The Challenge Ahead: A Critical Perspective on Meeting U.S. Growth Targets for Sustainable Aviation Fuel

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National Renewable Energy Laboratory

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List of Acronyms

ATJ	alcohol-to-jet
CAGR	compound annual growth rate
CI	carbon intensity
CO_2	carbon dioxide
EPA	U.S. Environmental Protection Agency
FOG	fats, oils, and greases
FT	Fischer–Tropsch
HEFA	hydroprocessed esters and fatty acids
SAF	sustainable aviation fuel
SPK	synthetic paraffinic kerosene

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The Sustainable Aviation Fuel Market Today

In 1903, humankind took flight for the first time, ushering in a new era for travel. Fast forward nearly 120 years, and an estimated 4.5 billion people are taking to the skies across 39 million flights each year [1]. Along with the rise in air travel has come substantial economic growth and globalization in which goods, people, and services can cross borders and reach all corners of the globe with an ease never before seen. However, increased access to air travel has not come without cost. Recent data find that more than 100 billion gallons of predominantly fossil-based jet fuel are consumed each year to power the global aviation sector, contributing to approximately 11% of all transportation-related carbon dioxide (CO_2) emissions and 3% of total anthropogenic CO_2 emissions [2, 3]. Further, in addition to CO_2, the combustion of fossil-derived jet fuel promotes sulfur oxides, nitrogen oxides, particulates, and contrail formation in the upper atmosphere, which are believed to contribute to additional greenhouse warming of our planet [4]. With demand for jet fuel expected to more than double by 2050 [5] and triple by 2070 [6], continued and accelerated efforts to decarbonize the global aviation sector are needed to curtail rising emissions and avert the worst outcomes of climate change [7].

In response to this call to action, the United States has unveiled the Sustainable Aviation Fuel (SAF) Grand Challenge, which seeks to expedite the development of alternative fuel pathways that offer a minimum of a 50% reduction in life cycle greenhouse gas emissions compared to conventional jet fuel. The SAF Grand Challenge also establishes ambitious domestic production volume targets of 3 billion gallons of SAF per year by 2030 and a stretch goal of meeting 100% of the projected domestic aviation fuel demand of approximately 35 billion gallons per year by 2050 [8]. The SAF Grand Challenge coordinates resources from the U.S. departments of Energy, Transportation, and Agriculture, and through recent legislation like the Inflation Reduction Act of 2022, these investments, regulations, and policies are already beginning to reshape the market for SAF in the United States.

Producing SAF requires two essential ingredients: a source of sustainable (i.e., non-fossil) carbon and a conversion pathway capable of yielding a product with a low carbon footprint. Specifically, with conventional jet fuel carbon intensity (CI) estimated at 84 g CO_2e/MJ [7], the guidelines of the SAF Grand Challenge mandate that any qualifying fuel have a maximum CI of 42 g CO_2e/MJ. Due to the high operability and performance demands of jet fuel, the properties of SAF are very tightly specified. As such, the downstream utilization and blending limits are rigorously evaluated by agencies such as ASTM International [5]. As of July 2023, 11 alternative jet fuel pathways have been approved by ASTM and certified for blending with conventional jet fuels, with seven additional pathways under investigation [9]. The approved pathways and associated technology developers are summarized in Table 1.

Table 1. Conversion Pathways Tested by ASTM [9]

ASTM Ref.	Conversion Process	Abbreviation	Commercial Developer	ASTM Certification	Max. Blend Ratio
ASTM D7566 Annex 1	Fischer–Tropsch (FT) hydroprocessed synthesized paraffinic kerosene (SPK)	FT	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Velocys, Sasol	2009	50
ASTM D7566 Annex 2	SPK from hydroprocessed esters and fatty acids (HEFA)	HEFA	World Energy, Honeywell UOP, Neste Oil	2011	50
ASTM D7566 Annex 3	Synthesized isoparaffins from hydroprocessed fermented sugars	SIP	Amyris	2014	10
ASTM D7566 Annex 4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	-	2015	50
ASTM D7566 Annex 5	Alcohol-to-jet (ATJ) SPK	ATJ-SPK	Gevo, Honeywell UOP, LanzaTech, Byogy	2016 (isobutanol), 2018 (ethanol)	50
ASTM D7566 Annex 6	Catalytic hydrothermolysis jet fuel	CHJ	ARA and Chevron Lummus Global	2020	50
ASTM D7566 Annex 7	SPK from hydrocarbon–HEFA	HC-HEFA-SPK	IHI Corporation	2020	10
ASTM D7566 Annex 8	ATJ derivative starting with mixed alcohols	ATJ-SKA	-	-	30
ASTM D1655 Annex A1	Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	Coprocessed HEFA	-	2018	5
ASTM D1655 Annex A1	Co-hydroprocessing of FT hydrocarbons in a conventional petroleum refinery	Coprocessed FT	Fulcrum	2020	5
ASTM D1655 Annex A1	Co-hydroprocessing of HEFA from biomass	Coprocessed biomass	-	-	5

