U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: **Sustainable Aviation Fuel**

NOVEMBER | 2024

Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff Report. Please direct all inquiries and input to liftoff@hq.doe.gov. Input and feedback should not include business sensitive information, trade secrets, proprietary, or otherwise confidential information. Please note that input and feedback provided is subject to the Freedom of Information Act.

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Context

The United States Department of Energy (DOE) has published a series of reports on The Pathways to Commercial Liftoff for emerging clean energy technologies. These Liftoff reports provide a roadmap for how the public and private sector can collectively accelerate the commercialization of the technologies needed to decarbonize the U.S. economy. Given the constantly and rapidly evolving market, technology, and policy environment, these reports are designed to be "living documents" and will be updated as the commercialization outlook on each technology evolves.

Spearheaded by DOE's Office of Technology Transitions (OTT), these Liftoff reports reinforce dialogue across not only DOE, but also other federal departments and agencies. They build upon learnings from DOE investments and continued engagement with industry stakeholders. DOE continues to solicit input through industry forums, requests for information, and other interactions. Direct public input can be submitted via email to liftoff@hq.doe.gov.

Executive Summary

In the United States, aviation currently represents roughly 3% of total greenhouse gas emissions, and fossil jet fuel consumption is forecasted to increase by 2-3% annually through 2050.[1] Although aircraft built in the last 15 years are up to 20% more fuel efficient than their predecessors,[2] the fuel that powers them remains carbon-intensive. Furthermore, hydrogen and electric planes may provide low-emission or zero-emission options for smaller planes and shorter flights, but these technologies remain in their infancy and are unlikely to service heavy payload and long-haul flights—which make up the bulk of aviation emissions. If the U.S. is to achieve net zero greenhouse gas emissions by 2050, low-carbon or no-carbon transportation fuel must be used at scale. Sustainable Aviation Fuel (SAF) presents the only viable solution to meaningfully decarbonize the aviation sector in the near-term.

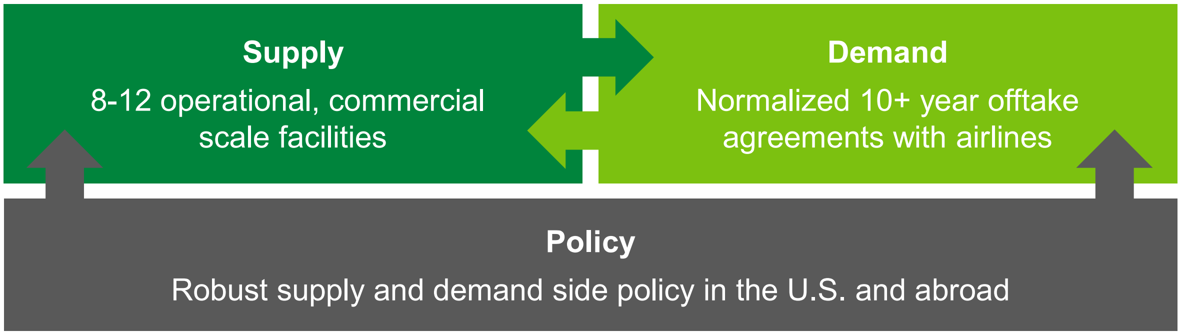
SAF is a drop-in jet fuel replacement that is produced through a variety of pathways and results in a reduction in lifecycle emissions compared to fossil jet fuel.[i] At present, all SAF must be blended with fossil jet fuel before it is certified and allowed for use in commercial aircraft. When certified, the blended fuel can be transported and combusted just like its fossil-based alternative. A scale-up of domestic SAF production can have positive economic, social, and environmental impacts in addition to the benefits associated with reducing greenhouse gas emissions. Certain SAF blends also have the potential to reduce air pollution surrounding airport communities and reduce contrails, the latter of which also warms the climate.

In September 2021, the U.S. set an ambitious target to scale domestic SAF production through the SAF Grand Challenge. Eligible SAF under the SAF Grand Challenge must achieve a minimum 50% reduction in lifecycle greenhouse gas emissions compared to fossil jet fuel. A consortium of U.S. federal agencies committed to supporting the research, development, demonstration, and deployment needed to produce 35 billion gallons of SAF per year domestically by 2050. This 35-billion-gallon target represents 100% of projected U.S. jet fuel demand in 2050. They also set a near-term (2030) target of three billion gallons of domestic SAF production per year to cover 10% of jet fuel demand. Reaching the 2030 SAF Grand Challenge target could support over 70,000 jobs across the SAF value chain. Early and ongoing engagement with key labor and community stakeholders are essential to meeting these Grand Challenge targets.

There is growing momentum for SAF production. Currently announced domestic projects represent over three billion gallons of annual SAF production capacity—correlating with $44 billion of announced investment—by 2030. However, total U.S. production volume will depend on factors including federal and state policy decisions, airline commitments, and demand for alternative low-carbon fuels (like renewable diesel) that use the same or similar feedstocks. The more certain demand comes from abroad. By 2030, current and proposed foreign mandates could require over two billion gallons of SAF consumption globally. For SAF to reach liftoff in the United States, action is needed to build upon this early supply-side momentum, capitalize on existing or proposed foreign mandates, and build domestic demand.

i "Lifecycle emissions" in this report refer to the amount of greenhouse gas emissions (in metric tons of carbon dioxide equivalent, or CO_2e) generated across a fuel's lifecycle–from feedstock production and collection, to fuel production and blending, and through fueling and combustion.

To establish SAF's commercial viability in the United States, which supports the SAF Grand Challenge's near-term and long-term targets, three imperatives must be met:



Scale Supply

Today, in the United States, there are only four operational SAF production facilities, which collectively represent a nameplate capacity capacity of 64 million gallons per year (MGPY). 16.5 million gallons of SAF have been produced this year (as of August 2024), representing less than 0.6% of both total fossil jet fuel consumption and the SAF Grand Challenge 2030 target.[3,4] Despite these low volumes, 2024 production has already surpassed 2023 production, which amounted to about 14 million gallons for the year.

To reach liftoff, the SAF market requires 8-12 commercial-scale (with an average 100 MGPY capacity each) plants in operation by 2030.[ii] This imperative represents the buildout of a meaningful SAF economy and a significant step towards meeting the SAF Grand Challenge in 2050. That number of projects and volume of production could represent a critical mass threshold for the domestic SAF industry, highlighting the utility of learning curves and associated cost reductions. Developers can de-risk investments and accelerate timelines as project designs mature from FOAK (first of a kind) to NOAK (nth of a kind). The target size of projects is large enough to support feedstock supply chains, midstream infrastructure and logistics, and storage and blending facilities all while helping build consumer trust in the fuel itself.

SAF produced via the Hydroprocessed Esters and Fatty Acids (HEFA) pathway will play an instrumental role, especially in the near-term (i.e. by 2030). HEFA SAF primarily uses fats, oils, and greases—many of which are readily available today—as its feedstock. SAF produced via the HEFA pathway uses the only technology proven at commercial scale today and could represent up to 70% of total SAF production by 2030. As HEFA production scales, feedstock supply may become constrained without interventions like the development of purpose-grown crops that do not compromise food security or have negative environmental outcomes. For SAF to continue scaling beyond 2030, newer technology pathways with fewer feedstock limitations—like alcohol-to-jet (AtJ) technology using biomass and waste-based feedstocks, and power-to-liquid (PtL) technology using captured carbon dioxide—will need to mature. These other pathways may also result in relatively more emissions reductions over time.

ii The size of facility that is considered "commercial-scale" is dependent on the corresponding pathway. Each SAF facility will range from 50-100 MGPY of production capacity and represent roughly 1 BGPY of SAF production capacity at a minimum.

Increase Certainty of Long-Term Demand

SAF currently costs 2-10 times more than fossil jet fuel,[iii] depending on the technology and pathway used to produce it. Airlines today operate with single-digit profit margins and cannot voluntarily afford the price premiums associated with SAF at scale. As a result, voluntary SAF demand (i.e. demand outside of mandate programs) has been short-term and low volume. Structural challenges also persist in bringing SAF to airports for end-use, further limiting demand. Normalized 10-year+ offtake agreements are necessary to establish the demand certainty needed both to improve financing terms for developers and encourage greater investment across the SAF value chain, supporting supply.

Today, airlines can transfer the additional cost of SAF relative to fossil jet fuel in two ways. One way is to sell the environmental attributes of SAF (i.e. its carbon abatement) to third-party offtakers looking to offset their Scope 3 emissions through a SAF credit (SAFc) using a book and claim system. This system separates the environmental attribute of SAF from the physical fuel so that they can be bought and used separately. In other words, airlines can procure the fuel while third-party offtakers buy and retire the SAFc to offset their emissions from business travel (insetting) or other activities (offsetting). The shortcoming of this approach is that, in the U.S., demand from these offtakers is both uncertain and typically short-term due to a lack of carbon standards or regulations. Today, most third-party offtakers purchase SAFc on the spot market in one- or two-year increments. This mostly benefits SAF projects that are already operational; projects still in development require 10-year+ offtake agreements to show sufficient revenue certainty to prospective investors. A second way to cover the SAF premium is for airlines to pass the additional costs to airline passengers using a ticket surcharge—an unappealing solution given airlines face cost-conscious consumers.

In the near-term, normalization of long-term offtake can occur through the activation of the Scope 3 offtaker segment, although over time, more demand-side policy support will be needed. Although airlines price SAF based on the gallons of fuel it represents, third-party offtakers price SAF based on the metric tons of carbon it abates. Given its high production costs, SAF remains a premium carbon reduction alternative. However, compared to other premium carbon management solutions, SAF may be competitive. On a per metric ton of carbon abated basis, SAF from a hypothetical NOAK facility could cost between $385-1,425 (unsubsidized) or $83-$1,049 (subsidized—see Appendix 4 for a detailed methodology and assessment of the impact of federal and state incentives). By contrast, a similarly-mature Direct Air Capture (DAC) plant might cost $250-1,200 per metric ton of carbon abated.[5] This report analyzes Scope 3 offtaker interest in DAC as it is the most frequently-cited alternative to SAF credits. This analysis demonstrates that if current SAF incentives extend beyond 2024 (see Appendix 2 for more detail on RFS, 45Z, and state-level policies), and if both SAF and DAC reach NOAK maturity, then SAF credits would be cheaper than DAC credits.

Shore Up Supportive Policy

Given the high cost of SAF, neither supply nor demand can scale without supportive policy. In the U.S., most policy is supply-oriented (see Appendix 2). Federal tax credits from the Inflation Reduction Act (IRA) complement the federal Renewable Fuel Standard (RFS) and state policies, including low carbon fuel standards, and help lower the cost premium of SAF relative to fossil jet fuel. Several of these key policies are short-term. The SAF Production Tax Credit (40B) in Internal Revenue Code § 40B of the IRA expires at the end of 2024 and the Clean Fuel Production Tax Credit (45Z) in Internal Revenue Code § 45Z of the IRA—for which SAF will also be eligible—is set to expire in 2027.

iii Fossil jet fuel prices vary by region but typically trend between $2.40-3.00 per gallon, with the higher end of the range in states like California. This Liftoff report uses a $2.41 per gallon estimate for this analysis, the average spot price between January and August 2024.

State-level incentives can be stacked with federal incentives and further help close the cost delta for project developers; however, most state-level incentives, similar to federal incentives, apply to all biofuels and do not call out SAF specifically. Given the relatively higher cost of production for SAF than other fuels, like renewable diesel (RD), federal and state incentives may be relatively more valuable to these other fuels, thus incentivizing producers to choose them over SAF.

On the demand side, only a handful of countries have passed SAF mandates. While the one billion gallons of potential 2030 SAF demand covered by these mandates is meaningful, it may not be sufficient to stimulate a global SAF economy. More long-term demand certainty will be necessary to stimulate U.S. SAF production at scale.

This report seeks to provide a common fact base on the current state of the SAF market and the importance of reaching liftoff by 2030. If 2030 goals are met, the SAF economy in the U.S. could reach between $4-11 billion, with a pathway to scaling up much more meaningfully in the years that follow.[iv] By 2030, the SAF economy could employ over 70,000 workers.[v] The U.S. would be well on its way to meet its net-zero target by 2050, with the SAF economy representing a $175-315 billion market.[vi]

iv Total addressable market is defined as: 8-12 operational production facilities, producing on average 100 MGPY of SAF, selling at between $3 and $10 per gallon.

v Soaring to New Heights: The Economic Impacts of Building an American SAF Industry – Third Way estimates adjusted for the projected 2030 production capacity in Figure 5 of this report.

vi Total addressable market is defined as: 35 BGPY of SAF production, selling at between $3 and $10 per gallon.

Chapter 1: Overview and Value Proposition

KEY TAKEAWAYS

- **In the U.S., aviation contributes over 200 million metric tons of carbon dioxide emissions, representing roughly 3.3% of total emissions. In a business-as-usual scenario, emissions are likely to double by 2050, due to increases in air travel and insufficient decarbonization plans.**
- **SAF is the only viable near-term option to meaningfully decarbonize the aviation sector. Other solutions either fall short of SAF's carbon abatement impact or SAF's technological maturity.**
- **The SAF Grand Challenge targets three billion gallons of annual SAF production by 2030. As of August, only 16.5 million gallons of SAF had been produced in 2024, highlighting the need for production to grow at an average annual rate of 138% between 2024 and 2030.**
- **Demand has materialized in short-term or low-volume airline offtake agreements to date, but more recent announced offtake agreements include longer durations or higher volumes.**
- **Relatedly, investment in SAF has been limited to date but is on track to increase through 2030.**

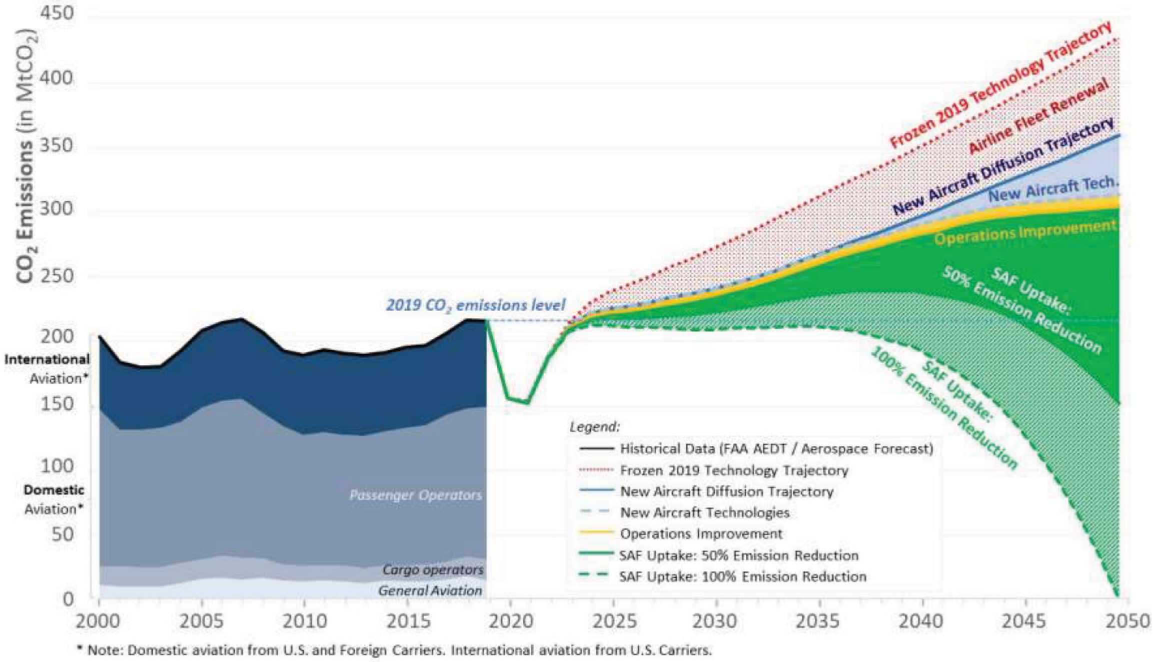
SAF in Context

Transportation fuels are a significant contributor to greenhouse gas emissions. Fossil jet fuel is the world's third-most consumed transportation fuel after diesel and gasoline, representing about seven million barrels per day (BPD) or 107 billion gallons per year (BGPY).[6] The U.S. alone consumed about 1.3 million BPD of jet fuel, or 20 billion gallons in 2023.[7] The overwhelming majority of jet fuel consumed in the United States is fossil-based (i.e. made from fossil kerosene) and which has a lifecycle emissions factor of 0.00977 metric tons of carbon dioxide (CO_2) per gallon.[8]

In the U.S., aviation contributes over 200 million metric tons of CO_2 emissions, representing about 11% of U.S. transportation-related emissions or 3% of total U.S. emissions.[1] U.S. air travel is increasing by 2-3% annually, and global air travel overall is increasing by over 3% annually.[1] Due to this growth in the sector, the U.S. Energy Information Administration (EIA) estimates that aviation-related emissions will nearly double by 2050, even when assuming that some decarbonization measures (e.g., aircraft efficiency improvements) are implemented in a "business as usual" scenario.[9]

In 2021, the Federal Aviation Administration (FAA) announced a goal of reaching net-zero emissions in the aviation industry by 2050 to align with the U.S. commitment to a net-zero economy by 2050 (see Figure 1). FAA and the United States government broadly have taken steps to support the development of new and improved aircraft, the implementation of operational improvements at airports and in the air, and the development of electric and hydrogen planes to service short- and medium-distance flights. However, by 2050 the largest contributor to aviation-related emissions reductions will be the usage of low-carbon or sustainable aviation fuels, also known as SAF. FAA has supported SAF development since 2007 and developed the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) with other countries. By 2050, FAA projects that SAF will account for at least 65% of reduced CO_2 emissions associated with domestic and international aviation. The latest International Air Transport Association (IATA) Net Zero Roadmap also calculates that roughly two-thirds of emissions reductions will come from SAF uptake.[10]

Figure 1: SAF uptake represents a large proportion of the FAA's Climate Action Plan.



Source: *FAA Climate Action Plan*[1]

Airlines are increasingly looking to SAF to decarbonize their operations as well (see Figure 2). Today, the majority of publicly announced decarbonization initiatives among airlines are focused on SAF.

Figure 2: SAF represents the largest proportion of decarbonization initiatives as announced by airlines.

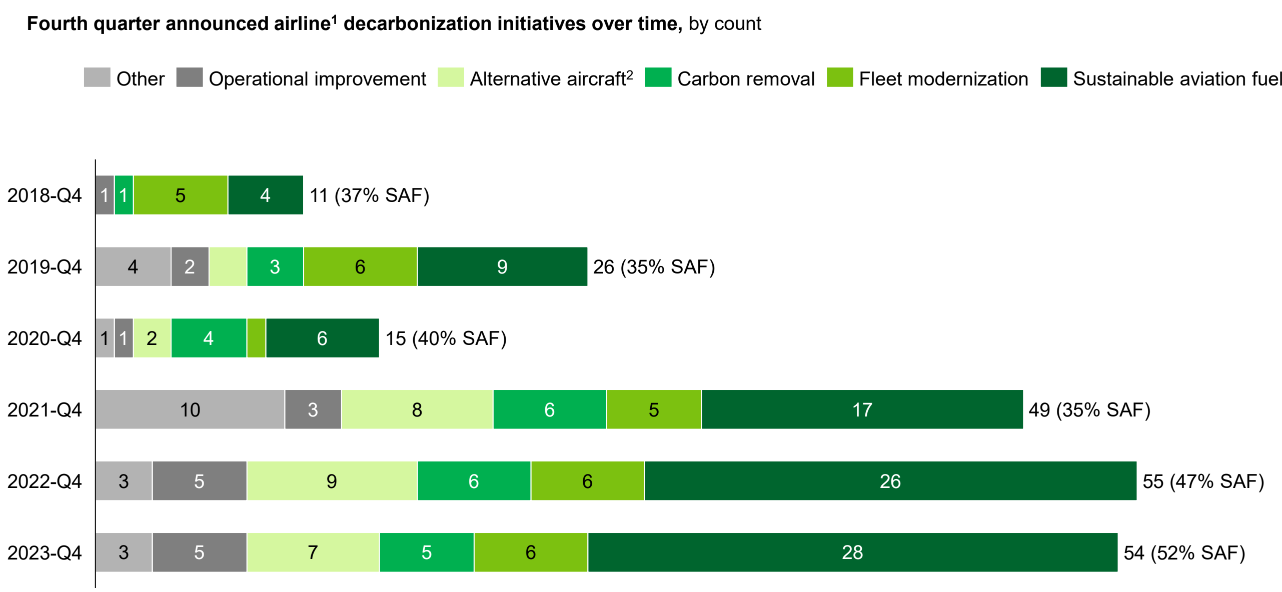


Figure Footnotes: *1. Total includes subset of all airlines; 2. Alternative aircraft includes electric and hydrogen planes and urban air mobility and last-mile delivery.*

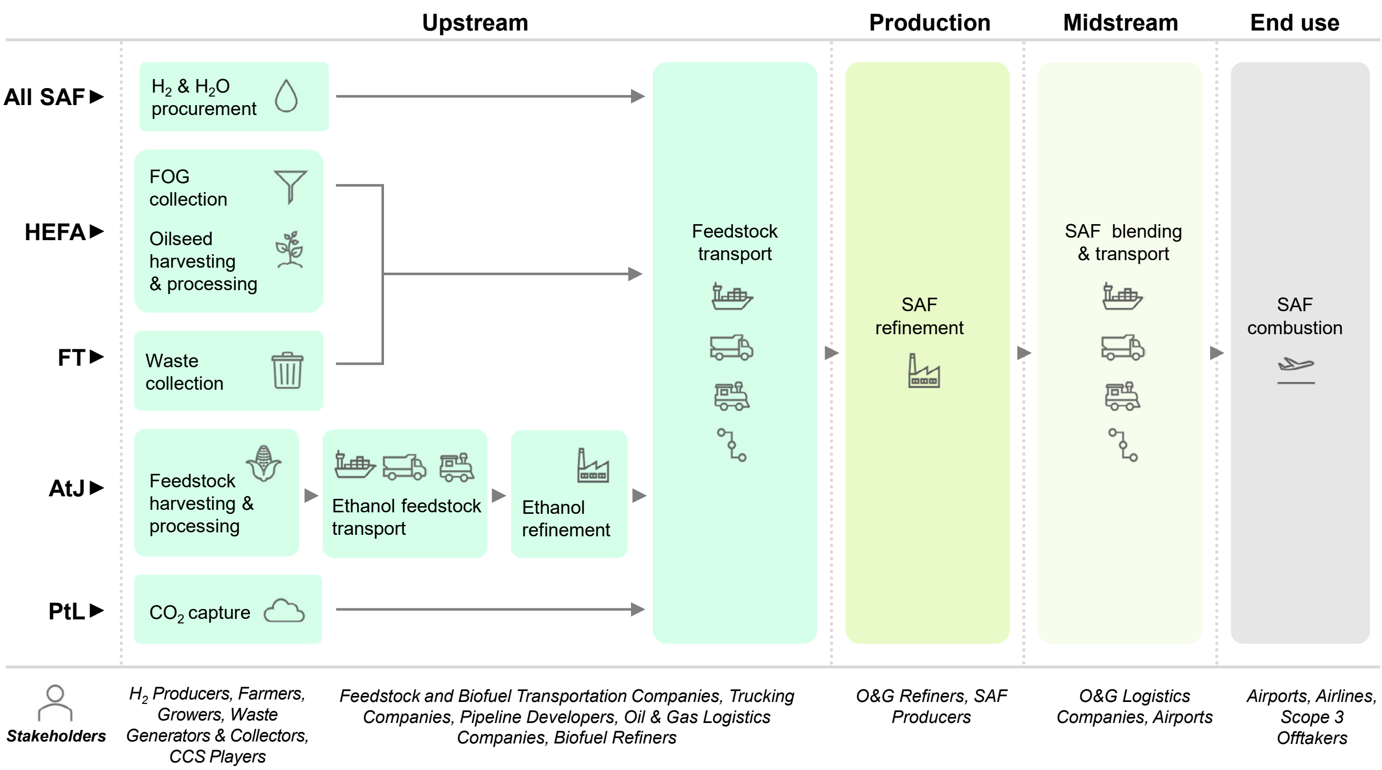
Data Sources: *BNEF*[11]

What is SAF?

SAF is a drop-in fossil jet fuel replacement. Chemically, it is similar to fossil jet fuel and it can be transported, stored, and burned nearly identically. However, unlike fossil jet fuel, SAF is made from biomass, waste, or clean synthetic resources and thus serves as a low-carbon alternative. Different countries have different specifications for SAF, including whether it can be produced from food or feed feedstocks like corn. U.S. policy towards SAF is feedstock agnostic, although the resulting SAF must result in at least a 50% reduction in lifecycle emissions compared to fossil jet fuel (Jet A/A-1).[vii] However, even with reduced carbon intensities, standalone SAF cannot be used in aircraft; the American Society for Testing and Materials (ASTM) sets specifications for how SAF blends are produced (ASTM D7566) and how they can be blended with fossil jet fuel (ASTM D1655).[viii] When blended with fossil jet fuel and approved to specification ASTM D1655, SAF can be transported and burned just like its fossil-based alternative and will behave in nearly the same way. To date, ASTM has approved 11 processes that convert a feedstock into a SAF blend stock to produce SAF, although several more are under evaluation.[12] This Liftoff report refers to these conversion processes as production pathways.

Figure 3: SAF's supply chain is both complex and extensive.

This Liftoff report analyzes four of the most commonly cited SAF production pathways that utilize different feedstocks and technologies and have varying degrees of technical and commercial readiness. Note that some production technologies for the Power to Liquid pathway are not yet approved by ASTM.



Hydroprocessed Esters and Fatty Acids (HEFA) requires triglyceride feedstocks such as oilseeds and waste fats, oils, and greases (FOGs). HEFA is the most mature technology pathway to produce SAF and is the only pathway that has been deployed at commercial scale.

vii [The American Society for Testing and Materials (ASTM)](#) sets technical standards for a wide range of materials, including sustainable aviation fuel. If SAF is produced at a standalone facility, it must meet the ASTM D7566 (the Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) specification prior to blending with Jet A. If SAF is produced at refineries co-processing biomass or intermediate renewable feedstock with crude oil, it must meet the ASTM D1655 (the Standard Specification for Aviation Turbine Fuels) specification. When Jet A and SAF are blended and tested for compliance with all applicable ASTM standards, the fuel is then designated as ASTM D1655, allowing it to be transported in pipelines and used in aircraft. For more information, visit: U.S. Airport Infrastructure and Sustainable Aviation Fuel (energy.gov).

viii Today, ATSM does not approve of the transport and use of 100% SAF. SAF "blend stock" must be blended with more than 50% of fossil Jet A/A1 fuel in pipelines and aircraft. This report refers to the production and utilization of SAF blend stock, although it uses the terminology "SAF."

