OVERVIEW OF CURRENT U.S. SAF POLICY

In 2021, the U.S. Departments of Energy, Transportation, and Agriculture signed a Memorandum of Understanding to collaboratively launch the SGC to accelerate the domestic development and deployment of SAFs to replace the use of fossil jet kerosene in the long-term (U.S. Department of Energy et al., 2021). The agencies proposed a production target of 3 billion gallons of SAF in 2030 and 35 billion gallons in 2050 from nearly zero at the time of the proposal. Ongoing planning and research workstreams are also underway at the interagency level to support rapid SAF deployment. Although the SGC is not a binding regulation, the agencies implementing it are tasked with providing funding for further research and development on conversion technologies and feedstock supply chains, conducting analysis on SAF infrastructure and higher blend limits, and performing stakeholder outreach (U.S. Department of Energy et al., 2022).

At the international level, the International Civil Aviation Organization (ICAO), adopted a long-term strategy in 2010 for carbon-neutral growth from 2020-onward (ICAO Secretariat, n.d.). The strategy includes measures such as operational and efficiency improvements, increased SAF blending, and the use of carbon offsets under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program. CORSIA provides an accounting framework for airline operators to monitor, report, and verify their emissions. However, CORSIA itself does not motivate the production of SAFs, leaving it up to Member States to develop their own policies and incentives to stimulate the SAF industry. Additional SAF deployment is expected to be motivated by ICAO's adoption of a 2050 net-zero CO_2 emissions goal in October 2022 (Mithal & Rutherford, 2023).

At the U.S. federal level, a variety of policy incentives can be used to subsidize the production of SAFs, though there are no policies that mandate their use. The 2022 Inflation Reduction Act (IRA) includes two tax credits to support SAF production: the Sec. 40B credit designed specifically for SAFs sold or used between 2023 and 2024, and the Sec. 45Z credit, which applies to all "drop-in" liquid hydrocarbon fuels sold between 2025 and 2027, apart from palm fatty acid distillates and petroleum-derived fuels. It is unclear whether these credits will be extended. The 40B credit offers between $1.25 and $1.75 per gallon for SAF, tied to the level of GHG reductions achieved from a fossil jet baseline. The IRA stipulates that the lifecycle GHG emissions intensity of SAF pathways must be at least 50% below the emissions for conventional fossil jet fuel, using a methodology developed by ICAO for the CORSIA program or a similar methodology consistent with Section 211(o)(1)(H) of the Clean Air Act (Inflation Reduction Act of 2022, 2022). Both methodologies include direct supply-chain emissions and emissions from land-use change, which together make up the carbon intensity (CI) value of eligible fuel pathways.

A January 2023 proposal from the Department of Treasury suggests that that the Department is considering using the default life cycle emissions values from CORSIA to determine the eligibility of SAF production pathways (Notice 2023-06). If adopted, the SAF eligibility threshold would be set at or below 44.5 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ), half the CI of jet kerosene adopted under CORSIA. Using this threshold, most food-based fuel pathways will be excluded from meeting SGC production targets. However, the exact interpretation of the IRA's life-cycle assessment (LCA) criteria is still under debate, so it is possible that high-risk feedstocks will remain eligible under the IRA's 50% GHG reduction threshold definition.

If the interpretation of the LCA criteria in the IRA is relaxed or broadened, it would expand the pool of eligible SAF pathways and weaken the effectiveness of the policy at reducing emissions from aviation.

Beyond the IRA, SAF production can also be incentivized by existing policies designed for the road sector, from which SAFs may be eligible to receive incentives or credits. The U.S. Environmental Protection Agency's Renewable Fuel Standard (RFS) sets biofuel blend mandates under which alternative fuel producers are awarded credits, or Renewable Identification Numbers (RINs), for each gallon of qualifying biofuel produced. These credits are traded among obligated parties and have a corresponding market value. Depending on the SAF in question, it could be eligible to generate RINs under the "D4" (i.e., biomass-based diesel), "D5" (i.e., advanced biofuel), or "D3/D7" (i.e., cellulosic biofuel) RIN categories. The RFS allows biofuel producers to combine RIN credits with other policy incentives to increase the value of fuel.

At the state level, SAF is eligible for credits under the California, Oregon, and Washington Clean Fuel Standards (CFSs), and programs in additional states are under development. CFSs are technology-neutral performance standards designed to decrease the average carbon intensity of a jurisdiction's transportation fuel pool. CFSs reward fuel producers with credits for achieving life cycle GHG emission reductions relative to their policy target; credits are proportional to a fuel's GHG reduction potential. Fuel producers with emissions higher than the annual target are obligated to purchase credits to offset their emissions in line with the annual standard. Under the three operational CFS programs, aviation fuel is an "opt-in" compliance pathway, which means fossil jet fuel does not generate deficits, although SAF producers can generate credits that are stackable with other federal incentives. The resulting imbalance of deficits and credits has done little to drive increased SAF production within these states (Pavlenko & Mukhopadhaya, 2023). In the absence of targeted support for SAFs, it is likely that renewable diesel producers will continue to optimize the production of drop-in renewable diesel to comply with road sector targets due to its higher policy and market value. Proposed updates to the California Low Carbon Fuel Standard (LCFS) program may change this incentive structure by obligating a portion of aviation fuel under the program (California Air Resources Board, 2023).

Again, there are no binding measures to mandate the use of SAFs in the United States. Moreover, there is little incentive to consume SAFs beyond voluntary goals, which have historically failed to promote their use. Therefore, meeting the SGC's production targets hinges on the cost of SAFs converging with the cost of conventional jet fuel. There is theoretically a robust framework for reducing the price gap between SAFs and fossil jet fuel in the United States when factoring in the multiple overlapping incentives and policies for alternative fuels. We assess the effectiveness of these policy levers in the context of resource supply, cost, and technological readiness to assess the ability of the United States to transition the aviation sector away from fossil fuel and achieve near- and long-term SGC production targets.

METHODOLOGY

This study assesses the resource potential and production cost of select existing and emerging SAF pathways that could be deployed to meet the U.S. SGC targets in 2030 and beyond. We develop four scenarios that simulate possible SAF production trajectories, outlined in Table 1. These exploratory scenarios are intended to illustrate the deployment of SAF based on loose or broad sustainability criteria, as well as existing or expanded policy support.

In the absence of binding SAF blending requirements, we assume that the net production costs for each pathway must reach a breakeven point with fossil jet kerosene to be sold on the market. Scenarios 1 and 2 factor in the maximum value of credits provided under the current U.S. policies, while Scenarios 3 and 4 assume that expanded and extended policy support allow SAF to breakeven with fossil jet kerosene in all cases.

Table 1. Overview of SAF deployment scenarios.

		Feedstock eligibility	
		Exclusion of purpose-grown crops & whole trees	**All biomass-based pathways eligible**
Policy support	Existing policy support	Scenario 1 (Low-risk growth)	Scenario 2 (High-risk growth)
	Expanded and extended incentives	Scenario 3 (Low-risk, high growth)	Scenario 4 (High-risk, maximum volume)

SUSTAINABLE AVAILABILITY OF SAF FEEDSTOCKS

Table 2 summarizes the feedstocks and pathways included in our assessment. Pathways that achieve at least 50% lifecycle GHG emission reductions relative to the fossil baseline under the CORSIA framework are shaded in green while pathways with higher emissions are shaded in red. Pathways that have not been assessed under CORSIA are shaded in grey. We label each pathway as “low” or “high” sustainability risk and list its technology readiness level (TRL), as defined by the International Energy Agency (2022). Low-risk feedstocks refer to fuels that meet 50% lifecycle GHG emission reductions under the CORSIA framework while high-risk feedstocks exceed that threshold.

Table 2. Summary of feedstocks and pathways included in two resource scenarios.

🟥 Exceeds 50% life cycle GHG emission reductions under CORSIA framework

🟩 Meets 50% life cycle GHG emission reductions under CORSIA framework

Feedstock	Conversion pathway	Direct production emissions (gCO$_2$e/MJ, CORSIA default)	Indirect land-use change emissions (gCO$_2$e/MJ, CORSIA default)	Total well-to-wake emissions (gCO$_2$e/MJ, CORSIA default)	High risk feedstock?	Technology readiness level
Soy oil	HEFA	40.4	24.5	64.9[a]	Y	9
Corn oil	HEFA	17.2	N/A	17.2	N	9
Used cooking oil (UCO)	HEFA	13.9	N/A	13.9	N	9
Animal fats	HEFA	22.5	N/A	22.5	N	9
Agricultural residues	FT-Gasification	7.7	N/A	7.7	N	6
Forestry residues	FT-Gasification	8.3	N/A	8.3	N	6
Energy crops	FT-Gasification	10.4	-32.9 to -3.8	-22.5 to 6.6	N	6
Municipal solid waste (100% biogenic)	FT-Gasification	5.2	N/A	5.2	N	6
Corn grain	ATJ	55.8	22.1	77.9[a]	Y	6
Sugar cane	ATJ	24.0	7.3	31.3	Y	6
Corn kernel fiber	ATJ	N/A	N/A	46.1[b]	N	6
Industrial flue gas	ATJ	29.4	N/A	29.4	N	6

[a] We consider the inclusion of soy HEFA and corn grain ATJ as SAF pathways under the SGC in some circumstances, though their default LCA emissions under CORSIA fall above the 50% GHG reduction threshold. Soy renewable diesel is certified as an advanced biofuel with 50% lifecycle GHG savings relative to fossil diesel in the federal Renewable Fuel Standard. DOE has estimated that corn grain ATJ can achieve more than 100% GHG emission reductions from a fossil baseline with the use of on-farm and process-related emission reduction strategies (Spaeth, 2021).

[b] Sum of 2022 GREET value for combined ethanol-to-jet upgrading and average carbon intensity of corn kernel fiber ethanol pathways certified under the California Low Carbon Fuel Standard

Although some SAF feedstocks are available in theory, their use poses important sustainability risks. These risks include high direct GHG emissions that may cause them to exceed the SGC's 50% GHG reduction threshold. The consumption of conventional SAF feedstocks also pose indirect impacts such as food price spikes, land conversion, and indirect GHG emissions when feedstocks are diverted from existing end-uses. Research has also found that biofuels produced from purpose-grown trees with long harvesting cycles may have significant GHG emissions impacts that occur before biogenic carbon is sequestered during plant regrowth (Baral & Malins, 2014; Kendall et al., 2009).