As shown, most utilized pathways to SAF incorporate biomass or biomass derivatives like fats, oils, and greases (FOG) as feedstocks due to their ease of handling and compatibility with petroleum refinery processes. From the latest estimates and projections, it is expected that when accounting for all of the various domestic biomass sources available, the United States could likely meet the entirety of the 2050 35-billion-gallon target [10]. However, with the demand for sustainable carbon resources anticipated to rise sharply in the coming decades across multiple other use cases (green chemicals, biohydrogen, bioenergy plus carbon capture, biomethanol, and other strategic fuels including marine and renewable diesel), there is some concern that as competition for this limited resource grows, it could impact the ability to wholly satisfy the projected sharp rise in demand for SAF. This sentiment is amplified on the global stage, where recent analysis by the International Civil Aviation Organization has studied this question of global supply dynamics, finding that as the demand for SAF continues to expand into 2050, biomass and its derivatives may only be able to meet approximately 50% of the total global demand (Figure 1) [1, 10].

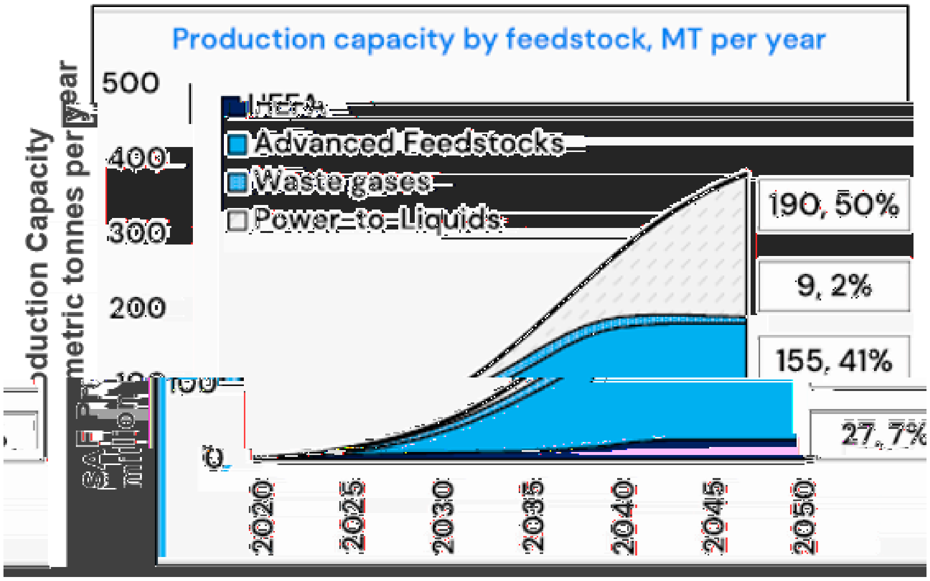


Figure 1. Projected global SAF demand and production capacity by source [1]

With these possible limitations of resource availability in mind, combined with growing risks of adverse impacts on future biomass production from climate change and a rising incidence of extreme weather events, recent research has proposed de-risking the feedstock supply chain through the use of CO_2 as a complementary carbon source for fuels and chemicals. Data collected from the U.S. Environmental Protection Agency (EPA) shown in Table 2 highlight that as of 2019, nearly 2.6 gigatons of CO_2 (about 710 million metric tons of carbon) is emitted per year across all domestic industrial point sources [11]. For perspective, reaching the annual 35-billion-gallon SAF target would consume approximately 90 million metric tons of carbon per year, meaning CO_2 point sources currently exceed the amount of carbon required by more than 7 times. Thus, although point-source carbon emissions are likely to decline over time with future industrial decarbonization efforts, these data suggest CO_2 point-source emissions combined with rising supply from direct air capture efforts have the potential to complement and offset any supply gaps for biomass-derived SAF and other decarbonization use cases.