Companies operating HEFA facilities in the U.S. include Chevron, Montana Renewables (a subsidiary of Calumet, Inc), and World Energy. DOE's Loan Programs Office (LPO) recently announced a conditional commitment to expand Montana Renewables' facility (see Appendix 2).

Alcohol to Jet (AtJ) converts alcohols, such as ethanol and isobutonal, into SAF. Common feedstocks for the process include corn and sugarcane, but any type of two- to five-carbon alcohol feedstock can be used.[13] The first operational AtJ plant, LanzaJet's Freedom Pines demonstration in Georgia, started operations this year.

Gasification with Fischer-Tropsch (FT) starts with the gasification of feedstock (such as woody biomass, municipal solid waste, and other cellulosic feedstocks) to produce syngas, and then a synthesis reaction converts the syngas into SAF. Although FT has been used for decades to make waxes and synthetic crude, the gasification of these new feedstocks at the start of the process remains less proven. In May 2022, Fulcrum BioEnergy started operations on a first-of-a-kind (FOAK), commercial scale waste-to-SAF plant in Nevada; however, in 2024, the plant ceased operations due to technical, financial, and managerial challenges.

Power to Liquid (PtL) typically requires water and clean electricity to produce hydrogen via electrolysis. It also requires carbon dioxide, which developers secure primarily through point-source capture today—although direct air capture (DAC) may become technically and commercially viable as an alternative method for capture as soon as 2030. The hydrogen converts the captured carbon dioxide to synthetic gas, which can be upgraded to SAF by FT reaction or methanol-synthesis. The carbon intensity (CI) of PtL is dependent on its inputs. For example, if the process uses 100% clean electricity and the captured CO_2 comes from DAC, the resulting SAF could be close to zero-carbon. PtL is the least technically mature of the four pathways described in this report. Some types of PtL production are not yet approved by ASTM.

SAF's Value Proposition

SAF is the most meaningful decarbonization solution for the aviation sector in the near-term. The FAA anticipates that 50-80% of U.S. aviation emissions reductions through 2050 will result from SAF uptake; the remaining emissions reductions will result from other decarbonization solutions like novel propulsion technologies, carbon capture and storage, carbon offsets, and aircraft efficiency gains (see Figure 1).

Hydrogen and battery-powered aircraft might also help decarbonize aviation, but these technologies remain in their infancy due to size, density, and safety considerations. Furthermore, these solutions will only serve short haul flights, whereas the majority of aviation emissions result from long-distance flights.[1] These solutions also introduce relatively more airport and airline capital expenditure as they will require new fueling and charging infrastructure. SAF, by contrast, is a drop-in fuel that can be used nearly identically to the fossil jet fuel in operation today.

In addition to SAF's emissions reduction potential and ease-of-use, there are numerous environmental and economic benefits associated with SAF that are not always internalized in its price. These benefits can extend far beyond where SAF facilities are sited and include improving air quality for communities collocated with airports to supporting jobs for upstream feedstock suppliers.[14]

Other Environmental Impacts

Early evidence suggests certain blends of SAF can reduce health-relevant particulate matter emissions and the formation of climate-warming contrails.[15] Contrails are trails of condensed water vapor which can form behind jet engines and contribute to global warming, trapping heat radiating from the Earth's surface that would otherwise escape into space. Poor air quality and climate change disproportionately impact socially vulnerable populations.[13]

Other environmental co-benefits might include improvements in soil health, water quality, nutrient management, and soil organic carbon sequestration associated with SAF produced from bio-feedstocks (e.g., HEFA, AtJ and FT). There may be additional benefits associated with climate smart agriculture (CSA) practices, forestry practices, and other co-benefits associated with the utilization of waste biomass.

Local environmental impacts will vary by project design. For example, biorefineries could negatively affect air quality in local communities, especially if there are no additional pollution controls. Additionally, the increased truck traffic to transport feedstock and SAF blend stock is another important consideration. For facilities producing SAF using low-density feedstocks, such as woody biomass and agricultural waste for the AtJ or FT pathways, even relatively small facilities can create significant truck traffic and related air pollution.[16] Socially vulnerable populations have already felt these impacts due to the similar and more polluting operations of traditional petroleum refineries producing fossil jet fuel. The implementation of emissions control technologies and utilization of low-emission vehicles could reduce these impacts.

Social and Economic Impacts

By 2030, SAF production capacity may require approximately 7,000[ix,17] permanent jobs to operate production plants across the country. However, this is a small fraction of the total jobs that will be created by SAF scale-up. When direct jobs associated with plant construction, select feedstock supply and collection, and energy infrastructure are accounted for, the SAF industry could support over 70,000[18] people in 2030. This forecast does not include additional jobs needed for sustainable fuel distribution, blending, and other indirect processes and impacts. Governments should work with industry and labor to ensure retention, reskilling, and transfer opportunities for those facing potential job loss due to decreased fossil jet fuel production. They should also ensure that SAF jobs have comparable and competitive pay and benefits. In fact, much of the announced SAF production is located in communities with existing refinery operations which can facilitate the ongoing development, training, and re-skilling of an existing and local skilled workforce (see Figure 7).

Figure 4 illustrates that roughly 45% of announced SAF production expected to come online by 2030 is sited in counties where a majority of the population lives in disadvantaged communities, or communities that suffer disproportionate environmental or socioeconomic burdens.[x] In 2030, disadvantaged communicates could host 33% of greenfield SAF production (SAF produced from existing or adapted facilities) and 50% of greenfield SAF (SAF produced from newly constructed facilities). Developers should proactively engage and partner with communities, Tribes, and labor to maximize local benefits and avoid, mitigate, and reduce potential harms associated with SAF production, including through the use of community benefit planning and community and workforce agreements. The development of these types of negotiated, binding agreements will be especially important for projects that impact disadvantaged communities to help ensure that projects develop and operate equitably, safely, effectively, and on time.[19]

ix Estimates generated using NREL data and projected 2030 production capacity shown in Figure 5 of this report.

x For more information on disadvantaged community qualifications and locations, see the Climate and Economic Justice Screening (CEJST) tool at screeningtool.geoplatform.gov.

Figure 4: In 2030, 45% of announced SAF production (with announced locations) is located in disadvantaged communities.

Estimated 2030 production capacity by state,[1] million gallons per year **2030 production capacity located in disadvantaged communities,**[1,2] %

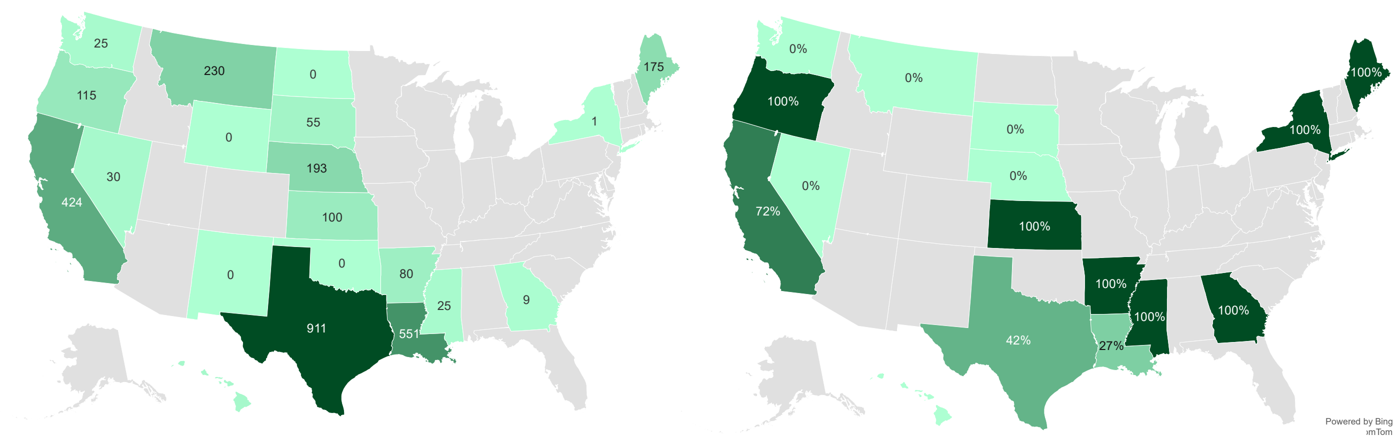


Figure Footnotes: *1. Gray states indicate states with no announced production facilities expected to come online by 2030 with a location that could be identified at the county level. On the left map, colored states with a "0" in the middle indicate states with currently operational RD facilities with undefined/ unannounced SAF production capacity. These states are gray on the right map; 2. "Disadvantaged communities" for this analysis are defined as counties with over 42% of the population identified as traditionally defined, census-tract disadvantaged communities. County-level designations for disadvantaged communities are used for this analysis due to uncertainty in exact locations of announced greenfield production projects.*

Data Sources: *BNEF;[3] Climate and Economic Justice Screening Tool;[20] Industry input*

SAF Grand Challenge & Liftoff

In September 2021, the United States federal government, in partnership with industry, set an ambitious target to scale domestic SAF production through the Sustainable Aviation Fuel Grand Challenge (SAF Grand Challenge). A consortium of federal agencies, including the U.S. Department of Energy (DOE), U.S. Department of Agriculture (USDA) and U.S. Department of Transportation (DOT) committed to supporting the research, development, demonstration, and deployment needed to produce 35 billion gallons per year (GPY) of SAF by 2050 to meet forecasted jet fuel demand in the United States. This consortium also set a near-term target of three billion gallons of domestic SAF production per year by 2030 to meet 10% of forecasted jet fuel demand. To enable the SAF Grand Challenge, the federal government has instituted a variety of policies that complement existing state-level and international measures that support the SAF industry more broadly (see Appendix 2).

Building on its role in the interagency SAF Grand Challenge, DOE launched the Clean Fuels and Products Shot. This Shot aims to advance the development of sustainable feedstocks and conversion technologies necessary to produce fuels and carbon-based products that have 85% lower net greenhouse gas emissions by 2035. By advancing cost-effective production technologies, it supports the SAF Grand Challenge and other DOE commercialization efforts in the SAF space.

Currently, SAF production is less than 1% of this 2030 target. In 2023, the U.S. produced about 14 million gallons of SAF and consumed 25 million gallons total.[xi] As of August 2024, the U.S. has produced 16.5 million gallons of SAF and consumed 62 million gallons this year.[xii] The shortage of supply relative to demand has required airlines to import SAF from foreign countries, although the EPA does not track the source of this fuel. The scale-up of SAF production in the U.S has posed challenges for myriad, interconnected reasons:

$	SAF faces sustained high production costs relative to fossil jet fuel and other low-carbon fuels like renewable diesel (RD).
?	SAF faces uncertain demand given insufficient mechanisms to fully value the environmental benefits of SAF relative to fossil jet fuel.
	Federal production tax credits for SAF and low-carbon fuels are expected to expire by 2027 and low-carbon fuel standards provide more of an incentive for other low-carbon fuels like RD than for SAF.
	Foreign mandates diverge in definitions and qualifications for SAF, limiting demand certainty for U.S. producers and international trade.
	The SAF industry is complex involving diverse stakeholders, including: farmers, waste collectors, logistics providers, chemists and other scientific and technical researchers, project developers and engineering, procurement and construction contractors, fuel pipeline developers and trucking companies, labor unions and community organizers, refinery workers, entrepreneurs, airline and airport management and operations specialists, corporate customers, aircraft passengers, investors, policymakers, and regulators. Achieving consensus is difficult.

This Liftoff report seeks to catalyze action to address these challenges so that SAF can reach a point of commercial liftoff within the decade.

xi Volumes calculated by RINs produced from "Renewable Jet Fuel" in the year 2023, see EPA, RINs Generated Transactions. SAF produced includes only "Domestic" volumes and SAF consumed includes "Domestic" and "Foreign Generation" volumes.

xii Volumes calculated by RINs produced from "Renewable Jet Fuel" in the year 2024, see EPA, RINs Generated Transactions, as of August 10, 2024. SAF produced includes only "Domestic" volumes and SAF consumed includes "Domestic" and "Foreign Generation" volumes.

Chapter 2: Current State of Technologies and Markets

KEY TAKEAWAYS

- **Current U.S. SAF nameplate capacity is 64 MGPY and is expected to reach 2-3 BGPY by 2030. This production capacity scale-up corresponds to $44 billion in investment.**
- **However, SAF is 2-10 times more expensive than fossil jet fuel today. Even HEFA SAF, which uses the most technically and commercially mature production technology, is expected to remain at a price premium to fossil jet fuel. Long-term, high-volume offtake has been challenged given these higher relative costs.**
- **U.S. government incentives at the federal and state levels can significantly decrease SAF's production costs and selling prices. An increasing number of demand-side incentives have emerged within U.S. states. Additionally, countries around the world have adopted and proposed mandates which help establish demand certainty and derisk SAF investment globally.**

SAF Production Capacity

In 2023, the U.S. produced 14 million gallons of SAF and imported 12 million gallons of SAF, thus consuming a total of 26 million gallons.[xiii] As of August 2024, the U.S. has produced 16.5 million gallons of SAF across four operational plants and used 62 million gallons.[xiv] Despite progress in 2024, production output must rapidly increase to meet the SAF Grand Challenge 2030 target output of three BGPY.

Recognizing SAF's importance in aviation, developers have announced projects that have projected capacities that collectively could meet the SAF Grand Challenge by 2030.[xv] If 100% of announced capacity comes online by its announced commercial operations date (COD), then production capacity will exceed the target. However, this development pipeline could face challenges pertaining to high production costs, lack of long-term offtake, high capital costs, policy uncertainty, and limited biofeedstock availability. As a result, many of these projects face possible delays, cancellations, or shifts in production to prioritize RD over SAF outputs. Given these possible delays, cancellations, and production shifts, only 53% of currently announced production may come online by 2030 (Figure 5). More work is needed to address these market challenges and build more top of funnel production capacity to meet the SAF Grand Challenge 2030 target.

Note that announced nameplate capacity for SAF is based on company announcements. However, it is possible that some announced production shifts to RD, as many facilities have announced plans to co-process RD and SAF.

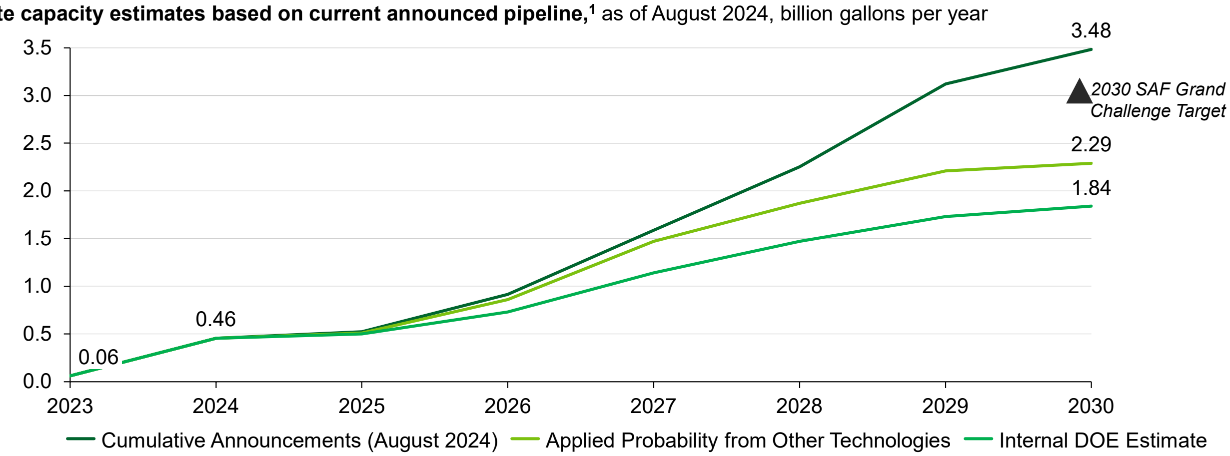
xiii Volumes calculated by RINs produced from "Renewable Jet Fuel" in the year 2023, see EPA, RINs Generated Transactions. SAF produced includes only "Domestic" volumes and SAF consumed includes "Domestic" and "Foreign Generation" volumes.

xiv Volumes calculated by RINs produced from "Renewable Jet Fuel" in the year 2024, see EPA, RINs Generated Transactions, as of August 10, 2024. SAF produced includes only "Domestic" volumes and SAF consumed includes "Domestic" and "Foreign Generation" volumes.

xv This analysis takes all publicly announced projects and applies a project success parameter and timeline based on industry interviews and DOE input. This analysis conservatively does not assume any net new project capacity announced between April 2024 and December 2026, a timeframe in which a project could be announced and successfully reach COD by 2030. Due to development timelines of approximately 4-6 years for greenfield sites, it is unlikely that any new announcements of greenfield sites in 2025 or later would be operational by 2030. Brownfield sites (i.e. co-processing at existing oil refineries) could feasibly be completed more quickly than the 4-6 year timeline. However, policy incentives for SAF today exclude co-processing sites and few co-processing sites are expected to come online.

Figure 5: Announced production capacity today exceeds the SAF Grand Challenge near-term target of three billion gallons per year by 2030; however, adjusting those figures for project delays and cancellations decreases expected capacity by roughly 50%.

U.S. SAF nameplate capacity estimates based on current announced pipeline,[1] as of August 2024, billion gallons per year



Success Factors	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Applied Probability from Other Technologies[2]	98%	98%	90%	90%	60%	40%	20%
Internal DOE Estimate[3]	99%	75%	60%	60%	50%	30%	30%

Figure Footnotes: *1. Announced capacity includes 100% of announced SAF production capacity from announced projects located in the U.S. Production capacity does not include any assumptions about additional capacity that may come online if projects convert more RD production to SAF production in later years. Total SAF capacity is not necessarily equal to total SAF production, as facilities may not be running at 100% production at all times. Of announced projects through 2030, 56% of nameplate capacity will be greenfield projects, while 44% will be brownfield projects; 2. Success factors are on based analogous clean energy technologies like offshore wind and clean hydrogen. This methodology assumes that projects with CODs in the next two years are less subject to project delays and cancellations than projects announced today that are not expected to come online until 2030; 3. Success factors are applied on a project-by-project basis according to DOE.*

Data Sources: *BNEF;[3] Company websites and public announcements; Industry input*

The projects most likely to meet their COD on time are those developed by established leaders in the biofuels space that apply key learnings from RD to SAF, tap into existing infrastructure like blending facilities and pipelines—either through partnerships or through in-house ownership and development—and that secure offtake from large corporates that are willing to commit to paying long-term premiums for SAF.

SAF Costs

One of the biggest challenges for SAF is its cost premium relative to fossil jet fuel. As Figure 6 highlights, SAF can cost anywhere from 2-10 times more than fossil jet fuel. Some producers are selling SAF below production cost in order to secure offtake. See Appendix 4 for details about the assumptions behind the SAF production cost estimates.

Figure 6: SAF costs are 2-10 times more than fossil jet fuel, although estimates vary across the industry.

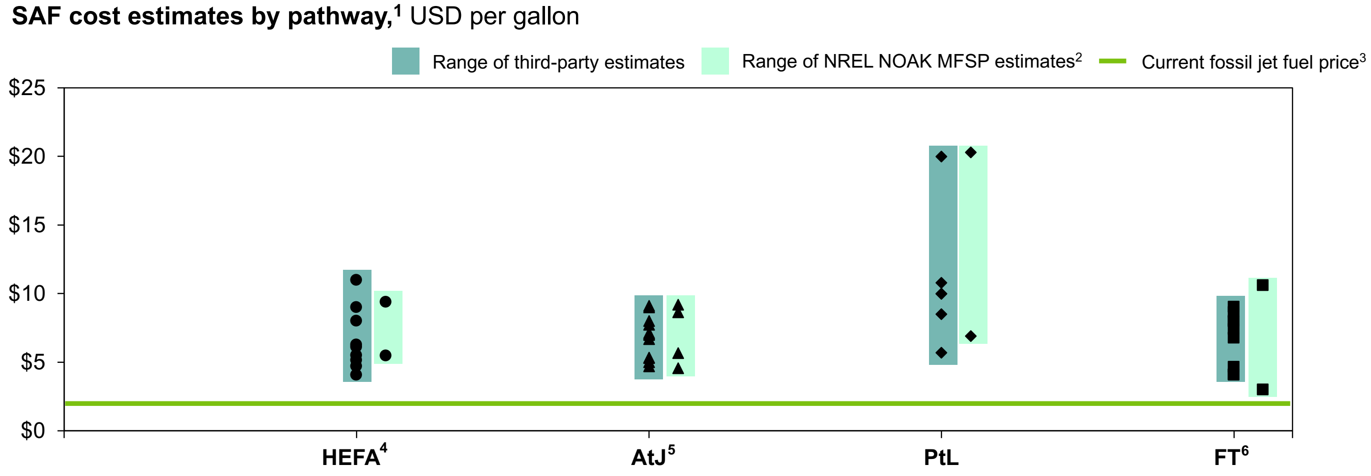


Figure Footnotes: *1. Prices are based on a range of production facility designs, inputs, and assumptions, including year, inflation, and NOAK vs. FOAK deployment. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary; 2. Minimum fuel selling price (MFSP) is the lowest possible price a producer could sell at to financially support operations; these estimates assume NOAK deployment;*
4. Estimates pull multiple feedstocks, including FOGs (lower end of range) and virgin oils and crops (higher end of range); 5. Estimates pull both starch and cellulosic feedstocks. The high end of the cellulosic AtJ range ($9.6 per gallon) exceeds the high end of the starch-based range ($8.60 per gallon) although the low ends of these ranges are similar ($4.50-4.60 per gallon); 6. Although FT prices appear lower than HEFA and AtJ, the gasification technology of these feedstocks is nascent and will require more time (e.g., after 2030) to validate these estimated ranges.

Data Sources: *Fueling the Future;[21] IATA;[22] Industry input; NREL;[23] NREL input; Reuters[24]*

Many operational and planned SAF production plants in the U.S. are either sited in states with clean fuels incentives (see Appendix 2) or in regions with existing fossil-based refineries and infrastructure to offset some of this premium. However, there may always be some premium with SAF as compared to fossil jet fuel due to its higher production costs.

Figure 7: Most announced SAF production facilities expected to come online by 2030 are located in states with low-carbon fuel standards or SAF policies (see shaded states), existing refinery infrastructure (see inset), or robust feedstock supply (primarily in the Midwest).

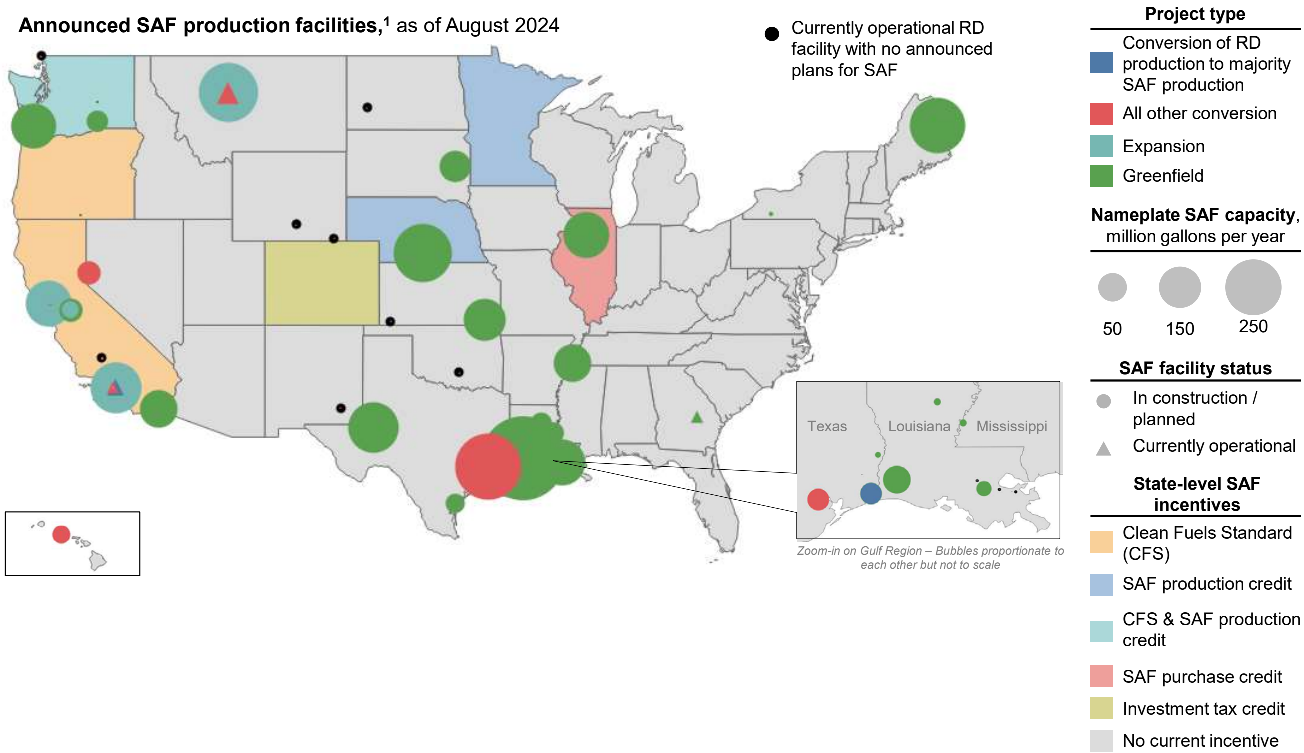


Figure Footnotes: *1. Locations are approximate when data does not specify the exact location of the facility. Project facility is excluded from the map if data does not include location that could be approximated. Seven out of 90 announced SAF projects are excluded due to lack of location data, which is 8% of total announced/in construction/operational SAF capacity. Most of these projects are early in development.*

Data Sources: *BNEF;[3] Industry input*

SAF Demand

Despite the price premium of SAF compared to fossil jet fuel, there is growing demand for SAF both in the U.S. and globally for a few reasons.[xvi] First, as outlined in Chapter 1, there are few immediate or near-term solutions to decarbonizing aviation. Airlines and air cargo companies prefer viable mechanisms to reduce their Scope 1 emissions. Second, corporates such as large tech companies and consulting firms are interested in addressing their Scope 3 emissions by buying the environmental attributes (i.e. carbon emissions reductions) associated with SAF and retiring them. Third, countries and jurisdictions like British Columbia, Singapore, and the European Union have mandated SAF usage (see Appendix 2).