We evaluate the availability, cost, and deployment potential of all SAF feedstocks assessed in the U.S. DOE's Billion-Ton Report (BTR) with the exception of whole trees (Langholtz et al., 2016) due to their nascent state of commercialization and high sustainability risks. As a point of comparison, the SGC interagency working group relied on the BTR study to estimate domestic SAF resource potential in their SGC Roadmap (U.S. Department of Energy et al., 2022). We also assess SAF feedstocks and production pathways certified under ASTM certification standards, including crop and waste oil HEFA and ATJ produced from corn grain, corn kernel fiber, and industrial flue gas to ethanol conversion processes.

After narrowing the set of applicable SAF production pathways, we evaluate the total quantity of domestic feedstocks we consider to be available for SAF production. We utilize a dataset from the U.S. DOE's 2016 BTR to estimate the resource potential for agricultural and forestry biomass, municipal solid waste, and dedicated energy crops (U.S. Department of Energy, 2016). We filter the BTR dataset for 2030 at an average feedstock sale price that factors in an average 1% increase in annual yields for agricultural biomass. The BTR considers some sustainability safeguards within its resource estimates, including the assumption that 30% of forestry residues remain in-situ to support soil management, the use of best practices to harvest timber, and the use of county-level retention assumptions for agricultural residues (Langholtz et al., 2016).

The yields for commercial-scale energy cropping remain uncertain due to limited real-world data, large variations across pilot studies, and a risk of lower yields when grown on marginal land. Energy crops may exhibit yields up to 40 tonnes per acre under closely managed trials (U.S, EPA, 2010); however, in practice, yields are often much lower due to harvesting inefficiency, soil quality, and edging effects (Searle & Malins, 2014). To adjust the BTR energy crop yield estimates to account for this trend, we adjust the modeled yields based on a meta-analysis of energy crop yields by feedstock developed by Searle and Malins (2014). We combine the quantities of energy crops by feedstock and state reported in the BTR with the median feedstock yield value reported by Searle and Malins to estimate future energy crop availability. We assume a temperate climate for all states apart from Florida using agro-ecological zone (AEZ) biome maps.

The BTR does not evaluate future availability of virgin vegetable and waste oils but does estimate the quantity of these materials that are currently consumed in the United States. We assume that the quantity of these feedstocks consumed in non-transport applications will not be diverted to SAF to avoid market distortions. We draw upon an analysis of vegetable oil feedstock availability in the United States conducted by Zhou et al. (2020) and later updated by O'Malley et al. (2022) to estimate the volume of soybean oil that could be converted to SAF. Due to rapid growth in waste oil crediting under the California LCFS, we assume that waste oil consumed as biomass-based diesel in 2022 in California represents the maximum volume of available domestic feedstocks (California Air Resources Board, n.d.).

In addition to biomass resources, this study incorporates resource estimates for industrial flue gas and corn kernel fiber. Industrial flue gas availability is estimated using U.S. steel production and process data from the World Steel Association (2020) and off-gas emission factors for carbon monoxide and hydrogen reported by Bazzanella and Ausfelder (2017). We assume that 80% of flue gas is recovered for heat and power (Collis et al., 2021), an increase over previous ICCT estimates. A more detailed description of industrial flue gas to ethanol methodology is discussed in O'Malley et al. (2021). Availability data for corn kernel fiber is calculated as a percentage of the quantity of corn grain converted to ethanol in 2022 on a mass basis (Alternative Fuels Data Center, n.d.). We assume that corn kernel fiber accounts for 10% of whole corn kernel by dry mass percentage (Kurambhatti et al., 2018), although other studies have estimated this figure to be as high as 25% (Gopalakrishnan et al., 2012). We assume that corn grain ethanol production remains nearly constant through 2030 due to a projected plateau in gasoline demand (Ramsey et al., 2023).

For Scenario 4, which includes all biomass-based pathways, we evaluate the potential contribution of corn grain ethanol and sugar cane ethanol diverted from the road sector to aviation. We also account for increased soybean oil production, assuming maximized soybean crushing rates, consistent with announced capacity expansion of 5 billion gallons renewable diesel production in the United States. (U.S. EIA, 2021). We source 2030 corn ethanol demand from the Energy Information Administration's (EIA) Annual Energy Outlook, which projects a 4% increase in demand from 2022 levels. U.S. Environmental Protection Agency (2022) projects that sugarcane ethanol consumption will increase to 110 million gallons through 2025, due to sustained financial support from the LCFS and RFS programs.

FUEL PRODUCTION

To determine yields for each feedstock, we multiply the availability of each feedstock by the estimated conversion yields (kg fuel per kg feedstock) for each production pathway, adjusting for the share of jet fuel generated in the final product slate. Yield data for the HEFA process is based on default yields estimated within the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne National Laboratory, 2022). We calculate feedstock-specific yields for the Fischer-Tropsch (FT) gasification pathways based on the calorific value of input feedstocks (IEA Bioenergy, 2003; Krajnc, 2015; Tumuluru, 2015). For all FT-Gasification pathways, we assume a process conversion efficiency of 45% (Daniell et al., 2012). For flue gas, we perform a stoichiometric adjustment on process data reported by Handler et al. (2016), assuming that carbon monoxide is the primary energy carrier. We calculate yield data for the corn kernel fiber to ethanol based on a laboratory study on dry ethanol milling conducted by Dien et al. (2005) that recorded an average conversion rate of 21.3 grams of ethanol per 100 grams of corn fiber. For the latter two pathways, we assume a conversion factor of 0.6 for upgrading ethanol intermediates to jet fuel (Tao et al., 2017).

We then adjust yields to account for the share of SAF produced relative to total output products for each pathway (M. Pearlson et al., 2013; Tao et al., 2017). A summary of our yield assumptions in kilograms of jet fuel per kilograms of feedstock is presented in Table 3.

Table 3. Process yield assumptions by feedstock and conversion pathway.

Feedstock	Conversion pathway	Yield (tonne fuel/ tonne feedstock)	% jet-optimized product slate	References
Vegetable and waste oils	HEFA	0.89	59%	Argonne National Laboratory, 2022
MSW	FT-Gasification	0.10	50%	Daniell et al., 2012; IEA Bioenergy, 2003
Agricultural residues	FT-Gasification	0.17	50%	Daniell et al., 2012; Tumuluru, 2015
Forestry residues	FT-Gasification	0.19	50%	Daniell et al., 2012; Krajnc, 2015
Energy crops	FT-Gasification	0.17	50%	Daniell et al., 2012; Tumuluru, 2015
Corn kernel fiber	ATJ	0.20	75%	Dien et al., 2005; Tao et al., 2017
Industrial flue gas	ATJ	0.40	75%	Handler et al., 2016; Tao et al., 2017
Corn grain and sugarcane ethanol	ATJ	0.60	75%	Tao et al., 2017; ICAO, 2023

COST ASSESSMENT

To evaluate the impact of the existing policy mix and better understand the remaining price gaps to address to meet the SGC's volume goals, we next determine the costs of different SAF pathways. Across the literature, there is generally a consensus that HEFA pathways are the lowest cost SAF pathway, particularly when using waste oils (Pearlson et al., 2013; Bann et al. 2016; Pavlenko et al., 2019, Wang et al. 2021). Second-generation fuel pathways using cellulosic materials are generally considered more expensive, although MSW is considered the cheapest of these feedstocks. There is a wide range of estimates for ATJ-produced fuels, with a general trend that cellulosic ATJ pathways are more expensive and capital-intensive than catalytic upgrading of commercially available ethanol (Pavlenko et al., 2019; de Jong et al., 2016). Wang et al. (2021) estimates that the upgrading of existing commercialized crop-derived ethanol is one of the cheapest SAF production pathways; similarly, ICAO estimates that SAF production from ethanol can be achieved at costs below $4 per gallon (ICAO, 2023).

Table 4 provides a range of levelized production costs in 2022 U.S. dollars for different SAF pathways, based on the literature described above. We compare SAF costs to the baseline cost of fossil jet fuel based on a 5-year U.S. average (2017–2021) for jet kerosene price reported by the Energy Information Administration and adjusted for inflation (U.S. Energy Information Administration, n.d.).

There are two pathways that could be utilized over the next decade that are not well-characterized in the techno-economic literature. ATJ production from industrial flue gases and corn kernel fiber likely requires much less capital expense and pretreatment than cellulosic production, but its exact cost remains uncertain. We source costs for corn kernel fiber ethanol and Lanzatech's flue gas ethanol production from Pavlenko et al. (2017) and Searle et al. (2017), respectively, and add the cost of ethanol upgrading from Tao et al. (2017) to estimate the levelized production cost for these ATJ pathways.

Table 4. Range of levelized SAF production cost estimates by feedstock and conversion pathway.

Feedstock	Conversion pathway	Levelized production cost range ($/gal)	Median levelized production cost ($/gal)
Waste oils	HEFA	$3.03 to 6.62	$4.06
Vegetable oils	HEFA	$4.16 to 5.68	$5.16
MSW	FT-Gasification	$2.64 to 6.19	$4.07
Agricultural and forestry residues	FT-Gasification	$5.45 to 8.23	$7.95
Energy crops	FT-Gasification	$6.83 to 11.41	$8.64
Corn grain	ATJ	$3.03 to 8.68	$6.68
Sugar cane	ATJ	$3.03 to $7.74	$7.06
Cellulosic	ATJ	$6.83 to 11.41	$9.12
Corn kernel fiber	ATJ	$7.12	$7.12
Industrial flue gas	ATJ	$5.34	$5.34

Policy incentives

We calculate the net production cost of SAF by subtracting the value of existing policy incentives from the levelized production costs. Incentives include federal RFS RIN credits, Section 40B or 45Z tax credits, and California LCFS credits. We assume SAF producers sell fuel in the California market because the California LCFS has the highest credit value of all active CFS programs.