Table 2. U.S. CO_2 Emissions by Point Source [11]

Source	2019 Emissions (million metric tons CO_2e/yr)	# of Reporting Facilities
Power plants	1,660	1,369
Petroleum and natural gas systems	259	2,383
Refineries	176	138
Chemicals	162	451
Other	86	1,208
Minerals	115	384
Waste	10	586
Metals	88	297
Pulp and paper	35	222
Total	2,592	6,948

However, although abundant, transforming CO_2 to useful products is not without its challenges [12]. On the surface, CO_2 could not be more different than conventional petroleum feedstock; CO_2 has no intrinsic energy content, is nearly 73% oxygen by mass, and is completely devoid of hydrogen. Therefore, whereas petroleum starts from a place of molecules with high molecular weight and high energy that are cracked down to size, CO_2 must be reconstructed molecule by molecule via energy-intensive processes to establish new carbon-carbon and carbon-hydrogen bonds to create fuels and products. While the precise energy demand depends on the conversion process utilized, estimates suggest an energy intensity on the order of 100 kWh required per gallon of CO_2-derived SAF. This implies that 35 billion gallons of SAF would require 3,500 TWh, about 85% of the current total U.S. electricity generation of 4,100 TWh. Research has proposed mitigating the greenhouse gas impacts of this energy-intensive process through the use of low-carbon renewable electricity. In reacting CO_2 directly with electricity, or indirectly through electrolysis-generated hydrogen, CO_2 can be transformed in a process dubbed as "power-to-liquids" or "e-fuels." Wind and solar renewable electricity generating capacity will need to be built out at very large scales to enable e-fuels.

While the reactions of CO_2 with hydrogen are generally well understood, multiple reaction and separation steps are required to generate the range of molecules required to be utilized as viable jet fuel. As a first step, current e-fuel processes emphasize the generation of smaller intermediates in the range of C1–C3 such as carbon monoxide, methanol, or ethanol [12]. From these core building blocks a variety of established downstream conversion processes can be utilized to reach SAF and other products including FT, alcohol-to-olefins processes, alcohol-to-aromatics processes, olefin oligomerization, and various other ATJ pathways as examples [7].

With these key differences in mind, techno-economic analyses and data from current commercial markets show that the generation of SAF from either biomass feedstocks or e-fuels pathways are almost certain to carry a higher cost than fossil-fuel-derived jet fuel. Maximizing the value proposition for SAF involves several factors including availability of low-CI feedstocks at low cost, simple and de-risked conversion technologies that exhibit high carbon yields at high energy efficiencies, and products that can be blended with fossil fuel jet fuel but with a path forward to eventually meet specifications for utilization as 100% SAF. While it is too early to identify which technologies will be commercialized, technologies that can generate billions of gallons of products that meet specifications at the lowest alternative cost and the lowest CI will have the best value proposition. Current petroleum refineries produce precursors for the chemicals industry as well as fuels. The biorefineries of the future will need to do the same in order to meet the demands of the chemical industry, and to augment cash generated through higher-value products.

To successfully stimulate the growth of SAF markets, robust SAF policies will be critical. A combination of incentives and multiple funding programs provides support for innovative research and the infrastructure for pilot plants, production, storage, and the overall supply chain. As covered in more detail, "market pull" policies have played a significant role in supporting mature technologies, such as production and use of ethanol and biodiesel. Although these policies have also helped develop drop-in biofuels such as renewable diesel, additional polices such as the Low Carbon Fuel Standard have increasingly emphasized the CI of biofuels (rather than volumetric targets such as 10% ethanol, 2% biodiesel). The Clean Fuel Production Credit establishes incentives for biofuels, determined by a base or alternative credit multiplied by an emissions factor based on life cycle greenhouse gas emissions. A growing number of both federal and state policies include fuel standards broadly supportive of biofuels and are increasingly supportive of SAF production through voluntary inclusion in standards or direct SAF-specific incentives [13]. This approach is in contrast other methods centered around carbon taxes, such those unveiled in Germany, where operators may potentially face stiff penalties for utilizing conventional fossil fuels in the future. When stacking all known state-level low-carbon fuel standards, federal-level Clean Fuel Production Credits, and EPA renewable identification number credits, the total carbon credit value can range from $4 to $6/gallon as estimated by the International Energy Agency (Figure 2) [14].