Figure 8 illustrates the significant growth in SAF demand following the passage of supportive legislation like the IRA in the United States and ReFuelEU in Europe. Note that Figure 8 only includes publicly announced SAF contracts with announced quantities and thus significantly undercounts actual offtake.

xvi Although this Liftoff report focuses on U.S. SAF supply, it takes a global view to SAF demand, given both the often-international nature of long-haul flights and the international support for SAF accounting systems (in which entities under SAF usage mandates can purchase SAF that qualifies for the regulation but not use it directly, similar to a virtual power purchases).

Figure 8: Announced global SAF offtake has increased significantly since the passage of the IRA in the U.S. (2022) and the ReFuelEU Act in Europe (2023).

Global demand for SAF based on announced airline offtake agreements,[1] as of May 2024, million gallons

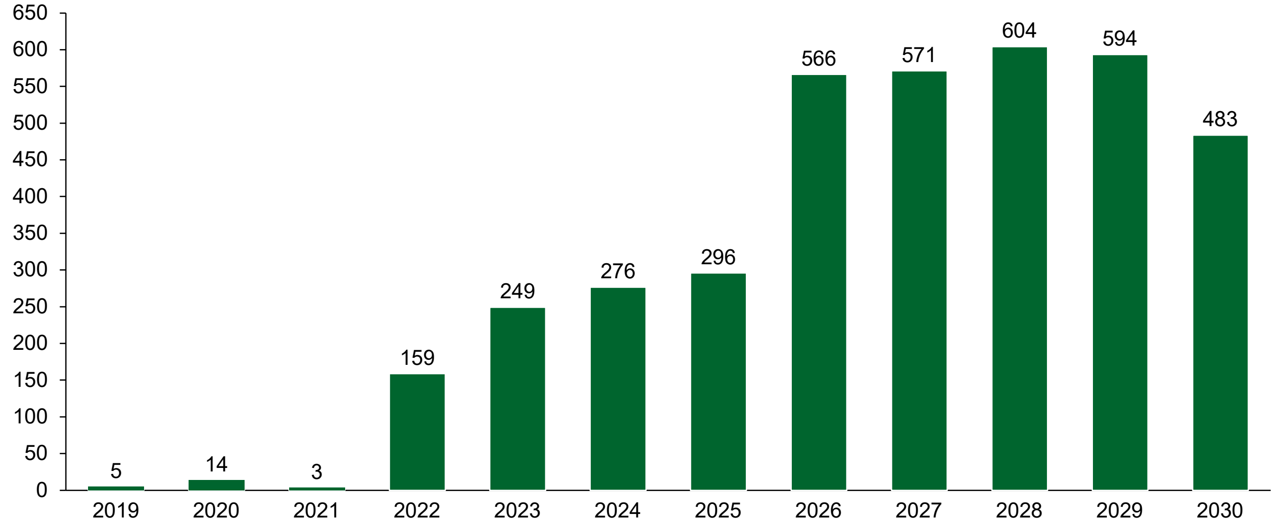


Figure Footnotes: *1. This analysis only includes offtake quantities based on publicly announced offtake agreements between SAF providers and global airlines. There is no inclusion or estimation for offtake without specific quantities. If the announcement mentioned blended SAF without a %, BNEF data assumes a 40% blending rate. ICAO data was included in this analysis to complement BNEF data for deals that were announced in 2024 as well as freight airline data that was not included in BNEF estimates. The majority of public offtake announcements do not include demand quantities and more demand is expected to be announced between 2024 and 2030, making this graphic likely to be an undercount of actual SAF offtake.*

Data Sources: *BNEF;[25] ICAO[26]*

As shown in Figure 9, of the 76 analyzed offtake agreements, roughly 70% include contracts for five years or less and roughly 50% are one-year contracts. Additionally, roughly 70% of contracts are for fewer than 50 million gallons of SAF. Many of these contracts price SAF below cost and at parity with Jet-A fuel in order to attract airline buyers, but this underpricing is not sustainable for developers over the long-term. Alternatively, developers might opt to sell SAF at higher prices but for lower volumes. Both longer-term and higher-volume contracts are needed to help stimulate the project development of new SAF facilities. 10-year+ offtake agreements provide the cash flow guarantee and assurance to investors that there is enough revenue and market certainty to derisk an investment in a 25-year+ project.

Figure 9: Offtake agreements are increasing in both average length and volume, driven largely by the establishment of SAF mandates and subsidies globally.

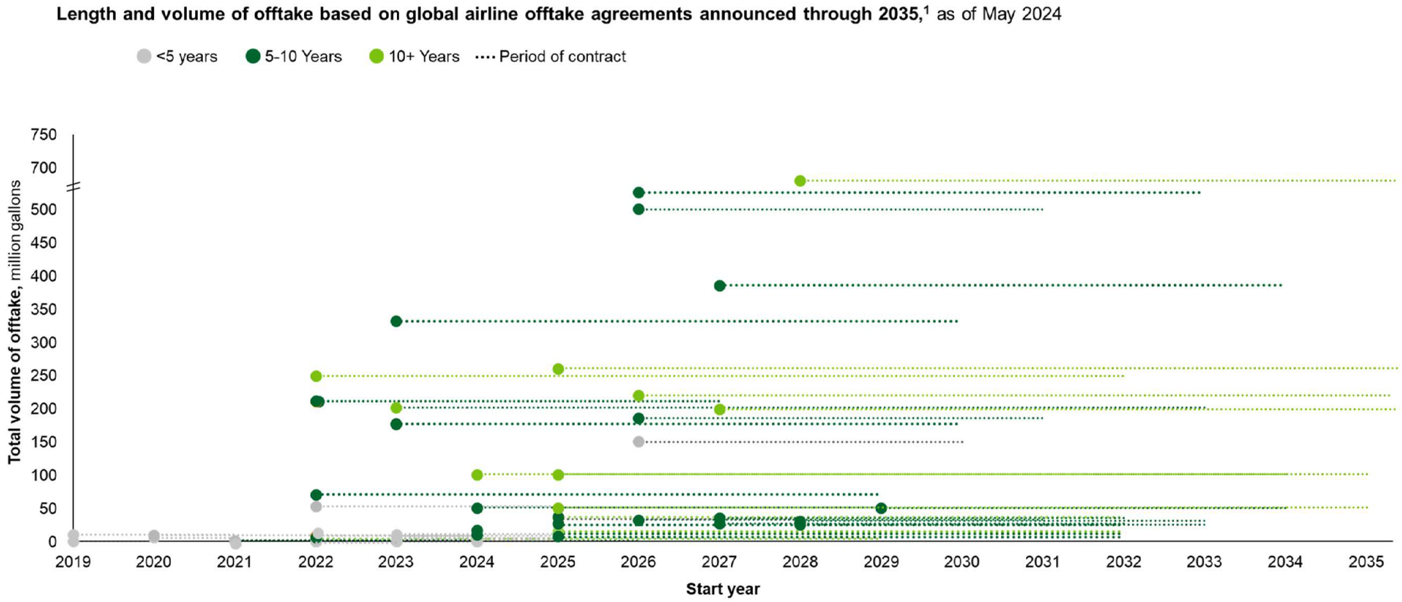


Figure Footnotes: *1. This chart provides offtake quantities based on publicly announced offtake agreements between SAF providers and global airlines that included specified quantities of SAF. No inclusion or estimation for offtake without specific quantities. If announcement mentions blended SAF without a %, BNEF data assumes a 40% blending rate. ICAO data was included in analysis to complement BNEF data. ICAO data was added for all deals that were announced in 2024 as well as freight airline data that was not included in BNEF estimates. Four offtake agreements extend past 2035, with the longest deal running until 2048 (see the four lines that continue on the chart).*

Data Sources: *BNEF;[24] ICAO[25]*

Of all announced offtake agreements, 39 are with European airlines, 38 are with North American airlines, 10 are with Asian airlines, five are with airlines in Oceania, and six are with Middle Eastern/North African airlines. For offtake agreements that are greater than 25 MGPY, there are 22 with European airlines, 23 with North American airlines, and six with Asian airlines. Any airline flying out of European airports are subject to ReFuelEU mandates.

Typically, in the United States, airlines buy the fuel directly from a producer and sell off the SAF premium (e.g., its environmental attributes) to their corporate partners looking to cover part of their carbon emissions footprint. These contracts are usually shorter in duration for several reasons:

- Given the nascency of the market, SAF production and delivered costs are still unknown, which may result in less trust between the contracting parties.
- Globally, national-level policies are inconsistent on the definition and qualification of SAF, so prices vary depending on country of production and country of end-use. Furthermore, book and claim systems have not been universally adopted or approved as a corporate decarbonization initiative, further limiting volumes.
- In the U.S., net zero goals are voluntary, meaning that corporate offtakers are not required to offset their emissions for any period of time.
- Relatedly, corporate offtakers may not want to commit to a particular technology or developer and close themselves off to cheaper or less carbon intensive SAF that may enter the market in the coming years.

- With single-digit operating margins, airlines lack the financial cushion to pay the SAF premium themselves. Without guaranteed buy-downs from corporate partners, airlines must pass on the cost of the more expensive, lower-carbon fuel to passengers. Given the price sensitivity of passengers, airlines are reluctant to take on any contract that risks increasing costs to passengers and losing market share.

2030 global SAF demand estimates range from 1.8-6.2 BGPY. Approximately one billion gallons of this demand will come through mandates in countries with required SAF usage; this volume may double from additional countries with proposed mandates (see Appendix 2, and more detail in Chapter 5). Much of the remaining demand will be driven by voluntary commitments from airlines or corporate offtakers. Five of the six largest U.S. based carriers (Alaska, American, Delta, JetBlue and Southwest) have announced 10% targets for SAF by 2030 either directly or through the OneWorld Airline Alliance. United does not explicitly state 2030 SAF targets, although they've procured SAF directly. If those six airlines were to reach those targets, their demand would total approximately 1.8 BGPY; however, given cost and feedstock considerations, it is possible that these airlines will not meet their voluntary commitments.

Figure 10: Global demand for SAF may reach 6.2 billion gallons per year by 2030.

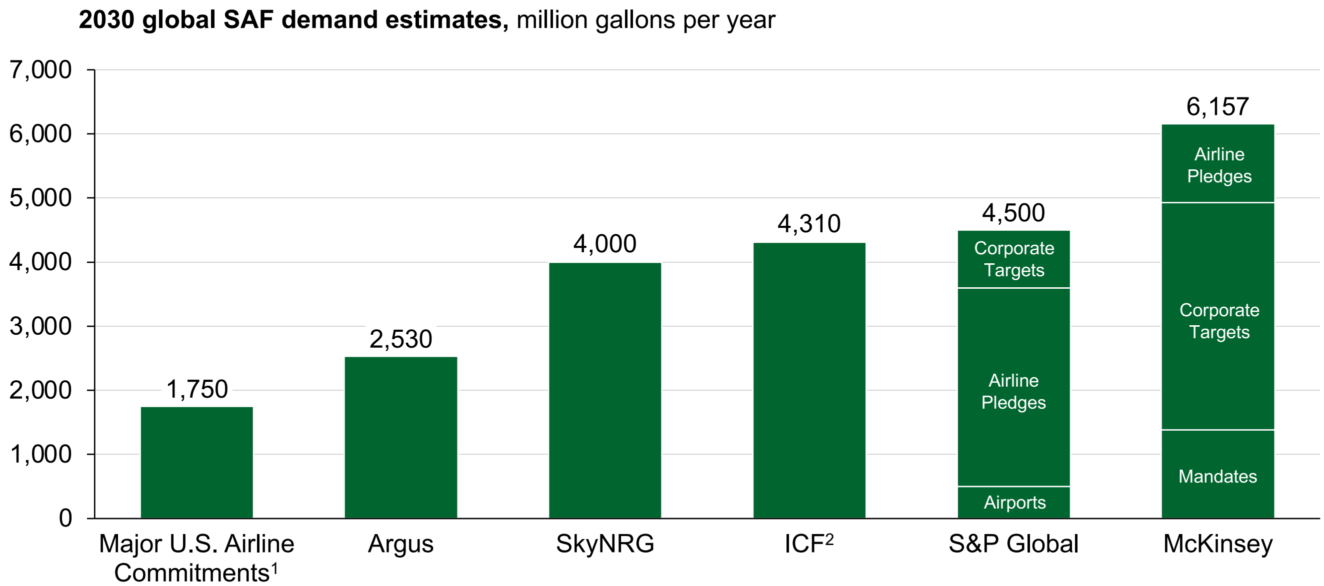


Figure Footnotes: *1. Although only five of the six largest U.S. airlines have explicit SAF targets, this analysis assumes that each of the six largest U.S. airlines increase jet fuel use by 20% between 2023 and 2030 and that each of the six largest U.S. airlines achieve 10% annual SAF uptake by 2030.*

Data Sources: *Argus Market Research 2024; ICF;[27] McKinsey;[28] SkyNRG;[29] S&P[30]*

By 2030, the U.S. is expected to represent half of global production and thus will be well-positioned to capture much of this global demand.

Figure 11: The U.S. is expected to be a major producer of SAF, accounting for 50% of global production by 2030.

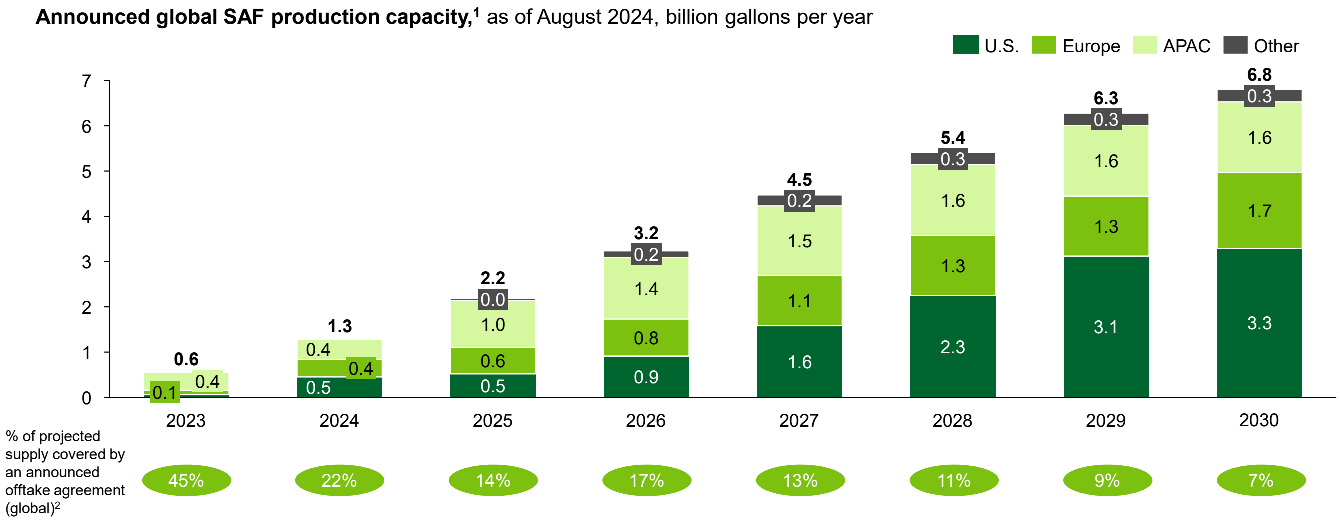


Figure Footnotes: *1. This analysis sums all announced SAF production facilities globally and assumes that all projects in construction, pending FID, or planned today will be operational by their announced COD. The total also assumes that no additional plants that are not already announced will come online by 2030; 2. See Figure 8 for total offtake.*

Data Sources: *BNEF Renewable Fuels Project Tracker;[3] BNEF SAF Procurement Agreements Tracker;[24] ICAO;[25] Industry input*

U.S. SAF Policy

U.S. governments across the federal, state, and local levels encourage SAF investment primarily through incentives, similarly to how they have supported the scale-up of other clean energy technologies. However, these incentives may not be sufficient to cover the cost gap between SAF and its fossil alternative, and as a result, liftoff may be challenged. Federal production tax credits are set to expire in 2027, and low-carbon fuel standards implemented at both the federal and state levels disproportionately incentivize RD over SAF production (see Figure 13).

RFS

Under the U.S. Renewable Fuel Standard (RFS), SAF producers can generate Renewable Identification Numbers (RINs) and sell them to generate additional revenue on top of the fuel itself. The RFS is a program managed by the EPA and requires that transportation fuel sold in the U.S. contains a certain volume of renewable fuel, which then translates into a Renewable Volume Obligation (RVO) for fuel producers and importers (obligated parties under RFS). RINs certify RFS qualification and can be traded amongst oil and gas majors and fuel purchasers, enabling obligated parties to meet their RVO. Recently, increased biofuel production has placed downward pressure on D4 RIN values, with D4 RINs decreasing in price from $1.50 per gallon in 2023 to $0.75 per gallon in 2024, on average (see Appendix 3, Figure A1 for a chart of D4 RIN prices over time).

Federal Tax Credits

The IRA introduced several tax credits for the production of SAF, clean fuels and its inputs (see Appendix 2 for the full list of credits). 40B directly subsidizes the production of SAF; however, it expires at the end of 2024. SAF will then be eligible for 45Z—a tax credit that incentivizes the production of a broad category of clean fuels, including both SAF and RD, from 2025 through 2027. Additional guidance for 45Z is forthcoming as of the time of writing.

Other federal tax credits could potentially lower the production cost of SAF by incentivizing inputs to the supply chain, including 45V for clean hydrogen production and 45Y and 48E for clean electricity production and investment.

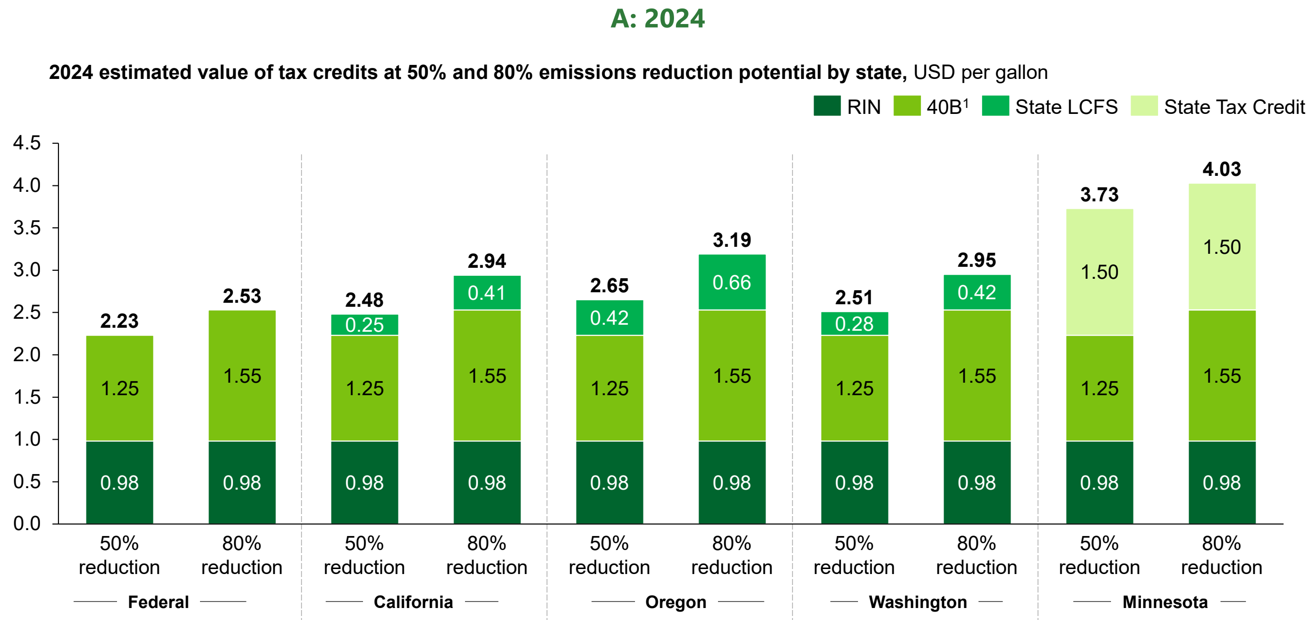
State-Level Incentives

Producers can stack state-level incentives with federal incentives. Several states, including California, Washington, and Oregon have passed Low Carbon Fuel Standards (LCFS) which provide credits to projects that either produce or sell low carbon fuels (including RD and SAF) in their jurisdictions. Minnesota, Nebraska, and Washington also have tax credits directly for SAF production in their states. On the demand side, Illinois recently passed a law that provides $1.50 tax credit for SAF purchased by a common air carrier in the state.

Figure 12 shows how the value of state-level incentives, policies, and programs can vary in the period 2024 (when 40B is in effect) and in 2025-2027 (when 45Z is in effect). This figure analyzes SAF with 50-80% lifecycle emissions reductions and does not include SAF that might reach over 80% reductions (i.e. e-SAF or waste-to-gas SAF). In 2024, the value of stacked state and federal incentives ranges from $2.23-4.03 per gallon depending on the carbon intensity and production location of the SAF. The combined value of these policies can meaningfully offset SAF prices and make SAF more competitive with fossil jet fuel (see Figures 23, 24 and Appendix 2 for additional analysis of current SAF cost and incentives).[xvii] In 2025-2027, incentives per gallon could decrease to $1.09-3.57, predominantly due to the lower anticipated value of the 45Z tax credit compared to 40B. These numbers are estimates, since guidance on incentive values for specific pathways is not currently available.

xvii Note, the price or delivered cost of SAF may be higher due to added transportation, storage, and blending costs on top of production costs.

Figure 12: State-level policies can double the credit value of SAF production, especially in states with SAF-specific incentives; state credit values may increase in 2025-2027.



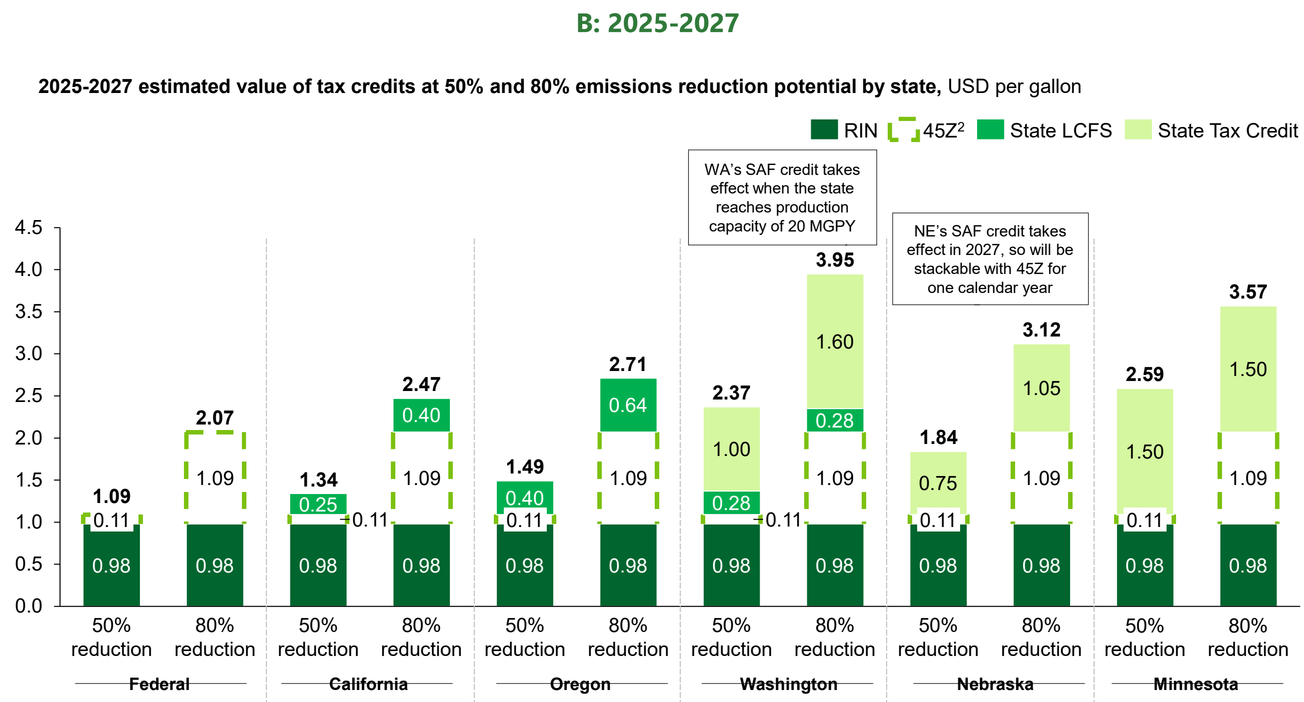


Figure Footnotes: *1. This analysis assumes projects meet the prevailing wage and apprenticeship requirements and does not include any demand-related incentives. The Illinois SAF Purchase Tax Credit could provide an additional $1.50 per gallon to any SAF purchased in the state of Illinois, irrespective of where it was produced. It can thus be added to any SAF produced in any state whose production tax credit or LCFS does not mandate that the SAF be purchased and used in that state; 2. 45Z guidance is not finalized, totals represent estimated values.*

Data Sources: *CA LCFS Regulation as of June 2024;[31] Nebraska Ethanol Board;[32] NREL;[15] Oregon LCFS Regulation as of June 2024;[33] RIN Prices as of June 2024;[4] RMI;[34] Washington CFS Regulation as of June 2024[35]*

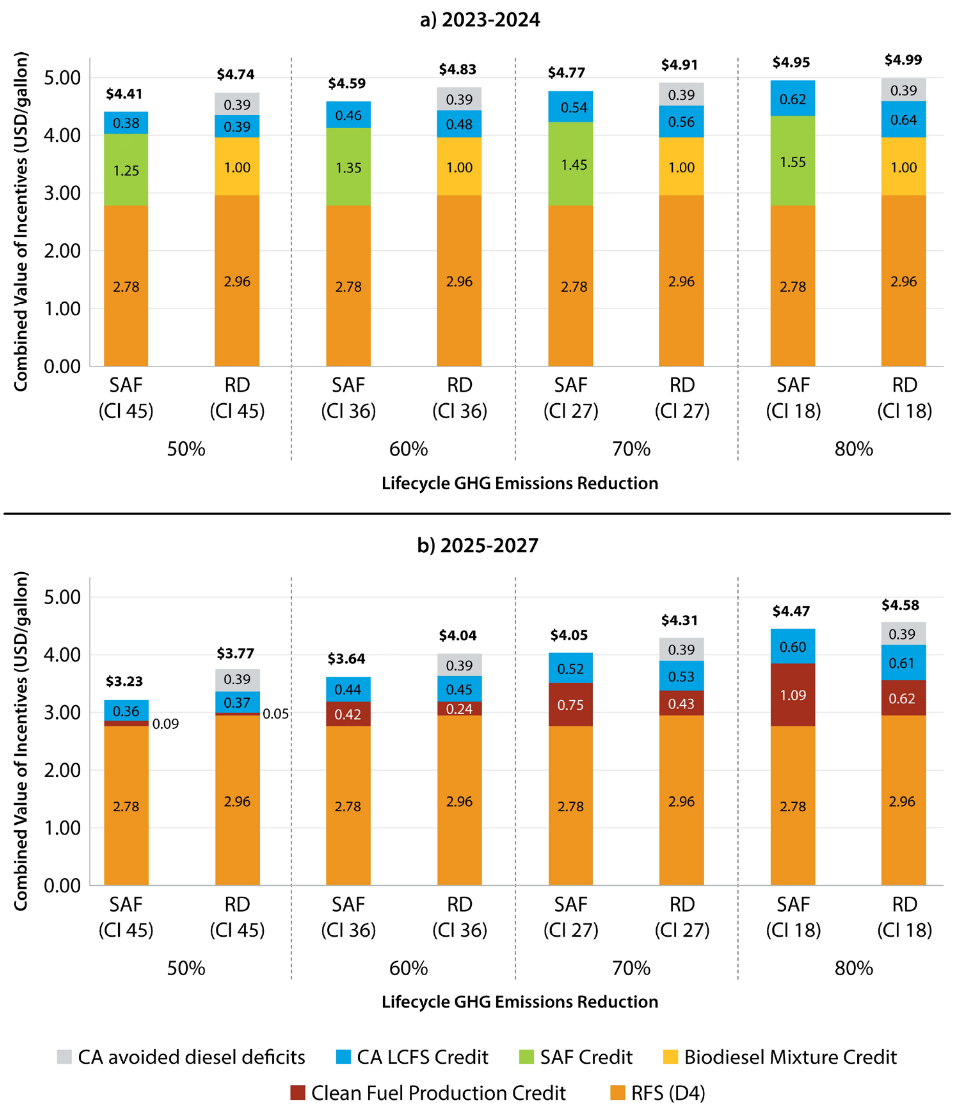
Despite the attractive value for policy-supported SAF, there are concerns in the industry about possible reductions in the value of compliance program credits and the expiration of existing incentives. This creates uncertainty and reduces future and longer-term investment in SAF.

