Sustainable Aviation Fuel (SAF) State-of-Industry Report:

State of SAF Production Process

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Oscar Rosales Calderon, Ling Tao, Zia Abdullah, Kristi Moriarty, Sharon Smolinski, Anelia Milbrandt,
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National Renewable Energy Laboratory

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List of Acronyms

ATJ	alcohol to jet
BGPY	billion gallons per year
CAAFI	Commercial Aviation Alternative Fuels Initiative
CFR	*Code of Federal Regulations*
CI	carbon intensity
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSA	Climate Smart Agriculture
EPA	Environmental Protection Agency
FT	Fischer–Tropsch
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
HEFA	hydroprocessed esters and fatty acids
ICAO	International Civil Aviation Organization
IRA	Inflation Reduction Act
IRC	Internal Revenue Code
LCA	life cycle analysis
LCFS	Low Carbon Fuel Standard
MFSP	minimum fuel selling price
NNSR	Nonattainment New Source Review
NO_x	nitrogen oxides
NSR	New Source Review
PM	particulate matter
PSD	Prevention of Significant Deterioration
PTJ	pyrolysis to jet
RD	renewable diesel
RFS	Renewable Fuel Standard
RIN	renewable identification number
SAF	sustainable aviation fuel
SPK	synthetic paraffinic kerosene

Purpose of the State-of-Industry Reports

This series of sustainable aviation fuel (SAF) state-of-industry reports aims to provide a thorough evaluation of the emerging SAF production industry, and foster communication among the stakeholders (both public and private) involved in the SAF supply chain. While the report is primarily concerned with the production of SAF, the nature of producing hydrocarbon fuels means that some of the information included will be relevant to the production of other liquid transportation fuels.

In addition to this report on the hydroprocessed esters and fatty acids (HEFA) pathway, the project team plans to release a series of reports covering the overall SAF framework, the alcohol-to-jet (ATJ) pathway, the Fischer–Tropsch (FT) pathway, and possibly the pyrolysis-to-jet (PTJ) pathway.

These reports center on identifying any weak links in the supply chain that have the potential to hinder the production of SAF, particularly in reaching the production goals set by U.S. Department of Energy, the U.S. Department of Transportation, the U.S. Department of Agriculture, and other federal government agencies as part of the SAF Grand Challenge. The reports focus primarily on hurdles for the 2030 goal of 3 billion gallons per year (BGPY) but also identify some of the challenges to achieving the 2050 goal of 35 BGPY. To identify these obstacles, the project team interviewed key stakeholders such as SAF and renewable diesel producers, crude oil refining companies, environmental organizations, airlines, biomass producers, pipeline owners, and other experts in relevant fields.

State of SAF Production Process Report

This report presents factors within the SAF production chain that are common to all pathways. **The aim of this report is to highlight potential challenges that can hinder SAF production scale-up regardless of which pathway is used.** We identified these challenges based on discussions, consultations, and collaborative sessions with stakeholders along the SAF supply chain.

Executive Summary

Due to their compatibility with existing fuel infrastructure, biofuels will play an important role in decarbonizing hard-to-electrify portions of the transportation sector in the coming years. Specifically considering the aviation sector, greenhouse gas (GHG) emissions related to commercial air travel were already significant prior to the COVID-19 pandemic, at 10% of domestic transportation emissions and 3% of total U.S. GHG emissions. Even with modest annual growth, air transportation and related emissions are expected to double by 2050.

Because sustainable aviation fuel (SAF) is the only way that medium- to long-haul commercial aviation can be decarbonized in the near term, a U.S. governmentwide "SAF Grand Challenge" was issued to encourage industry to develop capabilities to produce SAF, reduce cost, improve sustainability, build supply chains, and scale production capabilities [1]. The targets are to expand current domestic SAF production by 130 times (based on 2023 consumption numbers) to 3 billion gallons per year by 2030 and then further by 12 times to 35 billion gallons per year by 2050 while achieving life cycle GHG emissions reduction of at least 50% relative to fossil Jet A. Following the announcement of the SAF Grand Challenge, the U.S. Department of Energy, U.S. Department of Agriculture, Environmental Protection Agency, and Federal Aviation Administration collaboratively developed a comprehensive strategy, outlined in the SAF Grand Challenge Roadmap [2], to inform stakeholders of the actions necessary to achieve the above volumetric targets.

The purpose of this study is to provide an assessment of the current state of the SAF production industry and identify challenges and hurdles that industry may face in delivering the 2030 goals. This assessment is for the potential feedstocks and conversion pathways expected to contribute to 2030 goals and will generally follow action areas in the SAF Grand Challenge: feedstocks, conversion technology, supply chain, and policy and valuation.

The pathways we plan to investigate between fiscal years 2023 and 2025 include hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT), alcohol to jet (ATJ), and pyrolysis to jet (PTJ). The investigations are based on technical and commercial literature reviews, discussions, consultations, and collaborative sessions with industry stakeholders and subject matter experts on technologies, economics, sustainability, logistics, approvals, regulations, policies, and permitting that may impact the industry's ability to achieve the SAF Grand Challenge goals. In addition to this report, a report on HEFA will be published in 2024, and reports on FT, ATJ, and PTJ will be published during fiscal years 2024 and 2025.

This report presents factors within the SAF supply chain that may be common to all pathways. Based on industry feedback and our analysis, some of the key takeaway factors highlighted from this study include:

- **Both SAF and renewable diesel (RD) are necessary to decarbonize transportation.** RD supports the decarbonization of medium- and heavy-duty vehicles, and SAF enables the decarbonization of medium- and long-distance commercial aviation.
- **The demand for SAF is expected to increase because there are no alternative fueling options for medium- to long-haul commercial aviation.** Although there is likely to be strong demand for RD in the medium-term, long-term demand for RD will likely

decrease because of electrification and hydrogen fueling options for medium- and heavy-duty vehicles. Increasing production volumes of RD in the near term has the benefit of developing production/logistics infrastructure and improving fuel producers' skills in maintaining quality, problem-solving, efficiency, and cost reduction, as the technologies for RD and SAF are similar. The growth of the SAF market will be positively impacted by all of these learnings.

- In the present market and incentive structure, **RD competes with SAF because they have mostly similar process configuration, carbon numbers, and boiling points. At the time of publication, the combined incentives in some states will slightly favor RD production (federal and California State[1] incentives).** As evidence of the impact of incentives, only 8 million gallons of SAF were sold in California in 2021, which made up 0.3% of the total Low Carbon Fuel Standard (LCFS) credits sold. In contrast, 941 million gallons of RD were produced in the same year, accounting for 36% of the total LCFS credits. **The structure of the combined federal and state incentives for California (CA) indicates that RD currently has a slight advantage over SAF when carbon intensity (CI) values are equal. This advantage is mainly due to the extra $0.39 allocated to RD based on California avoided diesel deficit**. In the absence of California avoided diesel deficits, the federal and California LCFS incentives favor SAF for 2023–2024 and 2024–2027, when emissions reductions exceed 60%. **While current policy and market conditions may incentivize biofuel facilities to favor RD production, these same facilities could be used with some modifications to increase SAF production and support the Federal government's SAF production goals as the market for SAF grows.**
- **Effective and durable policy incentives are required for SAF production and encourage the growth and establishment of a SAF industry** while ideally providing low-carbon jet fuel to customers at costs comparable to fossil Jet A. Stakeholders emphasized the necessity of long-term durability of SAF policies because capital investments are large, with project lifetimes exceeding 10 years. **One major concern has been the frequent expiration and reinstatement of tax credits, as well as the consistency of these incentives.**
- **Establishing a global consensus on the definition and eligibility criteria for SAF is important because airlines will use SAF produced on international routes and will thus be subject to other countries' regulations.** Most of the feedstocks identified in the Billion-Ton Report [3], such as grains, oilseeds, animal fats, and forestry wastes, can comply[2] with the SAF Grand Challenge's 50% GHG emissions reduction requirement and the Commercial Aviation Alternative Fuels Initiative (CAAFI) definition of SAF [4] and may also be compliant with the International Civil Aviation Organization (ICAO) definition of SAF [5].
- **Feedstock availability may be a high risk in a supply chain because it embodies multiple risks that may compound and that are beyond the control of a SAF producer.** Compounding factors for certain biomass feedstock may include seasonality,

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[1] California was chosen in this case because of their unique state-level energy policies, which often lead to the production of high volumes of renewable transportation fuels within their borders. Other states may have different existing and proposed policies that will change the overall landscape of fuel production before 2030.

[2] Some feedstock and SAF pathway combinations, like corn-ethanol to jet fuel, may not meet the GHG emissions reduction threshold unless additional measures are taken to reduce the carbon intensity of the process.

pests, diseases, climate and weather, market demand, global trade and regulations, and labor. Some of this risk may be mitigated by conversion processes that have the flexibility to accept multiple, more diverse feedstock. However, project financiers typically require long-term supply agreements with credit-worthy counterparties. The challenge lies in the fact that, despite the availability of feedstock, the project may still not meet the necessary de-risk criteria—because of the factors mentioned above—to qualify for project financing. One way this feedstock risk may be mitigated is to have feedstock suppliers also become investors in SAF projects.

- For the HEFA pathway, **there is a significant overlap between jet and diesel hydrocarbon fractions**. Although overlap between jet and diesel fractions will allow producers the flexibility to choose which product to make, production of additional jet fuel from the diesel fraction may require additional capital expense, increase operating costs, require additional hydrogen and higher-severity operations, and reduce carbon yield to the desired product. Simple extraction of the jet fraction (approximate carbon number [C] 8 to 16) via distillation will result in the remaining diesel fraction (carbon number > 16) being too heavy (high pour point) to be used in the diesel market; however, this heavy fraction may be suitable for heavy fuel oil displacement in the marine fuel market. While the government has established SAF production as a priority, producing renewable diesel and/or marine fuel also contributes to decarbonizing the transportation sector. For the ATJ pathway, where smaller molecules are "built up" or oligomerized to make larger molecules, it may be possible to produce fuel molecules in the C8 to C16 range without having to produce larger molecules.
- At present, 100% SAF blendstock (without ASTM D1655 approval) is not approved to be transported via petroleum pipelines. In the future, pipeline transport may be permitted, but SAF blendstock is currently transported by truck, rail, or barge from stand-alone biorefineries where blending with fossil Jet A may not be possible. It may be **beneficial to consider biorefinery sites with barge and rail access in the near term until approval is given for 100% SAF transport via petroleum pipelines**. Delivery of less-dense feedstocks, such as woody biomass and agricultural waste, by truck, even for a modest-sized biorefinery producing 60 million gallons of SAF per year, will require a truck coming and going every 2 minutes. If fossil diesel is used for fuel, the increase in truck traffic can further contribute to GHG emissions. This may negatively impact surrounding communities unless there are options to bypass inhabited areas. Another option may be the use of "hub-and-spoke" logistics models where biomass is collected and densified at smaller scale, then moved in a densified form to a biorefinery.
- The Nation's pipeline fuels transportation infrastructure is already capacity-constrained when annual jet fuel use is approximately 22 billion gallons. If annual aviation fuel demand increases to 35 billion gallons by 2050, **fuel logistics may become a bottleneck constraining the growth of the aviation industry**. Although this constraint could be mitigated by reduced demand for gasoline (because of light-duty fleet electrification), there may also be **opportunities to produce SAF locally, near airports, to bypass the fuels transportation infrastructure constraints**. This strategy may be more applicable to ATJ or FT plants since HEFA facilities are predominantly repurposed fossil fuel refineries [6].
- **Biorefinery project permitting processes have been identified as onerous and deemed to be "substantial barriers" in the deployment of SAF facilities**, with projects

canceled or relocated due to lengthy, high-risk, and time-consuming permitting processes. While this is not a barrier exclusive to SAF, interviewed stakeholders felt that process simplification would be beneficial to speed deployment of SAF facilities.

- **Social resistance to new facilities has been raised by stakeholders as a potential bottleneck.** This stems from the environmental impact of new facilities but also from insufficient involvement of residents and energy/environmental justice advocates before a project is started and community buy-in is obtained. Social resistance is not exclusive to the SAF industry; however, community acceptance when siting a biorefinery is critical to avoid potential delays. Understanding how regulatory institutions incorporate stakeholder participation into their decision-making process could help simplify the permitting process while also including and considering public concerns and priorities.
- Current incentives directly benefit fuel producers, who would increase SAF production and create additional demand for feedstock. Farmers may benefit through increased demand for feedstock as an indirect benefit.
- **Fixed assets and the contractual arrangements (mainly for feedstock supply and product offtake) are not considered secure enough for project financing**. Project finance lenders would like to see multiple years of stable operation and cash flow for similar facilities before providing credit. Thus, programs such as the Bioenergy Technologies Office's scale-up funding opportunities for demonstration plants [7] and the Loan Programs Office's support for pioneer biorefineries are critical [8]. Other lenders such as equity finance have higher risk tolerance and may bridge the gap between federally supported projects and project financing structures. Petroleum refinery integration may also significantly reduce capital costs, lowering financing needs.
- The airline industry is extremely cost-competitive, with fuel contributing 20% to 30% of their operating expenditures. If any single airline agrees to lock-in to a long-term SAF premium for substantial fuel volume, its cost structure may become uncompetitive against its peers. However, one positive aspect of long-term price lock-in may be hedging against price volatility of fossil Jet-A.
- **SAF developers felt that carbon pricing or even a global carbon tax would "level the playing field"** for them to compete with other renewable industries and to ensure consistent decision-making processes across the available pathways. Incentives or mandates that affect each airline equally may mitigate cost imparity between SAF and Jet-A and reduce the impact of price volatility of Jet-A on airline profitability.

Producing SAF to meet the Grand Challenge goals is a great opportunity for economic development in the U.S. SAF will decarbonize flights within the U.S and enable U.S. carriers to fly globally with a lower carbon footprint. There are some challenges, such as the need to produce RD as well, which will put pressure on feedstock supply, but there are multiple pathways approved by ASTM that provide considerable feedstock flexibility. SAF biorefineries will have the potential benefit to reduce bottlenecks in the U.S. capacity-constrained fuel distribution systems if they can be built closer to airports. There are opportunities to make policies (at the state or federal level) to encourage more stable investments for producing SAF. The Bioenergy Technologies Office, Loan Programs Office, and other federal programs such as the Federal Aviation Administration's Fueling Aviation's Sustainable Transition (FAST) [9] are critically important at this nascent stage of the industry, as conventional lenders tend to be risk averse.

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1 Introduction

Key Takeaways

- Medium- and long-distance jet aircraft produce 95% of commercial aviation greenhouse gas (GHG) emissions; for these aircraft there is no near-term viable decarbonization alternative other than sustainable aviation fuel (SAF).
- The SAF Grand Challenge has called for the production of 3 billion gallons per year (BGPY) of SAF by 2030 (130 times scale-up from current production) and 35 BGPY by 2050 (12 times scale-up from 2030 production of 3 BGPY).
- It is expected that lipid-based pathways (hydroprocessed esters and fatty acids [HEFA]) may primarily contribute to the 2030 goal, with smaller contributions from waste, forest, and agricultural residue (Fischer–Tropsch [FT]), and alcohol-to-jet (ATJ) pathways.

Purpose of the Reports

- Assess the state of the HEFA, FT, pyrolysis-to-jet (PTJ), and ATJ SAF production pathways and identify R&D, engineering, business development, policy, and other investments that federal agencies, industry, and other stakeholders may make to actualize the 2030 SAF Grand Challenge goal. The reports also highlight challenges that could hinder achieving the 2050 goal of 35 BGPY.

Organization of the Report

- This report outlines the methodology for evaluating the state of the SAF industry, including permits, approvals, logistics, and policy factors affecting SAF from across all pathways for 2030.
- Separate reports will cover the HEFA, FT, and ATJ pathways.

GHG emissions related to commercial air travel are already significant, at 10% of the domestic transportation emissions, and 3% of total U.S. GHG emissions prior to the COVID-19 pandemic [10]. According to projections from the U.S. Energy Information Administration, even with modest annual growth, air transportation is expected to almost double by 2050 [11, 12]. The bulk of carbon dioxide (CO_2) emissions are generated by larger nonregional passenger and freight jet aircraft (Figure 1) [13].

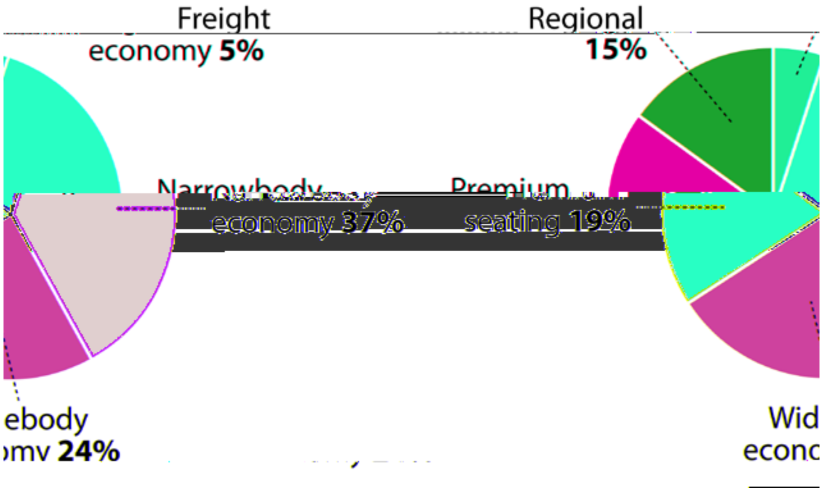

Figure 1. Ninety-five percent of GHG emissions are from narrow-body, wide-body, and freight aviation [13]

These aircraft will be difficult to electrify because of the weight limitations of current battery technology.[3] Although significant efforts are being made to power aircraft by hydrogen , completely new aircraft with much larger pressurized fuel tanks would be necessary.[4] Thus, aircraft that are powered by hydrogen remain a long-term solution.

SAF is the only near-term option for existing airplanes and is expected to play a key role in the decarbonization of long-distance travel and commercial flights [1, 2]. SAF must be "drop-in" blendstock, meaning it is compatible with existing commercial aircraft, and reduce GHGs relative to fossil jet fuel by a minimum of 50%. Ongoing efforts are assessing the utilization of 100% SAF (non-drop-in zero or low aromatic) in newer-generation aircraft and engines, as demonstrated by the November 2023 Gulfstream flight across the Atlantic [14].

A U.S. governmentwide "SAF Grand Challenge" was set to encourage industry to develop capabilities to produce SAF, reduce cost, improve sustainability, build supply chains, and scale production capabilities [15]. The SAF Grand Challenge targets are to expand production to achieve 3 BGPY of domestic SAF production to achieve a minimum of 50% reduction in life cycle GHG emissions compared to conventional fuel by 2030 and 100% of projected aviation jet fuel use (35-BGPY production) by 2050.

Figure 2 shows the magnitude of the SAF Grand Challenge [16]. As of November 2023, estimated SAF domestic consumption was approximately 23.3 million gallons per year (including domestic production and imports) [17]. In 2022, an estimated 8.0 million gallons of SAF were imported into the U.S. while approximately 1.0 million gallons were exported [18]. To achieve the 2030 target of 3 BGPY, production must be scaled up more than 2 orders of magnitude, by about 130 times (based on the consumption of SAF in 2023), in just 6 years while also supplying a growing renewable diesel (RD) market. After 2030, the scale-up factor will

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[3] Specific energy capacity of lithium-ion batteries is only 2.5% of jet fuel.

[4] Liquid Hydrogen only has 16% of energy density relative to conventional Jet A.

decrease to 12 times over 20 years. Assuming a very conservative $10/gal capital cost, achieving the 2030 goal will require raising at least $30 billion in capital to finance only the biorefineries if extensive integration with existing petroleum refineries is not achieved.

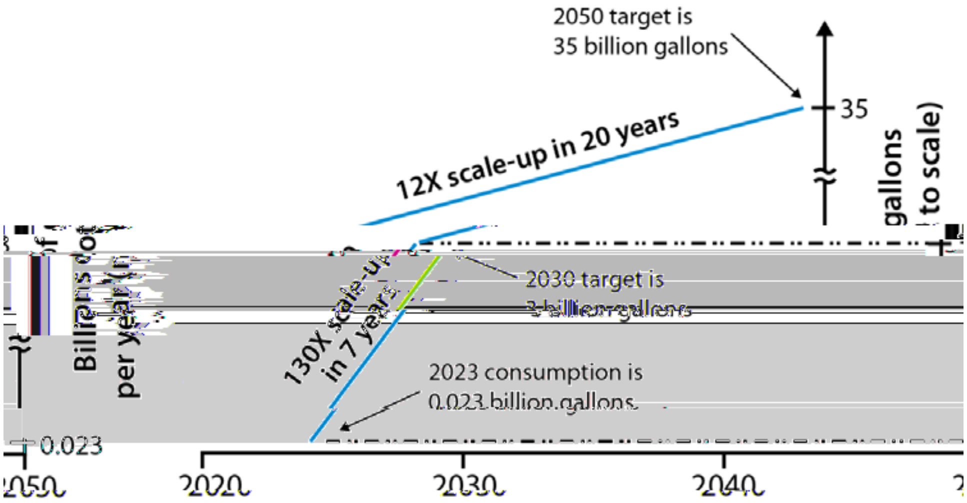

Figure 2. The SAF Grand Challenge requires 130 times scale-up in production in the next 7 years (considering 2023 consumption volume) and 12 times scale-up in the 20 years following 2030 [16]

To meet these very aggressive targets, the U.S. Department of Energy, U.S. Department of Agriculture, U.S. Environmental Protection Agency (EPA), U.S. Department of Transportation, and Federal Aviation Administration collaborated to develop a comprehensive strategy outlined in the SAF Grand Challenge Roadmap [2]. The roadmap delineates a "whole-of-government" approach across all government sectors, with synchronized policies and targeted activities that federal agencies should undertake to achieve both the 2030 and 2050 goals of the SAF Grand Challenge. The roadmap outlines six action areas that encompass all activities that could potentially impact the SAF Grand Challenge objectives of (1) expanding SAF supply and end use, (2) reducing the cost of SAF, and (3) enhancing the sustainability of SAF:

1. Feedstock Innovation
2. Conversion Technology Innovation
3. Building Supply Chains
4. Policy and Valuation Analysis
5. Enabling End Use
6. Communicating Progress and Building Support.

Each of the six action areas contains workstreams that delineate important subjects to be tackled. Given the limited time to meet the 2030 goal of 3 BGPY, the roadmap calls for an immediate focus on commercially ready or nearly commercially ready conversion technologies and feedstocks. The HEFA pathways, which use fats, oils, and greases as feedstock, are expected to be the primary fuel pathway leading up to 2030. The waste, forest and agricultural residue, and alcohol pathways are expected to make a smaller contribution.

1.1 Purpose and Methodology of This Study

The HEFA pathway is expected to be a contributor to the 2030 goal. If other pathways are also going to contribute to the 3 BGY goal, then demonstration plants for those pathways must be built. Considering the optimistic scenario in which it takes 2–3 years to build and start up a production facility,[5] and considering that at the time of publishing, there are only 6 years until 2030, demonstration plants must be built in the next 3 to 4 years. It will be important to assess the current state of the SAF production industry, independently of the chosen pathways, to understand what challenges these demonstration plants may face as they are rapidly built and brought online.

The assessment in this report is focused primary on the potential feedstocks and conversion pathways identified for meeting 2030 targets by the *SAF Grand Challenge Roadmap* and will generally follow the first four action areas: (1) Feedstock Innovation, (2) Conversion Technology Innovation, (3) Building Supply Chains, and (4) Policy and Valuation Analysis. The purpose of the assessment is to determine what challenges industry—which includes the entire supply chain (feedstock providers, logistics companies, converters, refiners, and blenders)—may need to overcome to be able to deliver 3 BGPY of SAF by 2030, given current policy incentives and business environments.

The assessments reported here span the entire supply chain starting from raw feedstock at the source to ASTM D1655-approved fuel delivered to the airport. Because supply chains are mostly serial constructs, an issue with one of the steps or unit operations can act as a bottleneck and negatively impact the throughput of the entire supply chain. Identifying potential bottlenecks in the supply chain may point to R&D, engineering, business development, policy, and other investments that federal agencies, industry, and other stakeholders may make to actualize the SAF Grand Challenge goals of 3 BGPY by 2030 and 35 BGPY by 2050. Because the ultimate objective is to achieve a path to 35 BGPY by 2050, the assessment will view the state of industry from the perspective of scalability.

Industry stakeholders provided significant input to this study; we conducted extensive interviews with stakeholders, including feedstock providers, RD and SAF producers, petroleum companies, logistics companies, and airports. Sample questions are shown in Appendix A.