To estimate RFS credit values, we adopt the 5-year average (2018–2022) RIN price for the D5 and D7 RIN categories. RIN credits apply to all biomass-based fuels and are assumed to remain constant between 2022 and 2030. We calculate the value of the 40B tax credit for each pathway based on the incremental emissions reductions that SAF achieves relative to a fossil baseline. The 40B SAF tax credit applies to all SAFs sold in the 2023 and 2024 calendar years. The 45Z tax credit applies to all alternative fuels sold within the U.S. transport sector between 2025 and 2027 and updates the credit generation formula for SAF. The value of the performance-based tax credits is matched to a fuel's CI, based on the formulas provided in Table 5.

We also estimate the value of credits for SAF in the California LCFS program. Although the LCFS assigns project-specific CI values to certified SAF pathways in practice, we input the default CORSIA CI values for each pathway into our credit price calculations for simplicity. We calculate credit values in USD per jet gallon equivalent (JGE) for the final year in which each policy is active (i.e., 2024, 2027, and 2030) and assume a constant LCFS credit price of \$100/metric tonne of CO_2e. The credit values for a given CI decrease gradually over time as the level of LCFS program ambition increases.

Table 5 summarizes the existing policy incentives for SAF that are assumed in this analysis. Net production costs reflecting the application of these policy incentives are summarized in Table 8.

Table 5. Summary of fiscal incentives for SAF production, 2023–2032.

Credit	Credit value	Period of eligibility
RFS RIN	• Cellulosic (D3/D7) RINs: \$3.60 • Biomass-based diesel (D4) RINs: \$1.48 • Advanced biofuel (D5) RINs: \$1.50 • Conventional biofuel (D6) RINs: \$0.84	Ongoing
California LCFS	\$100/mt CO_2e	Ongoing
IRA (§ 40B)	$\frac{\$1.25}{gallon} + \left(\frac{89\ gCO_2e/MJ - CI_{fuel}}{89\ gCO_2e/MJ}\right) - 0.5 \times \frac{\$0.01}{gallon}$	2 years (2023–2024)
IRA (§ 45Z)	$\frac{\$1.75}{gallon} + \left(\frac{CI_{fuel} - 50\ kgCO_2e/MMBTU}{50\ kgCO_2e/MBTU}\right) \times \frac{\$0.01}{gallon}$	3 years (2025–2027)

DEPLOYMENT RATES

The interagency SGC roadmap estimates that meeting the 2050 SGC target would require the deployment of approximately 400 biorefineries (U.S. Department of Energy et al., 2022), at an average capacity size of 87.5 million gallons. Because SAF is an emerging industry, we are unable to rely upon historical production trends to estimate construction timelines and production ramp-up; this is further complicated by the lack of meaningful trends in the deployment of second-generation biofuel facilities (Witcover, 2021). We therefore use a simplified deployment model to project the time lag between facility design and full-scale operation by conversion technology.

We first establish a capacity size for small and large facilities for each pathway (Table 6). Capacity estimates are drawn from techno-economic assessments, feasibility studies, and planned facility announcements.

Table 6. Capacity assumptions by SAF technology pathway.

Capacity assumptions	Small facility (Million gallons)	Reference	Large facility (Million gallons)	Reference
HEFA	50	Pearlson, 2011	250	Qantas, 2013
FT-gasification	50	van Vliet et al., 2009	250	van Vliet et al., 2009
ATJ	15	Geleynse et al., 2018	150	ICAO, 2023

We assume that it takes 3 years between initial construction and operation for first-generation feedstock facilities and 5 years for facilities that process cellulosic material. Apart from the commercialized HEFA pathway, we assume that ATJ and FT-gasification facilities take an additional 3 years to reach full operation (Bann et al., 2017; M. N. Pearlson, 2011). These assumptions are highly variable and are based on the long lead times associated with advanced fuel project development; for example, an MSW gasification facility that began operation in late 2022 took 6 years from initial construction to operation (Musulin, 2018). Other SAF facilities never reach commercialization due to long project delays (Sickinger, 2023).

We assume a linear production increase in the interim period, growing from 25% of total capacity in the first year of operation to 100% in the fourth year (Pavlenko et al., 2019). HEFA facilities are assumed to reach 100% of production output in the first year of operation. We also factor in technology lag times for both advanced production pathways; FT-gasification and integrated ATJ facilities are assumed to enter operation in 2023 while ATJ facilities processing cellulosic feedstocks (e.g., agricultural residues) are assumed to enter operation beginning in 2026. Entry years are based on planned facility announcements compiled by ICAO (n.d.). We assume that up to two facilities per technology pathway are deployed per year for mature technologies with a technology readiness level (TRL) of 9 and one facility per technology pathway is deployed per year for technologies in the demonstration phase (TRL 6). Our deployment model also depends on resource availability. For example, if only 200 million gallons of HEFA fuel for a certain feedstock is available, our model assumes a small rather than large facility is deployed. In all cases, the lowest cost feedstock per conversion technology is dispatched until pathways exceed cost parity with fossil jet kerosene. We assume that in the near-term, HEFA facilities comprise the greatest share of newly built facilities due to their higher TRL, while a greater share of FT-gasification and ATJ facilities enter operation by mid-decade.

RESULTS

We estimate the total theoretical availability of SAF from sustainably available domestic resources to be **12.2 billion gallons** and the maximum quantity to be **21.7 billion gallons**. Our maximum supply estimate assumes 100% soybean crushing rates and the use of other purpose-grown biomass with sustainability concerns. It also assumes that the share of these resources consumed in non-transport applications does not change. If first-generation feedstocks are included under the SGC target, it could maximize SAF output while increasing indirect emissions that could undermine the SGC's objectives. Our resource availability estimates by feedstock and fuel are summarized in Table 7, shaded by the assessment of risk described above.

Table 7. Feedstock and fuel resource estimates by feedstock.

🟥 Exceeds 50% lifecycle GHG emission reductions under CORSIA framework

🟩 Meets 50% lifecycle GHG emission reductions under CORSIA framework

Feedstock	Available quantity (Million tonnes of feedstock)	Theoretical jet fuel production potential (billion gallons)
Soybean oil	4.2	0.74
Soybean oil (with 100% crush rates)	15.3	2.67
Corn oil	2.1	0.37
UCO	2.8	0.48
Animal fats	2.4	0.42
MSW	75.8	1.35
Agricultural residues[a]	161.1	4.88
Forestry residues	33.6	1.14
Energy crops	89.7	2.72
Corn grain ethanol	43.9	6.89
Sugarcane ethanol	0.3	0.05
Corn kernel fiber	13.5	0.69
Industrial flue gas	0.65	0.06

[a] Includes estimates for secondary crop residues and wastes from Langholtz et al., (2016).

We find that the largest source of available biomass in the United States is agricultural residues such as stalks and husks that are typically left in the field to preserve soil quality (Searle & Malins, 2016). Energy crops, including Miscanthus, switchgrass, and short-rotation woody biomass, are the next largest source of available biomass, accounting for 89.7 billion metric dry tonnes. When factoring in adjusted yields, we estimate a 59% reduction from the energy crop availability values estimated by DOE. MSW, forest trees from timberland, and forestry residues make up the next largest share of resources.

The share of available feedstocks that is suitable for ATJ fuels is far lower. Corn kernel fiber makes up 10% of the mass of whole corn utilized for ethanol, or 13.5 million tonnes based on current production rates. The quantity of sustainably available industrial flue gas is also low due to nearly 80% of production being consumed by competing uses such as onsite heat and power. However, when including the quantity of corn grain and sugarcane ethanol currently consumed in the road sector, ATJ feedstock availability increases by nearly four times.

We find that the availability of domestic waste fats and oils converted to SAF via hydroprocessing is also highly constrained because most of these materials are consumed in competing sectors such as food, animal feed, and consumer products such as soaps and cosmetics. O'Malley et al. (2022) estimates that the supply of these materials could grow 13% between 2022 and 2030, primarily from higher soybean yields and increased UCO collection rates. Maximizing soybean crushing rates could yield an additional 1.9 billion gallons.

The potential supply of each SAF pathway and feedstock combination based on levelized production cost is shown in Figure 2. For comparison, the average jet kerosene price of $2.06 per gallon is represented by the dotted line. HEFA pathways and MSW cost between 2 and 2.5 times the value of fossil jet kerosene in 2030. SAF produced via gasified energy crops costs more than 4 times the cost of fossil-based jet kerosene.