Additionally, the combined value of incentives for RD is greater than the combined value of incentives for SAF produced by the same HEFA pathway, assuming the same CI scores. Figure 13 shows how from 2023 through 2024, for an illustrative CI of 18 gCO_2e/MJ (equivalent to 80% GHG emissions reduction compared to fossil jet fuel), SAF receives a combined \$4.95 in credits, and RD receives \$4.99. For 2025 through 2027, for a CI of 18 gCO_2e/MJ, SAF receives a combined \$4.47, while RD receives \$4.58. Tax credit values differ when using different illustrative CI scores.

Furthermore, SAF is more expensive to produce than RD. To produce a gallon of fuel, SAF requires more hydrogen and yields less carbon than RD. HEFA producers note that a facility producing 100% SAF will be 86% less efficient than the same facility producing 100% RD. In addition, fossil diesel typically sells at a higher price compared to fossil jet fuel, presenting an opportunity for higher margins for producers to sell RD over SAF. In other words, under current policy, RD producers can make more fuel and sell more fuel at higher margins, while also receiving more tax benefits than SAF producers. Much of the production cost disadvantage of SAF relative to RD comes from its relative technological nascence.

Notes on Figure 13: Other states have similar but different incentive structures. The credit values in Figure 13 vary slightly from the stacked incentives throughout the rest of this report, because this figure uses 2023 data for RFS and CA LCFS credits, while the other figures in the report use June 2024 RFS and LCFS credit values. In Figure 13 (a), representing 2023-2024, the "SAF Credit" refers to the 40B tax credit introduced with the IRA. In Figure 13 (b), representing 2025-2027, the "Clean Fuel Production Credit" refers to the 45Z tax credit introduced with the IRA. Note that this analysis, like that in every figure in this report, assumes that prevailing wage and apprenticeship requirements are met. The Illinois SAF Purchase Tax Credit could provide an additional \$1.50 per gallon to any SAF purchased in the state of Illinois, irrespective of where it was produced. It can thus be added to any SAF produced in any state whose production tax credit or LCFS does not mandate that the SAF be purchased and used in that state.

Figure 13: In California, RD production is more incentivized than SAF production.



Source: *NREL*[15]

SAF Blending, Transport and Storage

SAF is a drop-in replacement for fossil jet fuel because it can be blended with fossil jet fuel and then transported, stored, and utilized in the same way as fossil jet fuel, thus minimizing the need for midstream infrastructure build-out. Indeed, SAF producers can tap into existing pipeline, truck, and rail transport networks. That said, some new investments must be made to enable the blending process with fossil jet fuel.

Without significant financial and operational support, airports are unlikely to own or operate their own blending facilities due to the high cost of equipment and software required, so developers must establish a blending facility upstream from the airport itself to deliver the blended fuel. The lowest-cost option is to leverage existing refinery infrastructure for blending, although refineries are often sized to their own production capacity and may not be able to take in new blend stock. As a result, the next best option is typically to site a blending facility near an airport.[36]

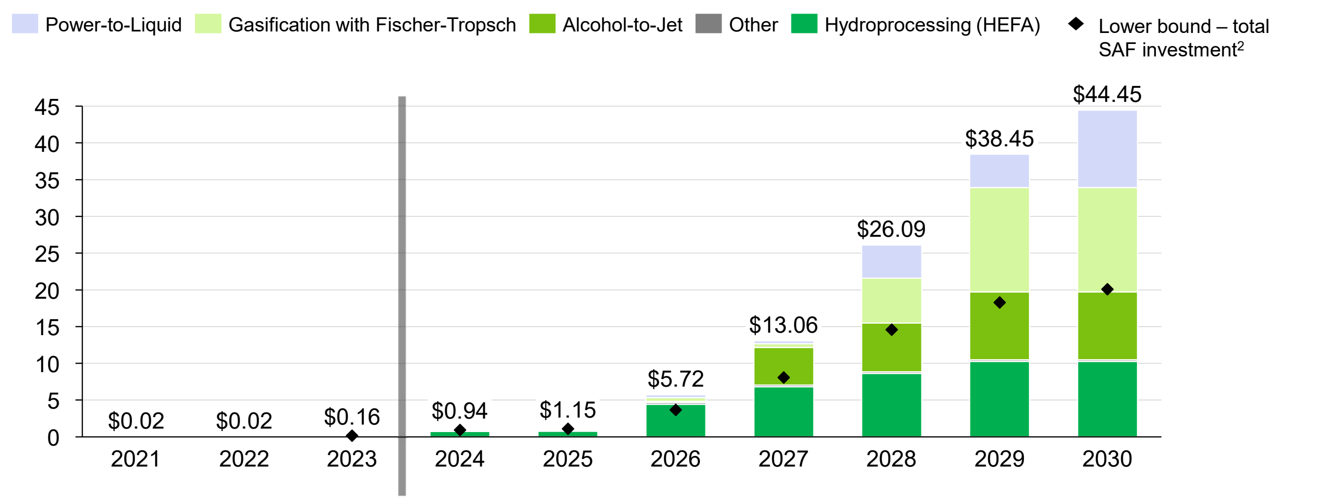
SAF Investment

Despite limited domestic investment in SAF to date, announced investment is projected to increase year over year through 2030, reaching $44 billion in 2030. By 2030, 15 projects of commercial scale (100+ MGPY in nameplate capacity) are expected to be operating.

However, like production estimates, industry expects that total investment in 2030 may be halved relative to announced investments given challenges associated with high production costs, lack of long-term offtake, and policy uncertainty, which could diminish total investment to as low as $20 billion through 2030.

Figure 14: Despite limited historic investment in SAF production in the U.S., planned investment is expected to increase year over year, reaching $44 billion in 2030 across 15 production facilities with a nameplate capacity over 100 MGPY.

Cumulative historic and planned U.S. SAF investments based on year of project completion,[1] as of August 2024, billion USD



Total # of announced facilities (cumulative), upper bound

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
>50 MPGY	0	0	0	2	2	5	10	14	18	20
>100 MPGY	0	0	0	2	2	3	6	9	13	15

Figure Footnotes: *1. Not all production necessarily achieves a 50% emissions reduction to qualify for SAF. This analysis uses the total investment associated with all announced SAF production facilities in the U.S. The total does not include additional investment from projects that will be announced from April 2024 through 2030. Investment amount attributable to SAF is calculated based on: A) If project is SAF-specific facility, assumes 100% of investment is attributable to SAF; B) If project is a co-processing facility, multiplies the % of total capacity dedicated to SAF by the total project investment; 2. Success factors for projects are based on DOE estimates and the proportion of investment for each technology remains similar in this lower bound.*

Data Sources: *BNEF;[3] Industry input*

Chapter 3: Pathway to Liftoff

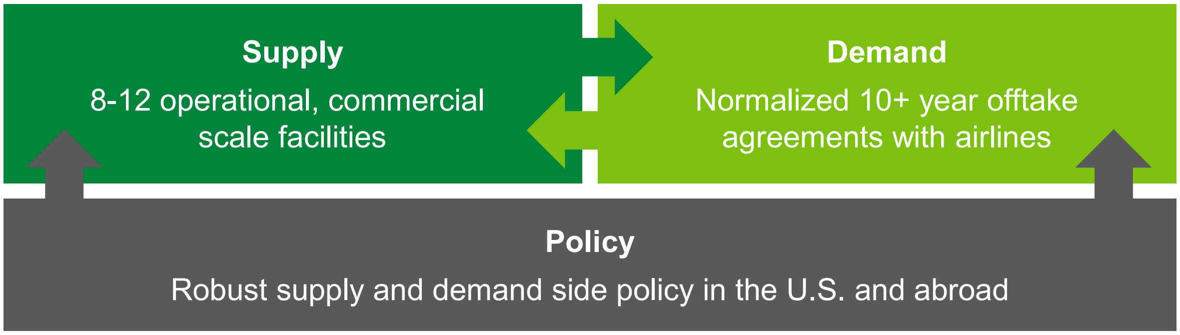
KEY TAKEAWAYS

- **Liftoff will require a near-term focus on the deployment of technologically ready pathways, but these bio-feedstock pathways will require significant investment in upstream supply chains. Investors should invest now in more technologically and commercially nascent pathways that may have fewer feedstock restrictions and lower CI scores over time.**
- **Liftoff will also require that airlines pursue innovative offtake agreements that can provide greater demand certainty. These agreements can include strategic investments into the SAF production chain to secure preferred pricing, or the activation of third parties looking to acquire SAF's environmental attributes.**
- **These agreements will require a reconfiguration of SAF's value, shifting from a per-gallon to a per-metric ton of CO_2 abated basis and including book and claim allowances in standards bodies like the Greenhouse Gas Protocol (GHG Protocol) and the Science Based Targets Initiative (SBTi).**
- **Even with these demand drivers, achieving SAF liftoff may require additional policy support.**

Defining Liftoff

For SAF to reach commercial liftoff, three correlated imperatives must be met:

1. **At least 8-12 commercial-scale production facilities, with an average production capacity of 100 MGPY each, must be operational.** This total capacity represents a meaningful step towards the SAF Grand Challenge targets and accounts for current challenges associated with higher interest rates and a more difficult financing environment in recent years. Most of these facilities will utilize the HEFA pathway given its relative technological maturity and commercial readiness. Many of these projects will be located in states with low-carbon fuel standards or SAF production tax credits or in states with existing refinery infrastructure that can be converted to SAF production (refer to Figure 7). These facilities may require only $10 billion of investment (refer to Figure 14), given that biofuel producers can leverage existing upstream and downstream infrastructure, in addition to brownfield sites and oil refineries. Additional investment will be needed to support non-HEFA pathways, which will be at a smaller by 2030.
2. **10-year+ offtake agreements must be normalized between airlines and producers.** Today, there is a structural disconnect amongst the parties to a SAF purchase, as each party derives value from different products. Airlines procure and use the fuel directly, fuel producers capture the value of certificates from renewable and low-carbon fuel standards, and third parties might benefit from the environmental attribute of the fuel (its carbon abatement potential). Depending on the location of the fuel's production and usage, different parties can capture different tax credit values. The complexity and variability in goals and values have limited SAF offtake to short-term, low-volume contracts. These contracts might benefit currently operational projects, but pre-operational projects require longer-term offtake to reach final investment decision (FID). Ideally, projects receive contracts for the duration of their plant life, although 10 years can be sufficient to build the plant and ramp operations.
3. **Additional policy support is needed to incentivize supply and demand for SAF.** SAF needs to become price competitive with fossil jet fuel to service widespread usage. Some additional policy levers—potentially including but not limited to incentives, mandates, and updated carbon accounting methodologies for aviation—would be needed to achieve cost-down and scale-up (see Figures 23-26). The federal and state SAF production and consumption incentives today meaningfully lower the cost of SAF. However, direct federal subsidies for SAF tax credits are set to expire at the end of 2027.



It is possible that these three imperatives can be met by 2030; the following sections articulate how.

Scaling Supply

Although SAF can be produced via multiple pathways that leverage multiple feedstocks, HEFA is the most technically and commercially mature technology. As a result, HEFA SAF will likely comprise 60-70% of domestic SAF production by 2030 under current global policy.

Note on Figure 15: The carbon intensity reduction was calculated using the 40BSAF-GREET 2024 model for available pathways. The values may differ from the values in future tax credit GREET models.

Figure 15: HEFA may be the most technically and commercially mature of analyzed SAF production pathways, although more nascent pathways introduce higher CI reduction capabilities.

Production Method *Feedstock*	**Carbon Intensity Reduction,[1,2] %** *Compared to Fossil Jet A*	**Expected 2030 Production,[3] %**	**NOAK cost,** USD per gallon	**TRL**	**ARL[4]**
HEFA *Used Cooking Oil*	80–90%	66%	$4 – 11	8–9	7
HEFA *Soy*	55–65%		$4 – 11	8	5
AtJ[5] *Corn*	15–50%	23%	$4 – 9	7	3
AtJ[5,6] *Corn + CCS*	55–90%		$5 – 9	6	3
FT[7] *Biomass*	Up to 100% depending on inputs and assumptions	0%	$3 – 11	4	1
PtL[8] *Captured CO_2 & Clean H_2*	Up to 100% depending on inputs and assumptions	8.6%	$6 – 20	3–4	1

Figure Footnotes: *1. For available pathways in the 40BSAF-GREET 2024 model, carbon intensity reduction (GHG 100-year reduction) is calculated using sample inputs unless otherwise noted. Note that these sample model values are illustrative only and meant to be modified by users to calculate lifecycle carbon emissions associated with their projects. For pathways in this table that are currently unavailable in 40BSAF-GREET (FT and PtL), carbon intensity reduction is calculated based on other publicly available models and literature; 2. Consistent with carbon emission reduction strategies provided in 40B guidance and 40BSAF-GREET, across all available pathways, the high-end of CI reduction assumes use of renewable electricity credits (RECs) to reduce grid-related emissions, use of landfill gas-derived renewable natural gas with a counterfactual of flaring in place of fossil natural gas, and use of 45V modeled H_2 with the sample 45V modeled H_2 CI (3 kg CO_2e/kg H_2) in place of fossil H_2; 3. HEFA production capacity is not broken out by feedstock and AtJ production capacity is not broken out by inclusion of CCS; 4. The methodology for ARL determinations is available in Appendix 5; 5. The high-end of CI reduction for AtJ pathways assumes use of landfill-gas derived renewable natural gas in place of fossil natural gas for ethanol production, in addition to the SAF production assumptions listed in Figure Footnote 2; 6. AtJ + CCS assumes 285,000 metric tons of CO_2 captured and stored as part of the ethanol production process; 7. FT is not an available pathway in 40BSAF-GREET, although FT with certain biomass feedstocks could result in 100% carbon intensity reduction depending on inputs and assumptions including but not limited to available co-products, transport emissions for biomass feedstock, and inclusion of CCS; 8. PtL is not an available pathway in 40B-SAF-GREET, although PtL can result in 100% carbon intensity reduction depending on inputs and assumptions including but not limited to the biogenic CO_2 source and electricity source for clean H_2 production.*

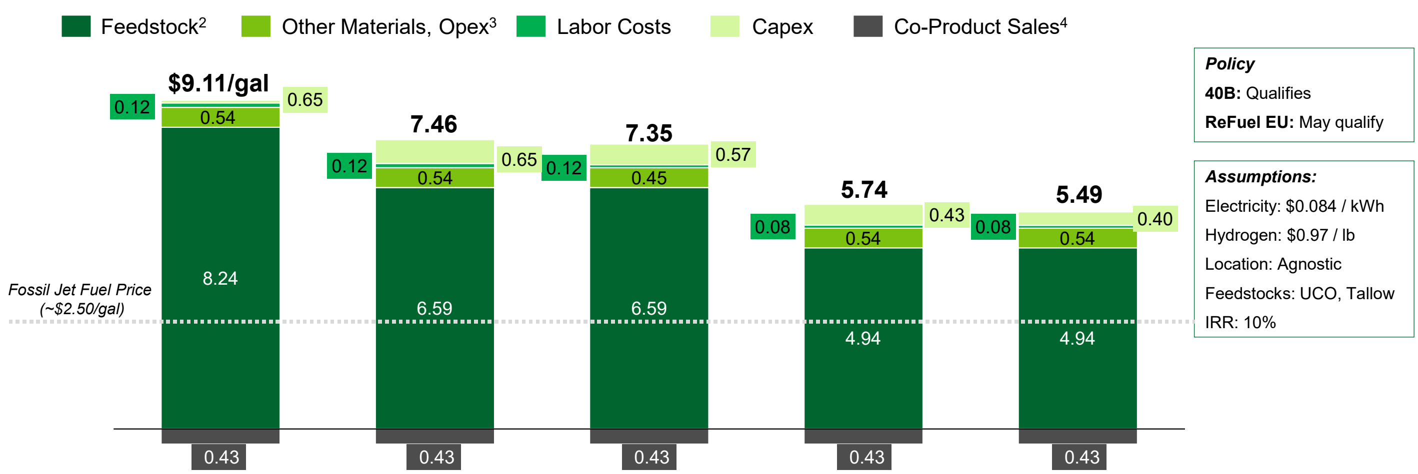
Data Sources: *40BSAF GREET 2024, accessed October 2024;[37] Other publicly available models and literature on carbon accounting*

The primary driver for HEFA's relative maturity is that HEFA technology is similar to RD technology. It also utilizes the same feedstocks, allowing developers to leverage existing upstream supply chains. RD is an industry that is already at commercial scale, with three billion gallons of annual production capacity today, so developers can not only convert existing RD facilities into SAF facilities but also apply technical know-how to new SAF facility construction and operations.[38]

Figure 16 illustrates the unit production costs for an illustrative HEFA facility using a blend of feedstocks (including UCO and tallow) and possible cost-reduction levers. 80% of HEFA costs are driven by feedstock prices, which are commoditized and unlikely to decrease over time. Figure 18 shows how feedstock costs have increased in recent years. There are some levers that can reduce HEFA costs from $7.46 per gallon to $5.49 per gallon.[xviii] For example, tripling the size of the production facility can decrease unit production cost estimates by 10-15%.

Figure 16: Feedstock costs represent over 80% of total unit production costs for HEFA SAF; 10-20% reductions in production costs can be achieved by decreasing financing costs or scaling up facility capacity to achieve economies of scale.

Unsubsidized unit production costs from an illustrative NOAK HEFA facility,[1] USD per gallon



Feedstock Price[4] (USD per pound)	$0.91	$0.73	$0.73	$0.55	$0.55
Facility Capacity (MGPY)	100	100	300	300	300
Debt Interest Rate	8.0%	8.0%	8.0%	8.0%	4.0%
FOAK cost estimate (USD per gallon)	10.69	8.98	8.84	7.17	6.77

Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary; 2. Feedstock scenarios are based on reasonable future prices based on expert input. Feedstock cost includes cost of collection/transport. Feedstock includes a combination of virgin oil and used cooking oil; 3. Cost includes hydrogen, electricity, other chemicals, waste disposal and excludes corporate overhead; 4. Sales include revenue from gasoline and propane.*

Data Sources: *NREL input; RMI input*

Supply Chain Considerations

Given SAF's reliance on low-cost, readily available feedstocks, it is important to ensure a robust upstream supply chain to help keep costs low as production scales. Already, HEFA feedstock prices have increased since 2019 with the rise in SAF and RD production and with the more constrained quantities of those bio-feedstocks.

xviii That said, as HEFA continues to scale, upstream supply chains for bio-feedstock may become more constrained, thus pushing up feedstock prices and negating cost reductions.

Figure 17: HEFA feedstock prices have increased 10-15% in the last 3-5 years, with current prices ranging from $1,200-2,000/ton equivalent.

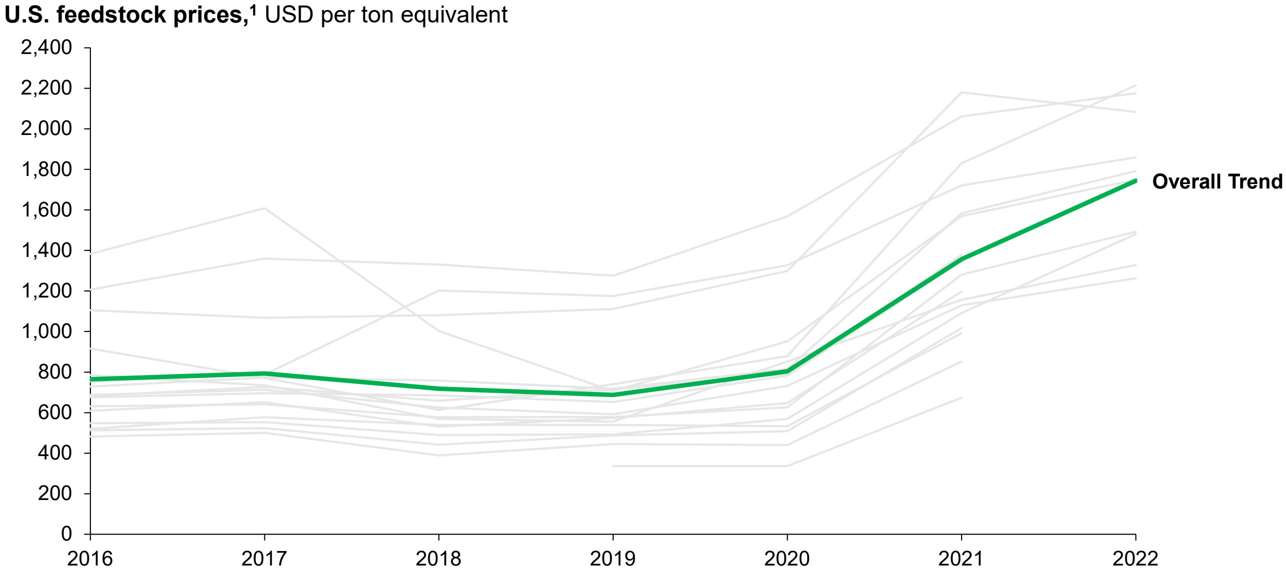


Figure Footnotes: *1. Gray lines include a range of feedstocks including but not limited to canola oil, corn oil, palm oil, soybean oil, tallow, yellow grease, brown grease. This analysis has increased FOG prices by 5%, because FOG feedstocks lose about 5% of volume during preprocessing due to contamination. All other oils, including vegetable oils, reflect market prices.*

Data Sources: *NREL[39]*

HEFA producers are concerned by rising prices and dwindling feedstock availability. Analysis suggests that by 2030, there may not be enough domestically sourced feedstock to supply 100% of planned SAF and 100% of planned RD (see Figure 18).

Figure 18: HEFA may make up to 70% of SAF production capacity by 2030, although production may be limited by domestic bio-feedstock availability; if all announced projects reach their expected COD, the amount of oilseed and FOG required to meet SAF and RD production could exceed forecasted supply.