This study includes insight on regulation and policy, procurement and supply chains, investments, and production and technology challenges and risks of current ASTM-approved pathways. Feedstock availability, harvesting, logistics, preprocessing, carbon conversion strategies, product qualification, and SAF delivery logistics and blending into Jet A are evaluated. Economic and sustainability metrics, including minimum fuel selling prices (MFSPs) (with and without policy impacts), GHG emissions reduction compared to a petroleum baseline, renewable hydrogen usage, water consumption, particulate matter (PM) emissions, and technology readiness, will be addressed for each of the pathways. The findings will be published

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[5] Industry stakeholders mentioned that the design, construction, and preparation for the startup of an HEFA facility is 2–5 years. This range applies to projects approved for expenditure and does not include the preliminary analysis steps like project scoping [6].

as a series of reports from the calendar years 2023 to 2025 by the National Renewable Energy Laboratory (NREL).

1.2 Content and Organization of This Report

This report is the first of the series and describes the common elements across all pathways. These include the overall methodology, logistics, policy impact, and economics/sustainability for potential SAF supply chains for 2030. Subsequent reports will conduct deep dives into specific feedstock conversion processes (HEFA, ATJ, PTJ, and FT). The HEFA report will be published concurrently with this report. The methodology for evaluating the economics and sustainability of HEFA, ATJ, FT, and PTJ pathways in subsequent reports is described in Appendix E.

2 Sustainable Aviation Fuels

Key Takeaways

- The Commercial Aviation Alternative Fuels Initiative's (CAAFI's) definition of SAF, along with the SAF Grand Challenge requirement of 50% reduction of GHGs, will enable production of SAF that will also be compliant internationally, contingent on the consistent application of the same life cycle analysis (LCA) methodology.
- There is significant overlap between jet and diesel hydrocarbon fractions from hydrotreatment processes. This overlap will give producers the flexibility to choose which product to make.
- Production of a jet fraction at the expense of a diesel fraction requires hydrocracking, which increases costs, requires more hydrogen and higher-severity operations, and reduces carbon yield. This would disincentivize an RD producer to produce SAF. In the absence of specific policy incentives or interests from airlines or consumers in paying higher prices for SAF, a refinery would almost always make a higher profit producing RD than SAF.
- Feedstock supply may be a high risk in a supply chain because it embodies multiple risks that may compound and that are beyond the control of a SAF producer. Compounding factors may include seasonality, pests, diseases, climate and weather, market demand, global trade and regulations, labor market, and opportunity costs.
- Risk mitigation options beyond supply agreements may include capabilities to process diverse feedstocks and contracts with a diversity of feedstock suppliers.
- For SAF pathways that rely on low-density feedstocks, such as woody biomass and agricultural waste for the ATJ or FT pathways, even relatively "small" supply chains producing approximately 2% of the 3-BGPY goal can create significant truck traffic (one feedstock truck either coming or leaving every 2 minutes). Depending on the facility's location, this may greatly impact quality of life in rural communities but may be mitigated by barge or rail delivery of feedstock or dedicated truck routes far from communities.
- The capacity of petroleum fuel transportation infrastructure is already constrained at many airports and major hub airports across the United States. While this is not a challenge exclusive to SAF, which is expected to replace Jet A fuel on a one-to-one gallon basis, SAF may require additional infrastructure for blending and storage. Therefore, if the increase in demand for aviation fuel is not offset by decreases in demand for both aviation and road fuels, SAF may encounter challenges due to infrastructure limitations. One approach to mitigate this is to site SAF production close to airports.
- 100% SAF blendstock (without ASTM D1655 approval) cannot be transported via petroleum pipelines at present. This may be a consideration for stand-alone biorefineries where blending with fossil Jet A may not be possible.

2.1 Definitions of SAF

From the SAF Grand Challenge [19]: “SAF is drop-in liquid hydrocarbon jet fuel produced from renewable or waste resources that is compatible with existing aircraft and engines.” SAF refers to drop-in hydrocarbon fuels for jets from a variety of pathways, not just oil-based pathways.

There are multiple meanings of the term “SAF”; most meanings are similar, but there are some nuances. Both the U.S. and global perspectives are presented here because commercial aviation is a global business. Although the SAF Grand Challenge is specific to the U.S., most major U.S. airlines also fly extensive global routes; therefore, global definitions of SAF are relevant.

From the U.S. perspective, as per CAAFI [20], SAF is Jet A fuel blendstock that:

1. Reduces net life cycle CO_2 emissions from aviation operations
2. Enhances the sustainability of aviation by being superior to petroleum-based jet fuel in economic, social, and environmental aspects
3. Enables drop-in jet fuel production from multiple feedstocks and conversion processes, so **no changes are required in aircraft or engine fuel systems**, **distribution infrastructure, or storage facilities**. As such, SAF can be mixed interchangeably (is fungible) with existing jet fuel.

SAF is defined slightly differently by the International Civil Aviation Organization (ICAO) [20] as renewable or waste-derived aviation fuels that meet the following sustainability criteria [5]:

1. Fuels that achieve net GHG emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Fuels that will not be made from biomass that is either obtained from land converted after Jan. 1, 2008, that was primary forest, wetlands, or peat lands or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands, as these lands all have high carbon stocks.
3. In the event of land use conversion after Jan. 1, 2008, as defined based on the Intergovernmental Panel on Climate Change land categories, direct land use change emissions will be calculated. If direct land use change GHG emissions exceed the default “induced” land use change value, the direct value will replace the default induced value.

It should be noted that the CAAFI definition does not state a specific target for GHG reduction relative to Jet A, and the ICAO definition specifies a target of 10% reduction relative to Jet A. The SAF Grand Challenge [2, 15] requires fuels to reduce GHG emissions by at least 50% relative to Jet A. For this report we use the CAAFI definition, with the additional constraint of a GHG reduction of 50% relative to Jet A. Because the *2016 Billion-Ton Report* [3] does not account for old-growth forestland as candidate feedstock for SAF, we will assume that criteria (2) and (3) of the ICAO definition are satisfied. With this approach, SAF produced in the U.S. will be compliant both domestically and globally, contingent on the consistent application of the same LCA methodology by all countries.

2.2 Key Adjacencies Between SAF and Major Transportation Fuels

A detailed technical description of jet fuels has already been provided in a previous report from the U.S. Department of Energy [1] and therefore will not be repeated here. However, key adjacencies and overlaps between gasoline, jet fuel, and diesel are important to highlight because there is already a healthy and growing market for RD and biodiesel being supplied by lipids; thus, SAF customers will have to compete with RD and biodiesel customers for lipid feedstock.

Gasoline, jet, and diesel fuels consist primarily of blended mixtures composed of hundreds of diverse hydrocarbon molecules. Molecules in gasoline fuel range from those containing 4 carbon atoms to those containing 12. At atmospheric pressure, gasoline has an initial boiling point of approximately 35°C and a final boiling point of around 200°C. Molecules in jet fuel range from those containing 8 carbon atoms to those containing 16. Jet fuel has an initial boiling point at atmospheric pressure of about 125°C and a final boiling point of about 290°C. The molecules present in diesel fuel span a range from 8 carbon atoms to 23 carbon atoms. Diesel has an initial boiling point at atmospheric pressure of about 150°C and a final boiling point of about 380°C [1].

As shown in Figure 3, jet fuel is the middle distillate product between gasoline and diesel [1]. A significant degree of overlap can be observed in the boiling point range of gasoline and jet fuel, with a nearly complete overlap observed in the boiling point range between jet fuel and the lower carbon number range of diesel. Refineries can strategically select between producing jet fuel or diesel, depending on market conditions and incentives. If the market value and incentives of biomass-based diesel are higher than those of SAF, then a refinery would be incentivized to produce RD rather than SAF [1].

Figure 3. Carbon numbers and boiling points for gasoline, jet, and diesel fuels [1]

It should be noted that the diesel fraction can be hydrocracked and isomerized to produce a jet fraction,[6] which increases costs, requires more hydrogen and higher-severity operations, and reduces carbon yield. This would further disincentivize an RD producer from producing SAF. Hydrocracking the diesel fraction to produce SAF will also divert some carbon to the naphtha fraction, which generally has lower value. In the absence of specific incentives, a refinery would almost always make a higher profit producing RD than SAF.

Figure 4 shows an average composition of Jet A, represented by four families of hydrocarbons: aromatics (~18%), cycloalkanes (~32%), isoalkanes (~30%), and *n*-alkanes (~20%) [1, 22].

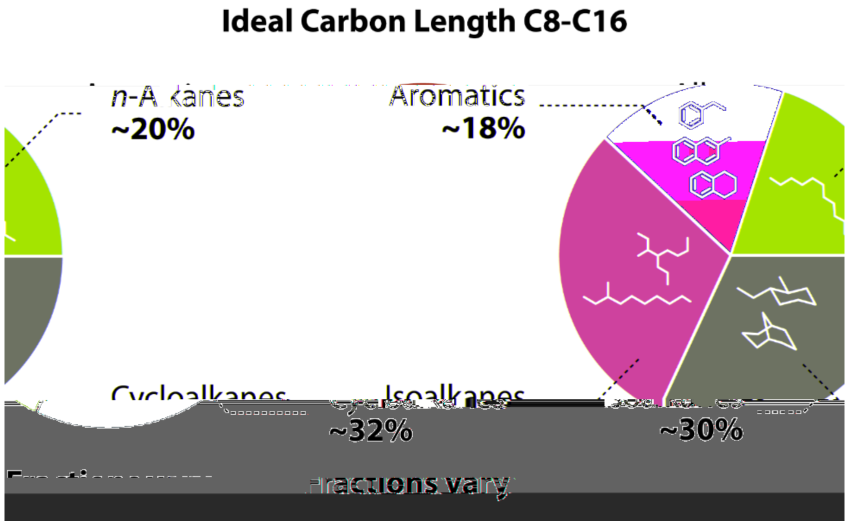

Figure 4. Composition of average Jet A [1, 12]

The composition of Jet A is relevant in the present context because in the HEFA pathway, triglycerides in the feed are converted to *n*-alkanes, which are limited to about 20%. *n*-Alkanes raise the freeze point, which is not desirable [1]. At present production rates, this is not a problem, but if production from the HEFA pathway is in the billions of gallons, there may be excess *n*-alkanes in local markets. In that case these may have to be diverted to the RD market. The option to isomerize the *n*-alkanes can require additional capital investment and more hydrogen consumption and would result in lower yields.

2.3 Overview of the Supply Chain

The SAF supply chain describes the sequence of operations, processes, and activities involved in the production and distribution of SAF from the feedstock to the final user. Supply chain analyses are important because uncertainties, risks, and GHG emissions must be reduced; yields, reliability, and returns must be increased across all operations; and bottlenecks must be identified.

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[6] The most recent revision of ASTM D1655-23 introduces a section in Annex A1 that allows hydrocarbons derived from hydroprocessed mono-, di-, and triglycerides, free fatty acids, and fatty acids (biomass) to undergo coprocessing via fractionation [21]. As a result, the fraction of hydrocarbons derived from hydroprocessed biomass acceptable for jet fuel manufacture can be separated and added to the jet pool product.

This section presents a high-level overview of a typical SAF supply chain embodying common elements for most feedstocks and pathways. Supply chains for the specific pathways (HEFA, FT, PTJ, and ATJ) will be discussed in greater detail in each of the reports specific to those pathways. A SAF supply chain can be divided into four major sections (Figure 5):

1. Feedstock supply, preprocessing, and logistics
2. Pretreatment, conversion, blending, and logistics
3. Supplies and inputs other than feedstocks
4. Permitting, approvals, and policies.

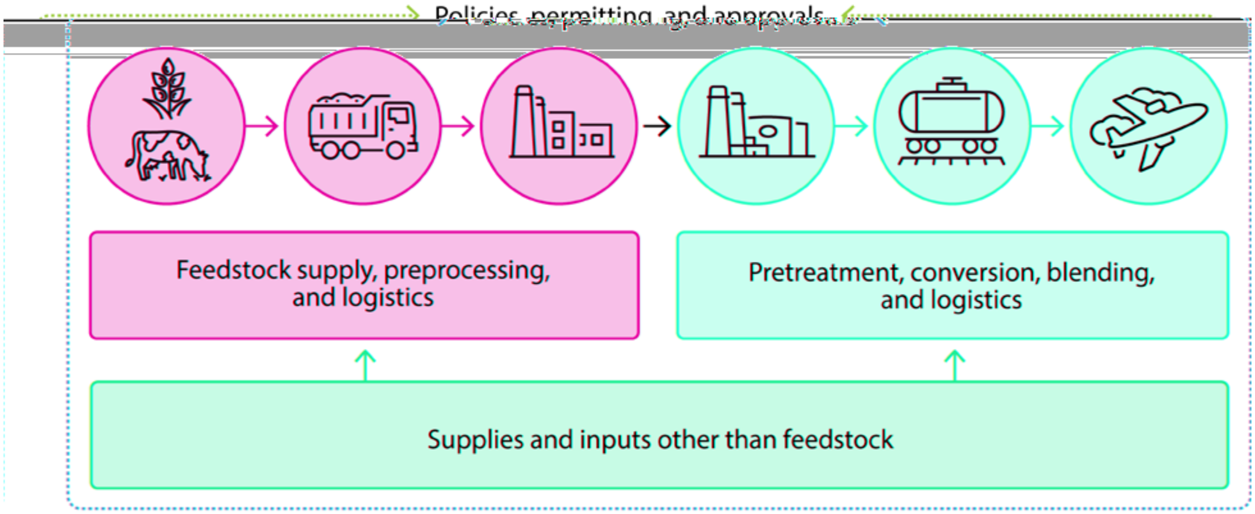

Figure 5. Overview of the SAF supply chain

In Figure 5, the blue section focuses on the supply, preprocessing, and logistics of feedstock, which includes generating, collecting, and transporting raw feedstock to a preprocessing facility, and then transporting it to the fuel facility. The type of feedstock depends on the selected SAF production pathway; examples include lipids from rendering facilities, oils from seed crops, starches, lignocellulosic biomass, and municipal solid waste.

Feedstock must be collected from (often widely) distributed generation locations and transported to a preprocessing or upgrading facility. For example, lipids are transported from rendering facilities, seed oil crops are transported to a crushing facility to extract vegetable oil, and then the lipids and oils are transported to conversion facilities. Feedstock availability can be impacted by multiple factors such as seasonality, location, collection methods, pests and diseases, climate and weather, market demand (consumer and sustainability nongovernmental organization acceptance), global trade and regulations, labor market, and economic factors. From a supply chain perspective, feedstock availability may be the highest supply chain risk because it embodies multiple risks that may compound and that are beyond the control of a SAF producer. A SAF producer may mitigate this risk via feedstock supply agreements, but such agreements may not be effective against disruptions associated with weather and pests. Another risk mitigation option may be to develop capabilities to process a diversity of feedstocks and contract with a diversity of feedstock suppliers.

Feedstock logistics may be an important consideration, particularly for less dense feedstocks such as woody biomass and agricultural waste that can be used in the FT or (cellulosic) ethanol to jet pathways. Consider a modest-sized (FT or pyrolysis) SAF production supply chain producing 60 million gallons of SAF per year. This supply chain would meet only 2% of the 3-BGPY goal. Using generous assumptions,[7] this supply chain will require almost 200 trucks per day to transport raw feedstock (5,715 U.S. tons biomass/day) to a preprocessing facility. Assuming the trucks operate 12 hours per day, this will generate two-way traffic of a truck on the route every 2 minutes. Transportation corridors in rural U.S. towns may pass through community "main streets," which often provide access to residences, schools, community centers, and shopping. A large truck passing through a town approximately every 2 minutes, 12 hours per day, 7 days a week would greatly reduce the quality of life in these towns—and if fossil diesel is used for truck fuel, the traffic would further contribute to GHG emissions [23, 24]. Mitigation options may include rail or barge delivery for high-volume feedstock. For trucks, bypass routes around small towns may be required as a minimum (e.g., corn transportation to corn ethanol plants), and hub-and-spoke logistics models could be helpful in reducing congestion.

Figure 5 illustrates the second section of the SAF supply chain (yellow) which involves transporting preprocessed feedstock to a fuel facility for upgrading into fuels and handling fuel logistics. This includes storage, blending, and transportation of fuel to the final user. Challenges in the transportation of SAF to terminals or airports are discussed in Section 2.4.

The production of SAF requires additional supplies and inputs besides feedstock. These may include fertilizers, catalysts, consumable chemicals (hydrogen, nitrogen, bleaching earth, acids, and bases), utilities, and adsorbents. These supplies and inputs would be specific to a pathway and the associated supply chain. Constraints in the supply of these inputs can potentially create bottlenecks in the pathway and supply chain.

Permitting, approvals, and policies will play a crucial role in shaping nascent SAF supply chains, incentivizing production, increasing demand, fostering innovation, simplifying logistics, and promoting international cooperation. Because the production cost of SAF is higher than that of fossil-based jet fuel, policies that support the use of SAF are vital to developing this industry.

2.4 Jet Fuel and SAF Movements

Conventional ASTM D1655-approved jet fuel (Section 3.1) from refineries and imports are primarily moved by a national network of pipelines (see Figure 6) from refineries, almost always to terminals, and from terminals to airports by pipeline or truck. Jet fuel may pass through multiple terminals prior to reaching the airport. Conversely, while uncommon, some refineries may be directly connected to airports by a dedicated pipeline. In general, new pipelines are

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[7] Biomass transportation capacity per truck: 60,000 lbs.; moisture: 50%; yield per dry U.S. tons: 60 gal SAF; truck operation: 12 hours per day, 350 days per year.

difficult to permit, and existing pipelines carry multiple fuels in batches and have limited excess capacity. Rail or barge transport tend to have fewer capacity constraints than pipelines.

Figure 6. Major U.S. pipelines transporting jet fuel.

Source: [25] with permission from Airlines for America

Fuel purchasers and marketers enter into lease agreements with terminal owners to store and blend fuels. Multiple types of terminal owners—petroleum companies, pipeline companies, and terminal companies—all lease space to fuel customers.

Jet fuel is stored in an airport fuel tank farm [26].[8] From the airport tank farm, the jet fuel is delivered to aircraft by an underground hydraulic "hydrant" system at most large airports or by fuel truck for smaller airports.

At this time, neat SAF is not being transported by pipeline but updates to pipeline company manuals with specific fuel quality requirements could enable those shipments per Federal Energy Regulatory Commission regulations. In cases where SAF is produced at stand-alone plants (without pipeline access), transport of the 100% SAF would be by truck, rail, or barge to a terminal where it would be blended with Jet A. The most affordable option to transport SAF blendstock (that is not ASTM D1655 approved) may be by barge if there is barge access. Rail, while more expensive, is efficient and has long been used to move biodiesel, RD, and ethanol. Trucking is the most flexible but expensive option and is ideally used for shorter distances, particularly when SAF is produced near a Jet A terminal and rail and barge options are not available. Thus, stand-alone biorefineries without convenient barge or rail access will be placed

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[8] Most RD and biodiesel fuels are moved by truck in the country today. Additional flexible transportation strategies will be needed when billions of gallons of renewable fuels are moved across states.

at a significant product logistics disadvantage. Figure 7 shows some possible supply chain movements for SAF and conventional jet fuel.

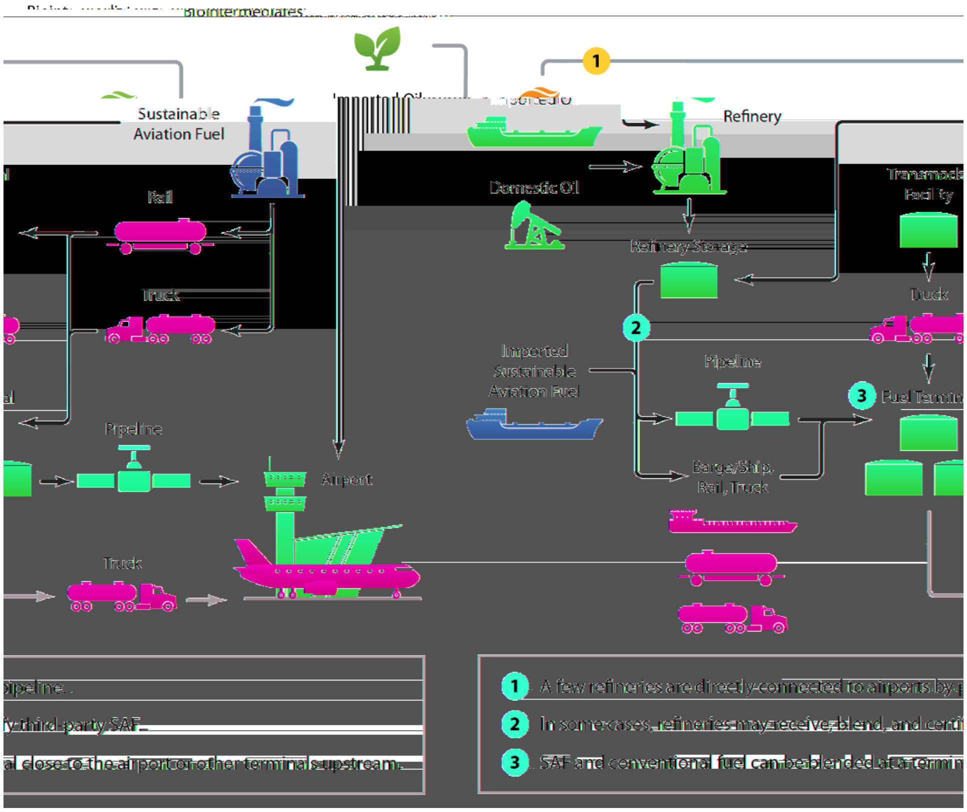

Figure 7. SAF and conventional jet fuel supply chains

SAF may be produced more economically at existing refineries if the refineries already have significant available infrastructure used for Jet A and required for SAF, co-feeds such as hydrogen, and a skilled workforce. If produced at an existing petroleum refinery,[9] SAF can initially be stored and blended in refinery tanks prior to moving in a business-as-usual model, largely through existing pipelines. There is some potential to move third-party-produced SAF to a refinery storage area if they have the infrastructure to receive the SAF and blend fuels. SAF is blended with Jet A within the allowable ratios (depending on the pathway) and considered the same as ASTM D1655-approved fossil Jet-A fuel.

2.5 Jet Fuel Supply Chain Constraints

Prior to the COVID-19 pandemic, jet fuel supplies were constrained by the lack of available capacity on multiproduct pipelines, as jet fuel must compete for space with gasoline and diesel, and dedicated pipelines from terminals to airports were operating at capacity in some geographic areas [27].

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[9] ASTM D1655 Annex A1 allows up to 5% vol. coprocessing of fatty acid esters or FT hydrocarbon and up to 24% vol. of hydroprocessed mono-, di-, and triglycerides, free fatty acids, and fatty acids esters with the balance being conventionally sourced hydrocarbons [1, 21, 36, 37].

Because it is very difficult to permit and build new pipelines, infrastructure constraints could impact aviation fuel logistics, including SAF, in the future if demand grows by 1.6 times from current levels to 35 BGPY in the future. Increases in demand to transport SAF may be offset by decreases in demand for transporting gasoline and Jet A.

Airports without pipelines rely on truck deliveries, which are severely impacted by a lack of qualified drivers. National Tank Truck Carriers reported in May 2021 that the previous 2 years saw a 42% decline in qualified driver applicants and an overall 23% decline of drivers [28].

To supplement pipeline constraints during high demand, more fuel can be transported to airports by truck, but this option is difficult to scale. A fuel tanker truck can only carry about 8,000 gal, just slightly more than the 6,875-gal fuel tank capacity of a Boeing 737-800 airplane. Airports generally only have one or two truck offloading positions, it can take up to 30 minutes to offload, and staff must be on-site. There are also the negative consequences of higher costs and GHG impacts to move fuel by truck, as well as increased truck traffic to an airport.

Oceangoing barges are constrained at water-based terminals, and by the Jones Act requirement that vessels be both U.S. owned and operated.

Figure 8 and Figure 9 illustrate that Jet A supply to large airports, major transportation hubs, and smaller regional airports across the U.S. is already constrained, when fuel delivery is via both pipelines and trucks [29].