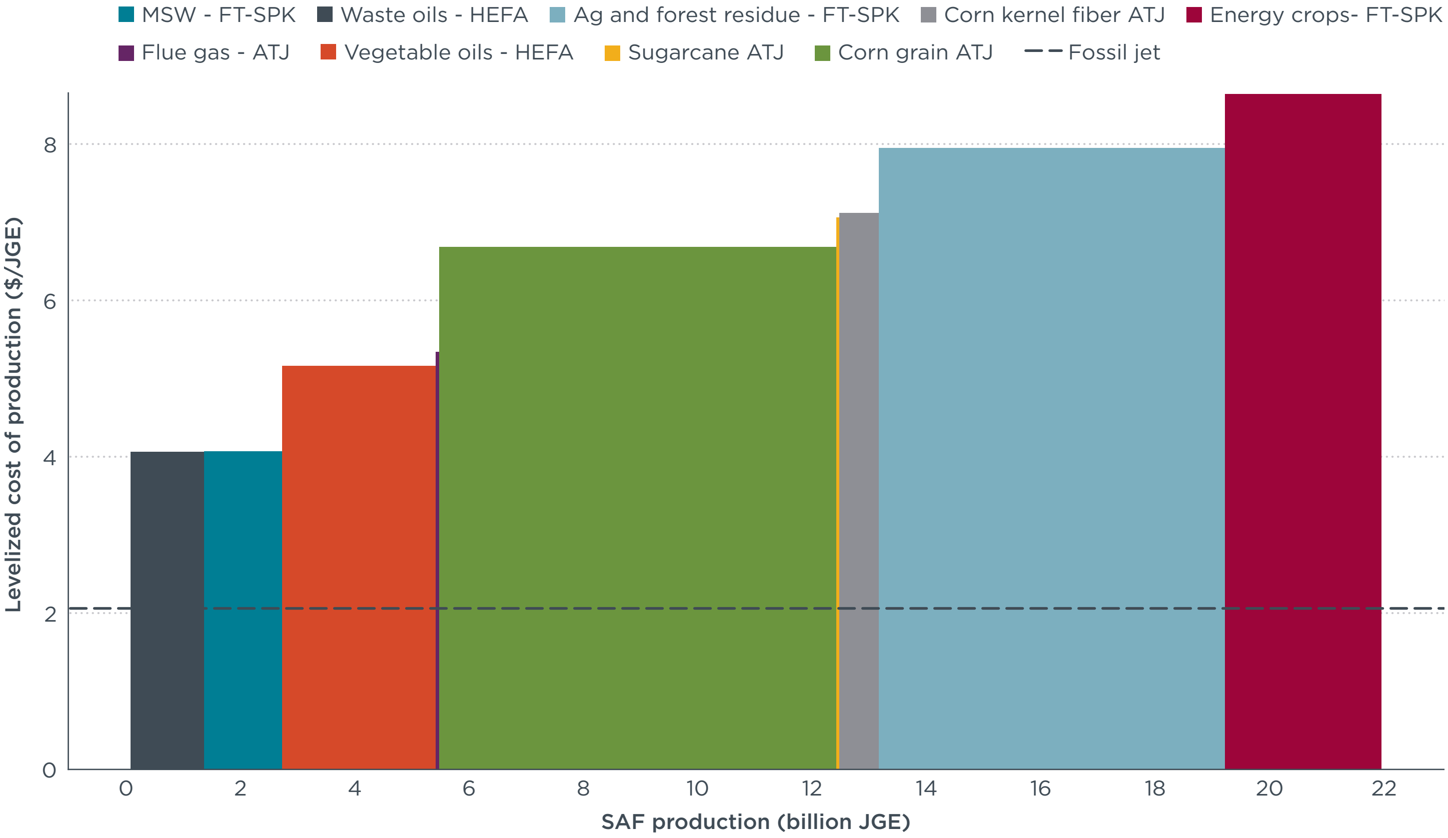


Figure 2. Supply and price of domestic SAF, by levelized production cost, relative to the average cost of fossil jet fuel.

No SAF pathways are cost competitive with conventional fossil jet fuel in the near-term without the use of policy incentives. To calculate the net cost of SAF in dollars per JGE, we combine the levelized production costs with their maximum policy incentives for each pathway in 2024 (Table 8). Pathways that achieve cost parity with fossil jet within a 5% margin are highlighted in green while pathways that have a higher adjusted production cost than fossil jet are highlighted in red.

Table 8. Estimated policy support and net production cost by SAF pathway in 2023–2024 ($/JGE).

🟩 Achieves cost parity with fossil jet with maximum policy incentives

🟥 Does not achieve cost parity with fossil jet with maximum policy incentives

Feedstock	Conversion pathway	Levelized production cost ($/JGE)	RFS RIN credit ($/JGE)	40B tax credit ($/JGE)	CA-LCFS credit ($/JGE)	Net production cost ($/JGE)
Soy oil[a]	HEFA	5.16	1.48	0 -1.30	0.29 – 0.61	1.77 - 3.39
Corn oil	HEFA	4.06	1.48	1.56	0.89	0.13
UCO	HEFA	4.06	1.48	1.59	0.94	0.05
Animal fats	HEFA	4.06	1.48	1.50	0.83	0.26
Agricultural residues	FT-Gasification	7.95	3.60	1.66	1.01	1.67
Municipal solid waste	FT-Gasification	4.07	3.60	1.69	1.04	-2.27
Forestry residues	FT-Gasification	7.95	3.60	1.66	1.01	1.69
Energy crops	FT-Gasification	8.64	3.60	1.75	1.21	2.08
Corn grain	ATJ	6.68	0.84	0	0.13	5.72
Sugar cane	ATJ	7.06	1.50	1.40	0.72	3.44
Corn kernel fiber	ATJ	7.12	3.60	1.23	0.53	1.76
Industrial flue gas	ATJ	5.34	0	1.42	0.77	3.15

[a] We calculate the range of policy subsidies for soy HEFA assuming a CI value of 42.2 kgCO$_2$e/MMBTU and 64.9 gCO$_2$e/MJ adopted under the RFS and CORSIA LCA programs, respectively.

Cellulosic and waste-derived biofuels receive high levels of policy support due to their low CIs, while vegetable feedstocks and other pathways with moderate CI values receive less financial support. Further, several pathways, including waste oil HEFA and gasified MSW, are cost competitive with fossil jet fuel without the 40B tax credit. For these lower-cost production pathways, IRA tax credit subsidies create an incentivize to shift fuel production from the diesel to jet markets without an additional climate benefit.

The relationship between the CI of a fuel and level of policy incentives becomes more pronounced in 2025 when the 45Z tax credit takes effect. This tax credit uses a greater weighting for fuels with the highest GHG emission reduction benefits. As a result, the credit value declines substantially for pathways closer to the minimum 50% reduction threshold, whereas the credit value for pathways with higher GHG emission savings remains more stable. The value of 40B and 45Z credit values in USD per JGE per pathway are shown in Table 9.

Table 9. 40B and 45Z tax credit value assuming CORSIA default CI values.

Feedstock	Conversion pathway	40B tax credit ($/JGE)	45Z tax credit ($/JGE)
Soy oil[a]	HEFA	0–1.30	0–0.27
Corn oil	HEFA	1.56	1.11
UCO	HEFA	1.59	1.24
Animal fats	HEFA	1.50	0.92
Agricultural residues	FT-Gasification	1.66	1.47
Municipal solid waste	FT-Gasification	1.69	1.56
Forestry residues	FT-Gasification	1.66	1.44
Energy crops	FT-Gasification	1.75	1.75
Corn grain	ATJ	0.00	0.00
Sugar cane	ATJ	1.40	0.59
Corn kernel fiber	ATJ	1.23	0.05
Industrial flue gas	ATJ	1.42	0.66

[a] We calculate the range of policy subsidies for soy HEFA assuming a CI value of 42.2 kgCO2e/MMBTU and 64.9 gCO2e/MJ adopted under the RFS and CORSIA LCA programs, respectively.

ATJ pathways struggle to financially compete with fossil jet due to their high production costs. Despite having a low CI, industrial flue gas receives one of the lowest policy incentives of all pathways because this feedstock is not classified as a biomass-based feedstock under the RFS. If CORSIA default LCA factors are adopted by the U.S. Department of the Treasury in forthcoming tax credit guidance, corn grain ATJ will not be eligible to receive IRA tax credits; however, if producers use CORSIA's Actual Life-Cycle Emissions Values methodology for specific projects (ICAO, 2019), this may allow some individual producers to meet the minimum 50% GHG reduction threshold.

Fuel pathways that can avoid expensive, capital-intensive pretreatment processes generally have lower production costs and are likelier to be cost competitive with fossil jet fuel. We find that all fuels produced via the HEFA pathway are cost competitive when factoring in policy incentives. Of the FT-gasification pathways, MSW and agricultural and forestry residues achieve cost parity through the continuation of the IRA tax credits; corn kernel fiber is the only feedstock to achieve cost parity for the ATJ pathways.

Figure 3 below illustrates a cost curve of fuel availability, sorted by policy-adjusted levelized production costs based on the 2023–2024 mix of policies. We organize fuels by feedstock and production pathway and group feedstocks that may be used as inputs to the same bio-refinery (e.g., waste oil HEFA) relative to their weighted net production cost. Policy support phases out in the later year periods, so this data represents a best-case scenario for breakeven SAF production. An estimated **12 billion gallons** of fuel is viable at a competitive cost based on maximum near-term policy incentives.

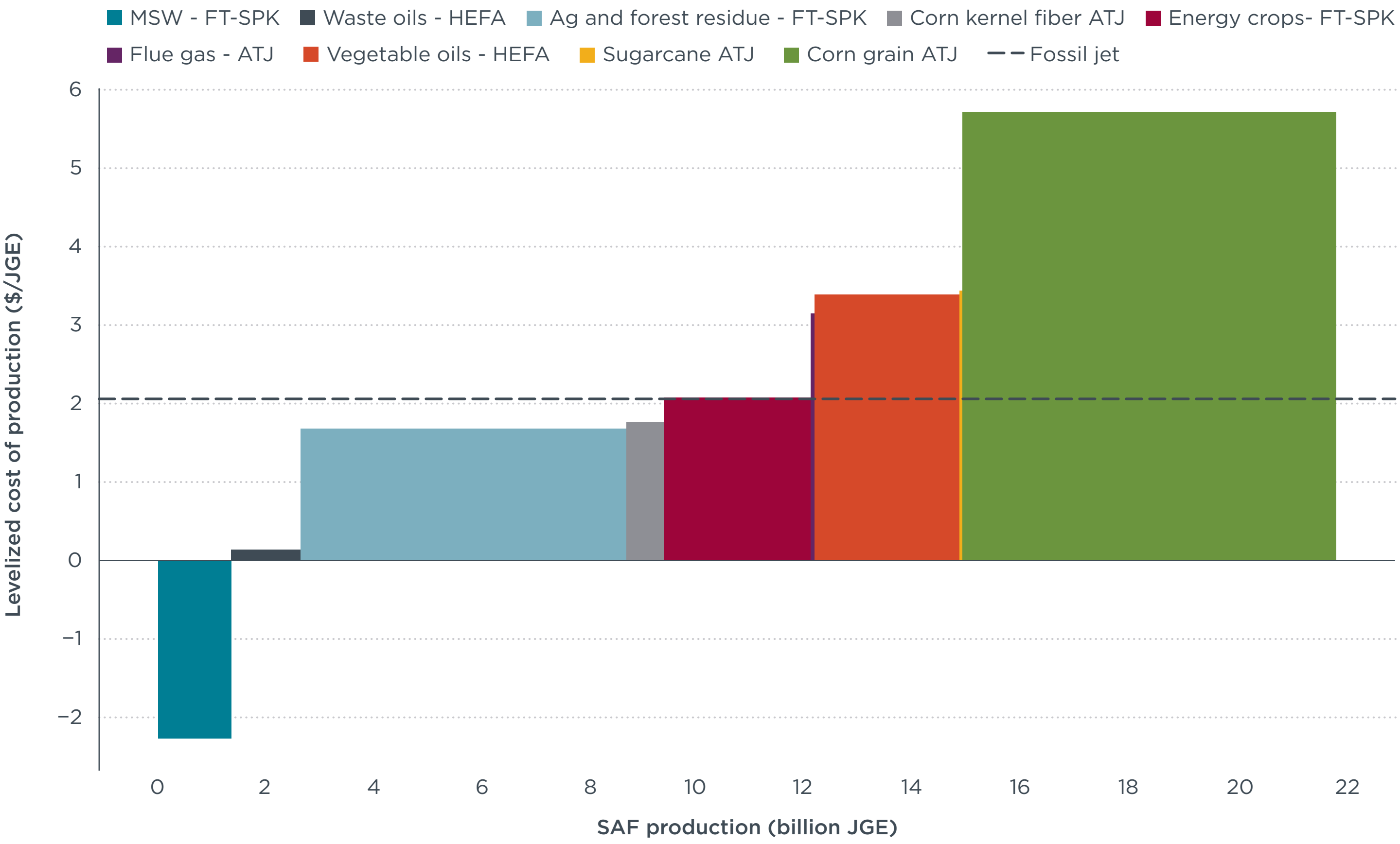


Figure 3. Estimated SAF production supply curve, relative to average cost of fossil jet fuel, adjusted for sustained 2022–2024 SAF policy incentives.