Feedstock requirements for SAF and RD compared to total U.S. feedstock available in 2030[1]

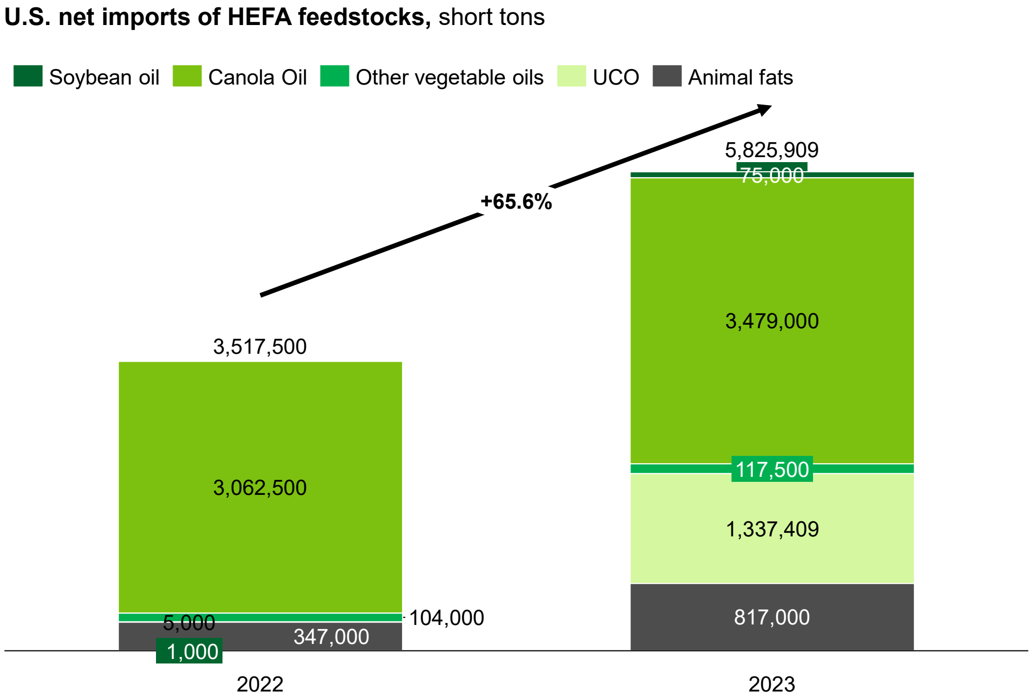
Production Pathway	Feedstock	Total % of U.S. 2030 feedstock supply used for SAF	Total % of U.S. 2030 feedstock supply used for RD	Total % of U.S. 2030 feedstock supply used for SAF and RD[1]
HEFA	**Oilseed and FOG**	**46%**	**148%[2]**	**194%**
AtJ	Starch-based	4%[3]	0.0%	4%
FT	Forest wastes	1%	0.8%	1%
FT	MSW and dry wastes	0.1%	0.0%	0.1%
FT	Agricultural residues	2%	0.0%	2%
FT	Wet wastes	6%	0.0%	6%

Figure Footnotes: *1. Estimates of total SAF and RD produced with each feedstock are based on announced projects and the feedstock that they would require. The Billion Ton report data included sustainability criteria in modelling, but site-specific factors will impact if an individual biomass SAF project would qualify for SAF tax credits or other incentives; 2. Although RD's planned capacity requires relatively more oilseed and FOGs than planned SAF, the same facilities can produce both RD and SAF, so production could be shifted during operations. Regardless, to meet planned production capacity, fuel producers must look to non-U.S. sources; 3. U.S. corn could supply over 3x of projected 2030 demand.*

Data Sources: *BNEF;[3] DOE Bioenergy Technologies Office;[40] NREL[41]*

Due to feedstock scarcity concerns, U.S. producers are increasingly looking to foreign countries to source low-carbon and low-cost feedstocks. Studies have shown that used cooking oil from China can be one-third of the price of domestic vegetable oil, although some stakeholders have noted that traceability and verification of these imported oils are challenging.[42] Some AtJ SAF producers may opt for Brazilian-grown sugar cane ethanol over corn ethanol as their feedstock due to the former's lower CI and potentially lower cost.[43] As SAF and RD production grew in 2022 and 2023, so too did imports. From 2022 to 2023, HEFA feedstock imports grew nearly 66% to 5.8 billion short tons in 2023. Feedstock imports might help lower production costs, but they also introduce traceability challenges (determining the carbon intensity of the delivered feedstock) and limit job growth potential in the United States.

Figure 19: As domestic SAF and RD production increased in 2022 and 2023, imports of corresponding feedstocks increased.



Data Sources: *NREL[39]*

The U.S. must meaningfully scale up and diversify its feedstock production if it is to grow SAF production and maintain American competitiveness. Aside from corn and soybeans, no purpose-grown biofuel feedstock crops are grown at scale today. Furthermore, these crops service food and feed systems in addition to the biofuel market. While there are hundreds of millions of acres of agricultural production lands suitable for cover crops, adoption remains below 10% nationally.[44] Industry can invest in a wide range of intermediate oilseed crops, including domesticated pennycress, carinata, and camelina. By 2030, these oilseed crops could generate up to 1.35 billion gallons of SAF and increase total U.S. oilseed feedstock by 38%, decreasing potential reliance on imported feedstock accordingly.[41] Intermediate oilseed crops can be grown over winter within existing crop rotations, providing the same environmental benefits as cover crops and minimizing impact on availability of cropland for food production. According to DOE's 2023 Billion Ton Report, the U.S. could triple its production of biomass and meet 100% of jet fuel feedstock demand by 2050, but steps need to be taken today to secure this future production.[41]

Consideration of Other Pathways

While HEFA is the most commercially mature pathway, investors and developers should be investing now in innovations across more nascent pathways in order to diversify feedstocks and production capabilities. AtJ, for example, could represent up to 10% of production capacity by 2030 depending on the success of early demonstration plants. PtL and FT, while unlikely to be deployed at commercial scale prior to 2030, should be researched further today so that they are ready for liftoff and can support the SAF market in the decades to come. Diversification of SAF pathways that are at commercial scale in the U.S. will be especially important if HEFA upstream feedstock supply chains become too much of a bottleneck to scale HEFA further.

Figure 20: Timeline for potential commercialization of different SAF production pathways.

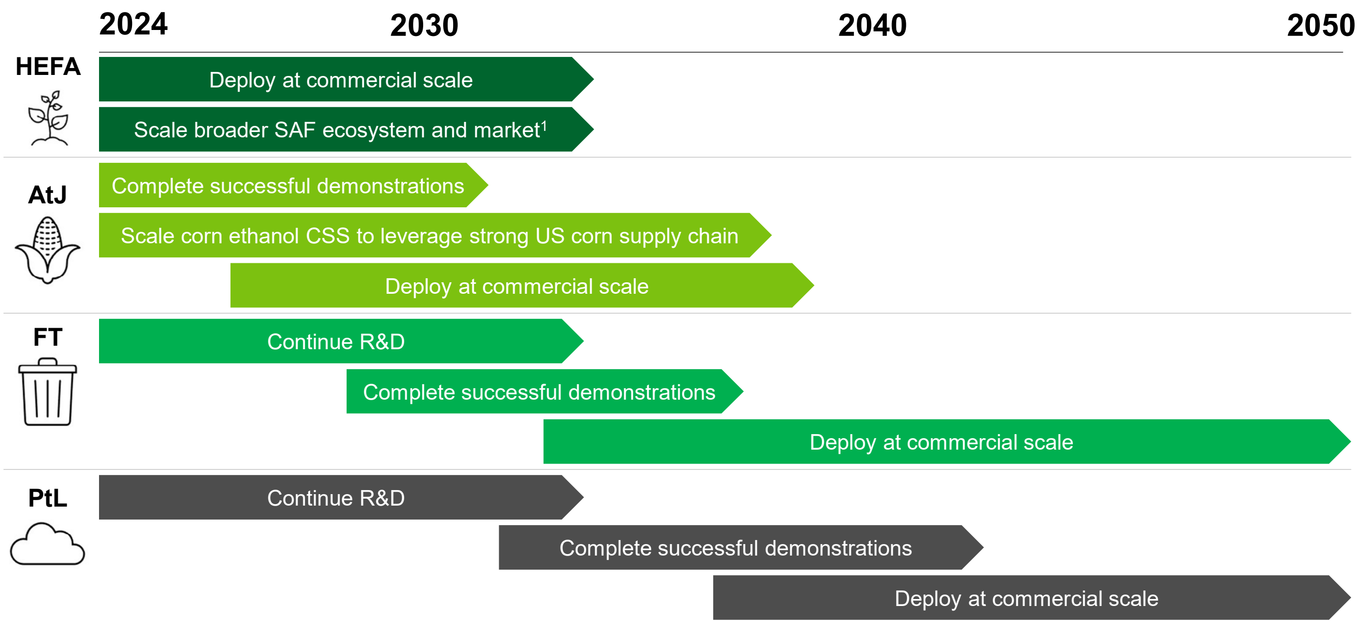


Figure Footnotes: *1. Represents the buildout of feedstock collection and transport infrastructure, pipelines and trucking pathways, SAF blending facilities.*

AtJ

Given some of the challenges with HEFA-related feedstocks looking out to 2030 and beyond, it is important to consider pathways with fewer constraints around feedstock. The next most commercially advanced pathway is AtJ, which could represent about 10% of total SAF production by 2030. The LanzaJet facility in Georgia, the first AtJ demonstration plant in the world, commenced operations this year. LPO recently announced a conditional commitment to Gevo's Net Zero 1 facility, which will produce 60 MGPY of SAF from corn ethanol when fully ramped (see Appendix 2).

Despite the challenges described above, AtJ feedstocks tend to cost less than HEFA feedstocks, which could give NOAK AtJ facilities a cost advantage and close the cost differential with fossil jet fuel over time (see Figure 21). The most commonly pursued pathway utilizes corn ethanol, which has a higher yield (2.9 gallons per bushel and 175 bushels per acre vs. 1.5 gals per bushel and 50 bushels per acre) and lower cost ($1.60 per gallon vs. $3.70 per gallon) compared to soybean oil.[45]

Figure 21: Feedstock costs for AtJ represent a significant portion (70%) of unit production costs, although relatively less than for HEFA (80% feedstock costs); cost reductions may be more readily achieved as technical capacity improves

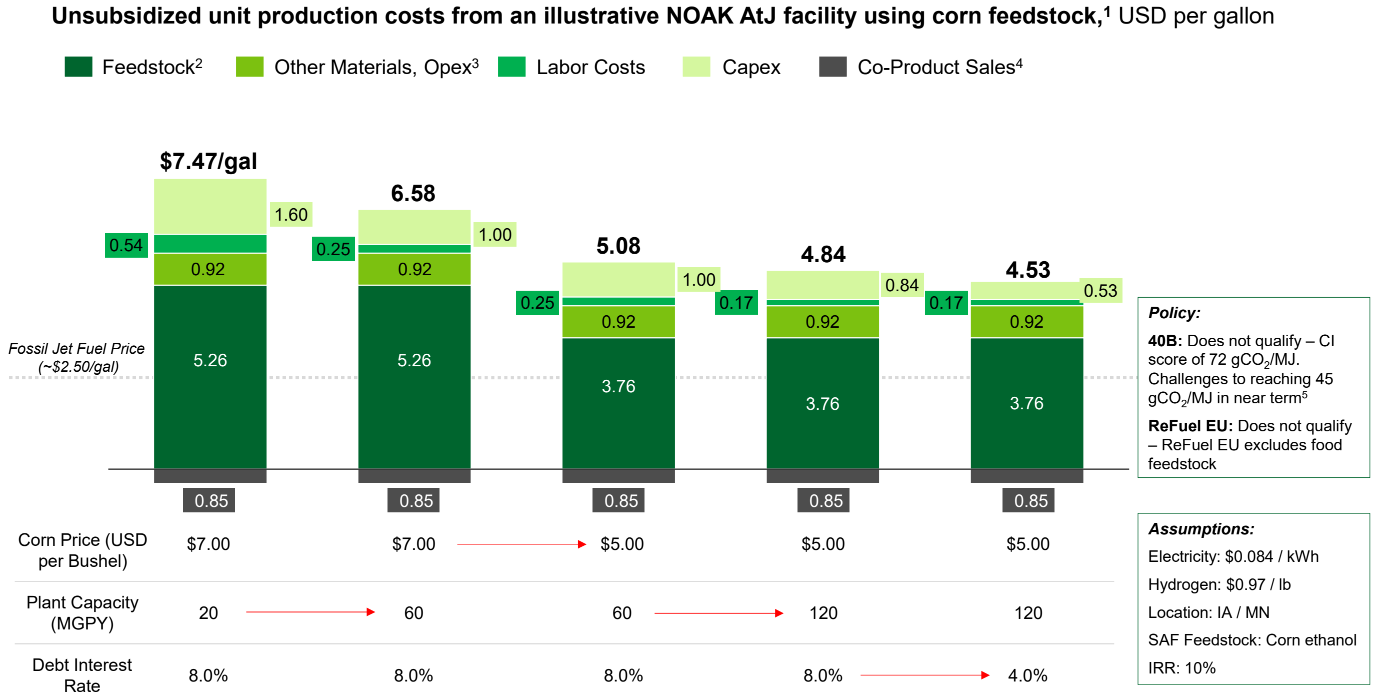
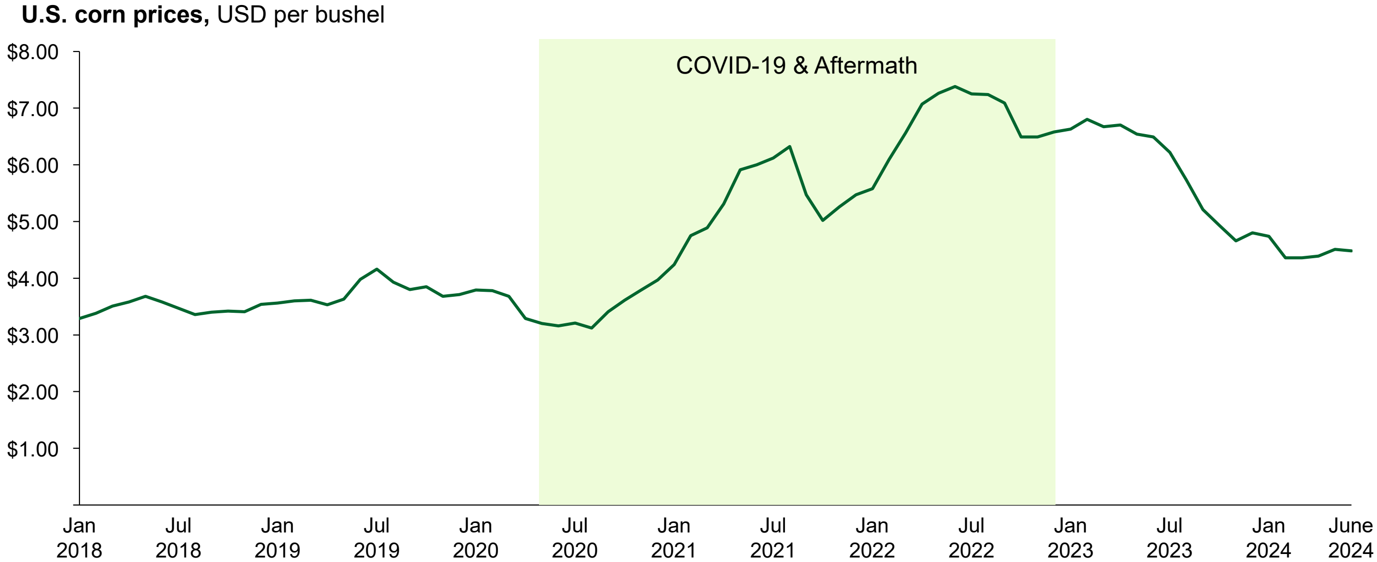


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary; 2. Feedstock prices based on expert input and include collection/transportation; 3. Costs include chemicals, hydrogen, electricity, natural gas, excludes corporate overhead; 4. Includes sales revenue from DDGS and corn oil; 5. CO_2 transportation and storage might challenge emissions reductions potential.*

Data Sources: *NREL input; RMI input*

Corn prices fluctuated and rose significantly during COVID and its immediate aftermath, but prices typically trend between $3-5 per bushel and today sell at $3.83-3.90 per bushel (see Figure 22). Furthermore, as electrification reduces road transportation's demand for ethanol, AtJ SAF could provide a valuable new end-market for corn growers and ethanol producers. Based on currently announced SAF projects, by 2030, up to 4% of all starch-based feedstocks produced in the U.S. could be used for AtJ SAF.

Figure 22: U.S. corn—a potentially large feedstock for AtJ SAF—has seen relatively stable prices apart from market disruption during and immediately following the COVID-19 pandemic; spot prices in August 2024 are closer to $3.90 per bushel.



Data Sources: *USDA*[46]

Despite the supply chain advantages for corn ethanol, its associated CI proves a disadvantage compared to HEFA. The CI today is too high to meet the SAF Grand Challenge criteria. It also may not qualify for the 40B or future 45Z tax credit.[xix] Additionally, any SAF produced directly from food or feed crops does not presently qualify for the EU's ReFuelEU mandate or the UK's proposed mandate.[xx]

To reduce the CI of AtJ SAF produced with corn ethanol, producers could consider adding CCS to their ethanol facilities,[xxi] sourcing corn from farms using climate smart agricultural practices, and replacing fossil gas with renewable natural gas (RNG), which could raise the unit costs of their SAF considerably. Cellulosic ethanol produced from agricultural residues or woody biomass feedstock also provide potential to decrease the carbon intensity of AtJ SAF in order to qualify for the 40B tax credit. See Chapter 4 for more example action items.

PtL and FT

Although less technically and commercially mature than both HEFA and AtJ, both FT and PtL have some of the lowest lifecycle emissions rates of all SAF production pathways. Both pathways can produce CI scores of near-zero when using zero-carbon (or in the case of FT's waste feedstocks, negative carbon) feedstocks. In the case of PtL, feedstock (water and electricity) may be more cost-constrained than supply-constrained. Without incentives, electrolytic hydrogen today costs roughly $5-7 per kilogram (45V tax credit guidance is still being finalized). Furthermore, the PtL process has a high energy intensity (100 kWh per gallon).[47] If a PtL plant were to divert the entire output of the Hoover Dam, approximately four billion kWh annually, to producing PtL SAF, that power would only produce 40-80 MGPY.[48]

It is unlikely that these two pathways reach demonstration scale by 2030; however, given the feedstock constraints for HEFA pathways and CI challenges associated with AtJ, these pathways will play an important role in the SAF economy in the 2030s and beyond.

xix Additional 45Z credit guidance is forthcoming.

xx This stipulation also applies to certain HEFA feedstocks.

xxi Or sell their captured carbon to a third-party for permanent storage

They not only introduce new, lower CI pathways, but they rely on synthetic or waste feedstocks which are unlikely to be limited or constrained over time. Although ASTM has not yet approved all production pathways for SAF produced by these technologies, investors should continue to invest in RD&D (research, development, and demonstration) for these technologies and their value chains, including the scale-up of waste collection infrastructure, and clean hydrogen and electricity sources so that the U.S. can diversify its fuel supply chain and prepare these pathways for commercial-scale deployment once approved. eFuels could become the most scalable and least carbon-intensive SAF available in the market in the long-term. Recently, a FAA Fueling Aviation's Sustainable Transition (FAST) Grant was awarded to a PtL facility: Arcadia eFuels in Gregory, TX.[49]

Additional Pathways

There are also additional SAF pathways that are currently undergoing R&D. Other SAF pathways that are ASTM certified today include synthesized iso-paraffins from hydroprocessed fermented sugars (SIP), synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA), and Catalytic hydrothermolysis jet fuel (CHJ).[11]

Increasing Certainty of Long-Term demand

Offtake agreements today are short-term given the high costs of SAF relative to fossil jet fuel and lack of demand mandates, but a few case studies highlight creative mechanisms to de-risk these premiums for airlines operating in voluntary markets.

There are two products associated with a SAF purchase: the fuel itself and its emissions reduction attribute. When an airline procures SAF directly from a producer, it is blended into Jet-A fuel following ASTM requirements. Once blended it can be transported and burned like fossil jet fuel. If the fuel is transported to an airport, it will enter the airport's hydrant system and get pumped into all the airplanes being fueled by that system. However, the airline that originally purchased the SAF will receive the credit for the low-carbon fuel. After the fuel is combusted in the airplane, airlines can sell the emissions reduction attribute of the SAF to a third-party offtaker in the form of a certificate through a book and claim system, similar to a Renewable Energy Certificate (REC) used in energy markets. Many of these third-party offtakers are large corporates with voluntary net zero commitments looking to offset their Scope 3 emissions.

However, these buyers are not incentivized to commit to long-term offtake agreements, since 1) their emissions reduction program is voluntary; 2) there may be cheaper SAF coming to the market in the next few years; and 3) it is unclear how SAF credits will be valued by SBTi and other standards organizations. As a result, most contracts in voluntary markets are short-term: one- or two-year agreements using spot market prices to procure SAF from already-operational projects. These kinds of offtake do not support projects still in development that need long-term offtake agreements in order to get financing prior to construction. Microsoft recently signed a 10-year offtake agreement with World Energy, which will sell the fuel to local airlines at fossil jet fuel prices, but there are few examples of these agreements in the market today.[50]

However, the combination of incentives in the U.S. for SAF at the state and federal level could make SAF cheaper than direct air capture (DAC) on a cost per metric ton of CO_2e basis (see Figure 26 and Appendix 4 for additional information). Despite extremely low production volumes, DAC credits are the most commonly cited alternative to SAF credits among third-party offtakers given their additionality, permanence and, other benefits.

The other buyers of these certificates are organizations mandated to reduce their emissions. If the mandated organization purchases the environmental attribute or certificate, but does not burn the fuel itself (e.g., it is a corporate partner of an airline flying out of the EU and subjected to the ReFuelEU mandate), then it is retiring the certificate under a book and claim policy. While an effective tool for spurring the SAF market, book and claim is not approved by the Greenhouse Gas Protocol, which has impeded its utilization. Most of the longer-term offtake agreements featured in Figure 9 are from these mandated markets.

Large, long-term (10+ year) SAF procurement contracts are rare today due to the shifting cost environment of the SAF industry, inability of airlines to add additional risk to balance sheets, and lack of mechanisms and accounting required for corporate buyers to participate in the demand market. This lack of demand certainty, particularly from creditworthy counterparties, precludes projects from reaching a final investment decision (FID), creating a chicken and egg problem with scaling up supply. To enable some of these long-term contracts, industry could explore the following mechanisms to mitigate demand risk.

Exploring Innovative Offtake Agreements

There are several strategies that airlines have used and could use to de-risk the price premium associated with SAF, almost all of which involve passing over the cost premium to corporate partners or passengers (see Table 1).

Table 1: A non-exhaustive list of strategies that airlines have used or could use to hedge pricing risk associated with SAF.

Not Exhaustive

Strategy	Description	Demand (current)	Demand (2030)	Examples
Three-Way Agreements for Long-Term Offtake	Airlines commit to buying the fuel (normally at the cost of jet) and third-party offtakers commit to buying the environmental attribute for that same duration. The price of those attributes can either be fixed or 'cost-plus' (floating at a variable premium).	**Medium:** Most of the purchases made by Scope 3 offtakers are either short term or low volume.	**Medium:** These agreements may scale somewhat, but are predicated on the GHG Protocol and the SBTi releasing methodology / standards for how to evaluate SAF credits attributes in the near-term.[51]	In 2022, Twelve, Microsoft and Alaska Airlines signed an offtake contract in which Microsoft accessed the SAF credits associated with Alaska's SAF usage.[52]
Call Options	Airlines can negotiate the right to purchase SAF at a specific price within a specified period.	**Low:** Airlines do not want to commit to long-term contracts without a guaranteed counterparty to buy down the risk.	**Low:** Call options may have a higher SAF premium than other strategies if prices go down.	N/A
Price Collars	Direct procurement of SAF from jet fuel producers to airlines with a set floor and ceiling price for SAF.	**Medium:** Adopting a price floor with shared upside between the airline and producer and a price ceiling with shared risk helps hedge some of the premium risk airlines face when selling out to third-party offtakers.	**High**: Price floors and ceilings are likely to grow in acceptance in mandated markets (e.g., the UK).	As part of their SAF mandate, the UK government has a SAF price collar that includes a price floor (through a buy-out mechanism) as well as a price maximum, designed with the goal to minimize the impact of SAF on ticket fares for passengers.[53]

Strategy	Description	Demand (current)	Demand (2030)	Examples
Direct Investment in SAF Projects	Airlines can strategically invest in SAF projects to derisk project development and access preferred pricing for SAF. Airlines could also strategically invest in other parts of the SAF value chain other than the facility itself (e.g., feedstock procurement upstream, blending facilities downstream).	**Low**: Several airlines have dedicated funds to make small, early-stage equity investments in strategic innovations to secure future offtake. Airlines may not have to invest off their balance sheet, but they are limited by the size of their fund to procure SAF at scale through their venture arms.	**Medium:** International, state-supported airlines might also play a larger role in direct SAF investment over time.	In 2023, United Airlines Ventures invested in Cemvita and secured offtake of up to a billion gallons over 20 years from Cemvita's first commercial facility.[54] Southwest Airlines has a strategic investment in the SAFFiRE facility, which broke ground in 2024.[55] KLM and Qantas Airlines are part of SAFFA (Sustainable Aviation Fuel Financing Alliance), an investment fund that bought and renovated another ethanol plant in the U.S. in 2024.[56]
Indirect Investment in SAF Projects	Financial sponsors can make investments in SAF projects while also partnering with airlines and/or other third-party offtakers and pass over the SAF credits to derisk projects.	**Medium:** With a growing recognition that SAF is difficult to procure, third-party offtakers are interested in procuring SAF credits at preferred prices (typically on a $/ton basis).	**High:** Financial sponsors are expected to support distributing risk over a larger cohort of counterparties that may be more creditworthy than airlines.	Breakthrough Energy Catalyst invested $75 million in project equity into an Infinium PtL facility, which partnered with American Airlines to guarantee offtake. In addition to this deal, American and Citi made a separate offtake agreement for Citi to procure the SAF credits from American's usage of this fuel.[57] Brookfield recently announced a $1.1 billion investment into the same company.[58]
Ticket Surcharges	Airlines could distribute additional cost associated with SAF procurement to passengers in the form of higher ticket prices.	**Low:** In a highly competitive market with price sensitive customers, airlines are unwilling to price their fares higher and risk losing market share.	**Low:** The competitive dynamics to keep costs as low as possible are likely to be sustained in the future; only if more markets follow Europe and Asia with mandates will ticket surcharges become the industry norm.	Lufthansa announced an environmental cost surcharge in June 2024, that will apply to all departures from EU-27 countries starting in 2025. The surcharge for economy tickets will range from $1-5 for short and medium haul flights and $6-12 for long haul flights. The long-haul, first-class ticket surcharge will range from $36-72.[59] The Singapore government is introducing a SAF levy that will range from $2-12 for economy tickets to help pay for SAF.[60]

Standardizing SAF's Environmental Attributes

If the market shifts its thinking of SAF from merely a low-carbon fuel alternative, priced in dollars per gallon, to a low-carbon alternative broadly defined, priced in dollars per CO_2e abated, the market size will expand dramatically. Due to the low margins of the airline industry, airlines are unlikely to voluntarily adopt SAF, as the benefits of being known as a "green carrier" and associated positive media attention may not offset the price of the more expensive "green" fuel. There are, however, other entities that would be willing to pay this premium. Corporate aviation partners are looking for low-cost, high-visibility instruments to reduce or cover their Scope 3 emissions impact. They value and price SAF according to its dollar value per metric ton of carbon reduction potential, rather than its dollar value per gallon.