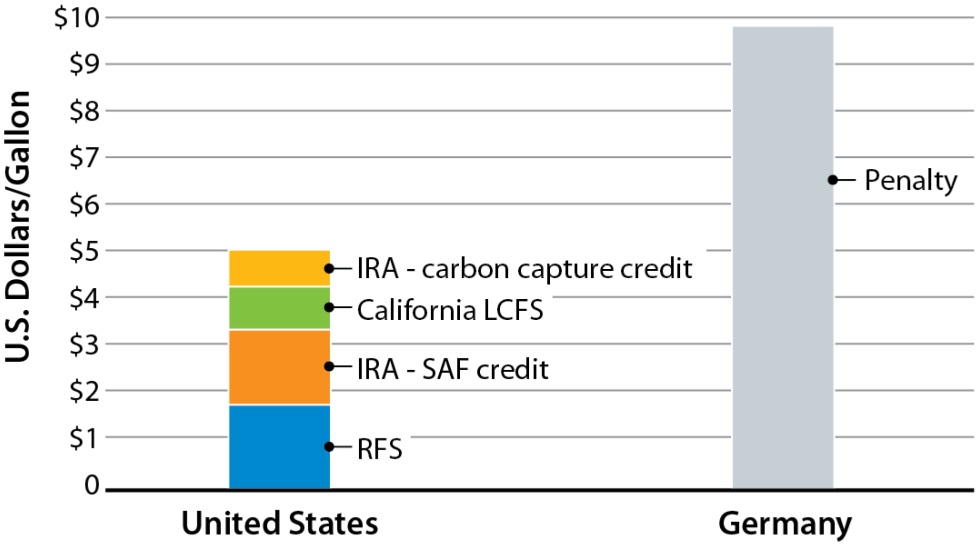


Figure 2. Estimated credit values in the United States and penalty value in Germany for SAF made from low-emission e-kerosene, 2023 [14]

The Path to 2030

Ultimately, independent of the chosen feedstock and conversion technology, numerous challenges persist across SAF production in seeking to drive down fuel cost and CI. Arguably one of the greatest near-term challenges to achieving the SAF Grand Challenge goals is technology scaling. In 2023, the United States consumed approximately 23 million gallons of SAF [15] collectively across various small-scale operations (Figure 3). To hit the 2030 target of 3 billion gal/yr, this means about a 100% compound annual growth rate (CAGR) in volumetric SAF production (about 130-times scale-up) will need to be realized. For perspective, from 2010 to 2020, U.S. solar electricity deployment and Apple iPhone shipments have grown at CAGRs of approximately 34% and 16%, respectively [16, 17]. Additionally, from 2000 to 2010, the U.S. bioethanol industry grew at a CAGR of 23% [18]. Thus, these data highlight that in order to meet this SAF target, production growth will need to expand at a rate nearly 3 to 6 times the CAGR of some of the world's hottest and fastest-growing sectors over the next 6–7 years. This finding points to a reality where *industry and policymakers must act quickly and utilize existing de-risked assets and infrastructure and emphasize the highest-technology-readiness-level production pathways,* as there is simply not enough time to rely significantly on emergent technologies or new capital investments before 2030. The SAF volumetric goal could potentially be achieved by licensing existing commercially ready conversion technologies (HEFA, ATJ, and FT synthesis) and utilizing existing refining assets. Investments are on hold as the biofuel sector is waiting for policy incentives to materialize to verify economic payback. As a result, in 2023, biofuel investment was only slightly over $1 billion, while the total global investment in the low-carbon energy transition was more than $1.7 trillion [19]. In practice, this means continuing to enhance the market pull for SAF through aggressive (and stable over the long term) incentives to a level required to close the gap in price with conventional jet fuel, as well as taking advantage of existing capital investments where possible. SAF producers have pointed out the need for incentives that are stable over the long term, comparable to payback periods for major capital investments.

In addition to exiting refining assets, one possible avenue for rapid expansion would leverage existing assets from the first-generation bioethanol industry. In 2023, the nameplate capacity for the U.S. bioethanol industry was more than 18 billion gallons of ethanol annually. However, due to mandated EPA renewable identification number volume blend limits, U.S. production was only 15 billion gallons. In other words, the refineries operated at an average capacity of about 87%. If these assets were utilized to their full potential and leveraged the additional 2+ billion gallons per year of bioethanol *within existing infrastructure*, combined with carbon capture and storage or other strategies to minimize the CI footprint, it could present a compelling near-term opportunity to help reach the 2030 Grand Challenge goals via ASTM-approved ATJ pathways. In addition, other high-technology-readiness-level strategies such as HEFA must continue to expand with diversifying FOG-type petroleum refinery feedstocks, with lipids or other compatible intermediate streams from energy crops, algae, and lignocellulosic biomass.