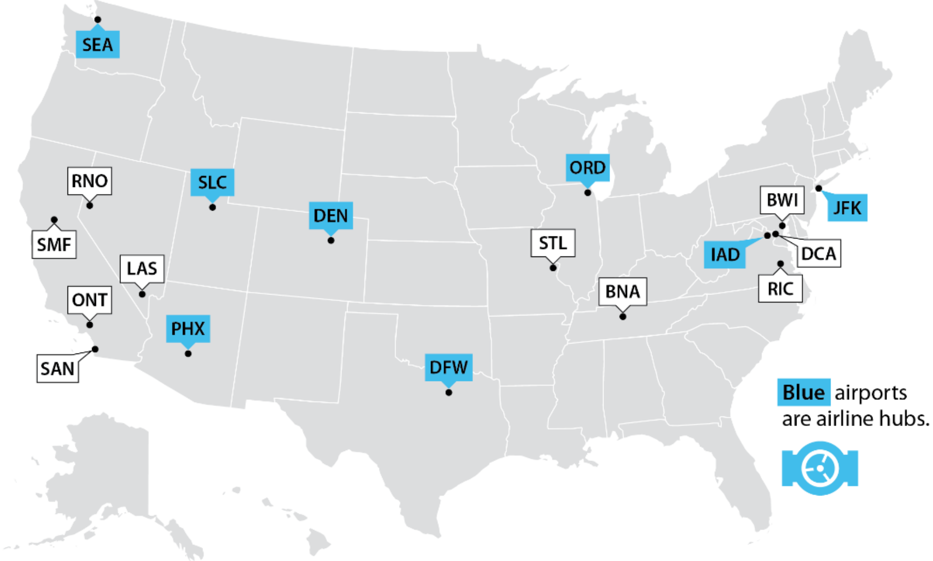

Figure 8. Airports served by capacity-constrained pipelines [29]

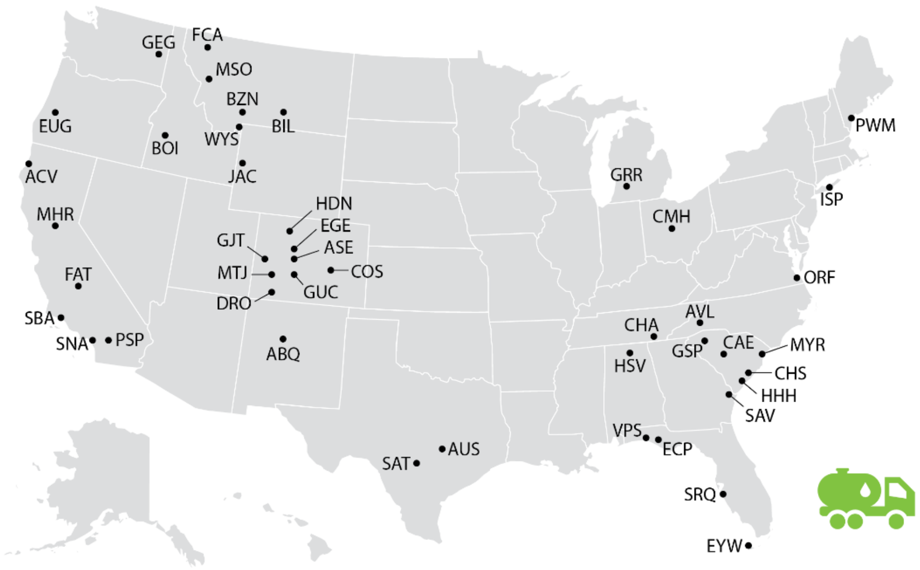

Figure 9. **Airports served by capacity-constrained trucks [29]**

2.6 Jet Fuel Quality Control

As mentioned in Section 2.3, conventional jet fuel—including fossil Jet A, fossil Jet A/SAF blend, or JetA/SAF produced via coprocessing at a refinery—must meet ASTM D1655 "Standard Specification for Aviation Turbines." SAF produced at a stand-alone facility must meet ASTM D7566 "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," after which it must be blended with fossil Jet A to be compliant with ASTM D1655 jet fuel and shipped in a business-as-usual model as Jet A [26, 30].

After production, each batch of fossil Jet A or Jet A/SAF blend produced at a refinery must pass a full conformity test to demonstrate that the fuel meets all fuel quality standards and generate a Refinery Certificate of Quality (RCQ) [26, 31]. The certificate must include batch number, manufacturing refinery, documentation of fuel quality testing, details of additives used, and a signature. Testing is done by the refinery, or a third-party laboratory certified by the International Organization for Standardization and accredited by a state or nongovernmental organization such as the American National Standards Institute National Accreditation Board. SAF blendstock must generate a similar quality documentation at the point of production [26]. Appendix B lists the properties tested to demonstrate jet fuel quality. Details of test methods and equipment used to conduct them are also available [31].

As jet fuel moves through the supply chain, its quality is governed by both the American Petroleum Institute Standard 1543 [32] and Airlines for America Specification 103 [33]. Each time a batch of jet fuel moves along the supply chain, it is retested to demonstrate that the fuel continues to meet either the ASTM D1655 standard (if it is Jet A or SAF blended with Jet A) or D7566 quality standard (if it is SAF blendstock). This is generally referred to as the "8-point test," but parameters tested may vary among organizations. Common tests include density, distillation, flash point, freezing point, existent gum, copper corrosion, water separation characteristics, color, electrical conductivity, and thermal oxidation stability. The testing is done by a third-party laboratory. If the fuel meets the quality standards, a certificate of analysis is issued. A Certificate of Analysis (COA) must include batch number, manufacturing refinery, tested properties, and a signature. This certificate is issued each time the fuel moves through the supply chain (e.g., at an intermediate terminal and at the airport). A COA would be generated at the point where Jet A and SAF are blended [26]. The certificate results are compared to previous documents that accompany the batch of fuel as it moves through the supply chain. If there are unexpected results, a full conformity recertification is required.

3 Permits and Approvals

Key Takeaways

- ASTM D1655-approved jet fuel, which consists of fossil Jet A blendstock and SAF blendstock, is considered the same as fossil Jet A. This is a significant benefit from a regulatory perspective because logistics, handling, and storage systems approved for fossil Jet A are also approved for ASTM D1655-approved jet fuel.
- Because the ASTM role is critical to safely deploying and scaling up SAF in commercial aircraft, our interviewees encouraged providing additional support to ASTM in its mission to approve and update SAF production pathways, which would benefit the entire SAF industry.
- Although treatment of ASTM D1655-approved jet fuel (which may consist of fossil Jet-A blendstock and SAF blendstock) as fossil Jet A is beneficial, permitting and regulatory approvals related to Jet A logistics are extensive, and obtaining these permits and approvals will be a significant hurdle for new entrants.
- ASTM has already approved eight SAF production pathways under ASTM D7566. Annexes A1, A2, A4, and A5—along with available feedstocks—have the potential to produce 3 billion gallons of SAF by 2030.
- Project permitting processes have been identified as onerous and deemed to be "substantial barriers" in the deployment of SAF facilities, with projects delayed, canceled, or relocated due to lengthy, high-risk, and time-consuming permitting processes. To speed up deployment, simplifying the processes would be beneficial.
- Permits and approvals for greenfield facilities are more extensive, multilayered, and complex. In some cases, re-permitting existing fossil petroleum refineries for SAF can be simpler than obtaining permits for greenfield sites. Difficulties with approvals and permits for greenfield facilities incentivize repurposing fossil facilities to renewables, rather than building greenfield facilities.
- The timing and difficulty of getting permits and approvals may depend on the geographic location of a site, magnitude of emissions, project novelty and complexity, and social, economic, and environmental impacts. These factors could vary significantly from project to project.
- Conducting comprehensive air quality analysis at the design or development stage of new SAF facilities or when repurposing an existing facility can de-risk permitting constraints and avoid triggering complex air permit requirements
- Social resistance to new facilities has been raised as a potential bottleneck. This stems partially from the environmental impact of new facilities and partially from a lack of attention to the concerns of residents and environmental justice advocates. These stakeholders should be involved in the process from the beginning, before resistance is hardened.

Total HEFA capacity (in construction or planned) is expected to reach about 6 BGPY by 2025 [6, 34, 35]; if completely executed, this would contribute both to RD and SAF, depending on market conditions and plant configurations and capabilities. Achieving 3 BGPY of SAF production will require a large number of biorefineries by 2030. Each of these facilities will have to be permitted and approved, and in most instances, financing will not be closed until all permits have been obtained. Permits will have to be secured not only to produce fuel, but also to transport it to blending facilities and then airports.

Because all of this must be completed for all the needed SAF facilities to achieve the SAF Grand Challenge goal in less than 7 years, permitting could become a significant hurdle in achieving the 2030 production goals. This chapter discusses permitting and approval requirements and highlights some concerns that must be resolved to accelerate deployment.

3.1 Fuel Approvals: ASTM Standards

Jet engines and airplanes are certified by the Federal Aviation Administration to operate on a fuel that is approved by ASTM. Any new fuel must meet ASTM specifications and be approved through the ASTM D4054 process [1]. At the time of writing (November 2023), ASTM has approved eight pathways listed in Annexes 1–8 of ASTM D7566, plus ASTM D1655 Annex A1, which allows 5% coprocessing of fatty acid esters or FT hydrocarbon and 24% hydrocarbons derived from hydroprocessed biomass streams with conventional jet fuel [1, 21, 36, 37] (see below, as well as Appendix B for details). Pathways that are potentially relevant for 2030 due to their commercial maturity are marked with asterisks (*). These include the FT pathway (Annexes A1 and A4 from ASTM D7566), the HEFA pathway (Annexes A2 and A1 from ASTM D1655), and the ATJ pathway (Annex A5). It should be noted that at present, the PTJ pathway has not been approved by ASTM.

ASTM D7566

SAF is approved for blending into commercial Jet A fuel under ASTM D7566, "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons." Conversion processes for different non-fossil feedstocks are approved and added as annexes to ASTM D7566 (Appendix B):

1. **Annex A1* (FT-Synthetic Paraffinic Kerosene [SPK])** was approved in June 2009 for up to a 50% blend with petroleum-derived jet fuel. FT-SPK is a mixture of iso- and *n*-alkanes derived from synthesis gas ("syngas") using the FT process. Syngas can be produced from reforming natural gas or from gasifying coal or biomass.
2. **Annex A2* (HEFA-SPK)** was approved in July 2011 for up to a 50% blend with petroleum-derived jet fuel. The molecular composition of HEFA-SPK is similar to FT-SPK, consisting of iso- and *n*-alkanes. The alkanes are the product of hydrotreating esters and fatty acids from fats, oils, and greases and from oilseed crops or algae.
3. **Annex A3 (Hydroprocessed Fermented Sugar – Synthetic Isoparaffins)** was approved in June 2014 for up to a 10% blend with petroleum-derived jet fuel. Unlike SPK from HEFA or FT, this is a single molecule—a 15-carbon hydrotreated sesquiterpene called farnesane—produced from fermentation of sugars. Today, the fermentation is done commercially from sugar cane juice and is used in higher-value applications.
4. **Annex A4* (FT-SPK/A, ASTM D7566)** was approved in November 2015 for up to a 50% blend. Biomass is converted to syngas, which is then converted to SPK and

aromatics by FT synthesis. This process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components.

5. **Annex A5* (ATJ-SPK)** was approved in April 2016 for SPK from isobutanol (30% blend with petroleum-derived jet fuel) and expanded in April 2018 for SPK from ethanol and for fuel blends up to 50% with petroleum-derived jet fuel. ATJ-SPK consists of isoalkanes of 8, 12, or 16 carbons when starting from isobutanol.
6. **Annex A6 (Catalytic Hydrothermolysis Jet)** was approved in January 2020 as a 50% blend. The fuel is produced from lipids using a supercritical hydrothermal process, creating a blendstock that contains all four hydrocarbon families: *n*-alkanes, isoalkanes, cycloalkanes, and aromatics.
7. **Annex A7 (HC-HEFA)** SPK from hydroprocessed hydrocarbons, esters, and fatty acids was approved in 2020 as a 10% blend. Annex 7 *only* recognizes the *Botryococcus braunii* species of algae as a biosource. The *Botryococcus braunii* species contains a high percentage of unsaturated hydrocarbons, known as botrycoccenes [38]. This annex centers on converting **hydrocarbons** in addition to free fatty acids and fatty acid esters. The product is rich in isoalkanes. This is the first approval through the fast-track process.
8. **Annex A8 (ATJ-SKA)** ATJ-SPK with aromatics, was submitted by Swedish Biofuels AB, passed ballot in June 2023, and was added into the ASTM D7566-23a [37]. The fuel is produced from single or a combination of C2 to C5 alcohols and is approved up to a 50% blend in Q3 2023 [37, 39].

D7566-approved SAF is blended with conventional Jet A up to its maximum allowed blend ratio specified in the applicable D7566 annex. After blending, the fuel receives D1655 approval, which makes it the same as Jet A (a “drop-in fuel”) [1, 40]. It is important for jet fuel that has SAF blended into it to be the same as Jet A, or drop-in—i.e., ASTM D1655-approved—because the blended jet fuel is transported through common pipeline networks and airport hydrant systems and used by all commercial airplanes fueling at airports.

At present, none of the pathways have been approved for 100% SAF (the maximum is 50% blending). This has not been an issue at present because the current supply of SAF (approximately 23 million gallons per year based on 2023 domestic consumption) is insignificant relative to Jet A use (approximately 25 BGPY in 2023) [17, 41, 42]. However, blend limits may become an issue in the future for single types of SAF molecules, such as *n*-alkanes, as SAF production volumes become significant. To alleviate this concern, one option is to isomerize *n*-alkanes; however, this approach necessitates additional capital and greater hydrogen usage and results in decreased yields.

To address blend limits, ASTM has commissioned a task force to restructure D7566 to set technical specification required for a 100% (drop-in) SAF standard by blending different synthetic components [35]. One hundred percent SAF has already been tested successfully in commercial aircraft [43], and Boeing has committed to deliver commercial airplanes capable and certified to fly on 100% SAF by 2030 [44].

Because ASTM's role is critical in the safe deployment and scale-up of SAF in commercial aircraft, additional support to ASTM in its mission to test, approve, and update SAF production pathways would benefit the entire SAF industry and was encouraged by our interviewees.

ASTM D1655

Aviation fuel is approved in the U.S. by ASTM International. Conventional (fossil) commercial aviation fuel, also known as Jet A, is approved under ASTM D1655, "Standard Specification for Aviation Turbine Fuels." ASTM D1655 describes the properties required for certifying aviation fuels as conventional Jet A aviation turbine fuels and lists acceptable additives [1].

Annex A1* allows coprocessing of up to 5% mono-, di-, and triglycerides; free fatty acids; and fatty acid esters, up to 5% of FT hydrocarbons, or up to 24% hydroprocessed renewable feed. Hydrocracking/hydrotreating and fractionation are required. No other coprocessing in refineries is allowed for jet fuel.

When blended (within the limits in the ASTM D7566 annexes) with fossil-sourced Jet A, the SAF approved under any of the ASTM D7566 annexes above are considered fully fungible as a D1655-approved fuel. The blended fuel is not treated differently than fossil Jet A, and can be transported and used in airport fuel storage and hydrant systems in an identical manner to Jet A.

Table 1 lists the approved SAF production pathways along with feedstock and conversion process summaries for pathways that may contribute to the 3 BGPY goal for 2030. Based on feedstock availability projections in the *2016 Billion-Ton Report* [3], as well as yields based on published information [45–48], there is more than sufficient feedstock (theoretical SAF production of 42 BGPY) to meet the 2050 Grand Challenge goals [49]. However, establishing collection, transportation, and processing systems for certain feedstocks—such as forestry and agricultural wastes—remains a necessary step, among others, and some SAF conversion technologies are yet to be demonstrated.

Table 1. SAF Production Pathways Likely To Contribute to 3 Billion Gallons by 2030

Pathway	Feedstocks	Chemical Process
D7566 Annex A1 FT-SPK **Blending limit: 50%**	Biomass, municipal solid waste, agricultural and forest wastes, energy crops	Lignocellulosic biomass is converted to syngas using gasification, and then an FT synthesis reaction converts the syngas to jet fuel.
D7566 Annex A2 HEFA **Blending limit: 50%**	Triglyceride feedstocks such as vegetable oils (e.g., jatropha, camelina); animal oils; waste fat, oil, and greases (e.g., yellow or brown greases); or algae feedstocks.	Hydroprocessing followed by hydroisomerization and hydrocracking.
D7566 Annex A4 FT-SPK with aromatics **Blending limit: 50%**	Same as A1	Gasification followed by SPK and aromatics by FT synthesis. The process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components.
D7566 Annex A5 ATJ-SPK **Blending limit: 50%**	Alcohols are derived from cellulosic (e.g., corn stover), sugar, or starch feedstock via fermentation or gasification	Conversion of alcohols (isobutanol and ethanol) into a drop-in fuel through dehydration, hydrogenation, oligomerization, and hydrotreatment.
D1655 Annex A1.2.2.1 **Fats, oils, and greases coprocessing** **Blending limit: 5%**	Same as A2	Fats, oils, and greases coprocessing with petroleum intermediates for SAF production.

3.2 Project Permits and Approvals

SAF biorefinery facility projects will generally require an extensive set of approvals and permits, not only for the manufacturing facilities, but also for the logistics for transporting the finished fuel to the airport.

- **Approvals** refer to the permissions granted by governing bodies that enable an organization to proceed with a specific project.
- **Permits** are permissions granted by regulatory agencies for each component of the project. They are typically detailed and specific.

Project permitting processes have been identified as a “substantial barrier” in the deployment of SAF facilities, with industry stakeholders mentioning projects delayed, canceled, or relocated due to lengthy, high-risk, and time-consuming permitting processes. It is crucial to involve local communities and other important stakeholders in the process for obtaining approvals and permits to ensure buy-in and address any concerns before the project moves too far along.

Project Approvals

The National Environmental Policy Act (NEPA) requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions [50, 51]. Therefore, NEPA is applicable to a broad spectrum of federal activities, encompassing federal construction projects, strategies for the administration and development of federally owned lands, as well as federal approvals. The environmental review under NEPA can involve three different levels of analysis [51]:

- Categorical exclusion determination
- Environmental assessment/finding of no significant impact
- Environmental impact statement.

For most major projects, the main **approval** comes in the form of an **environmental impact statement**, a document created by the applicant that explains how a proposed project will affect the environment in its surrounding area. This statement records the results of the project's **impact assessment**. SAF facility projects in the U.S. are legally required to include an environmental impact statement and can apply to greenfield and brownfield sites, as well as project expansions. Before starting a project, a comprehensive set of baseline studies is conducted to document the social and environmental context of the project. This is the beginning of the impact assessment process. Usually, the project hires an external consultant to conduct baseline studies, particularly on environmental and socioeconomic areas. Impact assessments aim to predict the future outcomes of project designs and decisions. The assessment will identify socioeconomic and environmental commitments, some of which will be obligations that the SAF production facility will be required to fulfill in the future when it is operating [51–53]. Environmental factors considered in these studies include air and water quality, hydrogeology, biodiversity, flora and fauna, hydrology, aquatic life, meteorology, and geochemistry. Anthropology, sociology, geopolitical science, economic analysis, and Indigenous studies are taken into account when examining social factors [51–53]. It is recommended that local communities are engaged in the baseline study.

Project Permits

After obtaining the necessary approvals for the major project, several individual **permits** must be obtained before the project can proceed with development. In addition to the environmental permits described below, necessary permits may include those for water usage and treatment, building, communication, and logistics. Every construction project must follow regulations and guidelines based on the location and government jurisdiction. Thus, it is important for the team to thoroughly research and comprehend the relevant regulations, laws, and guidelines specific to the project description and jurisdiction. It is also important to identify and consult with the appropriate governmental agencies and governing bodies [51].

3.3 Jet A Supply Chain's Regulations and Permits

ASTM D1655-approved fuel (considered Jet A) consisting of fossil Jet A blendstock and SAF blendstock is subject to the same federal permits as neat fossil Jet A. The barge, pipeline, rail, terminal, and truck companies moving Jet A already have the appropriate permits in place to move fossil Jet A, and all ASTM D1655-approved Jet A is treated the same as fossil Jet A. Airports also have permits for fossil Jet A in place for the operation of their tank farms, and these permits would be valid for ASTM D1655-approved fuel consisting of fossil Jet A blendstock and SAF blendstock.

The primary permit for moving and storing fuel is an EPA operating permit (often referred to as an air permit)[10] under Title 5 of the Clean Air Act. This permit is typically issued by state or local authorities as allowed under the Code of Federal Regulations (CFR) 40 Chapter 1 Subchapter C Parts 70 and 71. Detailed discussion is included in Section 3.4.

Federal environmental laws applying to jet fuel supply chain and logistics include:

- Clean Air Act
- Clean Water Act
- Resource Conservation and Recovery Act
- Comprehensive Environmental Response, Compensation, and Liability Act
- Toxic Substances Control Act
- Safe Drinking Water Act.

As an illustrative example, the federal Clean Air Act, along with its related regulations, permits, and the permitting process, is detailed in Appendix F.2. The EPA oversees the administration of these laws through a system in which state and Tribal governments may apply for and receive primary oversight and enforcement responsibilities. When a state has an EPA-approved delegated program, regulatory approvals are granted by the state government and EPA retains federal oversight over the state's implementation of the federal laws and regulations [51].

Permits issued through the National Pollutant Discharge Elimination System in 40 CFR § 122 ensure that there are no intrusions into groundwater from water ingress or storm water runoff.

Airport tank farms are not regulated by the EPA but are permitted by states with regulations that typically follow EPA requirements.

The Coast Guard issues permits to handle hazardous materials under Title 46 CFR 126.16 and 49 CFR 176.100 and 176.415.

The Pipeline and Hazardous Materials Safety Administration [53] is responsible for issuing pipeline permits.

3.4 Difficulties With Approvals and Permits

Obtaining project approvals and permits is a crucial stage in any major project, and its delay could jeopardize the project's timeline and even lead to a project's cancelation [55–57]. Consulted industry stakeholders consider the permitting process a major constraint in the deployment of SAF facilities. Interviewed industry stakeholders stated that renewable fuel projects have been canceled or relocated due to the lengthy, high-risk, and time-consuming permitting process. To speed up the deployment of renewable fuel facilities, industry stakeholders believe that government support in making the process easier would be beneficial. Some of the consulted fuel industry stakeholders noted that approvals and permits strongly incentivize complete fossil shutdowns and repurposing to renewable fuels over building new facilities.

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[10] "Petroleum storage and transfer units with a total storage capacity exceeding 300,000 barrels (12.60 Mgal)" are considered major sources [54].

Some stakeholders expressed concerns about social resistance as a major bottleneck for new facilities, which is not exclusive to the renewable fuel industry. **Social opposition often stems from insufficient involvement and addressing of concerns of residents and environmental justice advocates. Project delays and cancelations can happen if project developers or government entities do not acknowledge and address community concerns adequately.**

4 Policies and Incentives

Key Takeaways

- Effective and durable policy incentives are required for profitable production of SAF while providing jet fuel to customers at costs comparable to fossil Jet A.
- Stakeholders emphasized the necessity of long-term durability of SAF policies because capital investments are large. One major concern has been the frequent expiration and reinstatement of tax credits as well as the consistency of these incentives across administrations. Stakeholders pointed out that uncertainties across administrations is resulting in hesitation for signing offtake agreements exceeding 3 years, making financing more difficult.
- Current stackable policy incentives include the Inflation Reduction Act (IRA) (Sections 40B and 45Z) up to $1.75/gal, renewable identification numbers (RINs), and various state programs, including the Low Carbon Fuel Standard (LCFS) in California, Clean Fuels Program in Oregon, Illinois tax credits up to $2.00/gal, and Washington tax credits up to $2.00/gal.
- RD is a major competitor for HEFA SAF due to their similar production processes, forcing producers to decide which fuel to prioritize. Process yields, production cost, and policy incentives slightly favor RD.
- There are multiple LCA methodologies: LCA verification by the California Air Resources Board, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by ICAO, and the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model developed by Argonne National Laboratory. Because commercial aviation is a global industry, standardized LCA methodology and carbon intensity (CI) values (especially to address the differences between the U.S. and European Union) are concerns identified by stakeholders.
- For the SAF industry, the financing risks that financiers/investor must accept can include supply chain slowdowns, uncertain policies, technological uncertainties, and end-product market variability affected by public and political trends. Thus, SAF projects may encounter higher financings expenses and uncertain availability of financing due to the risk-averse nature of banks and lack of commercial data for novel SAF technologies.
- Current incentives directly benefit fuel producers, but there are yet no direct benefits that would incentivize farmers toward producing crops for renewable fuel. Farmers may benefit through increased demand for feedstock, but that is an indirect benefit and may not be sufficient to offset the risk a farmer takes when planting a new crop.
- The International Renewable Energy Agency reported that neither the fixed assets nor the contractual arrangement (mainly for feedstock supply and product offtake) are considered secure enough for project financing in the advanced biofuel business.
- SAF developers felt that carbon pricing or even a global carbon tax would “level the playing field” for them to compete with other renewable industries.