- Corporate offsets through SAFc could play a more significant role in scaling SAF if standards bodies like GHG Protocol and SBTi approve them and provide a more universally recognized framework for attributing SAF's environmental attributes. Today, neither organization has approved book and claim. As a result, SAF can only be used today to account for an airline or shipping company's Scope 1 emissions. This potentially stifles demand from corporate entities who are interested in buying SAFc to offset their Scope 3 emissions impact. Today, some third-party offtakers are already purchasing SAF credits, even though they cannot be formally counted as official emissions reductions under SBTi and the GHG Protocol.[61] Figure 26 highlights how the carbon abatement potential of SAF is cost competitive to the carbon abatement potential of other decarbonization solutions, like DAC. Should these widely accepted standards accept the virtual procurement of SAF to cover a corporate's carbon footprint, the SAF market could flourish.
- More work is needed before SAF's environmental attributes are accepted. All stakeholders need to support a singular carbon accounting standard globally to reduce uncertainty around SAF's associated carbon intensity. Today, traceability remains a key concern for biofuel feedstocks and collections processes must be better understood. SAF's value chain is complex and touches numerous stakeholder groups (see Figure 2), making emissions calculations and tracking difficult. DOE has begun this work by compiling data on SAF production.

Shoring Up Supportive Policy

Given the considerable and ensuring price premium associated with SAF, the industry cannot achieve liftoff without a long-term supportive network of supply- and demand-side incentives and mandates. The supply-side incentives in place today at the federal and state governmental levels can decrease the production cost of SAF by up to 60% in certain states, although it remains at a significant premium to fossil jet fuel on a per gallon basis. Similarly, demand-side support in the form of current and proposed national and supranational mandates is helpful but insufficient to scale the SAF economy.

Expanding Supply-Side Policies

Governments could support SAF's liftoff by supporting SAF's production in addition to the production and collection of its feedstocks. The RFS and most state-level LCFS do not account for the relatively higher production costs of SAF compared to other low-carbon fuels. SAF-specific incentives, such as the Minnesota SAF tax credit, could be more effective at scaling SAF production than general support for low-carbon fuels.

Current federal incentives can reduce the cost by 20% in the near-term, but the 40B SAF production tax credit expires at the end of 2024. Starting in 2025, the federal tax credit value under the 45Z clean fuel production tax credit may be smaller.[xxii] Federal incentives alone do not provide sufficient incentive to spur a SAF economy; state policies are crucial to making SAF more cost competitive with fossil jet fuel.

xxii 45Z guidance has not been released as of September 2024.

Figure 23: Federal incentives can help reduce the cost of SAF by 30% in 2024, although the value of incentives may decrease starting in 2025.

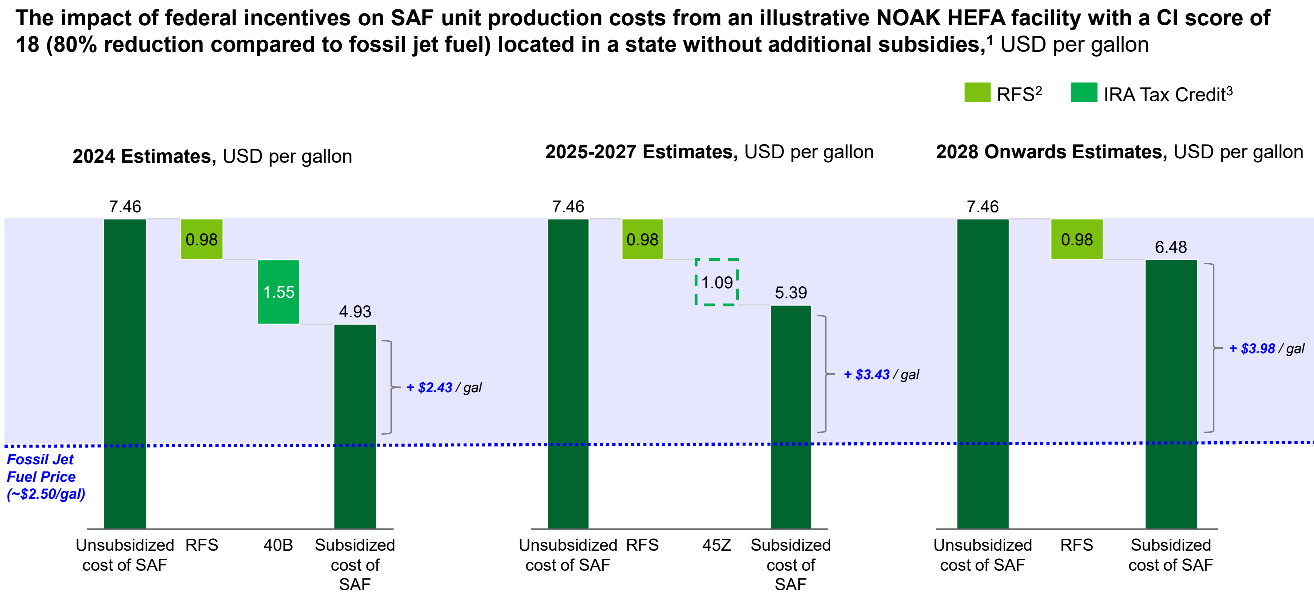


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN values; 3. Final treasury guidance for 45Z is to be released. Calculations for this analysis follow NREL's methodology.*

Data Sources: *NREL*[15]

The subsidized cost of a SAF gallon decreases significantly when stacking state and federal incentives. Figures 24 and 25 highlight the estimated production costs of HEFA SAF in California and Minnesota, respectively. In California, the LCFS can contribute an additional $0.40 per gallon to decrease the cost of a gallon of SAF to $4.52-6.07. In Minnesota, a state tax credit provides $1.50 per gallon of SAF, decreasing the price per gallon of SAF to $3.43-4.98. The impact is larger in Minnesota, where there is a SAF-specific tax credit, compared to in California, where the LCFS provides a smaller incentive for SAF, both in absolute terms and relative to the incentive provided for RD.

Figure 24: California's LCFS brings down the unit production cost of SAF by an additional 10% when stacked with federal incentives in the near-term.

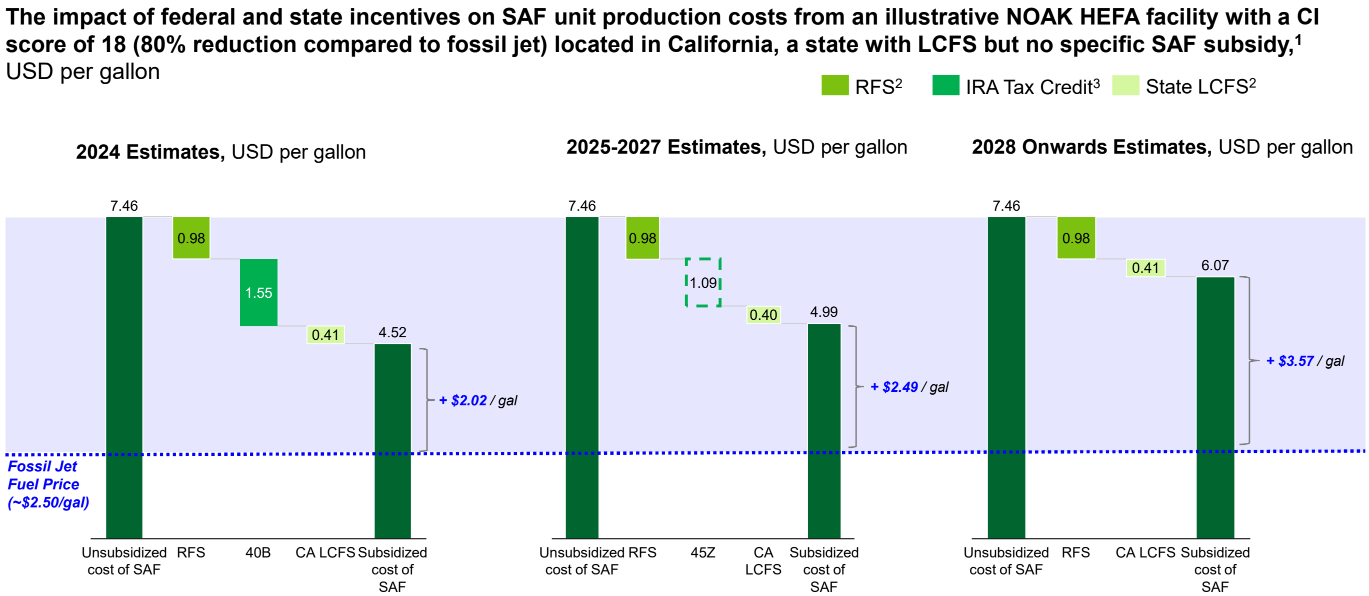


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN and LCFS values; 3. Final treasury guidance for 45Z is to be released. Calculations for this analysis follow NREL's methodology.*

Data Sources: *NREL*[15]

Figure 25: Minnesota's SAF-specific tax credit reduces production costs by an additional 30% when stacked with federal incentives, indicating a greater impact than more general LCFS.

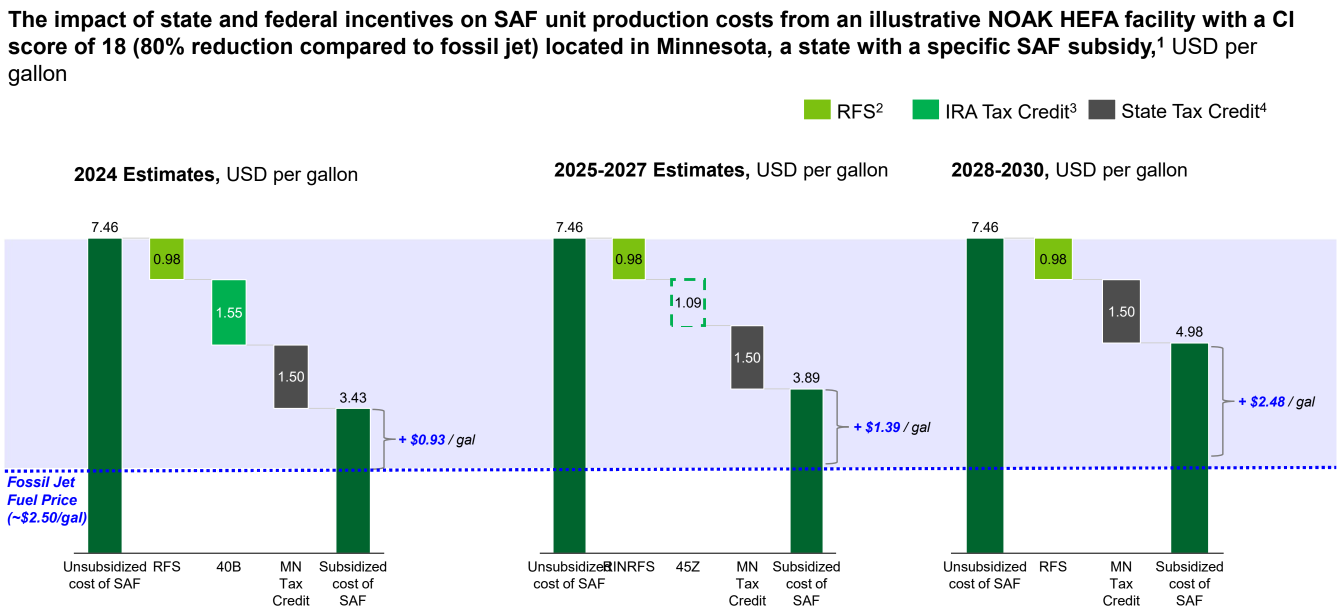


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN data; 3. Final treasury guidance for 45Z is to be released. Calculations for this analysis follow NREL's methodology; 4. MN tax credit expires in 2030, leaving only RIN credits in 2030 onwards.*

Data Sources: *NREL*[15]

See additional state-by-state analysis of cost of SAF when including federal and state credits in Appendix 4.

When federal and state credits are stacked, the economics of SAF significantly improve, especially when compared to other actions that carbon emitters might take to abate their aviation-related emissions, such as DAC credit purchases. These federal and state incentives help make SAF more attractive to both offtakers looking to decarbonize their aviation emissions (insetting) and offtakers looking to lower their emissions across all business operations (offsetting). These offtakers typically evaluate SAF not on the value per gallon of fuel but rather the value per metric ton of carbon dioxide abated that fuel represents.

Figure 26 highlights how federal and state incentives, if extended, play a critical role in making SAF more competitive on a per-metric ton basis, which would potentially encourage offtakers to buy SAF offtake rather than pursue other carbon credit options like DAC credits.

Note on Figure 26: This analysis is based on the federal and California incentives for SAF as of June 2024. Federal production tax credit 40B expires at the end of 2024 and 45Z will take effect from 2025 through year-end 2027. NREL's cost data reflects theoretical NOAK unit production costs and theoretical carbon abatement values. Furthermore, pathways including PtL and AtJ (80% carbon abatement) are unlikely to be seen at commercial-scale before 2030.

Figure 26: With 2024 incentives, HEFA and AtJ have competitive abatement costs relative to other carbon offset mechanisms, like Direct Air Capture (DAC) credits.

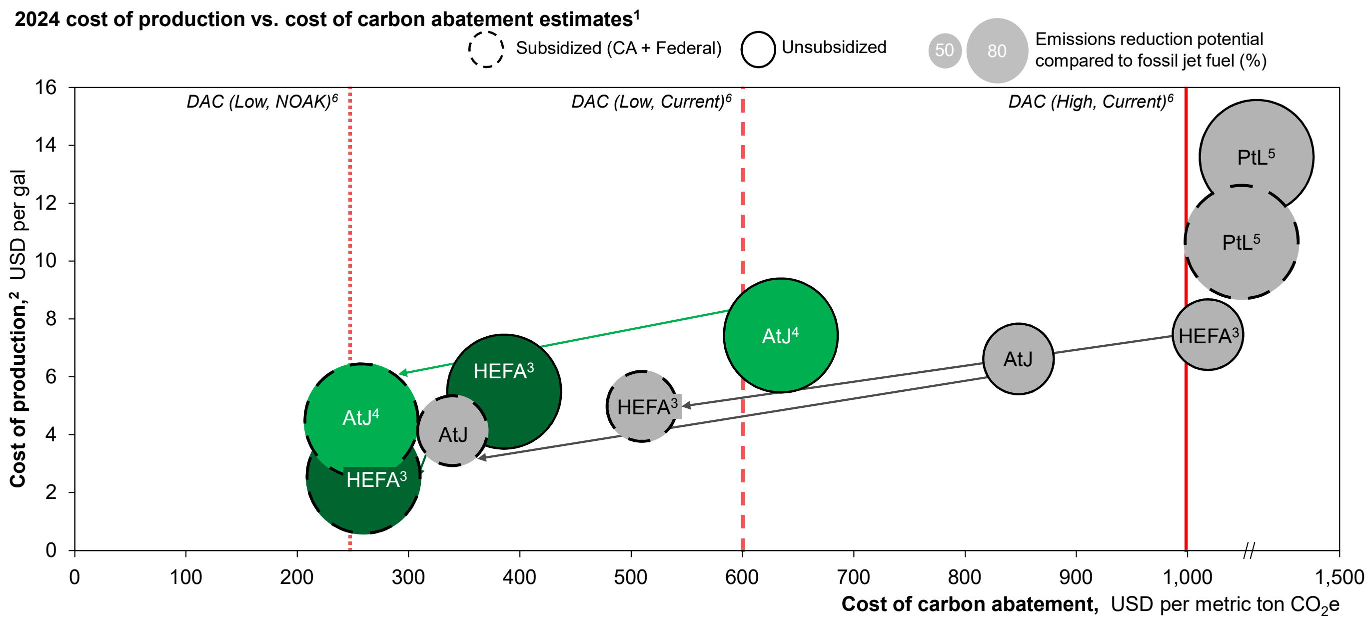


Figure Footnotes: *1. FT is not included in this figure due to significant uncertainty around its price range; 2. All production costs utilize a hypothetical NOAK facility using NREL estimates. See Appendix 4 for detailed assumptions behind each cost estimate; 3. Both HEFA estimates utilize a mix of oil-based feedstocks, with the 80% reduction estimate (dark green circles) using more FOGs, while the 50% reduction estimate (in gray) uses more virgin oils; 4. The AtJ with 80% carbon abatement estimate likely underestimates production and abatement costs because it underestimates the additional CCS required to generate this CI score; 5. PtL estimates use biogenic carbon captured from point sources, not DAC, as feedstock; 6. Industry estimates for DAC costs range between $600-1,000/metric ton. CDR puts the current DAC spot price at $690 based on real market data, which may be underpricing the cost of production. Over time, NOAK DAC facilities are expected to cost roughly $250/metric ton.*

Data Sources: *CDR.fyi;[62] DOE;[5] EPA and IEA Jet Fuel Emissions factors; FAA;[63] NREL[15]*

Today, the cost of DAC ranges from $600-$1,000 per metric ton of CO_2e abated. Even without policy support, HEFA and AtJ at 50% and 80% emissions reduction are in the same range or cheaper than the cost of DAC, with a range of $385-$1,018 per metric ton of CO_2e abated. When supported by federal and state incentives, these pathways are all significantly cheaper than DAC per cost of metric ton of CO_2e abated, with a range of $83-510 per metric ton of CO_2e abated.[xxiii] Additionally, the PtL pathway at 80% abatement becomes comparable to DAC in abatement cost. The fact that HEFA and AtJ pathways can be as cheap or cheaper than DAC on an emissions abatement cost level proves the importance of SAF for decarbonizing the aviation sector. When developing decarbonization strategies for corporate travel emissions, third-party offtakers could have cost savings if they purchase SAF credits in place of DAC credits under today's policies.

These policy incentives can also bring down the cost of SAF to potentially be similar to the price of fossil jet fuel under certain SAF pathways today. For example, with the incentives in place in 2024 at the federal level and in California, a hypothetical NOAK HEFA facility producing fuel with an 80% emissions reduction as compared to fossil jet fuel could theoretically reach a production cost of $2.55 per gallon, as shown in Figure 25. This cost is comparable to the average spot price of fossil jet fuel in 2024, which averaged $2.41 per gallon from January to August 2024.[35] If incentives make SAF more cost competitive with fossil jet fuel, then they create additional demand for SAF from the airlines themselves. In stakeholder interviews, airlines voiced enthusiasm to procure and use SAF, but also expressed concerns about the cost of SAF. Airlines today are unable to absorb the price premium of SAF due to the low margins across the industry. The 40B and 45Z tax credits, combined with state policies, decrease the price of SAF for airlines and expand its demand.

To complement federal and state SAF production incentives, supportive upstream policy could create the feedstock supply chain necessary to sustain SAF production at commercial scale and bring down cost further. Agricultural and forestry policy supportive of SAF feedstock investment would allow farmers and forestland owners to make economically-driven decisions to expand their production of SAF feedstock by integrating practices that reduce net emissions for growing purpose-grown crops or cover crops (see Box 1 in Chapter 4).

Considering Demand-Side Support

While there are important actions that industry can take to make SAF more cost competitive and SAF projects more bankable, demand-side policy would be instrumental to liftoff of the SAF market in 2030 and beyond. Figure 27 highlights how, although some analysis indicates that global SAF demand will range between 1.8-5.2 billion gallons per year (see Figure 10), only one billion of that estimated demand is certain. Currently, only a handful of national and supranational bodies have passed mandates, including British Columbia, Norway, Singapore, Sweden, and the European Union. The E.U's ReFuelEU mandates that SAF make up 6% of fossil jet fuel use by 2030, which could equal roughly 600 MGPY.[xxiv] Other countries exploring SAF mandates include Brazil, India, Japan, and the United Kingdom. If these proposed mandates are implemented in the next few years, high-confidence SAF demand could double. In 2030, the U.S. represents roughly 50% of the world's production capacity of SAF (Figure 11). If domestically produced SAF were to remain some of the most competitive globally, and if U.S. feedstocks were eligible under these international mandates, U.S. producers could expect to capitalize on a large portion of these mandated markets.

xxiii The low-end estimate assumes that a NOAK AtJ facility using starch-based feedstocks can meet the 50% abatement threshold to qualify for the 40B tax credit, in addition to qualifying for RFS and the Minnesota SAF tax credit. See Appendix 4 for more detailed assumptions and methodology.

xxiv ReFuel EU also includes a sub mandate that eFuels (e.g., PtL) represent 1.2% of jet fuel usage.

Figure 27: In 2030, more certain SAF demand stems from announced and proposed mandates in foreign countries, highlighting the importance of robust demand-side policy

2030 SAF demand from announced and proposed mandates and hypothetical policy scenarios, million gallons per year

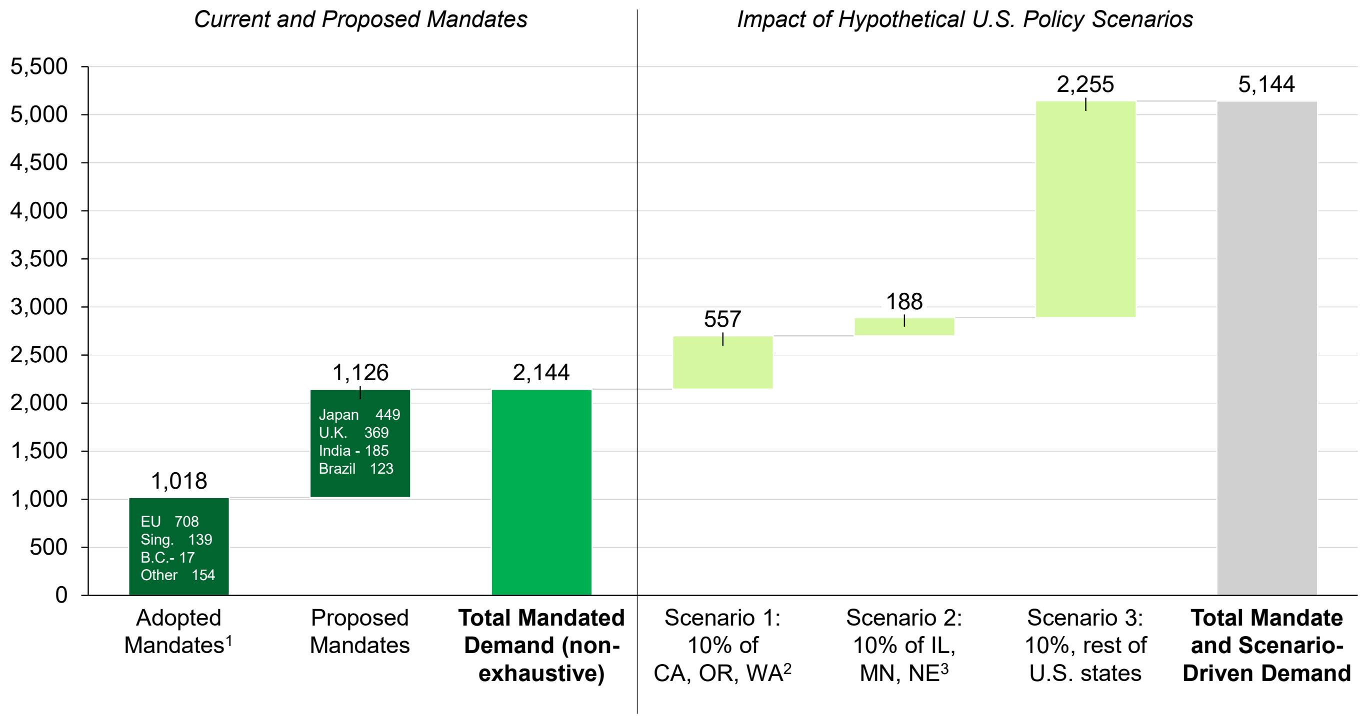


Figure Footnotes: *1. BC – British Columbia. Other includes Norway and Sweden; 2. California, Oregon, and Washington have implemented LCFS programs that subsidize the production and usage of SAF (although does not distinguish SAF from RD). Washington state has also implemented a SAF tax credit that can be stacked on the LCFS program. These states do not have a SAF mandate; 3. Illinois and Minnesota have SAF purchase tax credits; these states do not have a SAF mandate. Nebraska and Minnesota also have SAF production tax credits.*

Data Sources: *EASA;[64] EIA;[65] First Movers Coalition; [66] S&P;[67] S&P;[68] The Western Producer[69]*

No state in the United States currently has SAF mandates, however, the right-hand side of Figure 27 illustrates the impact of hypothetical state-level SAF mandates. Scenario 1 shows how, if California, Oregon, and Washington—early adopters of low-carbon fuel standards—implemented a 10% SAF mandate, global demand could increase by 557 MGPY, or more than 25%. If every U.S. state implemented such a target, global SAF demand would more than double currently projected targets, reaching 5.1 BGPY.

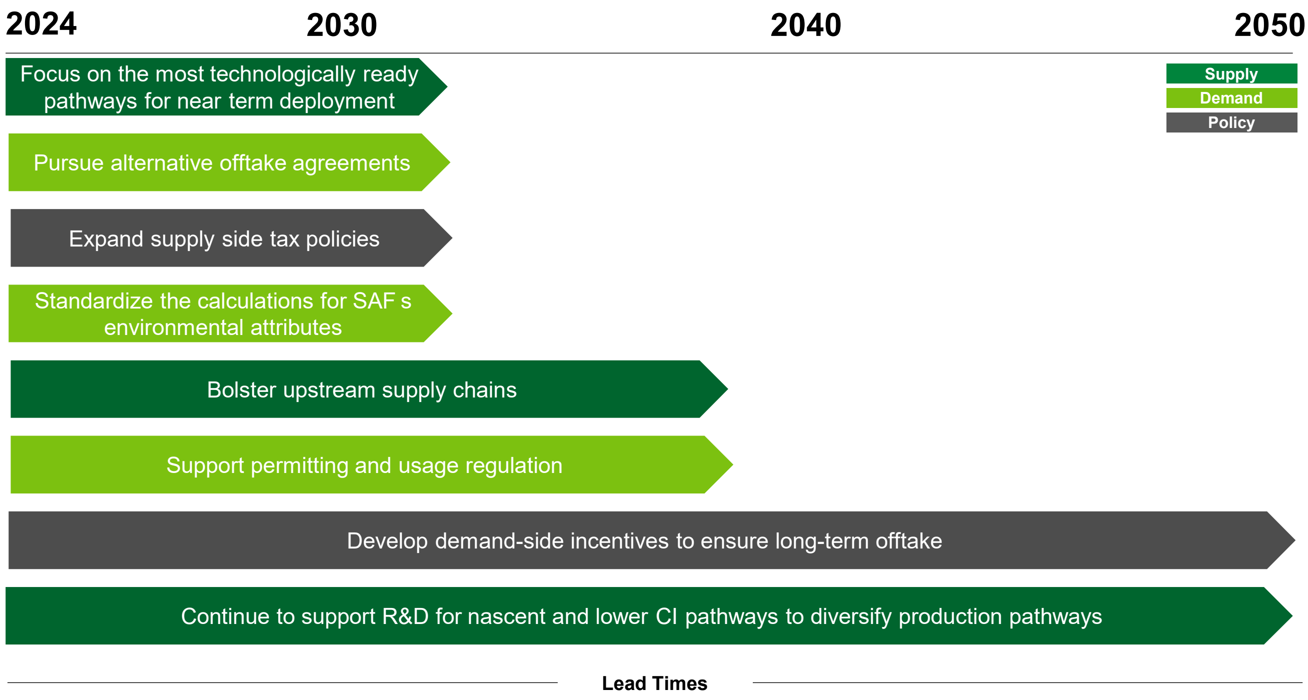
SAF is a global commodity because of the international nature of aviation. 60% of the emissions from passenger aviation stem from international flights, which, as noted in Chapter 1, cannot be meaningfully decarbonized other than through SAF usage.[70] International coordination could increase the impact of demand-side SAF policies by setting harmonized standards that could permeate through the entire market. This coordination would also mitigate the risk that airlines will attempt to minimize flights to and from those countries with SAF mandates, disadvantaging those countries and airports economically and subjecting those policies to carbon leakage. The U.S. has helped lead international coordination on international SAF policy through its membership in CORSIA, which serves as a key starting point to aligning SAF policies across member nations.