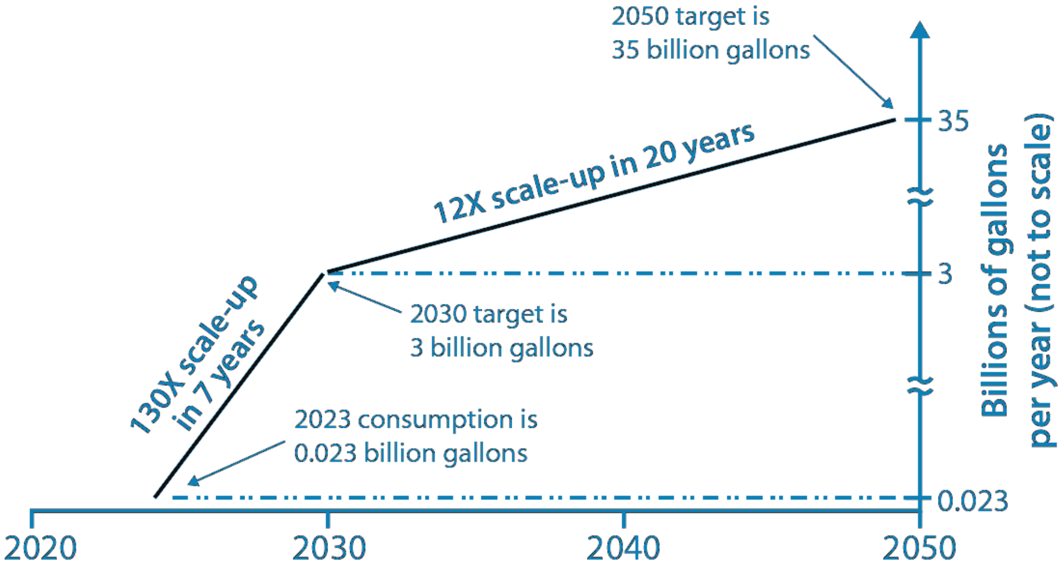


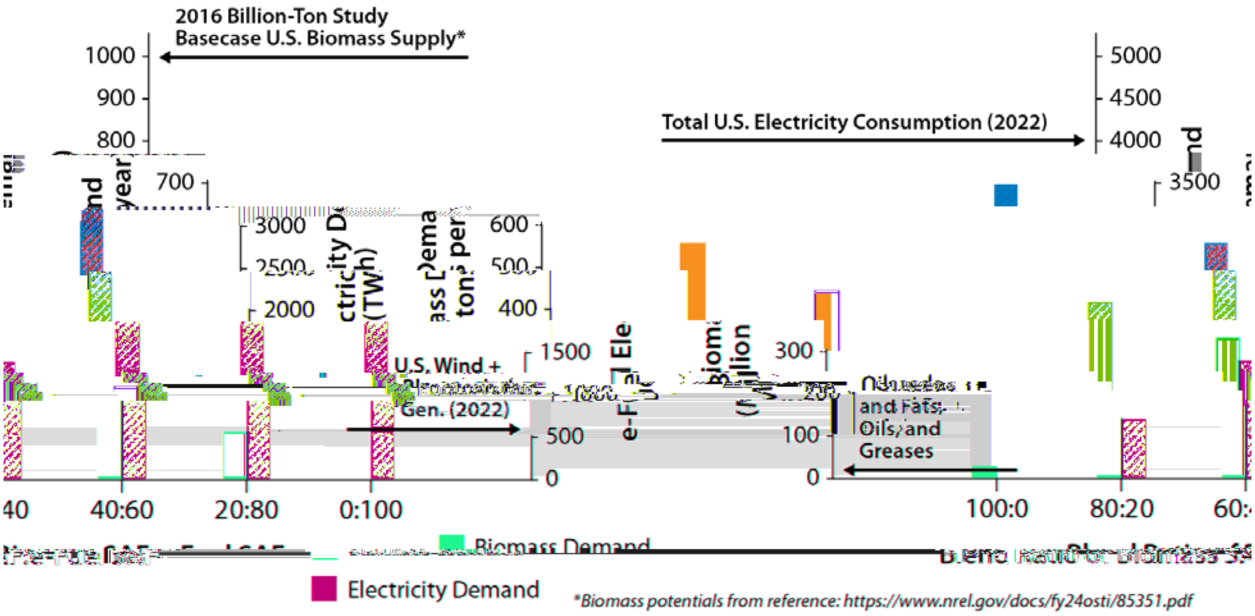
Figure 3. The SAF Grand Challenge requires 130-times scale-up in production in the next 7 years, and 12-times scale-up in the following 20 years