The production cost of SAF today is higher than that of fossil Jet A. As production increases and innovations and efficiencies of scale are introduced, SAF facilities are more likely to be profitable. However, as demand for feedstock increases, it is projected that feedstock costs will increase. Also, crude oil prices may decrease as decarbonization efforts across the globe lead to reductions in oil demand.[11] These contrary market demand forces on both renewable and fossil feedstocks, as well as the increased processing required for SAF, may continue to result in the total cost of SAF being higher than that of Jet A. Given these uncertainties, it is essential to introduce durable policies that encourage investment in SAF while providing jet fuel to customers at reasonable prices comparable to fossil Jet A.

Consulted industry stakeholders unanimously agreed that the development and implementation of SAF-supporting policies and incentives are central to the successful development of a SAF industry and to create a level playing field. They emphasized the necessity of long-term durability of SAF policies because capital investments in facilities are large and typically long term.

The U.S. and European Union have proposed significant policy legislation supporting the SAF industry. While the aim of the policies developed in these two parts of the world are the same, their approach and configuration are different. In the U.S., the federal government is implementing incentives to drive down the SAF cost for airlines and boost supply, whereas Europe is setting industrial targets and blending mandates.

This section describes key elements of SAF policies and assesses their impact and effectiveness in encouraging the development of SAF production capabilities in the U.S.

4.1 Inflation Reduction Act

In the U.S., the IRA, passed in August 2022, defines a SAF fuel credit for the sale or use of a qualified blend instead of a SAF mandate, and provides grants to support the production, storage, and distribution of SAF. Three relevant tax credit schemes are introduced with the IRA (40A, 40B, and 45Z) [58]. In addition, the IRA provided funding for a grant program administered by the Federal Aviation Administration's Fueling Aviation's Sustainable Transition (FAST) program [9].

IRA Sections 13201 and 13202

The IRA Sections 13201 and 13202 extend existing tax credits (Section 40A of the Internal Revenue Code, IRC) originally scheduled to end in 2022. These include the Biodiesel and Renewable Diesel Credit, Biodiesel Mixture Credit, Alternative Fuel Credit, and Alternative Fuel Mixture Credit—all are extended through 2024. While these credits are not applicable to SAF beginning in 2023 due to the federal SAF credit, these credits provide incentives for other biofuels such as RD, a fuel product that competes with SAF.

IRA Section 40B (2023–2024)

IRA Section 40B (Section 13203) provides a tax credit for the sale or use of SAF from 2023 through 2024 of $1.25/gal, which achieves a life cycle GHG emissions reduction of at least 50%

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[11] The phenomenon known as the rebound effect explains that the opposite could also be true. This means that efforts to promote the use of renewable energy sources or increase energy efficiency may have unintended consequences, leading to increased fuel or energy consumption overall, or a continued reliance on fossil fuels. This could happen if, for instance, increased energy efficiency leads to lower energy prices, thereby encouraging greater energy consumption in general. The rebound effect's magnitude can vary depending on factors such as policy measures, consumer awareness, and technological advancements.

compared with petroleum-based jet fuel [58]. SAF that achieves a greater reduction in life cycle GHG emissions is eligible for an additional \$0.01/gal credit for each percentage point of emissions reductions, up to \$1.75/gal of SAF. To qualify, SAF must meet the requirements of the ASTM D7566 or the Fischer-Tropsch provisions of ASTM D1655 Annex A1. For SAF to be eligible, it cannot be derived from coprocessing an applicable material (or materials derived from an applicable material) with a feedstock that is not biomass,[12] cannot be derived from petroleum or palm fatty acid distillates and must meet a 50% minimum reduction in life cycle GHG emissions [58]. In 2024, eligibility for the SAF Credit has been expanded to include ethanol from corn and soybeans if Climate Smart Agriculture (CSA) practices are used to grow the biomass feedstock [59]. CSA practices are an integrated approach that help farmers reduce GHG emissions and adapting and building resilience, while sustainably increasing agricultural productivity and income.

IRA Section 45Z (2025–2027)

For fuel produced after 2024 and used or sold before 2027, Section 45Z Clean Fuel Production Credit (Section 13704) provides a tax credit for domestic production (registered producers in the U.S.) of clean transportation fuels, including SAF [58]. For non-aviation fuels, the base credit is \$0.20/gal of fuel produced at a qualifying facility, meaning a transportation fuel production facility for which credits are not allowed for the production of clean hydrogen (under IRA Section 45V and Section 48 of the IRC) or carbon oxide sequestration (under IRA Section 45Q). An alternative credit of \$1.00/gal can be applied if it is produced at a qualified production facility that also meets wage and apprenticeship requirements. For SAF, the base credit is \$0.35/gal of SAF produced at a qualifying facility, with an alternative credit of \$1.75/gal of SAF, with facility requirements the same as for non-aviation fuels. SAF is defined as meeting the requirements of ASTM D7566 or the Fisher-Tropsch provisions of ASTM D1655 Annex A1, and also cannot be derived from petroleum or palm fatty acid distillates. Following the decision to allow additional GHG reduction credits for soybean-to-jet and corn ethanol-to-jet for the 40B SAF Credit, if a “bundle” of applicable CSA practices are followed, it is expected that this eligibility will be applied to the 45Z credit as well [60]. Both non-aviation and aviation fuels, which need to meet the Transportation Fuel definition, are not allowed to be derived from coprocessing an applicable material (or materials derived from an applicable material) with a feedstock that is not biomass. Applicable materials are monoglycerides, diglycerides, triglycerides, free fatty acids, and free fatty acid esters. Also, for both non-aviation and aviation fuels, to determine the full value of the incentive, the base or alternative credit is multiplied by an emissions factor, which is calculated as the quotient of 50 kg CO_2 equivalent (CO_2e) per million British thermal units (MMBtu) minus the emissions rate of a fuel, divided by 50 kg CO_2e/MMBtu. The determination of the emissions factor for a fuel is defined for both non-aviation and aviation fuels. Because the full value of the incentive is determined by multiplying the base or alternative credit by an emissions factor, the value of the incentive is dependent on the life cycle GHG emissions and is thus greater for fuels that have greater reductions in emissions. For fuels with zero emissions, the maximum credit would be \$1.00/gal of non-aviation fuel or \$1.75/gal of SAF. For fuels with negative emission less than -2.5 kg CO_2e/MMBtu, the value of the incentive would be greater than \$1.00 or \$1.75. To be eligible for

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[12] Incentives applicable to HEFA RD and SAF produced via standalone process and coprocessing are explored in the *SAF State of the Industry Report: HEFA Pathway* [6].

Section 45Z credits, a transportation fuel must have a life cycle emissions rate below 50 kg CO_2e/MMBtu [61, 62].

IRA Section 40007, FAST-SAF and FAST-Tech Grant Program

IRA Section 40007 directs the Secretary of Transportation to implement a “competitive grant program for eligible entities to carry out projects located in the U.S. that produce, transport, blend, or store sustainable aviation fuel, or develop, demonstrate, or apply low-emission aviation technologies.” Funding available is $244.53 million for projects relating to production, transportation, blending, or storage of SAF. Federal cost share is up to 75% of the total cost of the project. To be eligible, the SAF must achieve a life cycle GHG emissions reduction of at least 50% compared with petroleum-based jet fuel.

4.2 Renewable Fuel Standard

The Renewable Fuel Standard (RFS), which sets volumetric requirements for biofuels, was first established by the EPA in 2005 and later amended in 2007 as the first federal policy actions to increase the proportion of biofuels in fuels nationwide [63].

The RFS program requires refiners and importers of gasoline or diesel fuel to meet the Renewable Volume Obligation set by the EPA and uses Renewable Identification Numbers (RINs) to ensure compliance with these volumetric requirements. RINs are associated with each gallon of renewable fuel produced or imported. The RINs can be traded with the gallon of renewable fuel, or if a renewable fuel is blended, the RIN is separated from the gallon of fuel and can be traded [64, 65]. Supply and demand form a market for RINs, thus producing another source of revenue for renewable fuel producers. The EPA tracks this market to ensure compliance with the RFS [63].

The EPA sets target volumes for different categories of renewable fuels, including cellulosic biofuel, biomass-based diesel, advanced biofuel, and renewable fuel. The variability of these target volumes results in variability in the credit prices. SAF is eligible to generate credits as biomass-based diesel or advanced biofuel and must meet a minimum 50% reduction in life cycle GHG emissions [63]. However, a specific volumetric target is not set for SAF [63, 66]. Credits through the RFS that are earned by producing SAF can be stacked with other federal tax credits for SAF, such as those provided by the 2022 IRA, as well as state credits relevant to SAF. SAF is eligible for RFS credits depending on the feedstocks and pathways used to generate the fuel, and the ability to meet the required GHG emissions reduction, for the D3/D7, D4, D5, and D6 categories of RINs [67].

4.3 State and Local Policies

State-level policies support SAF production and consumption by providing credits in addition to federal incentives, which benefit state economies and sustainability and enable progress toward the national goals for SAF. Variations in state policies may provide competitive advantages in production capacity and consumption by airlines in different states.

California Low Carbon Fuel Standard

California established the California Low Carbon Fuel Standard (LCFS) in 2009 to reduce GHG emissions in the transportation sector and develop a range of low-carbon and renewable alternatives to reduce petroleum dependency. The LCFS is metricized via the life cycle CI of a renewable fuel relative to fossil gasoline and diesel fuel. Fuel producers must demonstrate their compliance with the LCFS CI standards, or benchmarks, for each annual period. As of 2019, SAF is eligible under the LCFS program as an “opt-in” fuel. SAF producers can create and sell LCFS credits to “obligated parties,” or fossil jet fuel producers, for revenue [68]. Although LCFS cannot mandate a specific CI for jet fuel, the only two major U.S. airports where SAF is regularly used are in California [69], and industry’s consensus is that the LCFS program will continue to encourage SAF production and use in California [69].

Additional State Fuel Standards and SAF Credits

Oregon adopted a Clean Fuels Program in 2016 with a target for a 20% reduction in CI of transportation fuels from 2015 levels by 2030 and 37% by 2035. The program includes SAF as eligible for credits for production and importation [70].

The **Washington** state Clean Fuel Standard is designed to incentivize the reduction of the CI of transportation fuels to 20% below 2017 levels by 2038. Adopted in May 2023, Senate Bill 5447 provides multiple incentives for SAF, including a tax credit for SAF production of $1.00/gal for SAF with at least 50% GHG reduction relative to fossil Jet A, and an additional $0.02/gal for each additional percentage point reduction past 50%, capped at $2.00/gal [71, 72]. Additionally, the package of incentives includes a credit for the use of SAF in flights departing from Washington. However, these tax credits can only be applied when one or more facilities in the state achieve a production capacity of 20 MGPY of alternative jet fuel.

Illinois adopted a SAF purchase credit in 2023. This program is valid between June 2023 and June 2033, limited to domestic feedstocks, and provides a credit of $1.50/gal for SAF sold to or used by an air carrier in Illinois [73].

Minnesota introduced an incentive for SAF at $1.50/gal at 50% life cycle GHG emissions versus petroleum jet. The SAF must be produced or blended in Minnesota and used in an aircraft in Minnesota, and the tax credits are limited to $7.4 million in 2025 and $2.1 million in 2026 and 2027 [74, 75].

New Mexico adopted a Clean Fuel Standard in March 2024, and rule-making is planned to develop and finalize the details [76].

The Pacific Coast Collaborative

The Pacific Coast Collaborative—which includes California, Oregon, Washington, British Columbia (Canada), and the cities of Vancouver, Seattle, Portland, San Francisco, Oakland, and Los Angeles—is working together to reduce carbon emissions. In addition to California, Oregon, and Washington, which have clean fuel standards, British Columbia adopted the British Columbia Low Carbon Fuel Standard to achieve a 30% reduction in the CI of transportation fuels by 2030 compared to 2010 levels. The adoption of the British Columbia Low Carbon Fuels Act aims to update the British Columbia LCFS and include SAF by 2024 [77].

The Pacific Coast Collaborative is a good example of cooperation between neighboring states and expansion into broader regional and national interaction to achieve a more concerted, consistent, peer-learning-based comprehensive effort to reduce emissions [78]. Table D-1 provides a complete summary of the state-level programs.

4.4 Life Cycle Analysis and Carbon Intensity

All the incentives discussed above and the SAF Grand Challenge are conditional on GHG reduction metrics, or the CI of the fuel product. CIs are determined based on LCAs. Because CI directly equates to the monetary value of incentives, it is very important to determine them accurately. Most stakeholders that we reached out to expressed concerns on clarity, standardization, accuracy, and reliability of the methodologies used to determine life cycle GHG emissions, land use change, and indirect land use change.

Air-quality-related environmental and health effects of SAF production and use related to the emissions or formation of pollutants, including NO_x, CO, PM, SO_x, volatile organic compounds, and ozone, are discussed in Appendix F.1.

LCA Definitions and Standards

Life cycle GHG emissions include GHG emissions that occur from all stages of the supply chain from feedstock production to fuel production and end use supply chain. CI is an estimate of the life cycle GHG emissions per energy unit of hydrocarbon fuel production (including SAF), expressed as grams of CO_2e emissions per megajoule of fuel (gCO_2e/MJ).

The International Organization for Standardization developed an LCA standard and included major principles and frameworks (ISO 14040) for LCA, as well as specified requirements and guidelines (ISO 14044) for performing consistent LCA [79, 80]. Both standards are updated and extended regularly.

LCA Methodologies

Methodologies used for RFS and LCFS: In the U.S. and California, LCA verification is performed by the EPA and the California Air Resources Board for the RFS and LCFS, respectively. The EPA LCA methodology was developed for implementation of the RFS program pursuant to the criteria under Section 211(o)(1)(H) of the Clean Air Act [81].

Methodology used by CORSIA: The CORSIA LCA methodology was developed and is extensively used by ICAO with the agreement of the European Union, United States, and other countries [82]. International SAF producers can use the default life cycle emissions values published in the ICAO document [83]—a CORSIA methodology for calculating life cycle emissions value is also available [84]—to see whether their SAF meets the 50% GHG emissions reduction threshold (note that the CI of global baseline petroleum jet in CORSIA is 89 g/MJ).

Methodology developed by Argonne National Laboratory: The third LCA methodology is GREET, a framework developed by Argonne National Laboratory. GREET has been used by the California Air Resources Board to develop LCA methodology specifically used in California. An interagency LCA working group formed under the SAF Grand Challenge is providing technical advice to the U.S. Treasury on methods and tools, including the use of GREET and comparisons with CORSIA, to determine GHG emission values for IRA Section 40B and 45Z.

4.5 Stakeholder Concerns Related to Policy

Consistent Definitions and Calculation Methodologies

Commercial aviation is a global industry, and many SAF producers are also global, with operations in the United States, Europe, and the rest of the world. CORSIA, a global scheme, initiated by ICAO, stands as the first globally adopted framework to calculate and credit life cycle GHG emissions for aviation fuels. For airlines and fuel producers, standardized LCA methodology and consistent CI values (especially to address the differences between the U.S. and European Union) are of concern. As an example, for SAF produced from soybean oil via HEFA, CORSIA uses a default induced land use change (ILUC) value of 24.5 gCO_2e/MJ. An updated version of Argonne National Laboratory's GREET model [85] uses a value of 9.3 gCO_2e/MJ. Several examples from literature reported different full life cycle GHG emissions for the soybean HEFA pathways [86, 87]. The CORSIA agreed core LCA value for soybean HEFA is 40.4 gCO_2e/MJ [82], resulting in an overall default GHG emissions value of 64.9 gCO_2e/MJ. This method clearly disqualifies fuel made from soybean HEFA for 40B and 45Z tax credits (reference fossil jet fuel value is 89 gCO_2e/MJ). In contrast, the ANL-GREET model calculates a core LCA value of 33.0 gCO_2e/MJ, resulting in an overall GHG emissions value of 42.3 gCO_2e/MJ, corresponding to a 52% reduction in GHG emissions.

SAF vs. RD Incentives

Combined incentives provide different levels of support for RD and SAF produced via HEFA pathway (Figure 10, with details in Appendix D.2), including the RFS, the 2022 IRA, and the California LCFS (which is used as a representative state-level incentive program). California is used as a model for state-level incentives because other states have adopted or proposed policies similar to California's LCFS, the first in the country, and California has demonstrated a decrease in the CI of transportation fuel [88]. The SAF incentives will vary for other states. The GHG emissions reductions considered include 50% (minimum required emissions reduction threshold to qualify for blender's tax credit), 60% (most of the LCFS alternative jet fuel certified pathways fall in the 60%–80% emissions reductions range) [89], 70% (DOE Bioenergy Technologies Office target) [90], and 80% (reported reductions from commercial SAF) [91, 92]. The pricing of RINs, LCFS credits, and costs applied to petroleum diesel reflect pricing in 2023 and are subject to change over time, which can affect the value of the credits. SAF is eligible for D3/D7, D4, D5, and D6 credits depending on the feedstocks and pathways used to generate the fuels [67].

For the time frame 2023–2024 (Figure 10a):

- **RFS**. The following scenario applies RFS incentives for biomass-based diesel (D-code 4), which is relevant for SAF produced by the HEFA pathway, and RD, equaling \$2.96/gal for RD and \$2.78/gal for SAF. The incentive value differs for RD and SAF because the equivalence values, which are used to determine the number of RINs assigned to renewable fuels, are different for RD (1.7) and SAF (1.6). RIN pricing from Jan. 2, 2023, is applied.[13]
- **IRA Section 40B SAF Credit**. The 2022 IRA introduced a new SAF-specific incentive that provides \$1.25/gal of SAF with a minimum of 50% reduction in life cycle GHG

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[13] **The RIN pricing fluctuates over time**. For example, the D4 RINs price (Q-RIN) from January to November 2023 ranged from \$0.54 to \$1.93 [93]. See RINs price variation over time in Appendix D.4.

emissions, and up to a maximum of $1.75/gal for 100% reduction in life cycle GHG emissions. For the samples fuels examined here, ranging from a CI of 45 (50% reduction in life cycle GHG emissions) to a CI of 18 (80% reduction in life cycle GHG emissions), the applicable credit ranges from $1.25 to $1.55/gal [58].

- **Biodiesel mixture credit**. The federal biodiesel mixture credit[14] is applied to RD for $1.00/gal [94].
- **California LCFS**. The California LCFS values are also based on CI. For SAF with a CI of 45 gCO_2e/MJ (50% GHG emissions reduction compared to fossil jet fuel), the credit is $0.38/gal, while the credit for RD with the same CI is $0.39/gal. Note that the California LCFS pricing from Jan. 3, 2023, is applied.
- **California avoided diesel deficits**. Value added to RD based on compliance costs incurred by petroleum diesel (California avoided diesel deficits: $0.39),[15] from the California **cap-and-trade** ($0.29) and LCFS ($0.10) policies, were based on Jan. 3, 2023, LCFS credit and carbon allowance pricing [95], similar to data published by Boutwell [96].
- **Total combined value of incentives** from 2023 through 2024, for a CI of 18 gCO_2e/MJ (equivalent to 80% GHG emissions reduction compared to petroleum jet), SAF receives a combined $4.95 in credits, and RD receives $4.99.

For the time frame 2025–2027 (Figure 10b):

- **RFS**. The following scenario applies RFS incentives for biomass-based diesel (D-code 4), which is relevant for SAF produced by the HEFA pathway, and RD. Equivalence values for (1.7) RD and (1.6) SAF are the same as for 2023–2024. Equivalence values are set until 2025 and are subject to updating by EPA. This comparison applies incentives through the RFS the same as 2023–2024 using 2023 (January) pricing.[13]
- **IRA Section 45Z SAF Clean Fuel Production Credit**. The 2022 IRA applies the Clean Fuel Production Credit for both SAF and RD [58]. The value of the credit is determined by multiplying the base or alternative credit by an emissions factor, so the value of the credit varies by the CI of the fuel. The base and alternative credits are higher for SAF compared to non-aviation fuel. Here the alternative credits for RD ($1.00) and SAF ($1.75) are used. For SAF with a CI of 18 gCO_2e/MJ (80% GHG emissions reduction compared to fossil jet fuel), the credit is $1.09/gal, while the credit for RD with the same CI number is $0.62/gal.
- **California LCFS**. The California LCFS values reflect the pricing for the 2025 compliance year, but with the pricing from 2023.
- **California avoided diesel deficits**. Value added to RD based on costs incurred by petroleum diesel (California avoided diesel deficits: $0.39),[15] from the California cap-

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[14] Biodiesel Mixture Credit: $1.00/gal of pure biodiesel, agri-biodiesel, or RD blended with petroleum diesel to produce a mixture containing at least 0.1% diesel fuel.

[15] Businesses that produce or import fossil fuels such as petroleum diesel are required to account for and mitigate their emissions under the California Cap-and-Trade Program and LCFS policies. To do this, they must purchase emissions allowances. The $0.39/gal cost represents the financial burden they bear to offset the carbon emissions generated during the production and use of that petroleum-based fuel (California avoided diesel deficits). RD producers have an advantage as they do not incur the same emissions allowance costs as petroleum diesel producers, incentivizing the transition to renewable fuels.

and-trade ($0.29) and LCFS ($0.10) policies, were based on Jan. 3, 2023, pricing [95], similar to data published by Boutwell [96].

- **Total combined value of incentives** for 2025 through 2027, for a CI of 18 gCO$_2$e/MJ, SAF receives a combined $4.47, while RD receives $4.58.

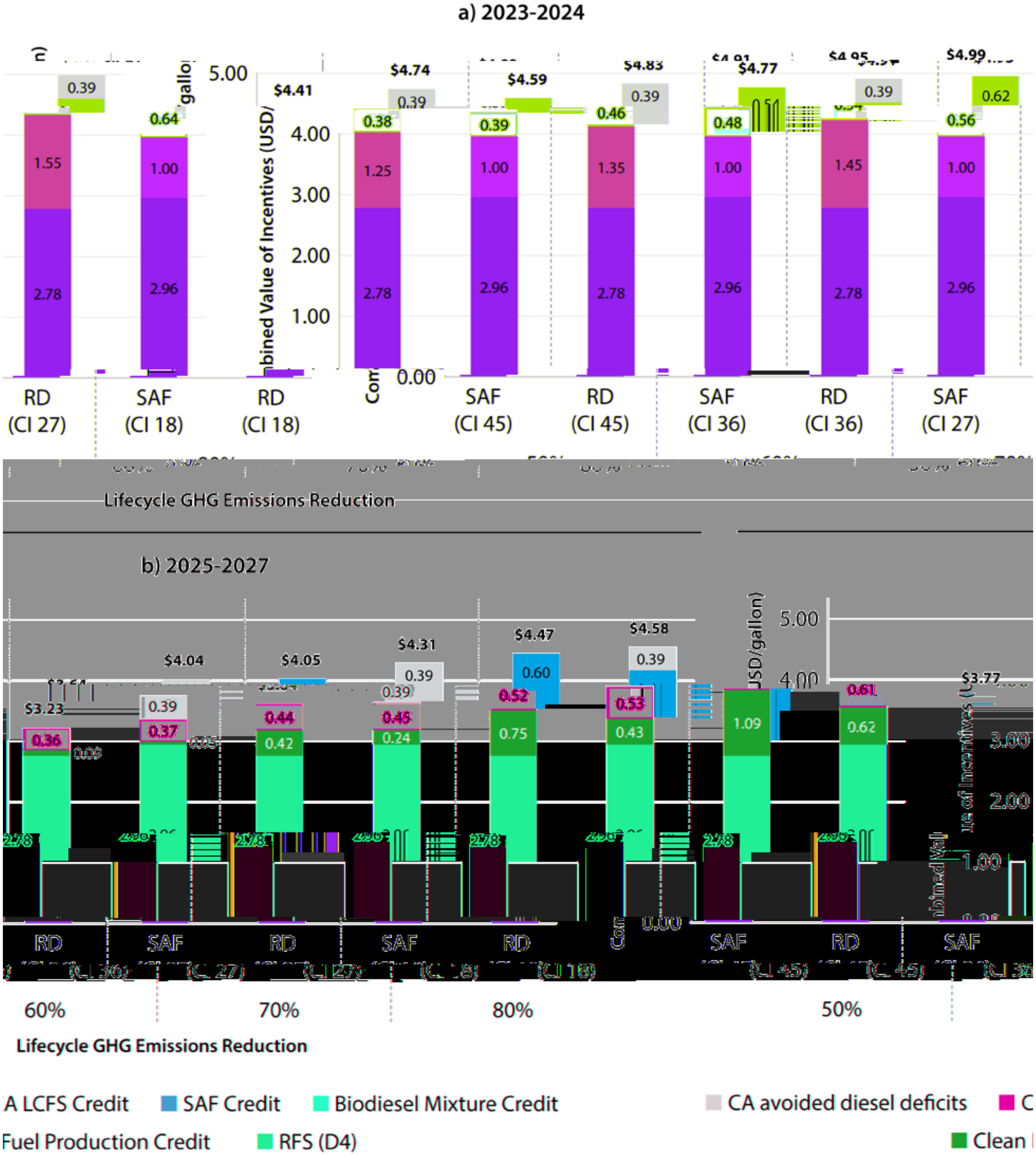

Figure 10. Comparison of federal and state incentives for RD and SAF: (a) 2023–2024 and (b) 2025–2027. Carbon intensity (CI) is in gCO$_2$e/MJ fuel (CA = California).