Chapter 4: Action Items for the Industry

KEY TAKEAWAYS

- Liftoff's three imperatives are more likely to be met if stakeholder groups pursue actions consistent with the eight action items described in this chapter. This chapter highlights a non-exhaustive list of examples that support each action i.e. broken out by stakeholder group. These action items have varying lead times and impact on SAF's pathway to liftoff.

Figure 28: Specific action items, with varied lead times, can be taken by different stakeholder groups to meet the three imperatives required for SAF's commercial liftoff.



1. Focus on the most technologically-ready pathways for near-term deployment.

- **Investors:** To account for the inherent risk associated with SAF projects, investors could take steps to decrease project risk, including:
  - Engage in tax equity transfers—IRA legislation allows for smaller projects to access the tax equity market and tap into new revenue streams.[xxv]
  - Find specialized project insurance—see recommendations from nonprofit consortia like the Geneva Association and the development of innovative insurance models developed by several emerging climate-focused brokerages.[71]
  - Leverage nontraditional, nondilutive capital—investors should facilitate the application process for developers to tap into government funding across federal, state and local levels (BIL and IRA have allocated unprecedented amounts of capital to SAF-related projects, see Appendix 2), but there is also interest among nonprofits. Additionally, investors can consider strategic capital from oil and gas majors looking to decarbonize.

xxv The IRA allows entities that cannot leverage direct pay but that qualify for eligible tax credits to transfer all or a portion of their eligible tax credits to a third-party buyer in exchange for cash. The buyer and seller determine terms and pricing.

- **Producers:** To build a SAF facility, it can take several years to receive the necessary permits, construct a facility, and then ramp up its production. Producers could:
  - Pursue co-processing operations at existing refineries to decrease permitting and construction timelines—SAF production at brownfield sites ramps within four years vs. greenfield sites which take longer. Oil and gas majors also have the refinery technical know-how and pre-existing relationships with OEMs and other stakeholder groups to accelerate project development. Furthermore, these projects would be able to leverage existing midstream infrastructure (e.g., pipelines or trucking routes) to deliver fuel to airports, thus reducing midstream costs and possible emissions associated with fuel transport and delivery.
  - Implement a hubs-based approach to decrease construction timelines—see the activity coming out of the Greater Minnesota SAF Hub, which exemplifies public-private partnerships in that the local economic development center partnered up with airlines (Delta), utilities (Xcel), offtakers and sponsors (Bank of America, Wells Fargo), local communities and organizations (Great Plains Institute, Minnesota Corn, University of Minnesota, Minnesota Forest Resources Council) and key industry players (Ambient Fuels, Gevo) to bring together one of the largest SAF production and utilization centers in the country.
  - Commit to early and regular engagement with communities, Tribes, and workers most immediately affected by a proposed SAF project or its supply chains. Community, labor, and other stakeholder engagement can build local support and streamline project development through negotiated community benefit and workforce agreements and workforce and training partnerships such as registered apprenticeships.
- **Federal and state policymakers, community organizers and labor unions:** Encourage underrepresented participants to engage in the SAF industry and support the requisite recruitment, retention, workforce and training pathways, such as pre-apprenticeship, re-skilling and up-skilling activities.

2. Pursue alternative offtake agreements.

- **All stakeholders:** To support both operational or soon-to-be operational SAF production facilities, stakeholders should collectively:
  - Support book and claim systems so that airlines can purchase SAF at or near price parity with fossil jet fuel and so that other corporates can purchase, own, and retire the certificate of abated or avoided emissions as part of a voluntary or mandated decarbonization program.
  - Support an industry-wide market maker—a singular entity that can pool SAF demand and procure larger quantities of SAF at scale, building upon the current efforts of Sustainable Aviation Buyers Alliance (SABA) which recently announced a $200M collective purchase of 50 million gallons of SAF to be produced and consumed over the next six years, the certificates of which will be allocated across 20 corporate aviation customers.[60]
- **Producers, airlines, and offtakers**: Explore different offtake agreement structures to decrease SAF pricing risk. Potential structures include: direct and indirect investment into developing facilities with preferred pricing structures; cost plus; three-way agreements to ensure long-term offtake; price collars, etc. (see Table 1 in Chapter 3 for more details). Share cost, price, and contracting information with the industry to increase trust, transparency, and replicability.
- **Producers and airlines**: Identify creditworthy corporates with climate commitments or equities in carbon markets—such as large consulting firms, technology companies, or oil and gas majors – to include as third-party offtakers. These entities will have high credit ratings to derisk project investments for infrastructure investors.

3. Expand supply-side policies.

- **Federal and state policymakers:** To expand SAF production and boost jobs, to position the U.S. as a net SAF exporter, and to help meet the SAF Grand Challenge targets, policymakers could:
  - Find opportunities to leverage existing liquid fuel production equipment to produce SAF.
  - Consider SAF-specific supply-side tax credits, similar to the tax credits in Nebraska, Minnesota, and Washington.
  - Expand SAF-related grant programs (such as BETO's Scale-Up or FAA's FAST program) to have increased continuity through follow-on investment.
  - Collaborate with Tribes to develop SAF-specific policy support and build discussion around environmental and societal impact mitigation concerns.

4. Standardize the calculations associated with SAF's environmental attributes.

- **DOE:** Continue to compile data and analysis on SAF production that can be used to more accurately quantify the environmental benefits of new and existing SAF pathways. Continue to make this data publicly available, via tools like the GREET model, to align industry on carbon accounting standards.
- **All stakeholders:** Support a singular SAF carbon accounting standard globally to decrease uncertainty around SAF emissions and eligibility for mandates and other programs globally. This could expand the market for SAF produced in the U.S., especially if including the standardization of carbon intensities associated with feedstock production and transport.
- **Standards organizations:** Provide clear guidance for SAF's role in carbon accounting and carbon management practices to support voluntary markets.

5. Bolster upstream supply chains.

- **Farmers and growers:** Invest in climate-smart agricultural practices for oilseed and starch crops to help ensure that purpose-grown feedstock meets SAF CI requirements (see Box 1). Expand SAF feedstock production by growing intermediate oilseed crops and dedicated energy crops on marginal land (e.g., domesticated pennycress, canola, camelina, switchgrass, and miscanthus). This is a considerable opportunity among rural and remote communities; more information can be found in DOE's Billion Ton Report.
- **Logistics solutions providers:** Scale supply chains to maximize collection of FOGs for HEFA. Share best practices around waste wood collection to prepare the FT SAF supply chain for 2030 onwards.
- **Producers:** Source facilities close to feedstock production/collection (i.e. in the Midwest). Consider engaging with Tribes for domestic feedstock supply.

Note that some HEFA feedstock concerns might be mitigated naturally as electric vehicle adoption grows (reducing need for RD) over time, causing RD facilities to shift towards SAF production. Access to renewable electricity, water, and clean hydrogen will also become a barrier as PtL scales in the years beyond 2030 and thus less in scope for this 2030 timeframe. For more information on electricity constraints, please read DOE's Liftoff Reports on VPPs and Innovative Grid Deployment. For more information on clean hydrogen considerations, please read the Clean Hydrogen Liftoff Report.[xxvi]

xxvi Visit liftoff.energy.gov to access DOE's latest liftoff reports

Box 1: 40B Climate Smart Agriculture guidance[72]

In conjunction with the 40B SAF tax credit, the USDA developed the USDA Climate Smart Agriculture Pilot Program (USDA CSA Pilot Program). If farmers implement specific emissions reduction practices when growing feedstock and other requirements are met, SAF produced using such feedstock can be credited with a lower carbon intensity for purposes of determining the tax credit. The specific practices included in the USDA CSA Pilot program are:

- **HEFA production pathway using soybean:** No-till farming and planting cover crops
- **AtJ production pathway using corn:** No-till farming, planting cover crops, and applying enhanced efficiency nitrogen fertilizer

6. Support permitting and usage regulation.

- **Standards organizations**: Today, the costs and time associated with ASTM testing, which is primarily paid for by industry applicants, could significantly bottleneck the commercialization of SAF. A streamlined ASTM approval process to enable the use of drop-in SAF blends up to 100% and enable 100% SAF transportation via pipelines could support SAF commercialization and decrease logistics challenges. This will potentially require new standards for transporting and distributing SAF.
- **Regulators:** Streamline permitting processes to allow infrastructure and associated facilities to be upgraded as needed and for new-build construction.

7. Develop demand-side incentives to ensure long-term offtake.

- **Federal policymakers:** Align with counterparts in the EU and elsewhere to harmonize SAF policies, both in terms of SAF's definition and qualification for international demand-side incentives.
- **Federal regulators:** Connect with counterparts in the EU and Singapore that are mandating specific quantities of SAF be used on departing flights to learn best practices.
- **Federal and state policymakers:** To shore up demand in the U.S., policymakers could:
  - Add SAF-specific demand-side tax credits, similar to the purchase credit in Illinois.
  - Consider authorizing funding with flexibility or designation to demand-side programmatic support.

8. Continue to support R&D for nascent and lower-CI pathways to diversify production pathways.[xxvii]

- **Producers:** Reduce resource risk through technical innovation and public funding.
- **Investors:** Internalize the longer lead times for these newer pathways in returns models—since these technologies are unlikely to be deployed at scale prior to 2030, consider investing out of evergreen funds or take alternative methods to long-term investment horizons.
- **State and federal agencies and policymakers:** Continue to fund research, development and demonstration for new SAF-related technologies in partnership with universities, research labs, and the private sector. These efforts will diversify production and feedstock supply chains.

xxvii Pathways include: FT, PtL, SIP, FT-SKA, CHJ, and algae technologies

Chapter 5: Metrics to Track Progress

Three types of key performance indicators can gauge progress towards commercialization of SAF:

- **Leading indicators** signal SAF's market readiness.
- **Lagging indicators** confirm that SAF has achieved technical or commercial milestones to demonstrate a path to reaching the 2050 SAF Grand Challenge targets.
- **Outcomes** show the impact of SAF on the U.S. broadly (e.g., emissions reduction, job creation).

This report has identified the following supply and demand indicators that are targeted to track SAF's progress towards liftoff. The SAF Grand Challenge: Tracking Metrics and Mid-2024 Dashboard provides complementary metrics to evaluate SAF's scale up more broadly.

Metric type	Year	Indicator
Leading indicators	2028	10+ year offtake agreements with airlines are common practice for offtake agreements
	2030	8-12 commercial scale SAF facilities are operational in the U.S., with total SAF capacity of at least 2 BGPY Subsidized HEFA SAF price falls to two times the price of fossil jet fuel (or lower) Several new ASTM-approved pathways announced
	2035	Announced cumulative project capacity by 2050 reaches 35-50 BGPY (to account for projects that fail to come online)
Lagging indicators	2040	Multiple SAF technology pathways are operational at commercial scale (e.g., PtL, FT, AtJ at 80% carbon abatement) SAF market price falls to two times the price of fossil jet fuel (or lower) across SAF production pathways
	2050	Total SAF production in 2050 is 35 BGPY
Outcomes	2030; 2050	Estimated emissions reduction due to SAF deployment, including analysis conducted at the community or census-tract level Estimated direct and indirect jobs created due to SAF investment, including analysis conducted at the community or census-tract level

Conclusions

The transition to a decarbonized aviation sector must be private sector-led and government-enabled. Developers must continue to tap into infrastructure and insights from refineries and other fossil industries to make SAF as inexpensive as possible while also looking to newer, lower-carbon innovations. They must also work closely with local communities and labor unions to ensure projects provide quality jobs and safe and equitable development. Offtakers should value SAF on the value per metric ton of CO_2e abated rather than the value per gallon. Nonprofit partners need to develop standards for how to measure the lifecycle emissions of SAF and provide standardized accounting in order to enable this reframing. In turn, governments across levels need to support these efforts. If each stakeholder group does its part, then SAF will be on a path to reach commercial liftoff in three, two, one…

Appendix 1: Key Terms and Abbreviations

ASTM	American Society for Testing and Materials (International)
ARL	Adoption Readiness Level
BETO	Bioenergy Technologies Office
BGPY	Billion Gallons Per Year
BPD	Barrels Per Day
CA	California
CI	Carbon Intensity
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COD	Commercial Operations Date
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSA	Climate Smart Agriculture
DAC	Direct Air Capture
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fueling Aviation's Sustainable Transition
FID	Final Investment Decision
FOAK	First Of A Kind
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
H_2	Hydrogen
H_2O	Water
HEFA	Hydroprocessed Esters and Fatty Acids
ICAO	International Civil Aviation Organization
IL	Illinois
LCA	Lifecycle Analysis
LCFS	Low Carbon Fuels Standard
LPO	Loan Programs Office
MGPY	Million Gallons Per Year
MFSP	Minimum Fuel Selling Price
MN	Minnesota
NE	Nebraska
NOAK	Nth Of A Kind
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
RD	Renewable Diesel
RD&D	Research, Development, and Demonstration
REC	Renewable Electricity Certificate
RFS	Renewable Fuel Standard
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
SAF	Sustainable Aviation Fuel
SAFc	Sustainable Aviation Fuel Certificate, similar to a Renewable Energy Certificate (REC)
TRL	Technology Readiness Level
USDA	U.S. Department of Agriculture
WA	Washington (state)

Appendix 2: Supportive SAF Policies

U.S. State Level Incentives

California	Since 2009, California has offered credit for low-carbon fuels used for transportation, including ethanol, biodiesel, RD, renewable natural gas, natural gas, renewable propane, propane, renewable naphtha, hydrogen, electricity, and SAF. Although credit amounts have varied over the years and updated rulemaking is still ongoing, it is assumed that the ~$140/credit rate will extend through 2032.
Illinois	From July 1, 2023, through December 31, 2032, SAF sold to or used by an air common carrier, certified by the carrier to be used in Illinois, earns a Sustainable Aviation Fuel Purchase Credit (SAFPC) in the amount of $1.50 per whole gallon of SAF purchased. Only that portion of each gallon of aviation fuel that consists of SAF, as defined in Section 3-87 of the Use Tax Act (35 ILCS 105/3-87), is eligible to earn the credit. This eligibility mandates that SAF is derived from U.S. feedstocks.
Minnesota	Minnesota has a SAF tax credit of $1.50 per gallon for any SAF produced or blended within the state. This program will run from 2024 to 2030.
Washington	Washington state has a $1-2 per gallon tax credit (depending on associated CI) for the production or use of SAF in the state. The credit will come into effect once there is 20 MPGY of SAF production capacity in the state, and then run for 10 years. Washington state also has a clean fuel standard to reduce the CI of transportation fuels 20% below 2017 levels by 2034. Similar to other clean fuel standards, fuels below the standards CI can qualify for credits that can be sold to producers of higher-emitting fuels. This program passed into law in 2021.
Nebraska	Nebraska has a SAF production tax credit that will run from 2027-2032. SAF produced in the state with a minimum 50% reduction in lifecycle emissions as compared to fossil jet fuel will be eligible for the credit. The credit starts at $0.75 per gallon with an additional $0.01 per gallon for each percent of emissions reduction above the 50% emissions reduction baseline.
Colorado	Colorado has a state tax credit from 2024 to 2033 to incentivize SAF production worth 30% of the cost of construction for a SAF production facility. There is a $3 million annual cap on the amount the state may pay for the duration of the credit (for year 1 and year 2 of the credit the cap is $1 million and $2 million, respectively). Colorado also has a state income tax credit for entities that use clean hydrogen to decarbonize high-value end uses, which includes aviation.
Oregon	Implemented in 2016, the Oregon clean fuels program aims to decrease the carbon intensity of fuels in the transport sector 20% from 2015 levels by 2030 and 37% by 2035. Similar to other clean fuels programs, lower-emitting fuel producers receive credits that they can sell to higher-emitting producers.
State-level LCFS or similar bill introduced	Illinois (introduced 2023), Massachusetts (introduced 2019), Michigan (introduced 2023), Minnesota (introduced 2023), New Mexico (introduced 2023, action paused), New York (introduced 2023), Vermont (introduced 2023)

U.S. Federal Incentives

RFS (RINs)	The RFS program provides a country wide level volumetric renewable fuel mandate and in turn offers tradeable incentives (RINs) to encourage production/blending that are applicable to RD/SAF and Bionaphtha. The per gallon incentive offered for RD is higher than that offered for SAF under the program. Established via the Energy Policy Act of 2005 and the Energy Independence Act of 2007, RINs are generated when renewable fuel is created. Issued by EPA under the RFS, RINs are unique serial numbers assigned to each gallon of renewable fuel produced. Companies that refine, import, or blend transportation fuels are obligated to meet certain individual RFS quotas based on the volume of fuel they introduce into the market, either by blending renewable fuels or purchasing RINs from others. By fulfilling these requirements, EPA anticipates that the industry will collectively satisfy the overall national quota they set. To ensure compliance, obligated parties are periodically required to demonstrate they have met their RFS quota by submitting a certain quantity of RINs to EPA. Each RIN represents biofuel blended, by obligated parties, into transportation fuels used in the United States. SAF receives 1.6 D4 RINs per gallon.
40B	40B is a SAF blenders tax credit for SAF sold or used in 2023 or 2024. The SAF credit starts at is $1.25 for each gallon of SAF in a qualified mixture. To qualify for the credit, the SAF must have a minimum reduction of 50% in lifecycle greenhouse gas emissions. There is also a supplemental credit of one cent for each percent that the reduction exceeds 50%. This incentive will expire at the end of 2024. Note that 40B is not eligible for direct pay, which might prevent Federally Recognized Indian Tribes from utilizing the credit. However, a tribal-related taxable entity may be able to use the credit.
45Z	45Z is a tax credit that applies to clean fuel produced at a qualifying facility after 2024 and sold before 2028 for qualifying purposes. Fuel must meet certain emissions standards. Note that 45Z is eligible for direct pay which enables Federally Recognized Indian Tribes to claim the tax credit.
45V	45V will provide a tax credit for clean hydrogen production. Guidance is still being finalized for a new 10-year incentive for clean hydrogen of up to $3.00/kilogram. The credit provides a varying, four-tier incentive depending on the carbon intensity of the hydrogen production pathway, and whether the project meets prevailing wage and apprenticeship requirements.
45Y / 48E	The Clean Electricity Production Tax Credit (45Y) provides a technology-neutral tax credit for the production of clean electricity. Starting in 2025, the credit is available to companies that produce electricity from qualified clean energy sources, such as wind, solar, and nuclear power. The Clean Electricity Investment Tax Credit (48E) provides a tax credit for qualifying facilities that generate clean electricity.

International Policies and Regulations

International (CORSIA)	Developed by the International Civil Aviation Organization (ICAO), an agency of the United Nations, CORSIA sets strategies for carbon-neutral aviation growth. The program is voluntary for participating nations (which includes the U.S.) through 2026 and becomes mandatory from 2027 to 2035. Airlines can reduce their emissions by buying carbon credits, which allows them to pay premiums for SAF and resell the environmental attribute to third-party offtakers.
Europe	ReFuelEU is an agreement between EU member states, signed in April 2023, that mandates that the percentage of SAF used in EU airports reach 2% in 2025 and 70% by 2050 (up from roughly 0.05% in 2023). This includes a sub-mandate for synthetic SAF minimum content to increase from 1.2% in 2030 to 35% by 2050. The mandate currently excludes SAF made from food-based feedstocks, including crops used for animal feed, and palm oil. RED III is an EU directive that supports the adoption of sustainable fuels through sets of rules and obligations. By 2030, RED III has a goal for a minimum of 42.5% of renewable fuels in total energy consumption.
Canada	The Canadian Clean Fuel Standard (CCFS) mandates liquid fuel distributors to lower the carbon emission intensity of their products, with the aim of significantly reducing GHG emissions. British Columbia Low Carbon Fuel Standard (BC LCFS) is designed to reduce the CI of fuels used in the province and applies to all transportation fuels used in BC (except for aircraft fuel or fuels for military operations). The program targets a 30% CI reduction by 2030 (implementation delayed until 2024). Credits may be earned by BC Part 3 Fuel Suppliers. Starting in 2028, the program will include the requirement to incorporate 1% SAF into jet fuel, 2% by 2029, and 3% by 2030. The Alberta Renewable Fuel Standard (AB RFS) requires a minimum annual average of 5% renewable alcohol in gasoline and 2% RD in diesel fuel sold in Alberta. Qualifying renewable fuels must demonstrate a minimum 25% reduction in greenhouse gas emissions relative to the petroleum fuel they replace.
Singapore	Starting in 2026, flights departing from Singapore will be required to use SAF, with a 1% SAF uplift target in 2026 and plans to subsequently raise it to 3-5% by 2030. The Civil Aviation Authority of Singapore will centrally procure SAF for aircrafts departing from the country.
United Kingdom	Subject to Parliamentary approval, a SAF mandate will start January 1, 2025 in the UK. The mandate will start at 2% of total UK jet fuel demand, increase on a linear basis to 10% in 2030 and then to 22% in 2040. From 2040, the obligation will remain at 22% until there is greater certainty regarding SAF supply. Included in the mandate is a cap on the feedstocks used for HEFA. HEFA supply will not be limited under the mandate for the first two years, fall to 71% of total SAF permitted in 2030, and then to 35% in 2040. Furthermore, eFuels represent a proportion of obligated SAF, reaching 3.5% of total jet fuel demand by 2040.
Norway	In 2020, Norway became the first country with a SAF mandate, which requires 0.5% SAF blending. The mandate is set to progressively increase to 30% by 2030.
Sweden	A 1% SAF blending mandate has been in place since 2021. Future targets will likely align with the EU-wide SAF mandate.
India	An indicative SAF blending target of 1% by 2027 has been set, increasing to 2% by 2028, and 5% by 2030. The SAF targets will initially apply to international flights.

Japan	A planned mandate is in place for 2030, where international flights departing from Japanese airports will be required to use at least 10% SAF.
Brazil	A SAF mandate is expected to be introduced that would take effect in January 2027, but details are yet to be released.
Malaysia	A SAF blending mandate of 1% has been established since 2023, which is expected to increase to 47% by 2050.
France	In 2022, a 1% SAF mandate came into effect. This was increased to 1.5% in 2024 and will be raised to 2% in 2025 to align with the EU-wide SAF mandate.
Germany	The use of eFuels has been mandated, starting at 0.5% by 2026 and rising to 1% in 2028 and 2% in 2030. Targets might be harmonized with the EU-wide SAF mandate.

Federal Assistance Programs

While substantial investment is ongoing across the federal government related to SAF, this table captures advanced stage investments (Technology Readiness Levels 5-6 or higher) as described in Chapter 5 (metric 4 from the SAF Grand Challenge Tracking Metrics and Mid-2024 Dashboard).

DOE	The Bioenergy Technologies Office has awarded $151 million in funding for 28 pre-pilot, pilot, and demonstration scale projects. This includes two SAF commercial deployment projects. Roughly $156M in private sector cost-share is anticipated to accompany this funding. BETO also recently announced a funding opportunity announcement for $12 million in funding to support the scale-up of integrated biorefinery technologies. The Loan Programs Office (LPO) has tens of billions of dollars of loan authority for direct loans and loan guarantees for SAF projects. On October 16, 2024, LPO announced two conditional loan guarantees for SAF production Facilities. The $1.44 billion loan guarantee to Montana Renewables, LLC, if finalized, will help finance the expansion of a renewable fuels facility in Great Falls, Montana, that will utilize vegetable oils, fats, and greases to produce SAF, RD, and renewable naphtha. The $1.46 billion loan guarantee to Gevo Net-Zero 1, LLC, excluding capitalized interest during construction, will help finance the first of a kind large-scale corn starch-to-jet fuel facility in the United States. Located in Lake Preston, South Dakota, this facility will source U.S.-grown, low-cost, low-carbon field corn and will use carbon capture and sequestration and renewable power to lower emissions. DOE ensures that its assistance programs meet the Biden-Harris Justice40 Initiative, which directs 40% of all federal investment into disadvantaged communities.
USDA	The USDA provided $12 million in AFRI Sustainable Agricultural Systems funding for the development of three integrated supply chain projects as well as $30 million for a SAF commercial deployment project. This funding is leveraging an estimated $175 million in private sector funding. USDA is also contributing to the development of sustainable feedstock supply chains through its Partnerships for Climate-Smart Commodities program.

FAA	FAA has invested $5 million in the ASTM fuels clearinghouse. Two new pathways have been approved and eight are currently at various stages of the approval process. This is leveraging an estimated $100 million in private sector funding. The Fueling Aviation's Sustainable Transition (FAST) discretionary grant program is making investments to accelerate production and use of SAF and the development of low-emission aviation technologies, with $291 million recently announced. $244.5 million is allocated to 22 projects that support the development of SAF including SAF supply chain studies along with projects that build infrastructure for SAF production, transportation, blending, and storage. This funding was made possible by the IRA of 2022 and is expected to leverage $82 million in private sector funding.
EPA	As described in the U.S. Federal Incentives table, the EPA runs the Renewable Fuel Standard (RFS) program, in consultation with the USDA and US DOE. This standard allows certain types of SAF to generate RINs in order to subsidize their production. Approved SAF pathways can qualify for RIN generation if they have a 20% GHG reduction as compared to a 2005 petroleum baseline.[73] The 2025 standard requires 22.33 billion gallons of renewable fuel, providing a marketplace for SAF to generate renewable fuel credits.[74]

Appendix 3: RIN Categories and Values Over Time

SAF can qualify for different RINs based on the feedstock and greenhouse gas reduction compared to petroleum fuel (see table describing D codes).