Despite dedicated policy support for SAF in the near-term, most pathways are unable to breakeven with conventional jet in the mid-to-long term (Figure 2). Further, production delays may limit SAF output before 2030. We investigate the impact of deployment constraints for our four scenarios below.

SAF DEPLOYMENT PROJECTIONS

We next present a series of projections based on a combination of policy incentives and sustainability safeguards in conjunction with the resource availability estimates and deployment assumptions described above. Each scenario is subject to different constraints regarding feedstock eligibility and cost. These projections represent illustrative cases of the volume of SAF from each feedstock and conversion pathway combination between 2023 and 2030. We do not extend our scenario volume projections beyond 2030 due to significant scale-up uncertainty. These estimates do not consider competing demand from the road sector, although in some cases it may be more cost-effective to produce a unit of renewable diesel than jet fuel with the same feedstock. Instead, they reflect the possible volume of SAF that is cost-viable with the eligibility criteria and policy support assumptions for each scenario, with an adjustment for deployment time.

Scenario 1 represents a low-risk growth case based on an interpretation of the IRA's LCA guidance that fully aligns with CORSIA emission values and excludes first-generation, food-based biofuels that fall short of the 50% GHG reduction threshold.

It also assumes that pathways must reach cost parity with fossil jet to be deployed. Under Scenario 1, the SGC target is met primarily via waste and residue materials with high GHG savings and high policy subsidies. Waste oil-derived HEFA is heavily supply-constrained and is projected to make up the majority of SAF volume in the near-term and 14% in 2030. Apart from an estimated 25 million gallons of existing HEFA production, new crop-based HEFA facilities are ineligible to count towards the SGC target. In 2024, HEFA production is projected to level off and be surpassed by second generation cellulosic SAF derived from MSW and agricultural and forestry residues by the end of the decade. Cellulosic feedstocks can either be converted to Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) via the gasification process or converted to jet fuel via ethanol-to-jet upgrading. In our scenario modeling, we assume that no ATJ facilities are deployed due to cost constraints; however, we group cellulosic feedstocks together in our results due to significant uncertainty regarding the economic and technical feasibility of technology scale-up.

As shown in Figure 4, we calculate that **3.3 billion gallons** of SAF are produced in Scenario 1, short of the 2030 production target. We estimate that, based on the weighted share of each pathway's LCA emissions, **the volume-weighted average CI of the Scenario 1 fuel mix is 10.6 gCO$_2$e/MJ in 2030**.

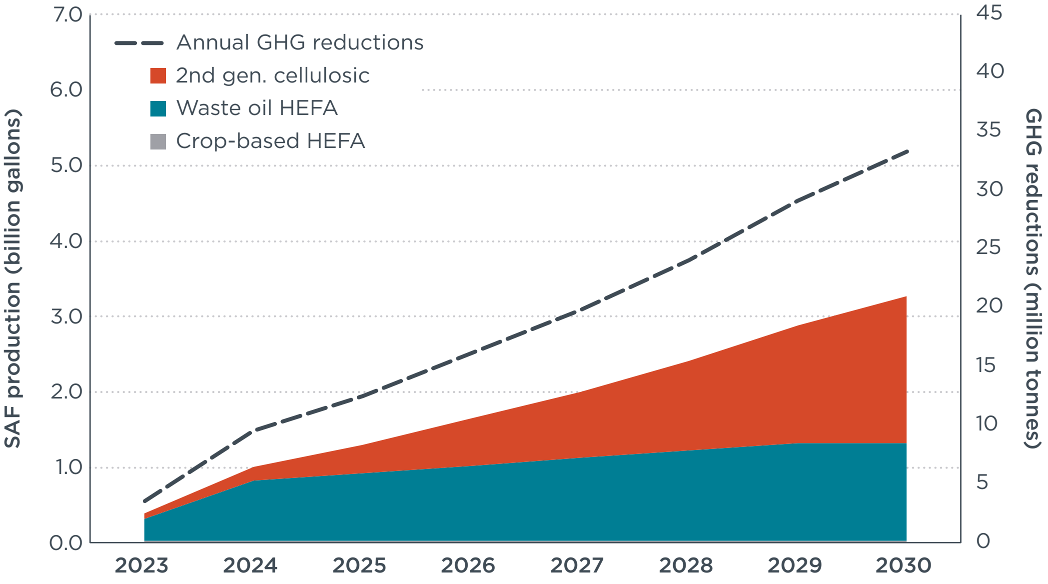


Figure 4. Scenario 1 (Low risk growth) volume projections by primary feedstock and conversion pathways.

Scenario 2 illustrates a high-risk growth case that loosens the eligibility criteria for tax credits and allows all feedstocks assessed to qualify. The primary impact of this change is that soy HEFA would be eligible for the SAF tax credits and would reach cost parity with fossil jet in the near-term. Because their eligibility remains unchanged, waste oil HEFA and cellulosic-derived SAF volumes are equivalent to Scenario 1. In total, we calculate that **4.2 billion gallons** of SAF would be produced in 2030 under Scenario 2 (Figure 5). However, we find that only a limited amount of growth is projected beyond this period, as the current set of policy incentives are insufficient to allow more challenging fuel pathways to reach a break-even point. **The volume-weighted average CI of the Scenario 2 fuel mix is 20.5 gCO$_2$e/MJ in 2030**.

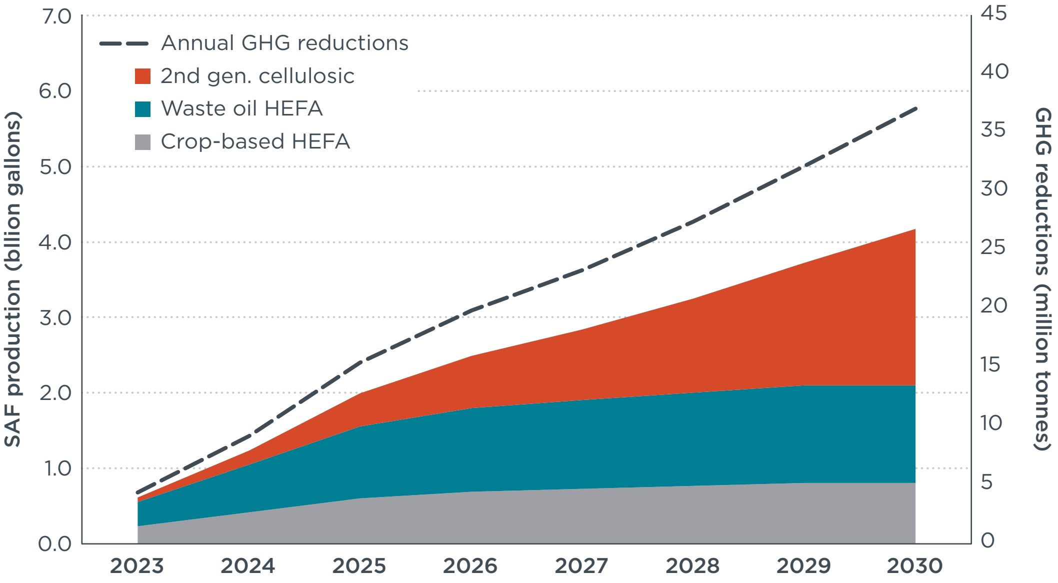


Figure 5. Scenario 2 (High risk growth) volume projections by primary feedstock and conversion pathways.

Scenario 3 represents a more aggressive scenario for SAF deployment, wherein the existing set of incentives is extended to 2030. Simultaneously, eligibility is limited based on a 50% GHG reduction when using CORSIA LCA factors, restricting eligibility to feedstocks with few competing uses and that do not rely on dedicated cropland. In this scenario, SAF production increases to **3.9 billion gallons** in 2030, with a higher contribution of cellulosic pathways, particularly for energy crops (Figure 6). ATJ from corn kernel fiber and flue gas ethanol are no longer cost-prohibitive, making up 15% of production volumes in 2030. **The volume-weighted average CI of the Scenario 3 fuel mix is 16.5 gCO_2e/MJ in 2030**.

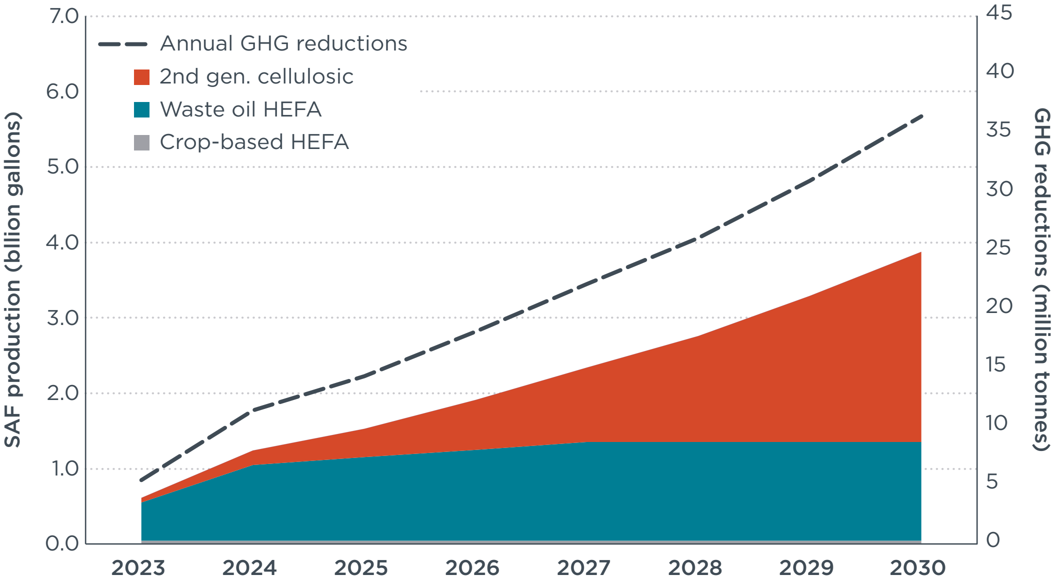


Figure 6. Scenario 3 (Sustainable maximum) volume projections by primary feedstock and conversion pathways.