RD is a major competitor for SAF because they have similar production processes and use the same feedstocks, forcing producers to decide which fuel to prioritize. **The structure of the combined federal and state incentives for California indicates that RD has a slight advantage over SAF when CI values are equal. This advantage is mainly due to the extra $0.39 allocated to RD based on California avoided diesel deficit**. The aviation fuel is an "opt-in" compliance pathway meaning that fossil jet fuel does not generate similar deficits [67]. In the absence of California avoided diesel deficits, the federal and California LCFS incentives favor SAF for 2023–2024 and 2024–2027, when emission reductions exceed 60%. In addition to incentives, another factor that may contribute to the slow growth in the production of SAF may be the high profitability of RD production and lower SAF yield.

The total value of combined incentives varies significantly over time (Figure 11) due to fluctuations in federal RFS RIN pricing, as well as California LCFS credit pricing and California carbon allowance pricing (Figures D-1, D-2, D-3, D-4 in Appendix D). The variations in the total value of combined incentives over time also reflect changes in policies over time, such as the adoption and implementation of the federal SAF credit through the 2022 IRA (beginning in 2023, which caused a significant increase in SAF incentives as shown in Figure 11), and changes in state policies, such as the amendment to make SAF eligible for voluntary California LCFS credits (beginning in 2019) [58, 97].

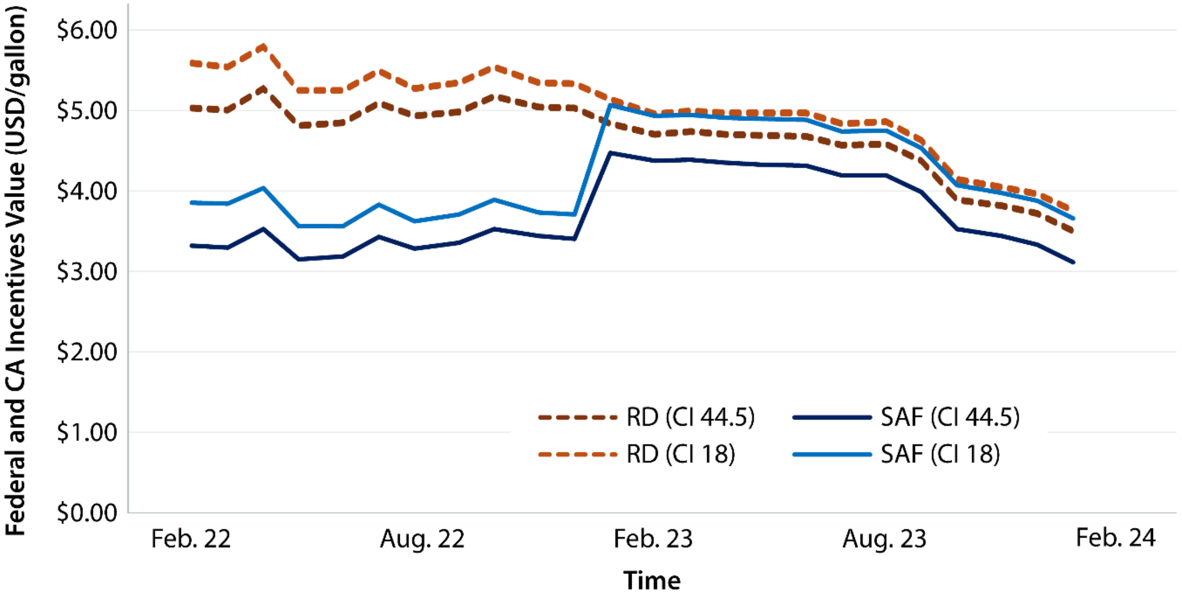

Figure 11. Combined federal and California incentive values, February 2022 through January 2024 (USD/gallon), for RD and SAF with CI values of 44.5 and 18.[16]

This approach applies **California as a test case for state policies**, while acknowledging the variation in policies across states. As of May 2024, a limited number of states have policies

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[16] Federal incentives include the RFS RIN credits for D4 fuels, the Biodiesel Mixture Credit (for RD), and the SAF Credit (beginning in January 2023). California incentives are the Low Carbon Fuel Standard (LCFS) credits (for RD and SAF), LCFS avoided deficits for petroleum diesel (adding to the value for RD), and state cap-and-trade avoided deficits for petroleum diesel (also adding to the value for RD).

supporting SAF (Section 4.3). Oregon and Washington have clean fuel standard policies similar to California that set CI limits for non-aviation transportation fuels and provide voluntary credits for SAF. New Mexico adopted a clean fuel standard policy in March 2024, and rule-making is underway [76]. California and Washington have cap-and-trade policies that incur taxes on select (non-aviation) GHG emission sources that exceed emission limits [98, 99]. More recently, Washington, Illinois, and Minnesota have adopted incentives specific to SAF [75, 100–104]. Additional states have proposed clean fuel standards, including Hawaii, Illinois, Michigan, Minnesota, and New York, which have proposed clean fuel standards designed to have SAF eligible for credits (see Appendix D.1) [105–110]. Providing SAF credits at the state level, such as those recently introduced in Washington (capped at $2.00/gal), are expected to result in a greater combined value of incentives favoring SAF in those states [71, 72, 96].

The combined values of federal incentives and federal and state incentives for California, Oregon, and Washington for RD and SAF with CI values of 18 and for January 2024, show variation in the total value of incentives (Figure 12). Figure 11 illustrates **the fluctuation in combined incentives over time in California, and this fluctuation generally applies to the states of Oregon and Washington**. The adoption and implementation of different policies can influence the overall incentive value for RD and SAF. These policies are also subject to being modified, such as the invalidation of Oregon's Climate Protection Program in December 2023, contributing to variation and uncertainty around the incentivization of biofuels [111]. This variability underscores the adaptive nature of incentive structures, reflecting the evolving economic and policy landscapes across different states.

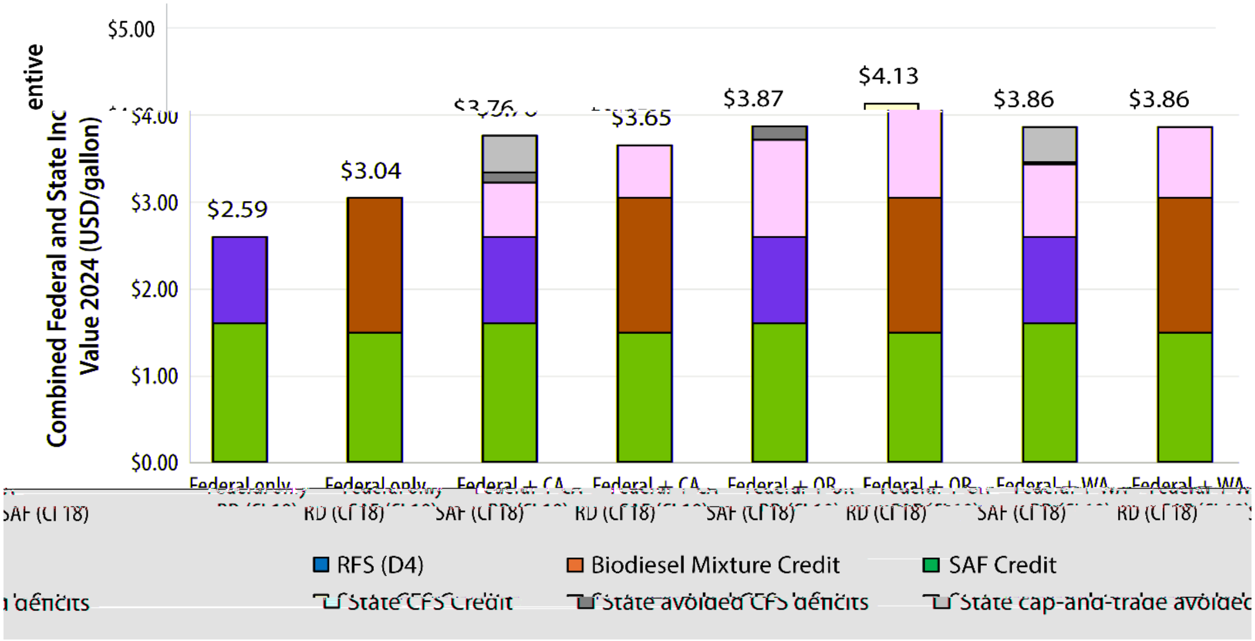

Figure 12. Combined incentive values for only federal incentives, federal and California state incentives, federal and Oregon state incentives, and federal and Washington state incentives, for January 2024, for RD and SAF with CI 18.[17]

Longevity and Stability of Policy Support

Industry stakeholders across the SAF supply chain have identified uncertainty related to the duration of policy incentives as a major obstacle to increasing SAF production, as it increases the risk of capital investment. Stakeholders who were consulted emphasized that investors require stability of policy for at least 10 years, as some new facilities depreciate over 10 to 15 years [112]. One major concern has been the frequent expiration and reinstatement of tax credits (for example, IRA Section 45Z only provides three years of incentives [2025–2027]) [58], as well as the consistency of these incentives across administrations [69]. Stakeholders pointed out that uncertainties across administrations is resulting in hesitation for signing offtake agreements exceeding 3 years, and some agreements are only related to finished products. Industry stakeholders emphasized the need for policies that are reliable, long term, simple, and transparent.

Incentives for Farmers

Some stakeholders interviewed expressed concern over the lack of incentives or guarantees for farmers to shift toward producing crops for renewable fuel. While biomass producers do not receive RINs or LCFS credits, converters felt that farmers can still see benefits through market

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[17] Federal incentives are the RFS RIN credits for D4 fuels, the Biodiesel Mixture Credit (for RD), and the SAF Credit (for SAF). California incentives are the Low Carbon Fuel Standard (LCFS) credits (for RD and SAF), LCFS avoided deficits for petroleum diesel (adding to the value for RD), and state cap-and-trade avoided deficits for petroleum diesel (also adding to the value for RD). Oregon incentives are the Clean Fuel Program (CFP) credits (for RD and SAF) and CFP avoided deficits for petroleum diesel (adding to the value for RD). Washington incentives are the Clean Fuel Standard (CFS) credits (for RD and SAF), CFS avoided deficits for petroleum diesel (adding to the value for RD), and state cap-and-trade avoided deficits for petroleum diesel (also adding to the value for RD).

responses and increases in commodity prices. The connection between incentives and a fuel's CI can be a powerful catalyst for adopting sustainable farming practices that may reduce renewable fuels' CI. Should sustainable farming practices become firmly established, a formal system of incentives and record-keeping may be needed.

Access to Financing

Access to financing to build or expand facilities was identified by stakeholders as a constraint for growing SAF production. The industry concerns about availability and cost of financing have been reported from past surveys [69, 113]. The financial community analyzes capital investments by assessing the risks associated with specific sectors and companies. The identification and measurement of individual risks and the overall risk level determine the likelihood of loan repayment and the expected return on investment. Emerging industries may face various risks; for the SAF industry, these risks can include supply chain slowdowns, uncertain policies, technological uncertainties, and end-product market fluctuations affected by public and political trends. Thus, SAF projects may encounter higher financing expenses and uncertain availability of financing due to the risk-averse nature of banks and lack of commercial data for novel SAF technologies. Supply chain participants can collaborate and share resources, capital, and expertise through equity partnerships to reduce risk in new SAF projects. For example, feedstock suppliers can become investors in SAF projects. Small companies, such as those developing new technologies, often struggle to secure financing and end up paying higher financing costs compared to larger, more established companies. Stakeholders felt that early entrant SAF producers will have an advantage in the future SAF market by securing limited feedstock sources and maturing their technology.

Level Playing Field

SAF developers felt that they will be competing for capital funding with other players in the renewables space. Consequently, they believe that policies should guarantee fairness among various technologies (considering the proven commercial status and higher risk associated with technologies under development), different size companies, and a future second wave of SAF producers (which may encounter challenges in sourcing feedstock). They felt that carbon pricing or even a global carbon tax would "level the playing field."

Offtake Agreements

SAF offtake agreements provide project owners with a reliable source of revenue, which helps them secure financing for their new projects. During our interviews, producers expressed concern about the reluctance for fuel purchasers to commit to long-term (more than 3-year) offtake agreements, making project financing more difficult. From the signed agreements since 2020 (Figure 13), 32% are commitments for less than 3 years, while 50% are signed for 4 to 8 years. Nonetheless, the International Renewable Energy Agency reported that neither the fixed assets nor the contractual arrangement (mainly for feedstock supply and product offtake) are considered secure enough for project financing in the advanced biofuel business [113].

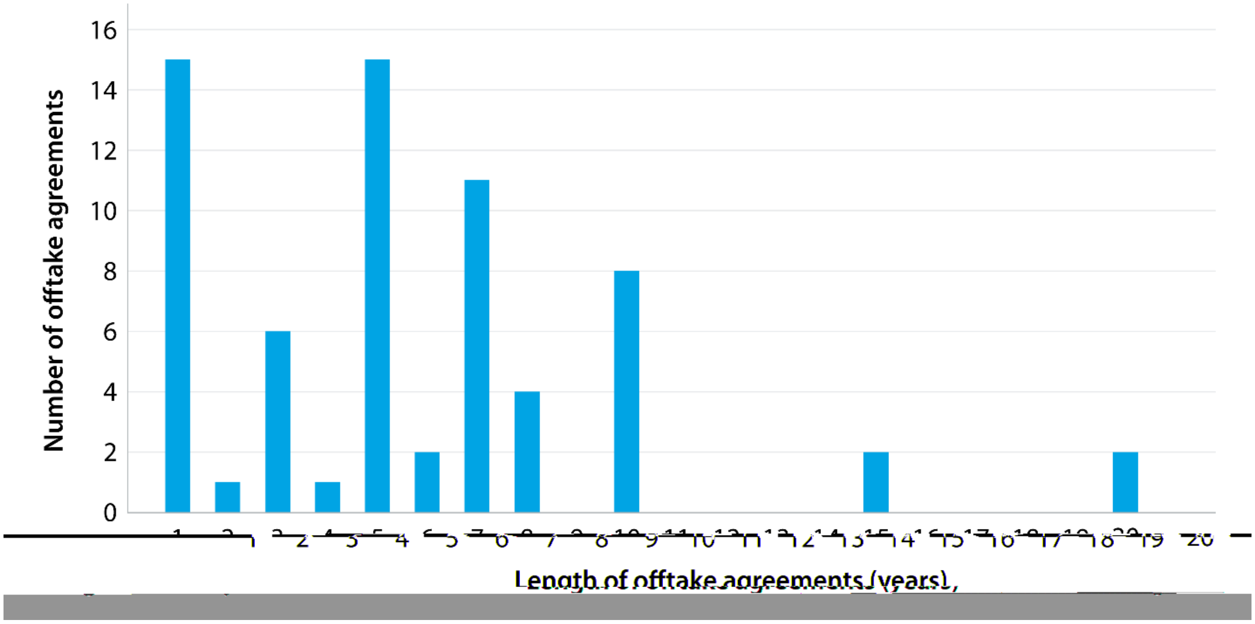

Figure 13. Number and length of offtake agreements signed between 2020 and 2023 [114]

Lack of a Proven Industry Inhibits Investments

Stakeholders emphasized the urgent need to develop a SAF industry. Without an industry, no one will reap the benefits of SAF policies, making it unlikely to be implemented in the first place. Industry stakeholders pointed out that fuel producers are currently evaluating SAF projects. If the SAF market develops quickly and shows that the pioneer SAF facilities are generating satisfactory returns, success will attract more investment into the industry. Thus, policies should facilitate the advancement of technologies, especially in the early stages, until the industry is established, and costs are lowered. Collaborators recommended that both industry and stakeholder designing policies should have well-defined goals and be open and collaborative, while understanding the technical and logistical complications of the supply chain.

There is a difference of opinion among stakeholders regarding policy design. Some believe that policies should be straightforward and easy to understand, while others think that trying to achieve too many goals with a single policy could result in unequal support for those goals and unintended consequences that could negatively impact the fuel supply chain and the environment. Industry stakeholders who were interviewed agree that setting ambitious targets or goals is important in order to encourage the industry to transition toward net-zero-carbon operations. However, they also emphasize that it is crucial to consider the significant investment and energy levels required to achieve these targets.

In summary, the future of SAF production and adoption hinges on a multifaceted approach, addressing the concerns raised by stakeholders, ensuring policy stability/longevity, and fostering an industry that is economically and environmentally sustainable. The success of these policies will play a pivotal role in the transition of the aviation sector toward net-zero-carbon operations.

References

1. Holladay, Johnathan, Zia Abdullah, and Joshua Heyne. 2020. *Sustainable Aviation Fuel: Review of Technical Pathways*. Washington, D.C. U.S. Department of Energy. DOE/EE-2041. https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

2. U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, and U.S. Environmental Protection Agency. 2022. *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel*. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

3. U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads). Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/TM-2016/160. https://www.srs.fs.usda.gov/pubs/books/2016/book_2016_abt_001.pdf.

4. Commercial Aviation Alternative Fuels Initiative. 2023. "Frequently Asked Questions - SAF Definition." https://www.caafi.org/resources/faq.html.

5. International Civil Aviation Organization. 2022. *CORSIA Sustainability Criteria for CORSIA Eligible Fuels*. International Civil Aviation Organization. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202022.pdf.

6. Rosales Calderon, Oscar, Ling Tao, Zia Abdullah, Michael Talmadge, Anelia Milbrandt, Sharon Smolinski, Kristi Moriarty, et al. 2024. *Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-87803. https://www.nrel.gov/docs/fy24osti/87803.pdf.

7. U.S. Department of Energy Bioenergy Technologies Office. 2023. "Bioenergy Technologies Office Funding Opportunities." https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office-funding-opportunities.

8. U.S. Department of Energy Loan Programs Office. "Loan Programs Office." https://www.energy.gov/lpo/loan-programs-office.

9. Federal Aviation Administration. 2023. "Fueling Aviation's Sustainable Transition (FAST) Grants." https://www.faa.gov/general/fueling-aviations-sustainable-transition-fast-grants.

10. U.S. Department of Transportation. 2022. "FAA Proposes Requiring More Efficient Jets and Turboprops to Lower Climate Impacts." https://www.transportation.gov/briefing-room/faa-proposes-requiring-more-efficient-jets-and-turboprops-lower-climate-impacts.

11. U.S. Energy Information Administration (EIA). "Analysis & Projections." https://www.eia.gov/analysis/index.php.

12. U.S. Department of Transportation. "Bureau of Transportation Statistics." https://www.bts.gov/.

13. Graver, Brandon, Dan Rutherford, and Sola Zheng. 2020. *CO_2 Emissions From Commercial Aviation: 2013, 2018, and 2019.* Washington, D.C.: International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf.

14. General Dynamics. 2023. "Gulfstream Completes World's First Trans-Atlantic Flight on 100% Sustainable Aviation Fuel." PR Newswire. https://www.prnewswire.com/news-releases/gulfstream-completes-worlds-first-trans-atlantic-flight-on-100-sustainable-aviation-fuel-301993029.html.

15. The White House. 2021. "FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation." https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.

16. Grim, R. Gary, Ling Tao, Zia Abdullah, Randy Cortright, and Brett Oakleaf. 2024. *The Challenge Ahead: A Critical Perspective on Meeting U.S. Growth Targets for Sustainable Aviation Fuel*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-89327. https://www.nrel.gov/docs/fy24osti/89327.pdf.

17. U.S. Environmental Protection Agency. Last updated November 2023. "Public Data for the Renewable Fuel Standard." https://www.epa.gov/fuels-registration-reporting-and-compliance-help/public-data-renewable-fuel-standard.

18. U.S. Environmental Protection Agency. Last updated November 2023. "RINs Generated Transactions." https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rins-generated-transactions.

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

20. International Civil Aviation Organization. 2017. *Sustainable Aviation Fuels Guide.* https://www.icao.int/environmental-protection/knowledge-sharing/Docs/Sustainable%20Aviation%20Fuels%20Guide_vf.pdf.

21. ASTM International. 2023. "ASTM D1655-23: Standard Specification for Aviation Turbine Fuels." https://doi.org/10.1520/D1655-23.

22. Edwards, James T. 2017. "Reference Jet Fuels for Combustion Testing." Presented at 55th AIAA Aerospace Sciences Meeting, Grapevine, Texas, Jan. 9–13, 2017. https://arc.aiaa.org/doi/10.2514/6.2017-0146.

23. VanHise, James L. 2023. "The Wood Pellet Industry: A Dual Threat to Poor, Rural Communities." Resilience. https://www.resilience.org/stories/2023-08-25/the-wood-pellet-industry-a-dual-threat-to-poor-rural-communities/.

24. Pete, Joseph S. 2022. "Group Says Fulcrum BioEnergy Plant 'a Bad Deal for Gary,' Calls for More Due Diligence." nwitimes.com. https://www.nwitimes.com/news/local/business/group-says-fulcrum-bioenergy-plant-a-bad-deal-for-gary-calls-for-more-due-diligence/article_2c1182bf-b75d-5d90-bf1a-d08f7775778e.html.

25. Airlines for America. 2021. "Major U.S. Pipelines Carrying Jet Fuel." https://www.airlines.org/media/major-u-s-pipelines-carrying-jet-fuel/.

26. Moriarty, Kristi., and Allison Kvien. 2021. *U.S. Airport Infrastructure and Sustainable Aviation Fuel*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-78368. https://www.nrel.gov/docs/fy21osti/78368.pdf.

27. Airlines for America. 2018. *Jet Fuel: From Well to Wing*. https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf.

28. National Tank Truck Carriers. 2021. "NTTC Fact Sheet Released: Petroleum Driver Shortage at a Glance." https://www.tanktruck.org/Public/Public/News/2021/NTTC%20Fact%20Sheet%20Released%20Petroleum%20Driver%20Shortage%20at%20a%20Glance.aspx#:~:text=Over%20a%20two%20year%20period,a%2023.3%25%20reduction%20in%20drivers.

29. NREL, Personal communications with Airlines for America.

30. Miller, Bruno, Donovan Johnson, Terry Thompson, Frank L. Rosenberg, Judith Driver, Gerard P. Biscardi, Madalina K. Mohtadi, and Nabil J. Mohtadi. 2012. *R&D Control Study: Plan for Future Jet Fuel Distribution Quality Control and Description of Fuel Properties Catalog.* Dulles, VA: Metron Aviation. DOT/FAA/AEE/2014-11, DOT-VTNSC-FAA-14-11. https://rosap.ntl.bts.gov/view/dot/12058.

31. Moriarty, Kristi, Anelia Milbrandt, and Ling Tao. 2021. *Port Authority of New York and New Jersey Sustainable Aviation Fuel Logistics and Production Study*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-80716. https://www.nrel.gov/docs/fy22osti/80716.pdf.

32. American Petroleum Institute. 2009. API RP 1543 - Documentation, Monitoring and Laboratory Testing of Aviation Fuel During Shipment from Refinery to Airport.

33. Airlines for America (A4A). 2023. "Spec 103: Standard for Jet Fuel Quality Control at Airports." https://publications.airlines.org/CommerceProductDetail.aspx?Product=322.

34. U.S. Energy Information Administration (EIA). 2023. "Domestic Renewable Diesel Capacity Could More Than Double Through 2025." Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=55399.

35. Kjelgaard, Chris. 2022. "Standard for 100 Percent Drop-In SAF Likely Two Years Away." Aviation International News. https://www.ainonline.com/aviation-news/air-transport/2022-07-18/standard-100-percent-drop-saf-likely-two-years-away.

36. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Alternative Fuels Data Center. "Sustainable Aviation Fuel." https://afdc.energy.gov/fuels/sustainable_aviation_fuel.html.

37. ASTM International. 2023. "ASTM D7566-23a: Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons." https://doi.org/10.1520/D7566-23A.

38. Rumizen, Mark A. 2021. "Qualification of Alternative Jet Fuels." *Frontiers in Energy Research* 9: 760713. https://doi.org/10.3389/fenrg.2021.760713.

39. Swedish Biofuels AB. 2023. "ASTM Decision Brings 100% SAF Certification Within Reach." Cision PR Newswire. https://www.prnewswire.com/in/news-releases/astm-decision-brings-100-saf-certification-within-reach-301893622.html.