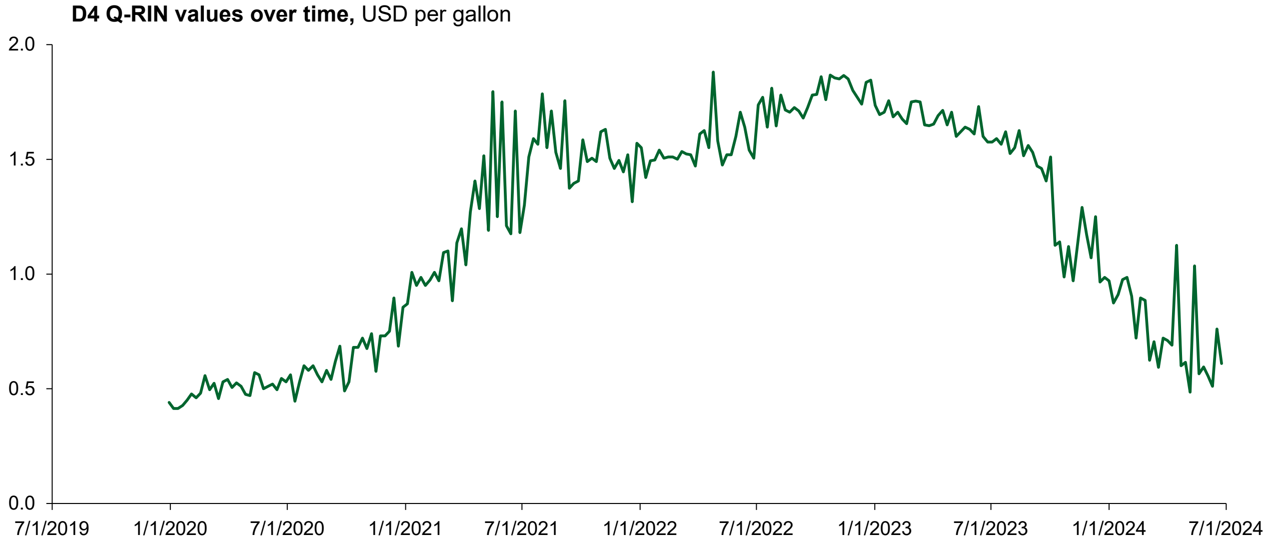
Table A1: RIN D-Codes and Specifications

D Code	End Products	GHG Reduction Requirement	Fuel Types
D3/D7	Cellulosic Biofuels	60%	Cellulosic ethanol, cellulosic naptha, cellulosic diesel, renewable LNG
D4	Biomass-Based Diesel	50%	Biodiesel, renewable diesel
D5	Advanced Biofuels	50%	Sugarcane ethanol, renewable heating oil, biogas
D6	Renewable Fuel	<20%	Corn ethanol

Data sources: *U.S. Environmental Protection Agency*[72]

Most RINS generated for SAF are currently D4 RINS because HEFA-produced SAF falls into this category, which have declined in value in recent years. That said, values for D5, and D6, D3/D7 (cellulosic biofuels) have increased.

Figure A1: D4 RINs over time



Data Sources: *U.S. Environmental Protection Agency*[4]

Appendix 4: Impact of Federal and State Incentives on SAF Production Costs

This analysis only considers supply-side subsidies (e.g., for SAF production) and does not include the Illinois purchase credit or any other purchase credits. The Illinois purchase credit provides up to $1.50 per gallon of SAF purchased or used in the state. All scenarios assume that the prevailing wage and apprenticeship requirements are met to qualify for the full value of the current or proposed tax credit.

California

Figure A2: Impact of federal and state supply-side incentives on SAF unit production costs in California

The impact of federal and state incentives on SAF unit production costs from an illustrative NOAK HEFA facility with a CI score of 18 (80% reduction compared to fossil jet) located in California, a state with LCFS but no specific SAF subsidy,[1] USD per gallon

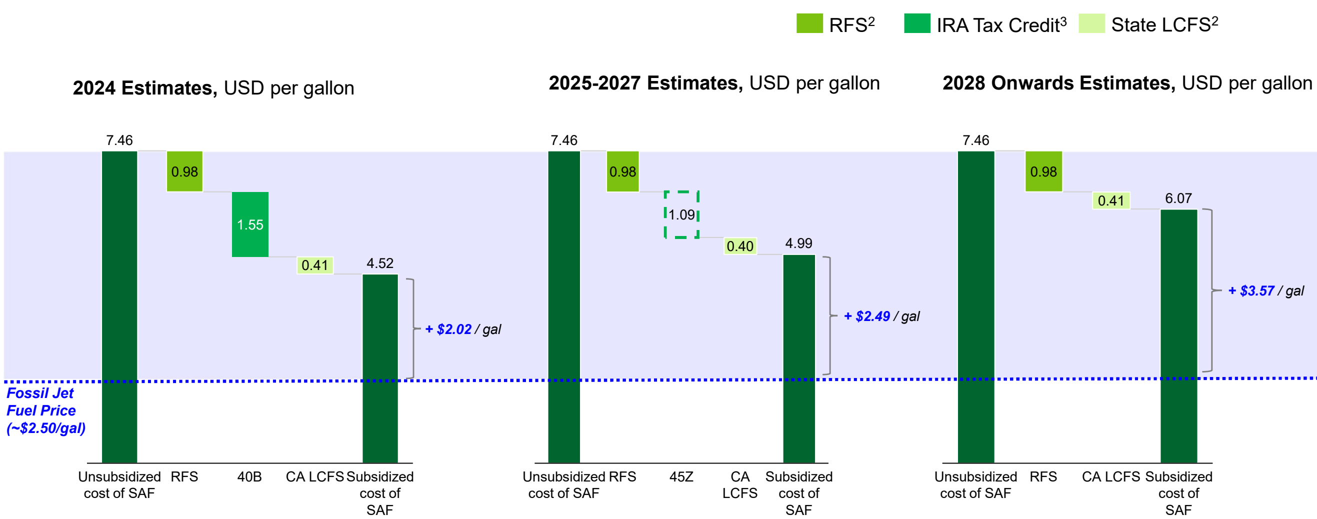


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN and LCFS values; 3. Final treasury guidance for 45Z is to be released. Calculations for this analysis follow NREL's methodology.*

Data Sources: *NREL[15]*

Figure A3: Cost per metric ton of carbon abatement in California

The cost of carbon abatement using illustrative NOAK facilities in California across pathways and carbon intensities,[1] USD per metric ton CO_2e

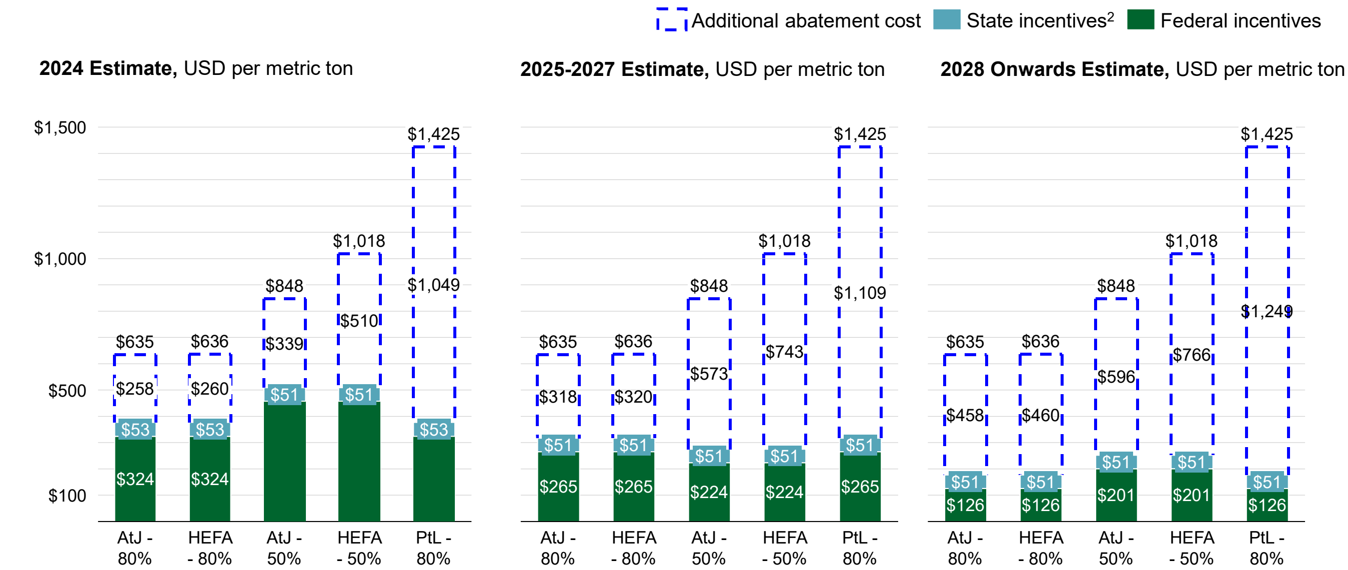


Figure Footnotes: *1. This analysis uses June 2024 RIN values; 2. State incentives include a LCFS program under which SAF can qualify.*

Data Sources: *CA LCFS as of June 2024;[30] NREL[15]*

Washington

Figure A4: Impact of federal and state incentives on SAF unit production costs in Washington

The impact of federal incentives on SAF unit production costs from an illustrative NOAK HEFA facility with a CI score of 18 (80% reduction compared to fossil jet) located in Washington,[1] USD per gallon

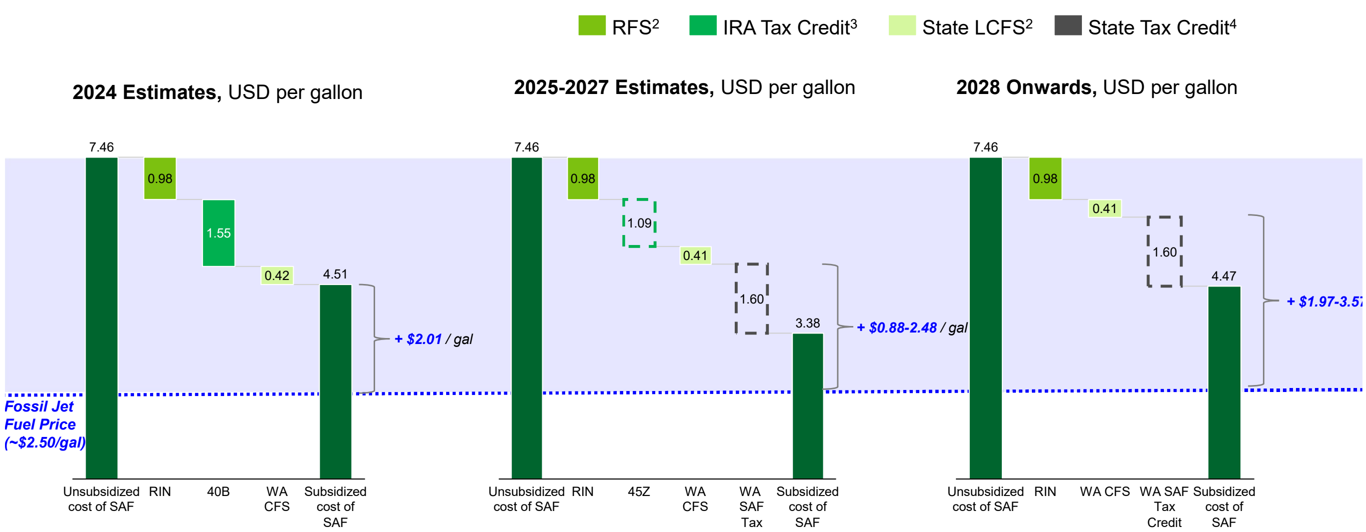


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN and CFS values; 3. Final treasury guidance for 45Z is to be released. Calculations for this analysis follow NREL's methodology; 4. WA state has a production tax credit for SAF that will come into effect for 10 years as soon as the state reaches 20 MPGY of SAF production capacity.*

Data Sources: *NREL[15]*

Figure A5: Cost per metric ton of carbon abatement in Washington

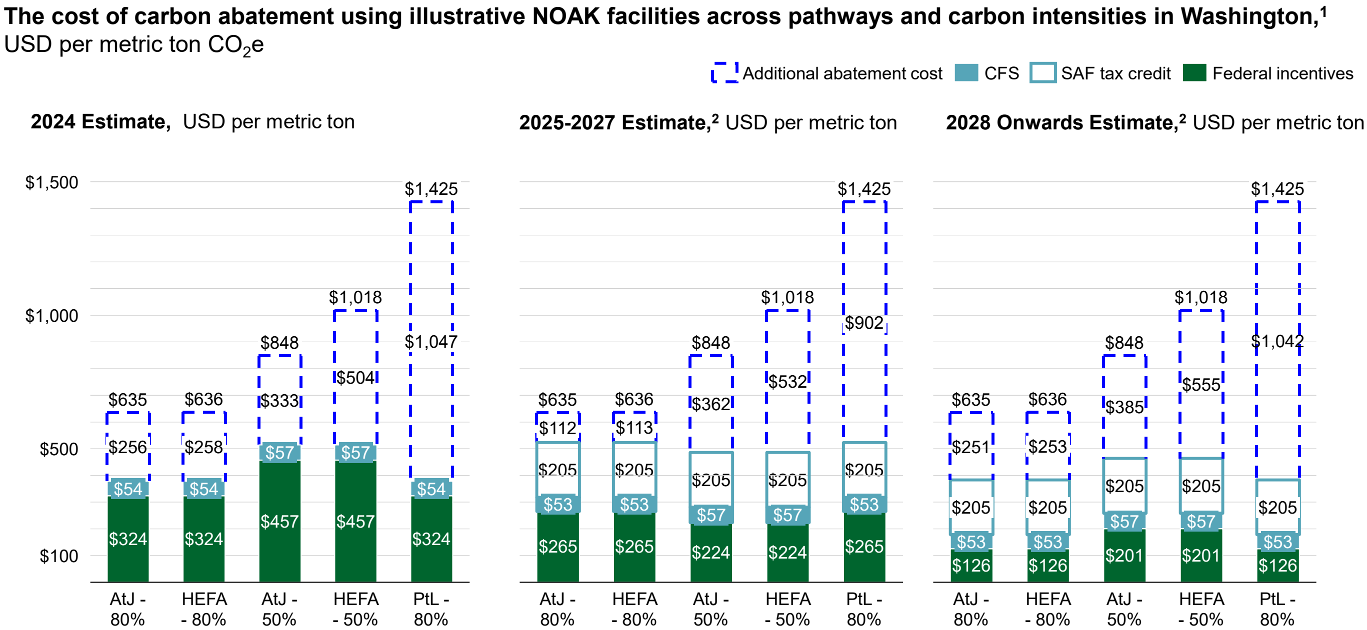


Figure Footnotes: *1. This analysis uses June 2024 RIN values; 2. State incentives include a CFS program under which SAF can qualify. WA state has a production tax credit for SAF that will come into effect for 10 years as soon as the state reaches 20 MPGY of SAF production capacity.*

Data Sources: *NREL;[15] WA LCFS as of June 2024[32]*

Minnesota

Figure A6: Impact of federal and state incentives on SAF unit production costs in Minnesota

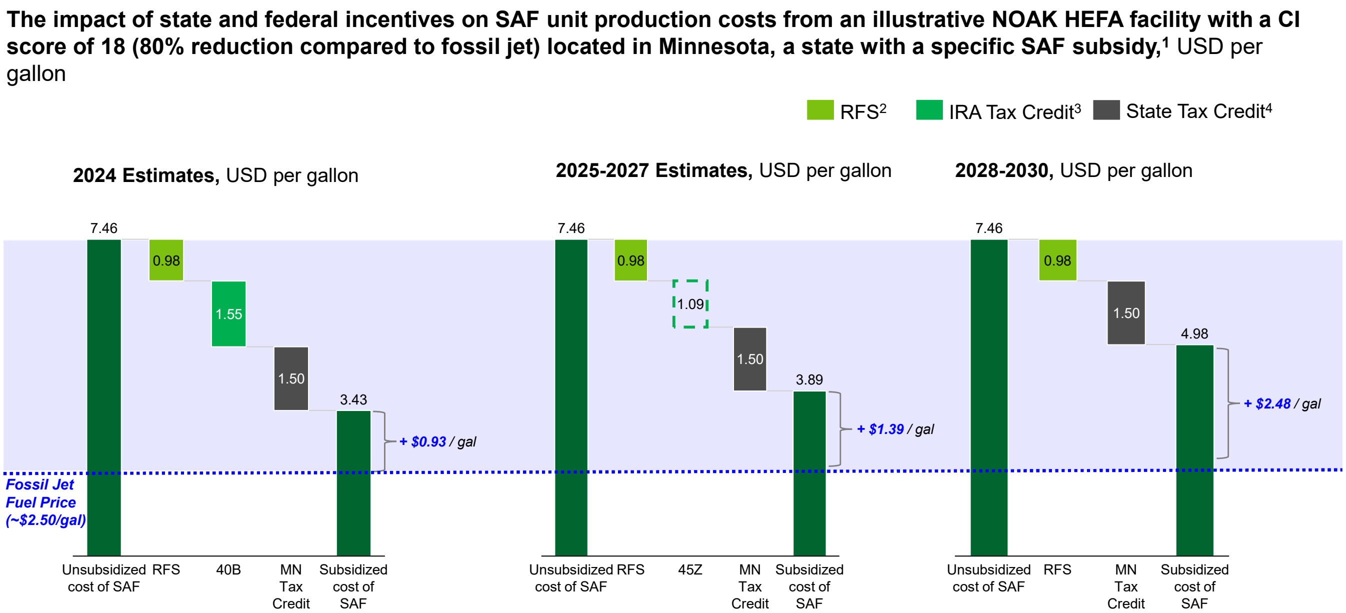


Figure Footnotes: *1. This analysis calculates the production cost of SAF. Delivered cost, or the price of SAF to airlines, includes blending, transportation and storage costs, which vary. This analysis assumes prevailing wage and apprenticeship requirements are met; 2. This analysis uses June 2024 RIN values; 3. Final treasury guidance for 45Z to be released. Calculations for this analysis follow NREL's methodology; 4. MN tax credit expires in 2030, leaving only RIN credits in 2030 onwards.*

Data Sources: *NREL[15]*

Figure A7: Cost per metric ton of carbon abatement in Minnesota

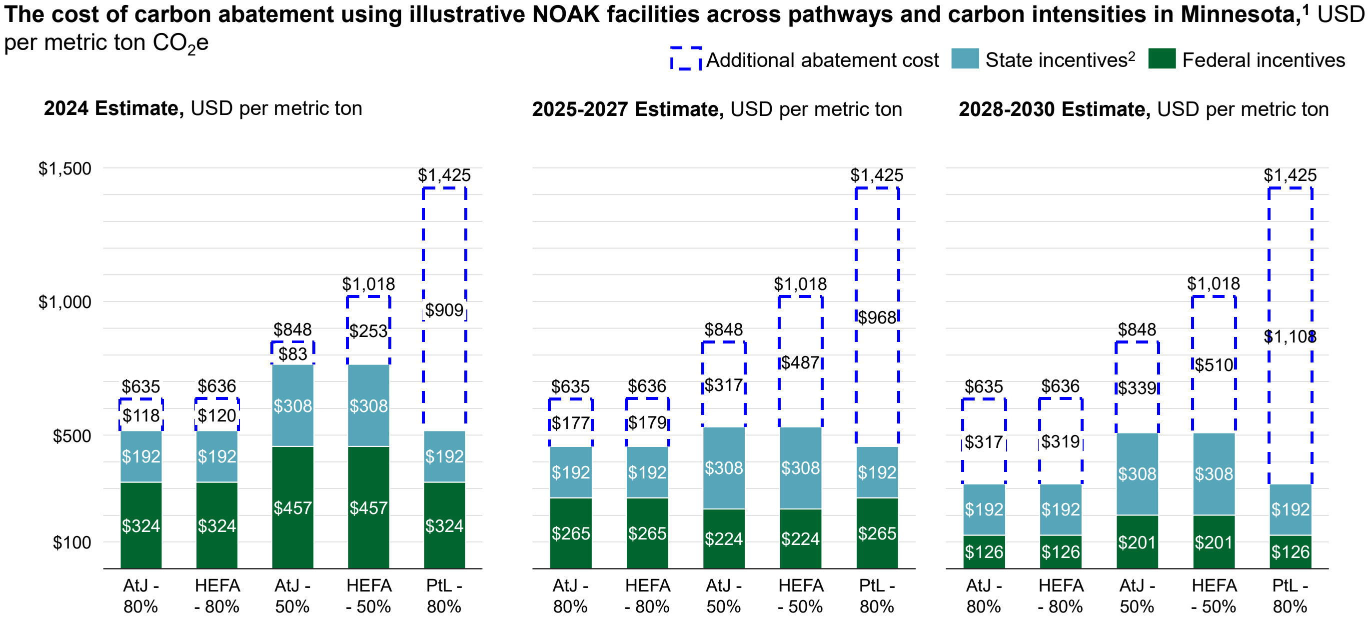


Figure Footnotes: *1. This analysis uses June 2024 RIN values; 2. State incentives include a SAF production tax credit.*

Data Sources: *NREL*[15]

Calculation Methodology

To calculate the cost per metric ton of CO_2e abated:

1. Calculate the cost of production for the different SAF pathways and the price premium as compared to fossil jet fuel.
2. Calculate the total CO_2e abated when using a gallon of SAF for the different SAF pathways (e.g., HEFA at 80% abatement).
3. Divide the price premium by the total CO_2e abated from a gallon of SAF to find total cost of abatement per metric ton.
   a. HEFA and AtJ (starch) low and high cost estimates are kept separate for this step as they have different % emissions abatement potential.
   b. FT, AtJ (cellulosic), and PtL low and high cost estimates are averaged for this step as they have the same % emissions abatement potential.
4. Use this value to identify how much various incentives contribute to the overall abatement cost, based on the % of the price premium per gallon that is covered by each incentive.

Table A2: Production Cost Assumptions

Note, these production costs are highly theoretical. They are location agnostic and for NOAK facilities. Other than for the HEFA pathway, it is unlikely that these costs will occur in the market before 2030, particularly for the cellulosic AtJ, FT and PtL pathways.

Pathway	Cost of production (USD per gallon)		Assumptions
	Low	High	
HEFA	5.49	9.40	**LOW** Facility Size: 300 MGPY Feedstock Price: $0.55/lb (UCO) Potential Lifecycle GHG % Reduction: 80% **HIGH** Facility Size: 10 MGPY Feedstock Price: $0.896/lb (oilseed) Potential Lifecycle GHG % Reduction: 50%
AtJ (starch) with Carbon Capture	4.57	8.66	**LOW** Facility Size: 120 MGPY Feedstock Price: $5.00/bushel (corn) Potential Lifecycle GHG % Reduction: 50% Carbon Capture additional cost: $0.04 / gallon ($0.1/kWh for electricity, 200% of compressor's baseline equipment cost) **HIGH** Facility Size: 10 MGPY Feedstock Price: $7.63/bushel (corn) Potential Lifecycle GHG % Reduction: 50% Carbon Capture additional cost: $0.06 / gallon ($0.02/kWh for electricity, 75% of compressor's baseline equipment cost)
AtJ (cellulosic)[1]	5.66	9.20	**LOW** Facility Size: 200 MGPY Feedstock Price: $84.45/dry ton (corn stover) Potential Lifecycle GHG % Reduction: 80% **HIGH** Facility Size: 7 MGPY Feedstock Price: $200/dry ton (corn stover) Potential Lifecycle GHG % Reduction: 80%
PtL	6.90	20.03	**LOW** Facility Size: 31 MPGY Electricity Price: $0.02/kWh H_2 Price: $2.50/kg H_2 Potential Lifecycle GHG % Reduction: 80% **HIGH** Facility Size: 5 MPGY Electricity Price: $6.82/kWh H_2 Price: $7.00/kg H_2 Potential Lifecycle GHG % Reduction: 80%

Table Footnotes: *1. Cellulosic feedstocks for AtJ SAF are unlikely to reach commercial scale by 2030. Where this report refers to AtJ SAF produced by 2030, it refers primarily to SAF produced using starch-based feedstocks with CCS.*

Data Sources: *NREL input*

Appendix 5: Applied Adoption Readiness Levels

A technology's [adoption readiness level]() complements its technology readiness level, but focuses on the progression of commercialization potential rather than innovation and performance. According to DOE's ARL Framework, there are 17 dimensions through which to evaluate the commercial risk. The below table provides a high-level overview for how to consider the risks associated for the SAF pathways described in this Liftoff Report.

Table A3: Applied ARL Scores, by SAF Production Pathway

Low risk · Medium risk · High risk

			HEFA - FOG	HEFA - Crop	AtJ	FT	PtL
ARL			**7**	**5**	**3**	**1**	**1**
Risk Level	Value Proposition	Delivered Cost	Medium risk	Medium risk	Medium risk	Medium risk	Medium risk
		Functional Performance	Low risk	Low risk	Low risk	Low risk	Low risk
		Ease of Use	Low risk	Low risk	Low risk	Medium risk	Medium risk
	Market Acceptance	Demand Maturity	Low risk	Medium risk	Medium risk	Low risk	Low risk
		Market Size	Low risk	Low risk	Low risk	Low risk	Low risk
		Downstream Value Chain	Low risk	Low risk	Low risk	Low risk	Low risk
	Resource Maturity	Capital Flow	Medium risk	Medium risk	Medium risk	High risk	High risk
		Project Development, Integration, Management	Low risk	Low risk	Medium risk	High risk	High risk
		Infrastructure	Medium risk	Medium risk	Medium risk	High risk	High risk
		Manufacturing and Supply Chain	Low risk	Low risk	Low risk	High risk	High risk
		Materials Sourcing	Low risk	Medium risk	Low risk	Medium risk	High risk
		Workforce	Low risk	Low risk	Low risk	Medium risk	Medium risk
	License to Operate	Regulatory Environment	Low risk	Low risk	Low risk	Low risk	Medium risk
		Policy Environment	Low risk	Medium risk	Medium risk	Medium risk	Medium risk
		Permiting and Siting	Low risk	Low risk	Medium risk	Low risk	Medium risk
		Environmental and Safety	Low risk	Low risk	Low risk	Medium risk	High risk
		Community Perception	Medium risk	Low risk	Low risk	Medium risk	High risk

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