Our final scenario represents the theoretical maximum quantity of SAF that could be produced in 2030 factoring in our deployment model constraints (Figure 7). This scenario assumes that SAF eligibility is broadened to include purpose-grown feedstocks, including corn grain and soybean oil. It also assumes 11.1 million tonnes of additional soybean oil production from maximized crush rates and the diversion of sugarcane and corn grain ethanol consumed in the road sector toward SAF. As a result, production volumes are split more evenly across different fuel pathways, albeit at a higher average GHG intensity. Like Scenario 3, Scenario 4 relies on up to $6.60 per gallon of policy support for all pathways to breakeven with fossil jet. In total, we calculate that SAF production reaches **6.70 billion gallons** in 2030. **The volume-weighted average CI of the Scenario 4 fuel mix is 39.9 gCO$_2$e/MJ in 2030**.

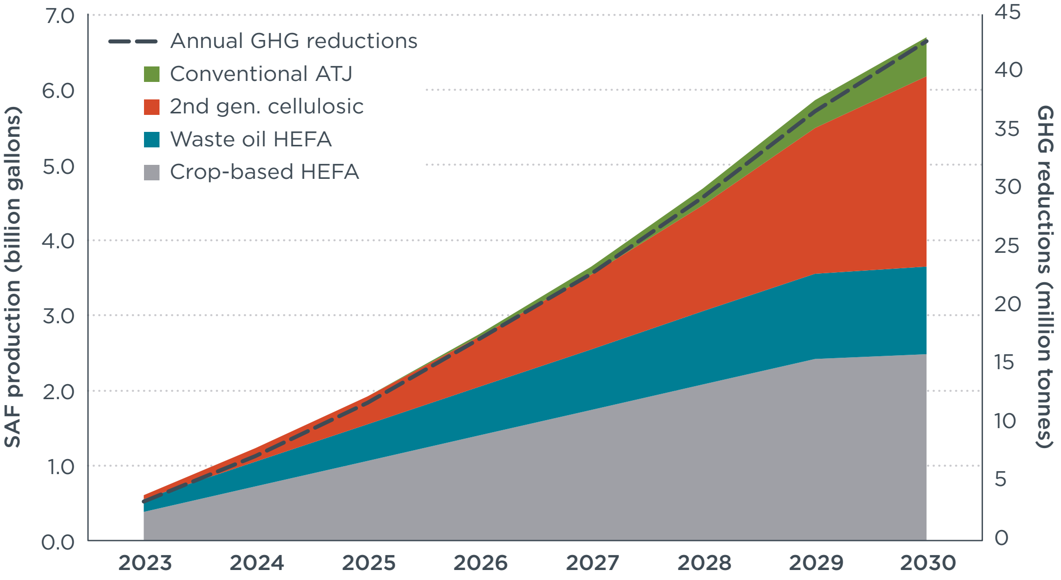


Figure 7. Scenario 4 (Theoretical maximum) volume projections by primary feedstock and conversion pathways.

DISCUSSION

We find that there is sufficient feedstock availability to meet the 2030 SGC target in theory, although there is insufficient biomass to meet the long-term 2050 target. Approaching the long-term SAF target would require substantial diversion of feedstock from other economic sectors. Due to the time delay and higher costs associated with some of the more abundant cellulosic fuel pathways, it is likely that meeting the 2030 SGC target will require extending and expanding SAF incentives so that facilities can be constructed and deployed in a rapid timeframe. Beyond 2030, we find that the current set of policies in place are insufficient to expand SAF deployment beyond 3 billion gallons, and further development of the SAF industry would be constrained by a combination of high costs and uncertain policies.

LONG-TERM SUPPLY OF BIOMASS

The interagency SGC roadmap concludes that the United States has enough biomass material that could be harvested sustainably to meet 35 billion gallons of aviation fuel demand by 2050 (U.S. Department of Energy et al., 2022). However, we find that U.S. domestic resource potential for SAF is lower, at a maximum of 21.7 billion gallons and 12.2 billion gallons if sourced sustainably, due to differing assumptions regarding feedstock availability and eligibility. When technology ramp-up delays are factored in, we estimate that the volume of cost-viable SAFs by 2030 could range between 3.3 and 4.2 billion gallons, depending on the eligibility criteria and the level of policy support.

HEFA fuels are the most likely to enter the market in the near-term. Many feedstocks suitable for HEFA conversion are already used in the road sector and could be diverted to aviation, depending on policy incentives. If policymakers introduce eligibility requirements that prevent high-risk crop-based biofuels from qualifying for tax credits and the SGC, HEFA production will be limited to an estimated 1.28 billion gallons sourced from domestic waste oil feedstocks. Cellulosic biofuels are abundant and have the potential to scale up substantially, but their contribution can be limited by construction delays and uncertain commercialization timelines. Across all scenarios, cellulosic pathways could comprise roughly 2.5 billion gallons of SAF production in 2030, with up to 11 billion gallons of production potential in later years. However, as demonstrated by the experience in the on-road sector, technology delays are likely to limit annual output from these pathways (Padella et al., 2019). We find that ATJ pathways have lower theoretical potential, especially for non-food-based feedstocks such as corn kernel fiber and industrial flue gas ethanol. If SGC eligibility is loosened to include ATJ derived from corn grain, ATJ fuel production could grow to an estimated 1.05 billion gallons of SAF in 2030.

Scenario 1, the low-risk growth case, has the lowest production potential (3.3 billion gallons) due to cost and eligibility constraints. Scenario 4, the which represents the theoretical maximum, has the highest production potential (6.7 billion gallons) assuming that policy incentives are expanded and extended beyond 2027 and that eligibility is widened to include SAF derived from soybean oil and corn grain. HEFA fuel makes up the majority of SAF volumes under Scenarios 2 (high-risk growth) and 4 (theoretical maximum), while Scenarios 1 (low-risk growth) and 3 (theoretical sustainable maximum) have a higher contribution from cellulosic pathways. Due to significant cost constraints, ATJ facilities are not deployed in Scenarios 1 and 2, the high- and low-risk growth cases that account for the current set of U.S. policy incentives. However, due to uncertainty in technology scale-up, we present cellulosic volumes together in the event that economic conditions favor the ATJ pathway over FT-gasification.

We find that the near-term 2030 production target can be met with sustainable resources, but the 2050 target will be far more challenging to reach. In the longer-term, biomass volumes will need to be supplemented with a combination of other fuel sources or fuel burn reduction to meet the energy needs of the entire U.S. aviation sector. All scenarios would require immense amounts of funding for SAF pathways to narrow the cost differential with fossil jet. Cumulatively, this corresponds to $84 billion in funding in 2030 based on the weighted volume mix of eligible feedstocks and $68 billion in funding if feedstock eligibility was restricted to low-risk feedstocks. Based on the current set of U.S. policy incentives, this funding will be sourced from taxpayer subsidies and pass-through costs from policies such as the RFS and LCFS that indirectly raise the cost of fuel for drivers.

E-fuels, or synthetic aviation fuels produced from renewable electricity, could help to bridge the supply gap in later years. Like the biomass SAF pathways evaluated in this study, e-fuels are compatible with existing aircraft engines and have a very low CI when produced from additional renewable electricity. Though the technology remains in the demonstration phase, e-fuels have gained significant interest in Europe and other markets due to their “drop-in” advantages and theoretically unlimited supply. For example, the EU has adopted an e-fuel mandate of 1.2% of aviation fuel, averaged over 2030 and 2031, and 5% of aviation fuel volumes by 2035 (European Commission, 2023). These e-fuels are estimated to be costlier than most biomass-derived SAFs in the near-future, but their costs could rapidly come down as electrolyzer technology matures and the cost of renewable electricity declines (Zhou et al., 2022). Zhou et al. estimate that the cost of e-fuel production in the U.S. lowers from $8.78 per gallon in 2020 to $4.02 in 2050, which is approximately 45% higher than the production cost of fossil jet in 2050. With the use of policy incentives, including the IRA’s 10-year production tax credits for hydrogen and carbon capture, utilization, and storage (CCUS), e-fuels will likely become cost-competitive within a much shorter timeframe.

RELAXED ELIGIBILITY FOR SAFS

The cost-constrained availability analysis above illustrates how achieving meaningful volumes of SAF will rely on substantial quantities of financial incentives. Given the level of public spending implied, rigorous sustainability criteria will be critical to ensure that the funding is cost-effectively driving emissions reductions. Though the SGC emphasizes a minimum 50% life-cycle GHG savings for a given fuel to qualify as SAF, it is not yet clear how the government intends to interpret and implement this requirement. Efforts to expand the sustainability criteria so that a broader pool of fuels could meet the 50% GHG savings threshold, such as applying lower ILUC LCA values than the default CORSIA ILUC factors, could blunt the intended impact of the SGC. The SAF Accuracy Act of 2023 proposes that the federal government only use the GREET model when estimating LCA emissions (Sustainable Aviation Fuels Accuracy Act of 2023), which would exclude ILUC values adopted under CORSIA. This proposal would maximize the volumes of potential biomass-based SAFs that could qualify, potentially at the expense of the integrity of the underlying incentives and policies.