40. SkyNRG. "Sustainable Aviation Fuel Certification and ASTM International: What Is It & Why Does It Matter?" https://skynrg.com/sustainable-aviation-fuel-certification-and-astm-international-what-is-it-why-does-it-matter/.

41. U.S. Energy Information Administration (EIA). 2023. "U.S. Product Supplied for Crude Oil and Petroleum Products." https://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbbl_a.htm.

42. U.S. Energy Information Administration (EIA). 2024. "U.S. Product Supplied for Crude Oil and Petroleum Products, Petroleum & Other Liquids." https://www.eia.gov/dnav/pet/pet_cons_psup_dc_nus_mbbl_a.htm.

43. Hardee, Howard. 2023. "Inside the Effort to Standardise 100% 'Drop-In' Sustainable Aviation Fuel." Flight Global. https://www.flightglobal.com/safety/inside-the-effort-to-standardise-100-drop-in-sustainable-aviation-fuel/152185.article.

44. Boeing. 2023. "Boeing Doubles Sustainable Aviation Fuel Purchase for Commercial Operations, Buying 5.6 Million Gallons for 2023." https://investors.boeing.com/investors/news/press-release-details/2023/Boeing-Doubles-Sustainable-Aviation-Fuel-Purchase-for-Commercial-Operations-Buying-5.6-Million-Gallons-for-2023/default.aspx.

45. Pearlson, Matthew, Christoph Wollersheim, and James Hileman. 2013. "A Techno-Economic Review of Hydroprocessed Renewable Esters and Fatty Acids for Jet Fuel Production." *Biofuels, Bioproducts and Biorefining* 7(1): 89–96. https://doi.org/10.1002/bbb.1378.

46. Pacific Northwest National Laboratory (PNNL). "Ethanol to Butenes in a Single Step." Battelle Number: 31265-E. https://www.pnnl.gov/available-technologies/ethanol-butenes-single-step.

47. Handler, Robert M., David R. Shonnard, Evan M. Griffing, Andrea Lai, and Ignasi Palou-Rivera. 2016. "Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks." *Industrial & Engineering Chemistry Research* 55(12): 3253–3261. https://doi.org/10.1021/acs.iecr.5b03215.

48. Tan, Eric C. D., Lesley J. Snowden-Swan, Michael Talmadge, Abhijit Dutta, Susanne Jones, Karthikeyan K. Ramasamy, Michel Gray, Robert Dagle, Asanga Padmaperuma, Mark Gerber, Asad H. Sahir, Ling Tao, and Yanan Zhang. 2017. "Comparative Techno-Economic Analysis and Process Design for Indirect Liquefaction Pathways to Distillate-Range Fuels via Biomass-Derived Oxygenated Intermediates Upgrading." *Biofuels, Bioproducts and Biorefining* 11(1): 41–66. https://doi.org/10.1002/bbb.1710.

49. Brown, Craig, and Ling Tao. 2023. *Biofuel Production and Greenhouse Gas Reduction Potential.*" Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-85351. https://www.nrel.gov/docs/fy24osti/85351.pdf.

50. Council on Environmental Quality, Executive Office of the President. 2007. *A Citizen's Guide to the NEPA: Having Your Voice Heard.* https://ceq.doe.gov/docs/get-involved/Citizens_Guide_Dec07.pdf.

51. U.S. Environmental Protection Agency. 2023. "National Environmental Policy Act Review Process." https://www.epa.gov/nepa/national-environmental-policy-act-review-process.

52. McPhee, Wayne, and Sabrina M. Dias. 2020. *Integrating Sustainability Into Major Projects: Best Practices and Tools for Project Teams*. Wiley. https://onlinelibrary.wiley.com/doi/book/10.1002/9781119557944.

53. U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration. "Latest News and Actions." https://www.phmsa.dot.gov/.

54. Code of Federal Regulations. 2023. 40 CFR Part 71 Subpart A -- Operating Permits (2023). https://www.ecfr.gov/current/title-40/part-71/subpart-A.

55. Susskind, Lawrence, Jungwoo Chun, Alexander Gant, Chelsea Hodgkins, Jessica Cohen, and Sarah Lohmar. 2022. "Sources of Opposition to Renewable Energy Projects in the United States." *Energy Policy* 165: 112922. https://doi.org/10.1016/j.enpol.2022.112922.

56. Batel, Susana, Patrick Devine-Wright, and Torvald Tangeland. 2013. "Social Acceptance of Low Carbon Energy and Associated Infrastructures: A Critical Discussion." *Energy Policy* 58: 1–5. https://doi.org/10.1016/j.enpol.2013.03.018.

57. Seetharaman, Krhana Moorthy, Nitin Patwa, Saravanan, and Yash Gupta. 2019. "Breaking Barriers in Deployment of Renewable Energy." *Heliyon* 5(1): e01166. https://doi.org/10.1016/j.heliyon.2019.e01166.

58. Public Law 117-169. 117th Congress. Aug. 16, 2022. https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf.

59. U.S. Department of the Treasury. 2024. "U.S. Department of the Treasury, IRS Release Guidance to Drive American Innovation, Cut Aviation Sector Emissions." https://home.treasury.gov/news/press-releases/jy2307.

60. Cope, Matthew, and Payne Williams. 2024. “US Treasury Updates SAF Tax Credit Guidelines.”. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2563971-us-treasury-updates-saf-tax-credit-guidelines.

61. Internal Revenue Service. 2022. “Request for Comments on Credits for Clean Hydrogen and Clean Fuel Production.” Notice 2022-58. https://www.irs.gov/pub/irs-drop/n-22-58.pdf.

62. Energy Communities Interagency Working Group on Coal & Power Plant Communities & Economic Revitalization. “Clean Fuel Production Credit - 26 U.S. Code § 45Z.” https://energycommunities.gov/funding-opportunity/clean-fuel-production-credit-26-u-s-code-%C2%A4-45z/.

63. U.S. Environmental Protection Agency (EPA). 2023. “Final Renewable Fuels Standards Rule for 2023, 2024, and 2025.” https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuels-standards-rule-2023-2024-and-2025.

64. U.S. Environmental Protection Agency (EPA). 2023. “Overview for Renewable Fuel Standard.” https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard.

65. U.S. Environmental Protection Agency (EPA). 2024. “Renewable Identification Numbers (RINs) Under the Renewable Fuel Standard Program.” https://www.epa.gov/renewable-fuel-standard-program/renewable-identification-numbers-rins-under-renewable-fuel-standard.

66. U.S. Environmental Protection Agency (EPA).2023. “Final Volume Standards for 2020, 2021, and 2022.” https://www.epa.gov/renewable-fuel-standard-program/final-volume-standards-2020-2021-and-2022.

67. O’Malley, Jane, Nikita Pavlenko, and Yi Hyun Kim. 2023. “Meeting the SAF Grand Challenge: Current and Future Measures to Increase U.S. Sustainable Aviation Fuel Production Capacity.” The International Council on Clean Transportation. https://theicct.org/publication/us-saf-production-capacity-nov23/.

68. California Air Resources Board. “Low Carbon Fuel Standard.” https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

69. U.S. Government Accountability Office. 2023. “Sustainable Aviation Fuel: Agencies Should Track Progress Toward Ambitious Federal Goals.” GAO-23-105300. https://www.gao.gov/products/gao-23-105300.

70. Oregon.gov. “Oregon Clean Fuels Program: Clean Fuels Program Overview.” https://www.oregon.gov/deq/ghgp/cfp/Pages/CFP-Overview.aspx.

71. State of Washington Dept of Ecology. “Clean Fuel Standard.” https://ecology.wa.gov/Air-Climate/Reducing-Greenhouse-Gas-Emissions/Clean-Fuel-Standard.

72. Washington State Legislature. 2023. "SB 5447 – 2023-24: Promoting the Alternative Jet Fuel Industry in Washington." https://app.leg.wa.gov/billsummary?BillNumber=5447&Year=2023&Initiative=False.

73. Illinois Department of Revenue. 2023. "FY2023-23, New Sustainable Aviation Fuel Purchase Credit Enacted." Informational Bulletin. https://tax.illinois.gov/en.html.

74. Kilpatric. 2023. "Partner Mark J. Riedy Speaking at the North American SAF Conference and Expo." https://kilpatricktownsend.com/en/Insights/News/News-Release/2023/8/Partner-Mark-J-Riedy-Speaking-at-the-North-American-SAF-Conference-and-Expo.

75. Minnesota Department of Revenue. 2023. "Sustainable Aviation Fuel Credit." https://www.revenue.state.mn.us/sustainable-aviation-fuel-credit.

76. The Office of Governor Michelle Lujan Grisham. 2024. "New Mexico Becomes Fourth State To Enact Clean Fuel Standards as Governor Signs Legislation - Landmark Legislation Set To Grow Economy, Reduce Emissions." https://www.governor.state.nm.us/2024/03/05/new-mexico-becomes-fourth-state-to-enact-clean-fuel-standards-as-governor-signs-legislation-landmark-legislation-set-to-grow-economy-reduce-emissions/.

77. Legislative Assembly of British Columbia. 2022 "Bill 15 – 2022: Low Carbon Fuels Act." https://www.leg.bc.ca/parliamentary-business/legislation-debates-proceedings/42nd-parliament/3rd-session/bills/first-reading/gov15-1.

78. Washington State Legislature. 2023. "SB 5447 – 2023-24: Engrossed Substitute – ESSB 5447." https://app.leg.wa.gov/billsummary?BillNumber=5447&Initiative=false&Year=2023.

79. ISO. 2006. "ISO 14040:2006 Environmental Management — Life Cycle Assessment — Principles and Framework." https://www.iso.org/standard/37456.html.

80. ISO. 2006. "ISO 14044:2006 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines." https://webstore.ansi.org/standards/iso/iso140442006.

81. U.S. Environmental Protection Agency (EPA). 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* EPA-420-R-10-006. https://19january2017snapshot.epa.gov/sites/production/files/2015-08/documents/420r10006.pdf.

82. International Civil Aviation Organization (ICAO). 2022. *CORSIA Eligible Fuels – Life Cycle Assessment Methodology*; *Version 5.* CORSIA. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf.

83. International Civil Aviation Organization (ICAO). 2022. *CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels*. CORSIA. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

84. International Civil Aviation Organization (ICAO). 2022. *CORSIA Methodology For Calculating Actual Life Cycle Emissions Values.* CORSIA. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

85. Argonne National Laboratory. "GREET." https://www.anl.gov/topic/greet.

86. Seber, Gonca, Neus Escobar, Hugo Valin, and Robert Malina. 2022. "Uncertainty in Life Cycle Greenhouse Gas Emissions of Sustainable Aviation Fuels From Vegetable Oils." *Renewable and Sustainable Energy Reviews* 170: 112945. https://doi.org/10.1016/j.rser.2022.112945.

87. Zemanek, Debrah, Pascale Champagne, and Warren Mabee. 2020. "Review of Life-Cycle Greenhouse-Gas Emissions Assessments of Hydroprocessed Renewable Fuel (HEFA) From Oilseeds." *Biofuels, Bioproducts and Biorefining* 14(5): 935–949. https://doi.org/10.1002/bbb.2125.

88. Seymour, Kendra. 2021. "California's LCFS Is Successfully Proliferating. Is It Also Successfully Decarbonizing Transport?" Stillwater Associates. https://stillwaterassociates.com/californias-lcfs-is-successfully-proliferating-is-it-also-successfully-decarbonizing-transport/.

89. California Air Resources Board. "LCFS Pathway Certified Carbon Intensities." https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities.

90. Sarisky-Reed, Valerie. 2023. "BETO Releases New Multi-Year Program Plan." U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office. https://www.energy.gov/eere/bioenergy/articles/beto-releases-new-multi-year-program-plan.

91. Neste. "Neste MY SAF – an Easy Leap Towards Sustainable Aviation." https://www.neste.com/products/all-products/saf.

92. Boutwell, Megan. 2022. "Inflation Reduction Act Sustainable Aviation Fuel Credit." Stillwater Associates. https://stillwaterassociates.com/inflation-reduction-act-sustainable-aviation-fuel-credit-carbon-intensity-matters/.

93. U.S. Environmental Protection Agency (EPA). 2023. "RIN Trades and Price Information." https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information.

94. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, Alternative Fuels Data Center. "Biodiesel Mixture Excise Tax Credit." https://afdc.energy.gov/laws/395.

95. OPIS. 2023. "Carbon Market Report." https://www.opisnet.com/product/pricing/spot/carbon-market-report/.

96. Boutwell, Megan. 2023. “SAF in the IRA Era – How Do the Incentives Stack Up?” Stillwater Associates. https://stillwaterassociates.com/saf-in-the-ira-era-how-do-the-incentives-stack-up/.

97. California Air Resources Board. “LCFS Regulation.” https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/lcfs-regulation.

98. California Air Resources Board. “Cap-and-Trade Program.” https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/about.

99. State of Washington Department of Ecology. “Washington’s Cap-and-Invest Program.” https://ecology.wa.gov/Air-Climate/Climate-Commitment-Act/Cap-and-invest.

100. Minnesota Legislature. 2023. “SF 2753 as Introduced - 93rd Legislature (2023 - 2024).” Office of the Revisor of Statutes. https://www.revisor.mn.gov/bills/text.php?version=latest&number=SF2753&session=ls93&session_year=&session_number=0.

101. Office of Governor Tim Walz & Lt. Governor Peggy Flanagan. 2023. “ICYMI: Governor Walz Highlights Efforts to Grow Sustainable Aviation Fuels Industry Using Minnesota’s Crop-Based Biofuels.” https://mn.gov/governor/newsroom/press-releases/?id=589989.

102. Oregon Secretary of State LaVonne Griffin-Valade. “Department of Environmental Quality Chapter 340, Division 253 Oregon Clean Fuels Program.” https://secure.sos.state.or.us/oard/displayDivisionRules.action?selectedDivision=1560.

103. Cooper, Perry. 2023. “New Washington Law Incentivizes Local Sustainable Aviation Fuel Production.” Port of Seattle. https://www.portseattle.org/news/new-washington-law-incentivizes-local-sustainable-aviation-fuel-production.

104. Voegele, Erin. 2023. “Illinois Lawmakers Approve $1.50 per Gallon SAF Tax Credit.” Biomass Magazine. https://biomassmagazine.com/articles/19698/illinois-lawmakers-approve-1-50-per-gallon-saf-tax-credit.

105. The New York State Senate. 2023. “Senate Bill S1292.” https://www.nysenate.gov/legislation/bills/2023/S1292.

106. Minnesota Legislature. 2023. “SF 2584.” https://www.revisor.mn.gov/bills/bill.php?f=SF2584&b=senate&y=2023&ssn=0.

107. Michigan Legislature. 2023. Senate Bill No. 275, Available at https://www.legislature.mi.gov/(S(ma4ve3tgfqp32z0rmxpp0syh))/mileg.aspx?page=home.

108. The Senate Thirty-Second Legislature, 2024 State of Hawaii. 2024. “S.B. NO. 2768 - A bill for an Act.” https://www.capitol.hawaii.gov/sessions/session2024/bills/SB2768_.HTM.

109. Illinois General Assembly. 2024. “Bill Status of SB3160.” https://www.ilga.gov/legislation/BillStatus.asp?DocNum=3160&GAID=17&DocTypeID=SB&LegId=152419&SessionID=112&GA=103.

110. Blackburn, Elliott. 2024. “Illinois CFS Will Take More Time.” Argus. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2550936-illinois-cfs-will-take-more-time.

111. Oregon.gov. 2024. “Climate Protection Program 2024.” https://www.oregon.gov/deq/rulemaking/Pages/CPP2024.aspx.

112. Gort, Michael, and Seong-Hoon Lee. 2002. “The Life Cycles of Industrial Plants.” Preprint at SSRN: 333643. https://doi.org/10.2139/ssrn.333643.

113. International Renewable Energy Agency. 2019. *Advanced Biofuels: What Holds Them Back?* Abu Dhabi: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf.

114. ICAO. “Tracker of SAF Offtake Agreements.” http://lookerstudio.google.com/reporting/8e9488a2-1811-4b13-b7eb-b3fc2e970160/page/FTHXC?feature=opengraph.

115. Reigle, Jacqueline, and Matthew Cope. 2023. “Illinois Passes Sustainable Aviation Fuel Tax Credit.” Argus. https://www.argusmedia.com/en//news/2412226-illinois-passes-sustainable-aviation-fuel-tax-credit

116. Center for Climate and Energy Solutions. “California Cap and Trade: At-a-Glance.” https://www.c2es.org/content/california-cap-and-trade/.

117. U.S. Environmental Protection Agency (EPA). 2018. “RIN Trades and Price Information.” https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information.

118. Schubert, Adam. 2022. “So Long BTC, Hello CFPC.” Stillwater Associates. https://stillwaterassociates.com/so-long-btc-hello-cfpc/.

119. California Air Resources Board. 2019. LCFS Credit Price Calculator. https://ww2.arb.ca.gov/sites/default/files/2022-03/creditvaluecalculator.xlsx.

120. California Air Resources Board. “Weekly LCFS Credit Transfer Activity Reports.” https://ww2.arb.ca.gov/resources/documents/weekly-lcfs-credit-transfer-activity-reports.

121. Dutta, Abhijit, Calvin Mukarakate, Kristiina Iisa, Huamin Wang, Michael Talmadge, Daniel Santosa, Kylee Harris, Frederick Baddour, Damon Hartley, Hao Cai, Longwen Ou, Joshua Schaidle, and Michael Griffin. 2021. *Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2020 State of Technology*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-80291. https://www.nrel.gov/docs/fy21osti/80291.pdf.

122. Tao, Ling, Anelia Milbrandt, Yanan Zhang, and Wei-Cheng Wang. 2017. "Techno-Economic and Resource Analysis of Hydroprocessed Renewable Jet Fuel." *Biotechnology for Biofuels and Bioproducts* 10: 261. https://doi.org/10.1186/s13068-017-0945-3.

123. U.S. Environmental Protection Agency (EPA). 2023. "Regulations and Volume Standards for Renewable Fuel Standards." https://www.epa.gov/renewable-fuel-standard-program/regulations-and-volume-standards-renewable-fuel-standards.

124. Internal Revenue Service. 2024. "How To Depreciate Property." Washington, D.C.: United States Department of the Treasury. Publication 946. http://www.irs.gov/pub/irs-pdf/p946.pdf.

125. Gary, James H., Glenn E. Handwerk, and Mark J. Kaiser. 2007. *Petroleum Refining: Technology and Economics, 5th ed.* Boca Raton: CRC Press.

126. Tan, Eric C. D. 2019. "An Integrated Sustainability Evaluation of High-Octane Gasoline Production From Lignocellulosic Biomass." *Biofuels, Bioproducts and Biorefining* 13(6): 1439–1453. https://doi.org/10.1002/bbb.2045.

127. Smith, Raymond L., Eric C. D. Tan, and Gerardo J. Ruiz-Mercado. 2019. "Applying Environmental Release Inventories and Indicators to the Evaluation of Chemical Manufacturing Processes in Early Stage Development." *ACS Sustainable Chemistry & Engineering* 7(12): 10937–10950. https://doi.org/10.1021/acssuschemeng.9b01961.

128. Ravi, Vikram, Allan H. Gao, Natalie B. Martinkus, Michael P. Wolcott, and Brian K. Lamb. 2018. "Air Quality and Health Impacts of an Aviation Biofuel Supply Chain Using Forest Residue in the Northwestern United States." *Environmental Science & Technology* 52(7): 4154–4162. https://doi.org/10.1021/acs.est.7b04860.

129. Yim, Steve H. L., Gideon L. Lee, In Hwan Lee, Florian Allroggen, Akshay Ashok, Fabio Caiazzo, Sebastian D. Eastham, Robert Malina, and Steven R. H. Barrett. 2015. "Global, Regional and Local Health Impacts of Civil Aviation Emissions." *Environmental Research Letters* 10(3): 034001. https://doi.org/10.1088/1748-9326/10/3/034001.

130. Dedoussi, Irene C. 2021. "Implications of Future Atmospheric Composition in Decision-Making for Sustainable Aviation." *Environmental Research Letters* 16(3): 031002. https://doi.org/10.1088/1748-9326/abe74d.

131. Arter, Calvin A., Jonathan J. Buonocore, Chowdhury Moniruzzaman, Dongmei Yang, Jiaoyan Huang, Saravanan Arunachalam. 2022. "Air Quality and Health-Related Impacts of Traditional and Alternate Jet Fuels From Airport Aircraft Operations in the U.S." *Environment International* 158: 106958. https://doi.org/10.1016/j.envint.2021.106958.

132. Booz Allen Hamilton. 2019. Alternative Jet Fuels Emissions: *Quantification Methods Creation and Validation Report.* McLean, VA: Booz Allen Hamilton. Final Report for Project ACRP 02-80. https://onlinepubs.trb.org/onlinepubs/acrp/acrp_wod_41.pdf.

133. Beyersdorf, A. J., M. T. Timko, L. D. Ziemba, D. Bulzan, E. Corporan, S. C. Herndon, R. Howard, R. Miake-Lye, K. L. Thornhill, E. Winstead, C. Wey, Z. Yu, and B. E. Anderson. 2014. "Reductions in Aircraft Particulate Emissions due to the Use of Fischer–Tropsch Fuels." *Atmospheric Chemistry and Physics* 14(1): 11–23. https://doi.org/10.5194/acp-14-11-2014.

134. Corporan, Edwin, Matthew J. DeWitt, Christopher D. Klingshirn, and David Anneken. 2010. *Alternative Fuels Tests on a C-17 Aircraft: Emissions Characteristics.* Air Force Research Lab Wright-Patterson AFB OH Propulsion Directorate. https://doi.org/10.21236/ADA536842.

135. Chan, Tak W., Wajid A. Chishty, Pervez Canteenwalla, David Buote, and Craig R. Davison. 2016. "Characterization of Emissions From the Use of Alternative Aviation Fuels." *Journal of Engineering for Gas Turbines and Power* 138(1): 011506. https://doi.org/10.1115/1.4031226.

136. Zhang, Yimin, Arpit Bhatt, Garvin Heath, Mae Thomas, and Jason Renzaglia. 2016. Federal *Air Pollutant Emission Regulations and Preliminary Estimates of Potential-to-Emit from Biorefineries. Pathway #1: Dilute-Acid and Enzymatic Deconstruction of Biomass-to-Sugars and Biological Conversion of Sugars-to-Hydrocarbons.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-62547. https://www.nrel.gov/docs/fy16osti/62547.pdf.

137. U.S. Environmental Protection Agency (EPA). 2023. "Phosphoric Acid Supply Chain – Executive Summary." https://www.epa.gov/system/files/documents/2023-03/Phosphoric%20Acid%20Supply%20Chain%20Profile.pdf.

138. U.S. Environmental Protection Agency (EPA). 2024. "Nonattainment NSR Basic Information." https://www.epa.gov/nsr/nonattainment-nsr-basic-information.

139. Bhatt, Arpit H., Yimin Zhang, and Garvin Heath. 2020. "Bio-Oil Co-Processing Can Substantially Contribute to Renewable Fuel Production Potential and Meet Air Quality Standards." *Applied Energy* 268: 114937. https://doi.org/10.1016/j.apenergy.2020.114937.

140. U.S. Environmental Protection Agency (EPA). 2015. "Final Rule on the Implementation of the New Source Review Provisions for Particulate Matter Less Than 2.5 microns (PM2.5) Fact Sheet." https://www.epa.gov/sites/default/files/2015-12/documents/20080508_fs.pdf.

141. Ulibarri, Nicola, Bruce E. Cain, and Newsha K. Ajami. 2017. "A Framework for Building Efficient Environmental Permitting Processes." *Sustainability* 9(2): 180. https://doi.org/10.3390/su9020180.

Appendix A. Stakeholder Engagement

A major part of the overall effort in this study was stakeholder interviews, followed by organizing and interpreting the information provided by the stakeholders.

The interviewed stakeholders shared their expert perspectives and opinions on the challenges of increasing sustainable aviation fuel (SAF) production to meet the SAF Grand Challenge goals. Their answers and feedback are industry-specific rather than business-specific. Thus, nondisclosure agreements were not required. Note that "stakeholders" and "review" do not imply endorsement of the analysis presented by either individuals or companies/organizations.

We held extensive discussions, consultations, and collaborative sessions with stakeholders in key positions along the SAF supply chain including consultant firms, fuel producers or suppliers, airlines, pipeline owners, fuel technology licensors or suppliers, government bodies, nongovernmental organizations, industry associations, nonprofit organizations, feedstock producers, research institutes, and others.