Getting From 2030 to 2050

To achieve the stretch goal of 35 billion gallons of SAF per year by 2050, volumetric production must increase by a factor of 12 from the 3-billion-gal/year 2030 target. In terms of CAGR, this increase represents a more modest annual growth rate of only about 13% over 20 years (2030–2050). However, when viewed from the current 2023 production numbers, this represents an average CAGR of about 31% that will need to be sustained over the next 27 years to hit this target. While lower than the CAGR required to achieve the 2030 target, maintaining such a growth rate over a long period remains ambitious, and every year that new projects are delayed, the more difficult the achievement becomes. Industry and policymakers must act swiftly and decisively to keep these targets within grasp.

The comparatively longer runway for 2050 combined with significant production volume growth suggests a more inclusive “all-hands-on-deck”-style approach will likely play a role. In addition to biomass-to-biofuel build-outs, the incorporation of e-fuels through power-to-liquids conversion processes and other technologies at low to moderate technology readiness levels are likely to factor significantly into achieving this target due to the discussed long-term concerns over biomass availability. However, as noted earlier, e-fuels by their nature will be reliant on the accessibility of abundant, very low-cost, and low-carbon electricity and/or hydrogen produced from sources such as wind, solar, hydropower, and nuclear. With an energy intensity on the order of about 100 kWh/gal e-SAF, moving forward, one of the greatest enablers to producing SAF will be the rapid and sustained build-out of renewable electricity infrastructure and power management systems to meet demand across the myriad use cases.

Ultimately, at this time it is unclear exactly what percentage of future SAF production will come from biomass versus the emergent e-fuel routes. In Figure 4 the estimated resource demands for achieving 35 billion gallons of SAF per year are provided for six hypothetical blends of biomass and e-fuel-derived SAF. Specifically, if produced entirely from biomass, projections estimate a total demand of 560 million tons of biomass per year will be required. It should also be noted that current SAF production is largely dominated by HEFA strategies involving FOG feedstocks. These data indicate that FOG feedstocks may contribute to a maximum of only about 2 billion gal/yr, and consequently other technology pathways (e.g., gasification, FT, ATJ) will need to be scaled appropriately to meet demand. On the other hand, if the 35-billion-gal/yr target were met entirely with e-fuels, estimates show that nearly 3,500 TWh of electricity would be required, representing a more than 5-times increase from current wind and solar generation levels and about 85% of the total electricity consumed in the United States. These data highlight that independent of the adopted blend, hitting 35 billion gallons of SAF per year would draw significantly from domestic low-carbon resources and likely face competition from a variety of other use cases. Further, and specific to the electrolyzers used in e-fuel production, many technical challenges remain warranting additional R&D such as lower unit capital expenses, improved stability and durability, and higher energy efficiencies [12].



*Biomass potentials from reference: https://www.nrel.gov/docs/fy24osti/85351.pdf

Figure 4. Resource demands of making 35 billion gallons of SAF annually

Achieving the SAF Grand Challenge targets is crucial for both climate health and positioning the United States as a leader in sustainable fuel. A key component in success lies in the coordinated research, development, demonstration, and deployment efforts by multiple federal agencies and industry partnerships. Leveraging and expanding the existing federal agency and industry collaborations through the SAF Grand Challenge will play a crucial role in accelerating research, development, demonstration, and deployment across various sustainable aviation challenges. These collaborations bring together diverse expertise and resources and lead to faster innovation, increased efficiency, and shared benefits.

These collaborations could also benefit with the inclusion of other federal agencies (e.g., Advanced Research Projects Agency–Energy, Office of Clean Energy Demonstrations, Department of Defense), along with SAF providers such as technology guarantors, original equipment manufacturers, fuel producers and logistics companies. Expanding this collaboration network could bring in additional funding, risk tolerances, capabilities, and thought leadership. Market influences and industry drivers need to be added to complete the holistic or ecosystem view that identifies all the challenges and to look at and solve this multidimensional problem. These collaborations also need to include users (e.g., airlines, Department of Defense); regulatory agencies (permitting); airports (hub, regional, and county); state aviation planning; and coordination with other renewable diesel users such as ground, marine, and rail transportation and chemical industries.

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