Some fuel pathways, such a soy-based HEFA and corn ATJ, could provide substantial volumes of fuel in the next decade through diverting existing consumption from the road sector and maximizing domestic crushing rates for soybeans. At a maximum, this could increase soy-based HEFA production to 2.67 billion gallons in 2030 and corn grain ATJ production to 6.89 billion gallons. However, shifting feedstock consumption between the road and aviation sectors has no net climate benefit due to the additional energy demands associated with optimizing bio-refineries to produce higher shares of HEFA jet fuel (Pavlenko et al., 2019). If domestic soybean oil production was maximized rather than the exportation of whole soybeans, this would leave a significant gap in the global vegetable oil market for countries that import high shares of U.S. soybeans (O'Malley et al., 2022). In turn, these countries would need use alternate sources of vegetable oil, which is likely to come from imported palm oil or soybean (USDA Foreign Agricultural Service, 2021). Palm oil, one of the lowest cost vegetable oils globally, is linked with high GHG impacts due to peat drainage and deforestation (Petrenko et al., 2016). Due to the high fungibility between vegetable and waste oils, there is evidence that increased demand for U.S. soy oil results in increased production of U.S. palm oil imports (Santeramo & Searle, 2019).

Efforts to maximize the quantity of SAFs deployed in the U.S. aviation sector without ensuring that they offer low life-cycle GHG emissions may undermine the sustainability goals of the SGC. We find that in the high-risk scenarios (Scenarios 2 and 4), the quantity of additional SAF production and implied policy support is not commensurate with their additional GHG savings. We estimate that GHG reductions from new SAF deployment range from 33.3 to 42.7 million tonnes in 2030 relative to the fossil jet baseline. Although the high-risk scenarios may lead to the highest GHG reductions in absolute terms, this does not translate to a proportional decrease in GHG savings per gallon of SAF produced. On a volume-weighted basis, Scenarios 2 and 4 correspond to a fuel-mix CI of 20.5 and 39.9 gCO_2e/MJ, respectively, while Scenarios 1 and 3 correspond to a fuel-mix CI of 10.6 and 16.5 gCO_2e/MJ. Sustaining policy support for high-risk pathways will not accelerate the decarbonization of the U.S. aviation sector but could, at best, modestly decrease the carbon intensity of the sector while directing investment toward mature technologies.

EXPANDING AND EXTENDING POLICY SUPPORT FOR SAFS

In principle, there is currently substantial policy support in place to lower the net cost of SAF, ranging from an estimated $0.96/JGE for corn grain ATJ to $6.56/JGE for energy crop-derived FT-SPK in 2024. However, policy support is expected to decrease after 2027 and its long-term value is uncertain, providing a weak policy signal for investors and developers interested in scaling up emerging pathways. We find that policy support for SAF is reduced between $0.10/JGE and $1.85/JGE across pathways between 2024 and 2030, and most pathways will lose approximately $1.50/JGE in policy support over this period due to the expiration of the 45Z tax credit in 2028. Even in the very-near term, the adjustment of value calculations for the 40B to 45Z tax credits will substantially alter the amount of policy incentives most SAF pathways receive. For example, at a policy-adjusted cost of $1.76/JGE under the 2023–2024 tax credit, we find that corn kernel fiber ATJ is cost-competitive with fossil jet; however, beginning in 2025, its policy-adjusted cost increases to $2.93/JGE. Significant fluctuations in RFS RIN and West Coast state credit prices due to credit surpluses and future program uncertainty also reduces the certainty of SAF costs in the mid-to-long term.

Given the uncertainty of long-term policy support, it is more likely that investment will focus on short-term gains through the use of existing commercial technologies that have greater feedstock constraints rather than the higher-cost emerging pathways with greater feedstock availability and GHG reduction benefits. Without long-term investment certainty, we expect that meeting the 2050 production target will prove challenging. To create greater certainty of the value of the tax credit, and better incentivize the production of advanced SAFs utilizing more abundant cellulosic biomass, an extension of the IRA SAF tax credit beyond 2027 will likely be necessary. A 10-year credit, such as the 45V credit implemented for hydrogen, would create greater policy certainty and enable more long-term investment than the 2-year 40B and 3-year 45Z tax credits in the IRA.

Some combination of new regulatory strategies and additional incentives to reduce the cost of SAF production could also overcome these barriers. For example, SAF blending mandates could be implemented via federal legislation, moving the SGC from a voluntary to a binding production target. U.S. legislators could set minimum energy or blend requirements on fuel consumed by federal agencies or aviation fuel sold at airports in the United States. Policymakers could also consider a low-carbon fuel standard specifically for aviation to provide a stronger, more direct incentive for SAFs. A recent Congressional bill proposed to establish an aviation-only CFS to reduce the CI of aviation fuel 20% by 2030 and 50% by 2050 (Bracmort, 2021; Sustainable Aviation Fuel Act, 2023). An aviation-only LCFS could increase SAF deployment by more than 30% if scaled at the federal level (Pavlenko & Zheng, In Press.).

In the absence of clear legislative support for binding SAF policies, the president could also use his executive order (EO) authority to establish procurement mandates for military and civilian federal agencies. However, because EOs can be readily overturned by subsequent administrations, they are a weaker policy signal than legislative action. Using data on historical civil and military aviation fuel consumption from the U.S. Greenhouse Gas Emissions Inventory (U.S. EPA, 2023), we determined the maximum volume of SAF that could be deployed via EOs beyond our current projections. Assuming that SAF is blended at a maximum 50% by volume blend rate, we calculate that a maximum of 1.3 billion gallons of SAF could procured by U.S. military and civilian agencies in 2030, which is nearly half of the SGC target.

CONCLUSION

The SAF Grand Challenge lays out ambitious targets for SAF deployment in the United States. We find that there is enough domestic biomass potential to meet the 2030 Grand Challenge target of 3 billion gallons of SAF, but there is insufficient sustainably available biomass to meet the longer-term, 2050 target of 35 billion gallons. We estimate the domestic resource potential for SAF is a maximum of 21.7 billion gallons, and 12.2 billion gallons if sourced from wastes and residues. The supply of virgin vegetable oils and waste oils suitable for conversion via the existing commercial HEFA process is highly constrained, whereas the more abundant cellulosic wastes and residues that provide the bulk of the potential require more complex conversion technologies with higher costs and uncertain commercialization timelines. We find that meeting the long-term 35-billion-gallon target will require both substantial scale-up of the cellulosic biofuel industry as well as support for alternative source of fuels.

Limitations on the availability of sustainable biomass also present several important risks to the implementation of the SAF Grand Challenge. Pressure to meet near-term targets may create an incentive to divert existing supply chains for biofuels used in the road sector to aviation, such as corn ethanol and soy biomass-based diesel. These pathways may pose sustainability risks that undermine their climate benefits; support for these pathways in the near-term also risks crowding out investment and support for the more challenging pathways necessary for long-term aviation decarbonization. While these pathways can make the 2030 Grand Challenge volume target easier to meet, over-reliance may undermine the climate goals of the policy and the feasibility of the 2050 target.

There are incentives to support SAF production in the near-term, but beyond 2027, policy support for SAF declines considerably. We find that policy incentives for SAF today range from $0.96 to $6.56 per JGE across pathways but decline after the phase out of the Inflation Reduction Act's SAF tax credits. In the absence of binding targets, such as a SAF mandate or national clean fuel standard, SAF deployment relies entirely on public subsidies and out-of-sector pass-through costs to bridge the cost gap between SAF's and conventional fossil jet fuel. Looking ahead, meeting the long-term goals of the Grand Challenge will require a more stable policy framework to establish long-term market certainty in addition to reducing the cost gap. Binding policies could create stable demand and incentivize long-term investment in the challenging SAF technologies necessary to use the most abundant, lowest risk sources of biomass in the United States.

REFERENCES

Alternative Fuels Data Center. (n.d.). *Maps and data—U.S. corn production and portion used for fuel ethanol*. Retrieved December 9, 2022, from https://afdc.energy.gov/data/10339

Argonne National Laboratory. (2020). *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)* (Version 2020) [Computer software]. https://greet.es.anl.gov/index.php

Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., Hileman, J. I., & Barrett, S. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. *Bioresource Technology*, *227*, 179–187. https://doi.org/10.1016/j.biortech.2016.12.032

Baral, A., & Malins, C. (2014). *Comprehensive carbon accounting for identification of sustainable biomass feedstocks*. International Council on Clean Transportation. https://theicct.org/publication/comprehensive-carbon-accounting-for-identification-of-sustainable-biomass-feedstocks/

Bazzanella, A. M., & Ausfelder, F. (2017). *Low carbon energy and feedstock for the European chemical industry*. DECHEMA e.V. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf

Bracmort, K. (2021). *A low carbon fuel standard: In brief* (R46835). Congressional Research Service.

California Air Resources Board. (n.d.). *Low carbon fuel standard reporting tool quarterly summaries*. Retrieved March 15, 2023, from https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries

California Air Resources Board. (2023, February 22). *Low carbon fuel standard public workshop: Potential regulation amendment concepts*. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/lcfs_meetings/LCFSpresentation_02222023.pdf

Collis, J., Strunge, T., Steubing, B., Zimmermann, A., & Schomäcker, R. (2021). Deriving economic potential and GHG emissions of steel mill gas for chemical industry. *Frontiers in Energy Research*, *9*, 642162. https://doi.org/10.3389/fenrg.2021.642162

Daniell, J., Köpke, M., & Simpson, S. (2012). Commercial biomass syngas fermentation. *Energies*, *5*(12), 5372–5417. https://doi.org/10.3390/en5125372

Dien, B. S., Johnston, D. B., Hicks, K. B., Cotta, M. A., & Singh, V. (2005). Hydrolysis and fermentation of pericarp and endosperm fibers recovered from enzymatic corn dry-grind process. *Cereal Chemistry Journal*, *82*(5), 616–620. https://doi.org/10.1094/CC-82-0616

European Commission. (2023). Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation). https://data.consilium.europa.eu/doc/document/PE-29-2023-INIT/en/pdf

Federal Aviation Administration. (2021). United States 2021 Aviation Climate Action Plan. https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

Freed, J. (2022, December 8). Corporate travel propels boom in sustainable aviation fuel. *Reuters*. https://www.reuters.com/business/aerospace-defense/corporate-travel-propels-boom-sustainable-aviation-fuel-2022-12-07/