Consulted stakeholders and interviews were classified in four categories in accordance with our division of the SAF supply chain:

1. Feedstock supply, preprocessing, and logistics
2. Pretreatment, conversion, blending, and logistics
3. Supplies and inputs other than feedstocks
4. Permitting, approvals, and policies.

To standardize our interviews, we generated a series of questions specific to these categories to use in the interviews. A sample of these questions is shown in Table A-1.

Table A-1. Sample Interview Questions and Categories

Category	Sample Question	Sample Answer
1	How can risk be shared along the supply chain to reduce the risk for investors?	All fuel-based incentives impact feedstock producers through indirect market responses like increased price for feedstock due to increasing production of renewable fuels.
1	If production of SAF ramps up, can feedstock output be increased to meet demand?	This is not a major challenge, as feedstock has been provided to fuel producers for many years.
1	What are the specifications of your preprocessed feedstock?	Not able to share the specifications But moisture and metals contents are the most critical material attributes.
2	Unless you render on-site, is the feedstock coming out of rendering plants of sufficient quality for SAF production? Does it need further processing/pretreatment on-site?	Pretreatment is required to process different feedstock types effectively. Handling and pretreatment operations differ from typical fuel processes and may present challenges requiring a learning curve.
2	What constraints do you see in feedstock availability? Does feed	Multiple feedstocks considered, but securing feedstock is a race. Different technologies or

Category	Sample Question	Sample Answer
	supply limit design capacity of a facility?	pathways may be required to meet SAF production goals.
2	What challenges arise when seeking investment for projects that involve producing SAF?	Due to the uncertainty in demand, it is challenging to secure financing. Players avoid agreements exceeding 3 years.
2	What challenges exist when it comes to transporting SAF to the end user?	We don't see major challenges. Pipeline companies can transport SAF as long as there are suppliers and buyers.
3	What inputs other than feedstock present a challenge for producing SAF or may limit the construction of new facilities?	Hydrogen sourcing will be an issue. Green hydrogen remains expensive. Exploring alternative options like converting byproducts into hydrogen can show promise.
3	Is the disposal of waste streams a challenge when producing SAF?	Waste management, such as solid waste management, is not an issue but it involves an additional expense. In the case of the hydroprocessed esters and fatty acids (HEFA) pathway, some companies take the solid waste and recover the oil to resell it.
4	What strategies are needed to improve security for investors?	Early adopters will have an advantage; thus, it is necessary to level the market for the upcoming second wave of producers.
4	What are your observations about permits?	Permitting depends on the local community and regulators. However, the common "not in my backyard" mentality persists.
4	Is the SAF industry effectively supported by policies and legislation? What additional support is required?	Policies should provide long-term stability and enhance credit support for SAF pricing.

During the interviews and consultations with stakeholders, the goal was to gather their perspectives on the SAF industry's primary obstacles and challenges. These questions were used to initiate discussion and prompt critical topics that the stakeholders deemed important.

The information, opinions, questions, and answers shared during the interviews were carefully captured, meticulously recorded, and subjected to through processing to distill and extract the core key takeaways. The report further explores these key points and addresses them throughout its contents to present an overview of the current state of the SAF industry.

Appendix B. ASTM-Approved SAF Pathways

Table B-1. ASTM-Approved SAF Pathways

Pathway	Approved Name	Blending Limitation (by vol.)	Feedstocks	Chemical Process
Fischer–Tropsch synthetic paraffinic kerosene (FT-SPK)	FT-SPK, ASTM D7566 Annex A1, 2009	50%	Municipal solid waste, agricultural and forest wastes, energy crops	Woody biomass is converted to syngas using gasification, then an FT synthesis reaction converts the syngas to jet fuel. Feedstocks include various sources of renewable biomass, primarily woody biomass such as municipal solid waste, agricultural wastes, forest wastes, wood, and energy crops. Approved by ASTM in June 2009 with a 50% blend limit.
HEFA-SPK	HEFA-SPK, ASTM D7566 Annex A2, 2011	50%	Oil-based feedstocks (e.g., jatropha, algae, camelina, and yellow grease)	Triglyceride feedstocks such as plant oil; animal oil; yellow or brown greases; or waste fat, oil, and greases are hydroprocessed to break apart the long chain of fatty acids, followed by hydroisomerization and hydrocracking. This pathway produces a drop-in fuel and was approved by ASTM in July 2011 with a 50% blend limit.
Hydroprocessed fermented sugars to synthetic isoparaffins (HFS-SIP)	HFS-SIP, ASTM D7566 Annex A3, 2014	10%	Sugars	Microbial conversion of sugars to hydrocarbons. Feedstocks include cellulosic biomass feedstocks (e.g., herbaceous biomass and corn stover). Pretreated waste fat, oil, and greases also can be eligible feedstocks. Approved by ASTM in June 2014 with a 10% blend limit.
FT-SPK with aromatics	FT-SPK/A, ASTM D7566 Annex A4, 2015	50%	Same as A1	Biomass is converted to syngas, which is then converted to SPK and aromatics by FT synthesis. This process is similar to FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components. Approved by ASTM in November 2015 with a 50% blend limit.
Alcohol to jet (ATJ) SPK	ATJ-SPK, ASTM D7566 Annex A5, 2016	30%	Sugar/starch biomass, Cellulosic biomass	Conversion of cellulosic or starchy alcohol (isobutanol and ethanol) into a drop-in fuel through a series of chemical reactions—dehydration, hydrogenation, oligomerization, and hydrotreatment. The alcohols are derived from cellulosic feedstock or starchy feedstock via fermentation or gasification reactions. Ethanol and isobutanol produced from lignocellulosic biomass (e.g., corn stover) are considered favorable feedstocks, but other potential feedstocks (not yet approved by ASTM) include methanol, isopropanol, and long-chain fatty alcohols. Approved by ASTM in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit.

Pathway	Approved Name	Blending Limitation (by vol.)	Feedstocks	Chemical Process
Catalytic hydrothermolysis synthesized kerosene (CH-SK) or Catalytic Hydrothermolysis Jet (CHJ)	CH-SK or CHJ, ASTM D7566 Annex A6, 2020	50%	Fatty acids or fatty acid esters or lipids from fat oil greases	(Also called hydrothermal liquefaction), clean free fatty acid oil from processing waste oils or energy oils is combined with preheated feed water and then passed to a catalytic hydrothermolysis reactor. Feedstocks for the CH-SPK process can be a variety of triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil. Approved by ASTM in February 2020 with a 50% blend limit.
Hydrocarbon (HC)-HEFA-SPK	HC-HEFA-SPK, ASTM D7566 Annex A7, 2020	10%	Algae	Conversion of the triglyceride oil, derived from *Botryococcus braunii*, into jet fuel and other fractionations. *Botryococcus braunii* is a high-growth alga that produces a high percentage of unsaturated hydrocarbons known as botryococcenes, instead of triglycerides or fatty acids. Approved by ASTM in May 2020 with a 10% blend limit.
ATJ synthetic paraffinic kerosene with aromatics (SKA)	ATJ-SKA, ASTM D7566 Annex A8, 2023	50%	Sugar/starch biomass, Cellulosic biomass	A non-aromatic product stream comprising dehydration, oligomerization, hydrogenation, and fractionation, and an aromatic product stream comprising dehydration, aromatization, hydrogenation, and fractionation, both derived from any single C2 to C5 alcohol or combination of two or more C2 to C5 alcohols
Fats, oils, and greases (FOG) coprocessing (HEFA coprocessing)	FOG Co-Processing ASTM D1655 Annex A1	5%	Fats, oils, and greases	ASTM approved 5% fats, oils, and greases coprocessing with petroleum intermediates as a potential SAF pathway. Used cooking oil and waste animal fats are two other popular sources for coprocessing.
FT coprocessing	FT Co-Processing ASTM D1655 Annex A1	5%	FT biocrude	In association with the University of Dayton Research Institute, ASTM approved 5% FT syncrude coprocessing with petroleum crude oil to produce SAF.
Hydroprocessed Biomass (Fractionation coprocessing)	Hydrocarbons derived from hydroprocessed biomass	24% (with up to 10% of synthetic hydrocarbons in the jet product)	Hydroprocessed fats, oils, and greases	Hydroprocessed mono-, di-, and triglycerides, free fatty acids, and fatty acids (biomass) to undergo coprocessing via fractionation.

Appendix C. Conformity Test ASTM Specification and Test Methods

Table C-1. Conformity Test ASTM Specification and Test Methods for Jet A or Jet A-1 as Defined in ASTM D1655 and ASTM D7566

Requirement	Specifications		ASTM Test Method
ASTM Standard	D1655	D7566	
Fuel	Jet A or Jet A-1	Jet A or Jet A-1	
Table No. in ASTM standard	Table 1	Table 1	
COMPOSITION			
Acidity, total mg KOH/g	max 0.10	max 0.10	D3242
1. Aromatics, vol %	max 25	max 25	D1319
		min 8 [a]	D6379
2. Aromatics, vol %	max 26.5	max 26.5	D3227
		min 8.4 [a]	
Sulfur, mercaptan, mass %	max 0.003	max 0.003	D1266, D2622, D4294, D5453
Sulfur, total mass %	max 0.30	max 0.30	
Distillation temp, °C	max 205	max 205	D86, D2887
T10 (10% recovered, temp)	report	report	
T50 (50% recovered, temp)	report	report	
T90 (90% recovered, temp)			
T50 – T10		min 15 [a]	
T90 – T10		min 40 [a]	
Final boiling point, temp	max 300	max 300	
Distillation residue, %	max 1.5	max 1.5	
Distillation loss, %	max 1.5	max 1.5	
Flash point, °C	min 38	min 38	D56 or D3828
DENSITY	775 to 840	775 to 840	D1298 or D4052
Density at 15°C, kg/m^3	775 to 840	775 to 840	D1298 or D4052
FLUIDITY			
Freezing point, °C max	−40 Jet A	−40 Jet A	D5972, D7153, D7154, D2386
	−47 Jet A-1	−47 Jet A-1	
Viscosity −20°C, mm^2/s	max 8.0	max 8.0	D445
Viscosity −40°C, mm^2/s		max 12 [a]	D445

Requirement	Specifications		ASTM Test Method
ASTM Standard	D1655	D7566	
Fuel	Jet A or Jet A-1	Jet A or Jet A-1	
Table No. in ASTM standard	Table 1	Table 1	
COMBUSTION			
Net heat of combustion MJ/kg	min 42.8	min 42.8	D4529, D3338, or D4809
One of the following requirements shall be met:			
(1) Smoke point, mm, or	min 25	min 25	D1322
(2) Smoke point, mm, and	min 18	min 18	D1322
Naphthalenes, vol %	max 3.0	max 3.0	D1840
CORROSION			
Copper strip, 2 h at 100°C	max No.1	max No.1	D130
THERMAL STABILITY			
(2.5 h at control temperature of, °C min)	260	260	
Filter pressure drop, mm Hg	max 25	max 25	D3241
(1) Annex A1 VTR, VTR Color code	less than 3	less than 3	
CONTAMINANTS			
Existent gum, mg/100 mL	max 7	max 7	D381,[a] IP 540
Without electrical conductivity additive	min 85	min 85	
ADDITIVES			
Electrical conductivity pS/m (with electrical conductivity additive)	max 600	max 600	D2624
Antioxidants, mg/L	max 24.0	max 24.0	
Lubricity mm		0.85 [a]	D5001

[a] Extended requirements

Appendix D. SAF Policies and Incentives

D.1 State-Level Standards and Incentives Relevant for SAF

Table D-1. State Standards and Incentives Relevant for SAF

Sources: [68, 70, 71, 78, 102–104, 115]

State	Standards and Credits
Adopted	
California	Low Carbon Fuel Standard (LCFS) (2009, 2018): • Overall 20% reduction in carbon intensity (CI) (life cycle greenhouse gas [GHG] emissions) of transportation fuels by 2030, structured as successive reductions starting in 2019 • Fuels with CI < annual limits produce credits, > annual limits result in deficits for non-aviation fuel • Lifecycle GHG emissions: California Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model • Producers and importers • SAF: eligible for credits
	Cap-and-Trade (2011) [98, 116]: • Set limit on GHG emissions for select sources that emit at least 25,000 metric tons CO_2e per year, with taxes incurred for emissions exceeding limit. • **Aviation fuels exempt.** Producers of other fuels such as renewable diesel subject to GHG emissions limit.
Oregon	Clean Fuels Program (2016, 2021): • 20% reduction in CI of transportation fuels by 2030, 37% by 2035, structured as successive reductions • Fuels with CI < annual limits produce credits, > annual limits result in deficits for non-aviation fuel • Life cycle GHG emissions: California GREET model • Producers and/or importers or providers • SAF: eligible for credits
Washington	Clean Fuel Standard (2019): • 20% reduction in CI of transportation fuels from 2017 levels by 2034 • Fuels with CI < annual limits produce credits, > annual limits result in deficits for non-aviation fuel • Life cycle GHG emissions: Consideration of methods developed by national labs or use similar state methods • Producers and/or importers, infrastructure investments • SAF: eligible for credits
	SAF Credit (SB 5447, Promoting the alternative jet fuel industry in Washington) (2023): • Business and Operation (B&O) preferential tax rate for SAF manufacturing and sale (produced or blended in Washington) • Manufacturing credit: credit allowed against tax otherwise due for manufacturing alternative jet fuel ($1/gal SAF with min 50% less CO_2e emissions than petroleum

State	Standards and Credits
	jet fuel, credit increases by $0.02 per additional 1% in CO_2e emissions beyond 50%, not to exceed $2/gal • Credit for use of SAF: $1/gal of alternative jet fuel with minimum 50% less CO_2e emissions than conventional petroleum jet fuel (for use in flights departing from Washington) • **Tax credits available when one or more facilities in Washington produce minimum of 20 million gallons of SAF per year** • Eligibility for sales of SAF: Produced in qualifying county in Washington (population <650,000), or blended in Washington • Eligibility for purchase of SAF: Used for flights leaving Washington
	Cap-and-invest program (Climate Commitment Act) (2021) [99]: • Set limit on GHG emissions for select sources, taxes incurred for emissions exceeding limit. • **Aviation fuels exempt**. Producers of other fuels subject to GHG emissions limit.
Illinois	SAF Purchase Credit (2023): • Tax credit generated per gallon of SAF sold to or used by air carrier in Illinois (June 2023–June 2033) • Life cycle GHG emissions: CORSIA (International Civil Aviation Organization, ICAO) methodology or Argonne National Laboratory GREET model • Limited to domestic feedstocks June 2028–June 2033 • $1.50/gal of SAF with minimum 50% reduction in carbon dioxide emissions compared to conventional jet fuel **Maximum value $1.50/gal** (if requirements met)
Minnesota	Sustainable Aviation Fuel Credit (proposed 2023) [75, 100, 101]: • Tax credit for SAF produced or blended in state, or sold for use in flights leaving from state • $1.50/gal of SAF for minimum 50% reduction in life cycle GHG emission reduction compared to conventional jet fuel. **Maximum value $1.50/gal.** • Life cycle GHG emission: Argonne National Laboratory GREET model
Proposed	
Hawaii	Clean Fuel Standard (proposed 2024) [108]
Illinois	Clean Transport Standard (proposed 2023) [109, 110]
Michigan	Clean Fuel Standard (SB No. 275) (proposed 2023) [107]: • Reduce CI of transportation fuels to 25% below 2019 level by 2035 • Market for trading CI credits • SAF: eligible for credits
Minnesota	Clean Transportation Fuel Standard (SB No. 447) (proposed 2023) [100, 106]: • Reduce CI in transportation fuels supplied to the state, compared to 2018, 25% reduction by 2030, 27% reduction by 2040, 100% reduction by 2050 • SAF: voluntary eligibility for credits

State	Standards and Credits
New York	Clean Fuel Standard (S1292) (proposed 2023) [105]: - Reduce CI in transportation fuels, 20% reduction by 2031 - SAF: voluntary eligibility for credits

D.2 SAF and RD Incentives

Table D-2. Comparison of Select Federal Incentives for Renewable Diesel (RD) and SAF, 2023–2024 and 2025–2027

Applies Renewable Identification Number (RIN) Pricing, LCFS Pricing, and Other Cost Values Applied for 2023

Incentives 2023–2024	RD (maximum credits USD per gal)	SAF (maximum credits USD per gal)
CI 18 (80% reduction in life cycle GHG emissions)		
Federal RFS RINs **D4, biomass-based diesel** **Equivalence values: 1.7 RD, 1.6 SAF** **RIN price Jan. 2, 2023, $1.74** [117] **(**RIN pricing fluctuates over time**. D4 RINs price January to November 2023 ranged from $0.54 to $1.93)**[13]	$2.96	$2.78
Federal biodiesel mixture credit [58]	$1.00	N/A
Federal SAF Credit [58] **Base credit of $1.25/gal SAF meeting minimum 50% life cycle GHG emissions reduction** **Supplemental credit of $0.01/gal per additional percentage point in life cycle GHG emissions reduction**	NA	$1.55
State: California LCFS credit **LCFS credit pricing, $69.00/mt, Jan 3 , 2023** **2023 compliance year**	$0.64	$0.62
State: (California avoided diesel deficits) Value added to RD based on cost incurred by petroleum diesel (California LCFS) **Pricing Jan. 3, 2023**	$0.10	N/A
State: (California avoided diesel deficits) Value added to RD based on cost incurred by petroleum diesel (California cap-and-trade) **Pricing Jan. 3, 2023**	$0.29	N/A
Total federal and state: If value added to RD by costs incurred included toward RD value	$4.99	$4.95
Incentives 2025–2027	**RD (maximum credits USD per gallon)**	**SAF (maximum credits USD per gallon)**
CI 18 (80% reduction in life cycle GHG emissions)		
Federal RFS RINs	$2.96	$2.78

Incentives 2023–2024	RD (maximum credits USD per gal)	SAF (maximum credits USD per gal)
D4, biomass-based diesel **Equivalence values: 1.7 RD, 1.6 SAF** **RIN price Jan. 2, 2023, $1.74 [117]**		
Federal Clean Fuel Production Credit [58, 92, 118] **Base credit $0.20, alternative credit $1.00, multiplied by emissions factor (alternative credit applied to example)** **SAF Credit base credit $0.35, alternative credit $1.75, multiplied by emissions factor (alternative credit applied to example)**	$0.62	$1.09
State: California LCFS credit **LCFS credit pricing, $69.00/mt, Jan 3, 2023** **2025 compliance year**	$0.61	$0.60
State: (California avoided diesel deficits) Value added to biomass-based diesel based on cost incurred by petroleum diesel (California LCFS) [a] **Pricing Jan. 3, 2023**	$0.10	N/A
State: (California avoided diesel deficits) Value added to biomass-based diesel based on cost incurred by petroleum diesel (California cap-and-trade) [a] **Pricing Jan. 3, 2023**	$0.29	N/A
Total federal and state: If value added to RD by costs incurred included toward RD value	$4.58	$4.47

[a] Additional California incentives added to RD to reflect costs incurred by petroleum diesel from California's cap-and-trade and LCFS policies, based on pricing from Jan. 3, 2023 [95] and similar to comparison by [96].

D.3 Calculating Incentive Values

The combined value of federal and state incentives for RD and SAF are calculated by adding incentive values for the periods of 2023 through 2024 and 2025 through 2027, to reflect different incentives established or extended by the 2022 IRA in effect for those periods. The example in Table D-2 shows sample calculations for RD and SAF with a CI of 18. The value of some incentives, such as the federal SAF Credit and Clean Fuel Production Credit, are dependent on life cycle GHG emissions reductions and emission factors, respectively, and thus variation in fuel CI will impact incentive values, as shown in Figure 10. Additionally, this approach applies RIN pricing of $1.73/gal for D4 fuels for Jan. 3, 2023, with equivalence values of 1.7 for RD and 1.6 for SAF [117]. This approach also applies incentives from California's LCFS based on pricing of $69.00/mt for Jan. 3, 2023 [95]. The compliance years of 2023 and 2025 were used for California's LCFS credit calculation [119]. Pricing is subject to change over time, yet the same values are used here for 2023 through 2024 and 2025 through 2027 to allow for a comparison of combined incentives for these time periods. The value of the Clean Fuel Production Credit was calculated similar to as described by [92, 118]. This comparison applied value added to RD to reflect costs incurred by petroleum diesel from California's LCFS and cap-and-trade, based on pricing for Jan. 3, 2023 for mean carbon cents per gallon diesel of 10.485 cents per gallon for the LCFS and "cap-at-the-rack" prices 29.08 cents per gallon [95], similar to [96]. Finally, while this comparison applies California incentives, policies and the level of support for RD and SAF vary by state, with some states lacking LCFS-type policies, and other states providing SAF-specific credits and greater combined advantage to SAF [72, 96].

D.4 Value of Federal and State Incentives Overtime

The federal RFS RIN and California state (LCFS) credit pricing overtime are presented in this section. RIN pricing for D4 and D5 for RD and SAF.

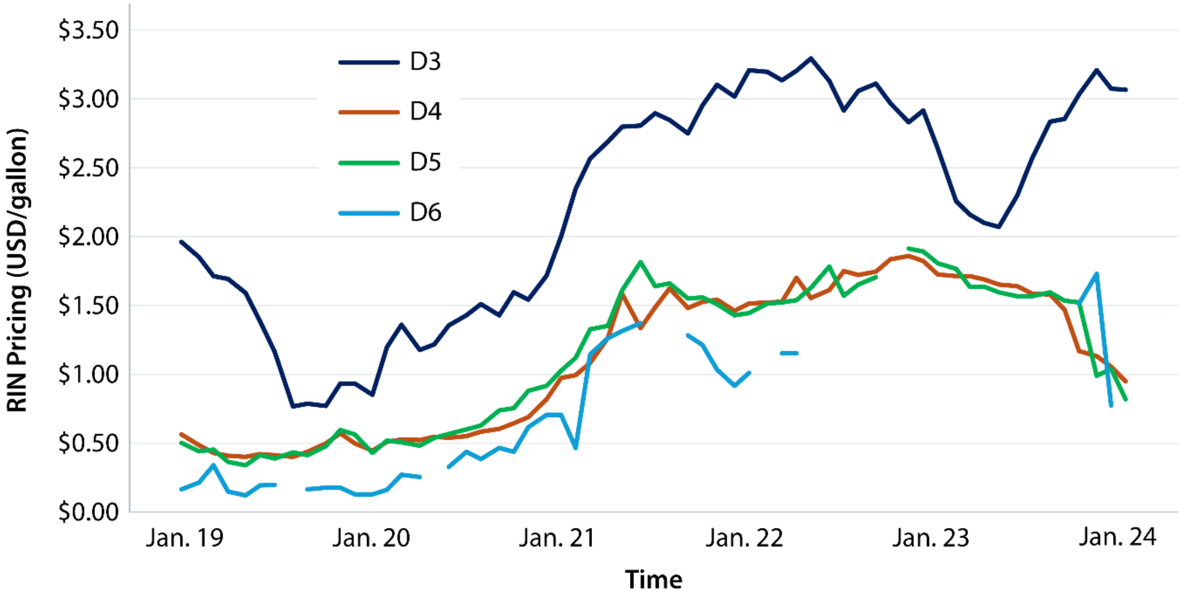

Figure D-1. RIN pricing January 2019 through January 2024 (USD/gallon), based on pricing data from [93]

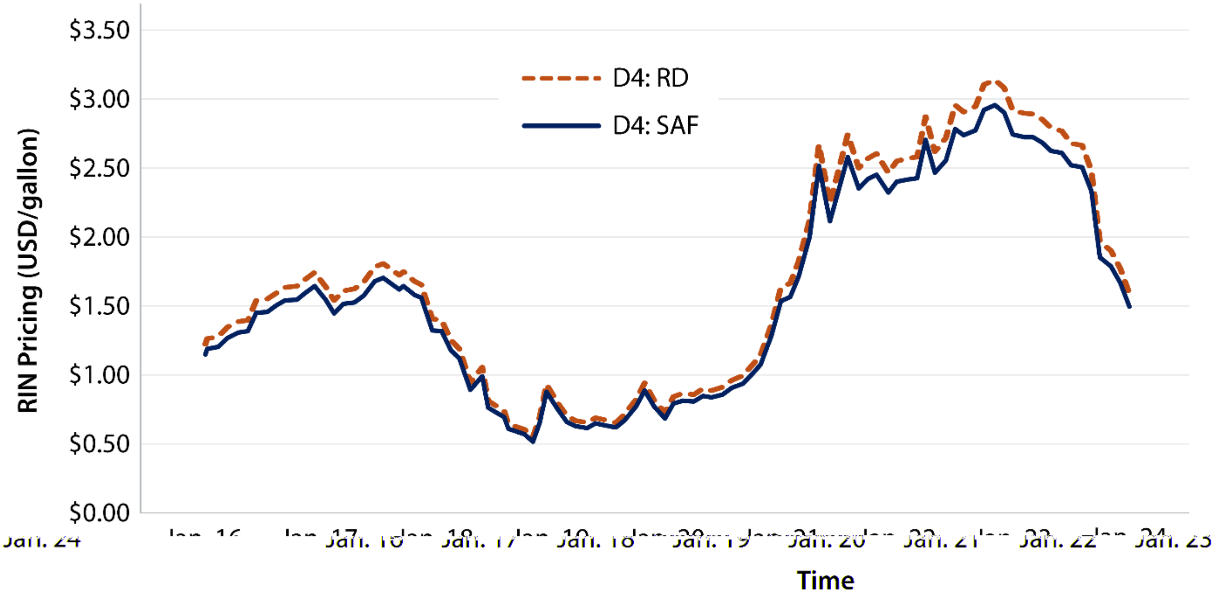

Figure D-2. RIN pricing for D4 RD and SAF, January 2019 through January 2024 (USD/gallon), based on pricing data from EPA [93], as calculated using the equivalence values of 1.7 for RD and 1.6 for SAF

Note that the D5 values provided in Figure D-3 are specifically pertinent to fuels produced via coprocessing.