Geleynse, S., Brandt, K., Garcia-Perez, M., Wolcott, M., & Zhang, X. (2018). The alcohol-to-jet conversion pathway for drop-in biofuels: Techno-economic evaluation. *ChemSusChem*, *11*(21), 3728–3741. https://doi.org/10.1002/cssc.201801690

Gopalakrishnan, K., van Leeuwen, J., & Brown, R. C. (Eds.). (2012). *Sustainable bioenergy and bioproducts: Value added engineering applications*. Springer London. https://doi.org/10.1007/978-1-4471-2324-8

Handler, R. M., Shonnard, D. R., Griffing, E. M., Lai, A., & Palou-Rivera, I. (2016). Life cycle assessments of ethanol production via gas fermentation: Anticipated greenhouse gas emissions for cellulosic and waste gas feedstocks. *Industrial & Engineering Chemistry Research*, *55*(12), 3253–3261. https://doi.org/10.1021/acs.iecr.5b03215

ICAO [International Civil Aviation Organization]. (n.d.). *ICAO SAF facilities map*. Looker Studio. Retrieved February 21, 2023, from http://lookerstudio.google.com/reporting/2532150c-ff4c-4659-9cf3-9e1ea457b8a3/page/p_2sq3qol5nc?feature=opengraph

ICAO [International Civil Aviation Organization]. (2019). *CORSIA methodology for calculating actual life cycle emissions values*. https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions.pdf

ICAO [International Civil Aviation Organization]. (2023). *SAF rules of thumb*. https://www.icao.int/environmental-protection/Pages/SAF_RULESOFTHUMB.aspx

ICAO Secretariat. (n.d.). *Introduction to the ICAO Basket of Measures to mitigate climate change*. Retrieved April 11, 2023, from https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg111-115.pdf

IEA [International Energy Agency]. (2022, September 21). *ETP clean energy technology guide*. IEA. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IEA Bioenergy. (2003). *Municipal solid waste and its role in sustainability*. https://www.ieabioenergy.com/wp-content/uploads/2013/10/40_IEAPositionPaperMSW.pdf

Inflation Reduction Act of 2022, Pub. L. No. 117–169 (2022). https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

Kendall, A., Chang, B., & Sharpe, B. (2009). Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environmental Science & Technology*, *43*(18), 7142–7147. https://doi.org/10.1021/es900529u

Krajnc, N. (2015). *Wood Fuels Handbook*. Food and Agriculture Organization of the United Nations.

Kurambhatti, C. V., Kumar, D., Rausch, K. D., Tumbleson, M. E., & Singh, V. (2018). Ethanol production from corn fiber separated after liquefaction in the dry grind process. *Energies*, *11*(11), Article 11. https://doi.org/10.3390/en11112921

Langholtz, M. H., Stokes, B. J., & Eaton, L. M. (2016). *2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy* (DOE/EE-1440, ORNL/TM-2016/160, 1271651; p. DOE/EE-1440, ORNL/TM-2016/160, 1271651). https://doi.org/10.2172/1271651

Mithal, S., & Rutherford, D. (2023). *ICAO's 2050 net-zero CO_2 goal for international aviation*. International Council on Clean Transportation. https://theicct.org/publication/global-aviation-icao-net-zero-goal-jan23/

Musulin, K. (2018, May 22). *Fulcrum BioEnergy's Nevada waste-to-fuel project begins final construction phase*. Waste Dive. https://www.wastedive.com/news/fulcrum-bioenergy-construction-nevada-waste-to-fuel/524056/

O'Malley, J., Pavlenko, N., & Searle, S. (2021). *Estimating sustainable aviation fuel feedstock availability to meet growing European Union demand*. International Council on Clean Transportation. https://theicct.org/publication/estimating-sustainable-aviation-fuel-feedstock-availability-to-meet-growing-european-union-demand/

O'Malley, J., Pavlenko, N., Searle, S., & Martin, J. (2022). *Setting a lipids fuel cap under the California Low Carbon Fuel Standard*. International Council on Clean Transportation. https://theicct.org/publication/lipids-cap-ca-lcfs-aug22/

Padella, M., O'Connell, A., & Prussi, M. (2019). What is still limiting the deployment of cellulosic ethanol? Analysis of the current status of the sector. *Applied Sciences*, *9*(21), 4523. https://doi.org/10.3390/app9214523

Pavlenko, N., & Mukhopadhaya, J. (2023). *A roadmap for decarbonizing California in-state aviation emissions*. International Council on Clean Transportation. https://theicct.org/publication/ca-aviation-decarbonization-jan23/

Pavlenko, N., Searle, S., & Christensen, A. (2019). *The cost of supporting alternative jet fuels in the European Union*. International Council on Clean Transportation. https://theicct.org/publication/the-cost-of-supporting-alternative-jet-fuels-in-the-european-union/

Pearlson, M. N. (2011). *A techno-economic and environmental assessment of hydroprocessed renewable distillate fuels*. Massachusetts Institute of Technology.

Pearlson, M., Wollersheim, C., & Hileman, J. (2013). A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioproducts and Biorefining*, *7*(1), 89–96. https://doi.org/10.1002/bbb.1378

Petrenko, C., Paltseva, J., & Searle, S. (2016). *Ecological impacts of palm oil expansion in Indonesia*. International Council on Clean Transportation. https://theicct.org/publication/ecological-impacts-of-palm-oil-expansion-in-indonesia/

Ramsey, S., Williams, B., Jarrell, P., & Hubbs, T. (2023). *Global demand for fuel ethanol through 2030*. U.S. Department of Agriculture Economic Research Service.

Santeramo, F. G., & Searle, S. (2019). Linking soy oil demand from the US Renewable Fuel Standard to palm oil expansion through an analysis on vegetable oil price elasticities. *Energy Policy*, *127*, 19–23. https://doi.org/10.1016/j.enpol.2018.11.054

Searle, S. Y., & Malins, C. J. (2016). Waste and residue availability for advanced biofuel production in EU Member States. *Biomass and Bioenergy*, *89*, 2–10. https://doi.org/10.1016/j.biombioe.2016.01.008

Sickinger, T. (2023, January 7). *Never-opened $300 million-plus biofuels refinery facing foreclosure in southern Oregon. The Oregonian*. https://www.oregonlive.com/business/2023/01/never-opened-300-million-plus-biofuels-refinery-facing-foreclosure-in-southern-oregon.html

Spaeth, J. (2021). *Sustainable aviation fuels from low-carbon ethanol production*. Energy.Gov. Retrieved May 17, 2022, from https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuels-low-carbon-ethanol-production

Staples, M. D., Malina, R., Olcay, H., Pearlson, M. N., Hileman, J. I., Boies, A., & Barrett, S. R. H. (2014). Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. *Energy & Environmental Science*, *7*(5), 1545–1554. https://doi.org/10.1039/C3EE43655A

Suresh, P., Malina, R., Staples, M. D., Lizin, S., Olcay, H., Blazy, D., Pearlson, M. N., & Barrett, S. R. H. (2018). Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste. *Environmental Science & Technology*, *52*(21), 12055–12065. https://doi.org/10.1021/acs.est.7b04277

Sustainable Aviation Fuels Accuracy Act of 2023, H.R. 4862, 118th Cong. (2023). https://www.govinfo.gov/app/details/BILLS-118hr4862ih

Sustainable Aviation Fuel Act, H.R. 2747(IH), 118th Cong. (2023). https://www.govinfo.gov/content/pkg/BILLS-118hr2747ih/pdf/BILLS-118hr2747ih.pdf

Tao, L., Markham, J. N., Haq, Z., & Biddy, M. J. (2017). Techno-economic analysis for upgrading the biomass-derived ethanol-to-jet blendstocks. *Green Chemistry*, *19*(4), 1082–1101. https://doi.org/10.1039/C6GC02800D

Tumuluru, J. S. (2015). Comparison of chemical composition and energy property of torrefied switchgrass and corn stover. *Frontiers in Energy Research*, *3*. https://doi.org/10.3389/fenrg.2015.00046

U.S. Department of Agriculture, Foreign Agricultural Service. (2021). *Oilseeds: World markets and trade*. https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf

U.S. Department of Energy. (2016). *2016 billion ton report*. Bioenergy Knowledge Discovery Framework. https://bioenergykdf.net/2016-billion-ton-report

U.S. Department of Energy, U.S. Department of Transportation, & U.S. Department of Agriculture. (2021). *Memorandum of understanding Sustainable Aviation Fuel Grand Challenge*. https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf

U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, & U.S. Environmental Protection Agency. (2022). *SAF Grand Challenge roadmap: Flight plan for sustainable aviation fuel*. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf

U.S. Energy Information Administration. (n.d.). *U.S. Kerosene-Type Jet Fuel Wholesale/Resale Price by Refiners (Dollars per Gallon)*. Retrieved December 20, 2022, from https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=ema_epjk_pwg_nus_dpg&f=m

U.S. Environmental Protection Agency. (2022). *Draft regulatory impact analysis: RFS standards for 2023-2025 and other changes* (EPA-420-D-22-003). https://www.epa.gov/system/files/documents/2022-12/420d22003.pdf

U.S. Environmental Protection Agency. (2010). *Renewable Fuel Standard Program (RFS2) regulatory impact analysis* (EPA-420-R-10-006).

U.S. Environmental Protection Agency. (2023). Annex 3: Methodological description for additional source or sink categories. In *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021*. https://www.epa.gov/system/files/documents/2023-02/US-GHG-Inventory-2023-Annex-3-Additional-Source-or-Sink-Categories-Part-A.pdf

Witcover, J. (2021). *What happened and will happen with biofuels? Review and prospects for non-conventional biofuels in California and the U.S.: Supply, cost, and potential GHG reductions*. https://doi.org/10.7922/G26W98D7

World Steel Association. (2020). *2020 world steel in figures*. https://www.worldsteel.org/en/dam/jcr:f7982217-cfde-4fdc-8ba0-795ed807f513/World%2520Steel%2520in%2520Figures%25202020i.pdf

Zhou, Y., Baldino, C., & Searle, S. (2020). *Potential biomass-based diesel production in the United States by 2032*. International Council on Clean Transportation. https://theicct.org/publication/potential-biomass-based-diesel-production-in-the-united-states-by-2032/

Zhou, Y., Searle, S., & Pavlenko, N. (2022). *Current and future cost of e-kerosene in the United States and Europe*. International Council on Clean Transportation. https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/