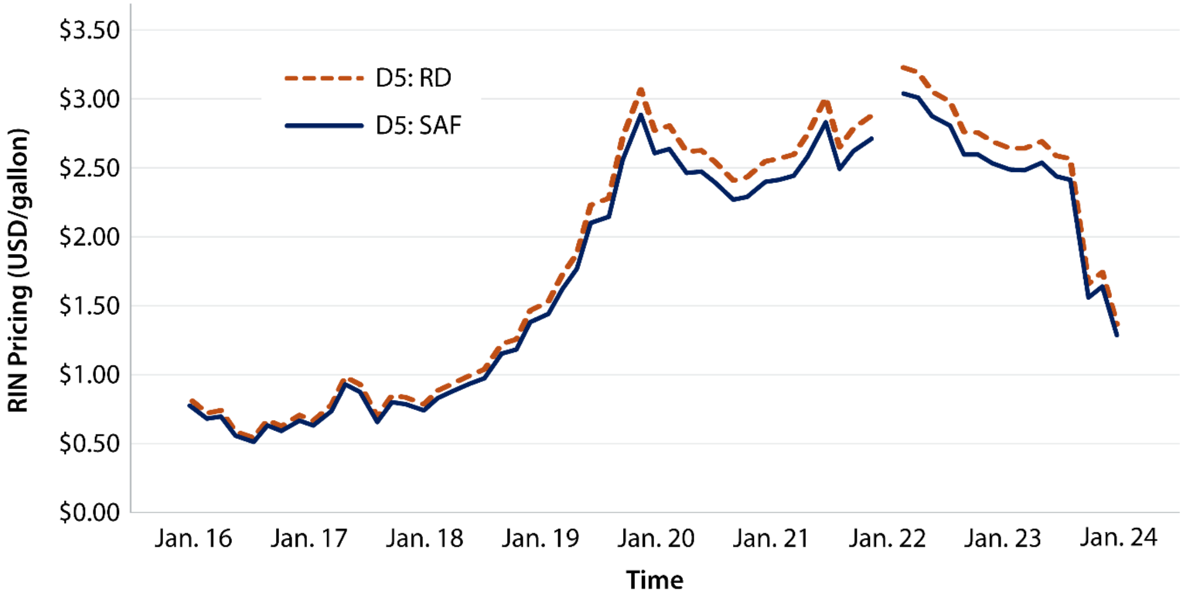

Figure D-3. RIN pricing for D5 RD and SAF (produced via coprocessing), January 2019 through January 2024 (USD/gallon), based on pricing data from EPA [93], as calculated using the equivalence values of 1.7 for RD and 1.6 for SAF

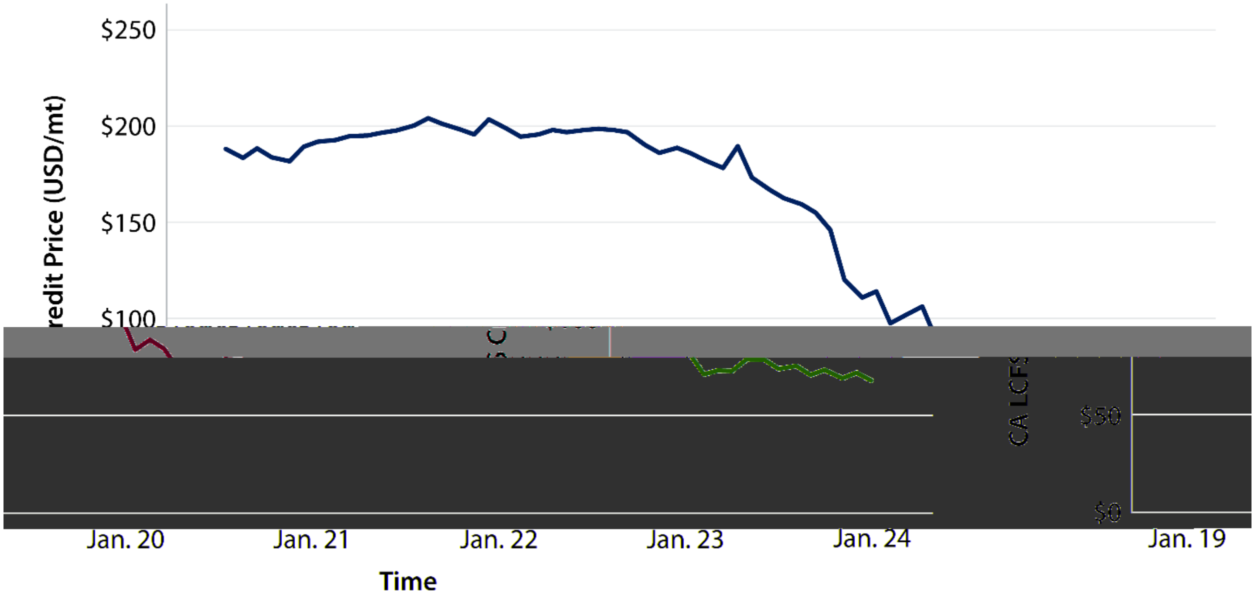

Figure D-4. California LCFS credit pricing, January 2019 through January 2024 (USD/metric ton), based on the average price per month from the LCFS credit transaction log [120]

Appendix E. Economics and Sustainability

Key Takeaways

- This section outlines the methodology used to assess the economic and sustainable aspects of HEFA, ATJ, and FT pathways in the SAF state-of-industry report. The methodology used combines technical reports, commercial technology reviews, input from industry partners, process modeling, equipment cost estimation, and discounted cash flow analysis.
- Two main metrics for economic and environmental sustainability are determined: the minimum fuel selling prices (MFSPs), as a gallon of reference fuel-equivalent product that yields a net present value of zero for the project, and the marginal abatement cost for CO_2, which is widely utilized to compare the economics of climate change mitigation.
- Land use change contributions to CI scores are complex and specific to feedstock source and location. Thus, the impact of land use change on product CI scores is not considered in our assessment.
- While air quality impacts of aviation emissions are well recognized, there is little understanding of the benefits of using SAF. Thus, there is a knowledge gap regarding the benefits of blending SAF with traditional jet fuel at different levels at a national scale.
- Evaluating a more comprehensive range of sustainability metrics beyond costs and GHGs can facilitate more comprehensive comparisons between design modifications and alternatives. By utilizing the Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a Multi-Objective Process Evaluator (GREENSCOPE) methodology, areas for further improving SAF production through sustainable performance assessment of ASTM-approved jet fuel pathways can be identified.

E.1 Methodology

The approach for economics and sustainability analysis is shown in Figure E-1 and is consistent with analysis efforts funded by the U.S. Department of Energy [121, 122]. This report includes information from published technical reports, other data sources, reviews of commercially available technologies, input from industrial collaborators, process modeling using Aspen Plus and Aspen HYSYS software, equipment cost estimation, and discounted cash flow analysis. Based on financial inputs and economic calculations, the techno-economic analysis yields an MFSP for the finished fuel products.

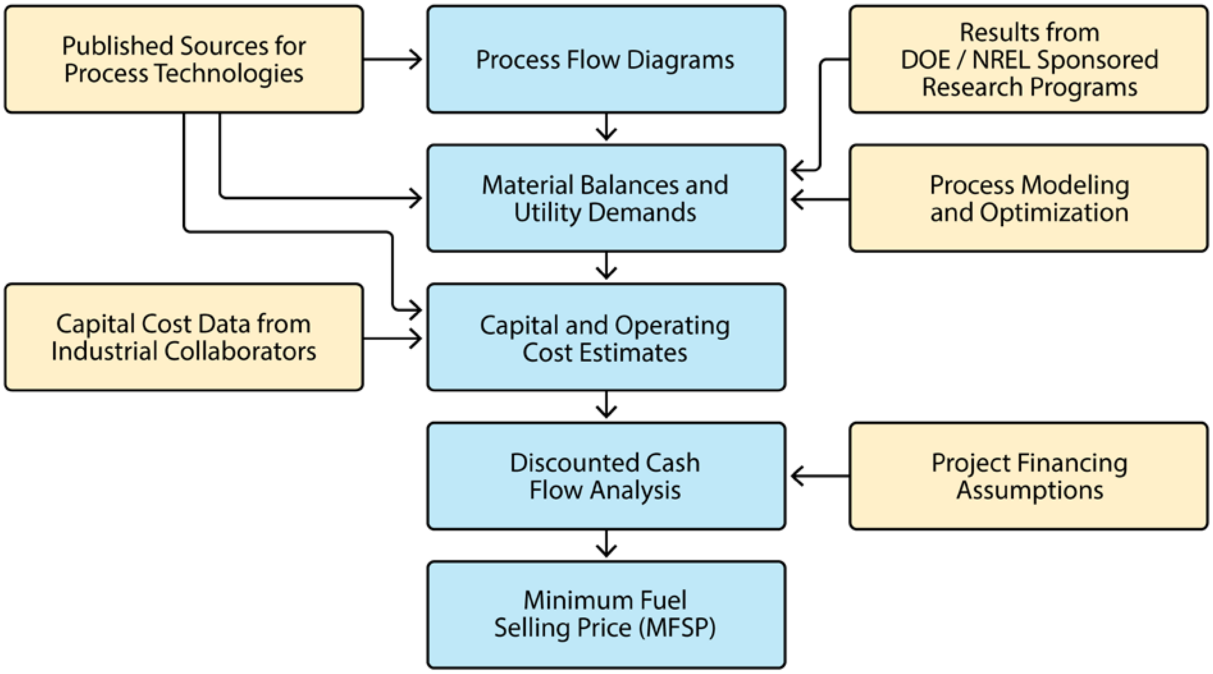

Figure E-1. Approach for techno-economic analysis

Data from the published sources for biomass-based diesel and SAF served to establish the process mass balances and basis for raw materials and utilities required for each technology.

Definition of n^{th}-Plant Economics

The techno-economic analysis reported here uses n^{th}-plant economics. The key assumption associated with n^{th}-plant economics is that several plants using the same technology have already been built and are operating. This assumption reflects a future in which a successful industry has been established with many operating plants. A summary of the n^{th}-plant assumptions applied in this report are listed in Table E-1. These financial assumptions are consistent with assumptions used for other economic analyses supporting the U.S. Department of Energy's Bioenergy Technologies Office [65, 123], with an update to cost basis year from 2016 [121, 122] to 2020.

Table E-1. Summary of nth-Plant Assumptions for Techno-Economic Analysis

Description of Assumption	Assumed Value
Cost year for analysis	2020
Internal rate of return	10%
Plant financing by equity/debt	40%/60% of total capital investment
Plant life	30 years
Income tax rate	21%
Interest rate for debt financing	8% annually
Term for debt financing	10 years
Depreciation schedule	7-year modified accelerated cost recovery system (MACRS) schedule [124]
Construction period (spending schedule)	3 years (8% Y1, 60% Y2, 32% Y3)
Plant salvage value	No value
Startup time	6 months
Revenue and costs during startup	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
On-stream percentage after startup	90% (7,884 operating hours per year)

Fixed Operating Costs

Fixed operating costs, which include employee salaries and benefits, overhead, plant maintenance costs, insurance, and taxes (other than income taxes), are generally incurred in full, whether or not the plant is producing at full capacity. The fixed operation costs were estimated and verified using data from the industry.

Variable Operating Costs

Variable operating costs, which include raw materials, coproduct credits, and utility demands provided from external sources in the analysis, are incurred only when the process is operating. Quantities of raw materials and utilities consumed are combined with pricing data and on-stream factors to calculate annual variable operating costs for each pathway. Because feedstock values are variable, feedstock cost ranges based on historical feedstock data are evaluated. All default pricing values are corrected for the basis year using plant cost indices per the techno-economic analysis approach from the National Renewable Energy Laboratory (NREL) [121, 122].

Capital Costs

Ranges of capital cost curves for different pathways are built based on various process technologies, published cost resources, and industry feedback. In addition to the ranges of capital cost curves, another variable included in the analysis is scale or plant capacity.

The costs represent total capital investment, and each cost curve equation is represented as a power function that corresponds to the capital scaling approach applied in analysis from NREL per Eq. 1:

$$\mathit{Scale\text{-}Up\ Equipment\ Cost} = \mathit{Base\ Equipment\ Cost} \left(\frac{\mathit{Scale\text{-}Up\ Capacity}}{\mathit{Base\ Capacity}} \right)^{n} \qquad \text{(Eq. 1)}$$

Capital cost data are adjusted as needed to account for varying cost basis years using Eq. 2 and historical *Chemical Engineering* Plant Cost Index values [125]:

$$\begin{aligned} &\mathit{Corrected\ Equipment\ Cost} \\ &\quad = \mathit{Base\ Equipment\ Cost\ x}\ \frac{2022\ \mathit{Cost\ Index\ Value}}{\mathit{Base\ Year\ Cost\ Index\ Value}} \end{aligned} \qquad \text{(Eq. 2)}$$

Calculating Minimum Fuel Selling Price

Once the capital and operating costs are determined, the MFSPs of the biofuels are determined using a discounted cash flow rate of return analysis. The general methodology used is the same as that applied in previous publications from NREL [121, 122]. The discounted cash flow analysis determines the MFSP as a gallon of reference fuel-equivalent product that yields a net present value of zero for the project. The default reference fuel is gasoline. Diesel and jet fuel products contribute to the overall product energy yields for the MFSP calculation, while gasoline, liquefied petroleum gas, and fuel gas are considered coproducts valued at $80 per barrel ($1.9/gal) West Texas Intermediate benchmark price.

The financial parameters used to compute the net present value are listed below. These values discussed are defaults and can be changed in the Excel tool:

- *Internal rate of return:* For this analysis, the cash flow discount rate was set to an internal rate of return of 10%.
- *Equity financing:* For this analysis, it was assumed that the plant would be 40% equity financed. The terms of the loan on the remaining 60% debt were taken to be 8% interest for 10 years. The principal is taken out in stages over the 3-year construction period. Interest on the loan is paid during this period, but principal is not paid back.
- *Depreciation:* Capital depreciation is computed according to the Internal Revenue Service modified accelerated cost recovery system. The bulk of the plant capital is depreciated over a 7-year recovery period.
- *Taxes:* The federal corporate tax rate applied for the analysis is 21%. State taxes are not included. Corporate state tax rates range from 0% to >10% depending on tax year and state.
- *Construction time:* The construction time was taken to be 24 months for both grassroots and conversion units. Twelve months are added before construction for planning and engineering.
- *Startup time:* Startup was taken to be 25% of the construction time, or 6 months in this case. It is assumed that the plant achieves 50% production during the startup period while incurring 75% of variable expenses and 100% of fixed expenses.
- *Lifetime:* The plant equipment is assumed to have a 30-year life. No end-of-life salvage value is assumed.

Carbon Intensity and Marginal CO_2 Abatement Cost

In addition to quantifying MFSP, the NREL team applied an approach to incorporate carbon intensity data into calculations to estimate marginal abatement cost for CO_2. Marginal abatement cost is a metric utilized by policymakers and industry analysists to compare the economics of climate change mitigation [125]. For the calculation in this project, the team applied the results of a recent life cycle GHG emissions analysis on RD by Argonne National Laboratory [125]. Land use change contributions to CI scores are complex and specific to feedstock source and location. Therefore, the impact of land use change on product CI scores is not considered in this assessment.

The total GHG emissions are used to quantify the GHG reduction relative to baseline values (defaults are 95.58 gCO_2/MJ for gasoline, 89 gCO_2/MJ for jet, and 91.4 gCO_2/MJ for diesel), and marginal abatement cost is calculated by Eq. 3:

$$MAC = f\ x\ \frac{MFSP - Market\ Price}{Energy\ Content\ x\ GHG\ Reduction} \qquad \text{(Eq. 3)}$$

Where:

MAC = Marginal abatement cost (\$/ton CO_2).

f = Factor for mass conversion (g/ton) = 907,185.

MFSP = MFSP for target product (\$/gal reference fuel).

Market price (\$/gal reference fuel).

Energy content (MJ/gal reference fuel).

GHG reduction (gCO_2/MJ) for target product.

The market price is set at \$2.50/gal of gasoline equivalent, which corresponds to \$80 per barrel (\$1.9/gal) West Texas Intermediate benchmark price.

GREENSCOPE

When evaluating SAF conversion technologies, two main assessments are typically carried out: techno-economic analysis and LCA or supply chain sustainability assessment [126] . Techno-economic analysis assesses the technical and economic viability of new processes and technologies, identifies cost reduction potential, and evaluates progress across different pathways and technologies. LCA and supply chain sustainability assessment estimate environmental impacts such as GHG emissions, fossil energy consumption, and water footprint.

It is important to integrate sustainability into the design of SAF production processes as a best practice in biorefinery design [126]. Evaluating a wider range of sustainability metrics beyond costs and GHGs can facilitate more comprehensive comparisons between design modifications and alternatives. A systematic framework can help understand the impact of design variation, evaluate alternative technologies, and track progress. By assessing process sustainability, the platform can identify areas needing improvement, challenges, and opportunities for achieving sustainability targets, and where to allocate resources.

The GREENSCOPE methodology can be used for sustainability performance assessment of ASTM-approved jet fuel pathways for SAF production. GREENSCOPE evaluates process sustainability across four areas: economic, environmental, material efficiency, and energy [126, 127]. Integrating sustainability into process design should be done early in development, rather than at the end. By comparing technologies and design modifications using multiple metrics, informed decisions can be made by looking at the design as a whole. The GREENSCOPE sustainability assessment can identify areas for further improvement in the process under consideration.

Appendix F. Air Quality and Regulations

F.1 Air Quality

Air-quality-related environmental and health effects of SAF production and use can be divided into three distinct categories:

1. Feedstock production/preprocessing and its logistics
2. Production of SAF and its logistics (e.g., transportation from biorefinery to terminals)
3. Combustion of SAF in jet engines.

Each of these phases can lead to direct emissions or formation of various pollutants, including NO_x (which represents the NO and NO_2 family), CO, PM, oxides of sulfur (SO_x), volatile organic compounds, and ozone.

Emissions from processing feedstock to produce SAF occur at a renewable fuel facility or biorefinery, which are regulated by complex air permitting discussed in more detail in Section 3. Emissions from logistics here refers to any emissions that would occur from transportation of feedstocks, as well as the finished fuel to terminals and end users, where it can be stored or used. Conventional fuel benefits from availability of an existing network of pipelines, which is currently lacking for neat SAF. Fossil Jet A SAF blends that are ASTM D1655-approved can be transported in a "business-as-usual" model as transportation of fossil Jet A. If neat SAF (not ASTM D1655-approved) must be transported to a blending terminal, truck, rail, or barges may be used, some of which can lead to additional emissions. While the magnitude of these emissions can be significant, these emissions are likely to occur over large, dispersed distances and thus unlikely to cause significant local air quality impacts [128].

Aviation-related air quality impacts have been broadly categorized into near-source (from landing and takeoff operations, usually below 3,000 ft) and full-flight (i.e., cruising altitude) impacts. There has been evidence that pollutants emitted at cruising altitude—not just the near-airport emissions—can also have significant impacts on air quality [129–131]. **While air quality impacts of aviation emissions are well recognized, there is little understanding of the benefits from use of SAF.**

We only found one recent study [131] that estimated the potential benefits from different blending levels of SAF with traditional jet fuel at a national scale, which uses a recent synthesis from the Airport Cooperative Research Program to quantify the emissions reductions from use of SAF [132]. The synthesis found that **emissions of several criteria air pollutants (CO, SO_x, and PM) decrease to varying degrees (all statistically significant) when using a blend of conventional Jet A with SAF, which does not contain aromatics** [129–131, 133–135]. The synthesis also found that **emissions of NO_x and volatile organic compounds were not found to be statistically significant**. Note that the analysis was a synthesis of test results from SAF produced via different pathways, which did not produce aromatics, and thus the emissions reductions are only indicative of SAF, which does not contain aromatics.

A national-scale analysis by Arter et al. [131] tested two blend levels—5% and 50%— of Jet-A and FT SAF (with no aromatics) and estimated the changes in emissions at all airports in the continental U.S. based on arrival and departure records for 2016. Within this report, the following conclusions were reached:

- Both 5% and 50% fuel blends decrease emissions during landing and takeoff by the following respective levels:
  - CO: 1% and 50%
  - Primary elemental carbon: 9% and 65%
  - SO_2: 4% and 38%.
- Decreases in emissions from the 5% and 50% fuel blends amounted to a potential reduction in premature mortality by 1% and 18%, respectively. Similar health improvements were found for asthma, respiratory and cardiovascular issues, and heart attacks.
- No emissions-level changes for NO_2 or ozone were observed in either of the blends, and as such, the corresponding health impacts around their exposure and atmospheric pollution remain the same.

These studies are limited but indicate knowledge gaps that need to be filled to understand the air quality impacts and human health benefits of reducing or eliminating aromatics as the transition to SAF takes place. A crucial consideration is comprehending the impact of low-aromatic SAF blending levels on air pollutant emissions and their relationship to blending levels and the potential environmental advantages of utilizing 100% SAF with low aromatic content. More work is needed to reduce the broad uncertainty levels in the Airport Cooperative Research Program synthesis report. **Additional analysis is also necessary to understand if different levels of adoption of low-or aromatic free SAF can provide additional air-quality-related environmental benefits. It should be noted that aromatics are a required component of jet fuel, and at present cannot be eliminated if the fuel is to be used as a drop-in fuel in existing aircraft.**

F.2 Air Regulations and Permits

Federal Clean Air Act

The federal Clean Air Act requires states to regulate stationary and mobile sources pursuant to an EPA-approved state implementation plan for the implementation, maintenance, and enforcement of the National Ambient Air Quality Standards. The National Ambient Air Quality Standards set ambient concentration limits for six air pollutants (ozone, PM, nitrogen oxides [NO_x], sulfur dioxide [SO_2], carbon monoxide [CO], and lead); this set is called “criteria air pollutants” [136].

The Clean Air Act established a New Source Review (NSR) program that requires a SAF facility to apply for a construction permit prior to the project being built or modified. There are three types of NSR permitting requirements, and biorefineries need to meet one or more of these:

1. Prevention of Significant Deterioration (PSD) permit, applicable for new facilities in attainment status that are major for at least one pollutant

2. Nonattainment New Source Review (NNSR) permits, applicable to new major source facilities in a nonattainment area
3. Minor source permits.

Determination of Applicability of Federal Air Regulations and Permitting Requirements to a SAF Facility

SAF facilities (typically considered chemical production facilities for air permitting purposes, as they produce hydrocarbon fuels[18]) are subject to environmental laws, including complex air quality regulations that aim to protect and improve the quality of the air. These regulations limit the acceptable levels of various air pollutants emitted by sources. Federal regulations under the New Source Performance Standards (CFR Title 40, Part 60) and National Emission Standards for Hazardous Air Pollutants (CFR Title 40, Parts 61 and 63) include criteria that are used to determine the applicability of a regulation to specific unit operations or the whole facility.

Project developers are responsible for identifying needed permits, compiling the requisite information (e.g., type and magnitude of regulated pollutants to be emitted), and drafting the permit application. The permitting authority will conduct reviews and, if necessary, require changes or additional mitigation. For most permitting processes that have legally mandated timelines, the timeline starts either when the application is received or when the agency deems the application complete [137]. Upon completion of the review process, the permitting agency approves or denies the permit. Figure F-1 shows a simplified illustration of air permitting process for SAF facilities in the United States.

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[18] Facilities producing hydrocarbon fuels are considered chemical production facilities, which is one of the 28 listed source categories: https://www.pca.state.mn.us/sites/default/files/aq4-25.pdf.

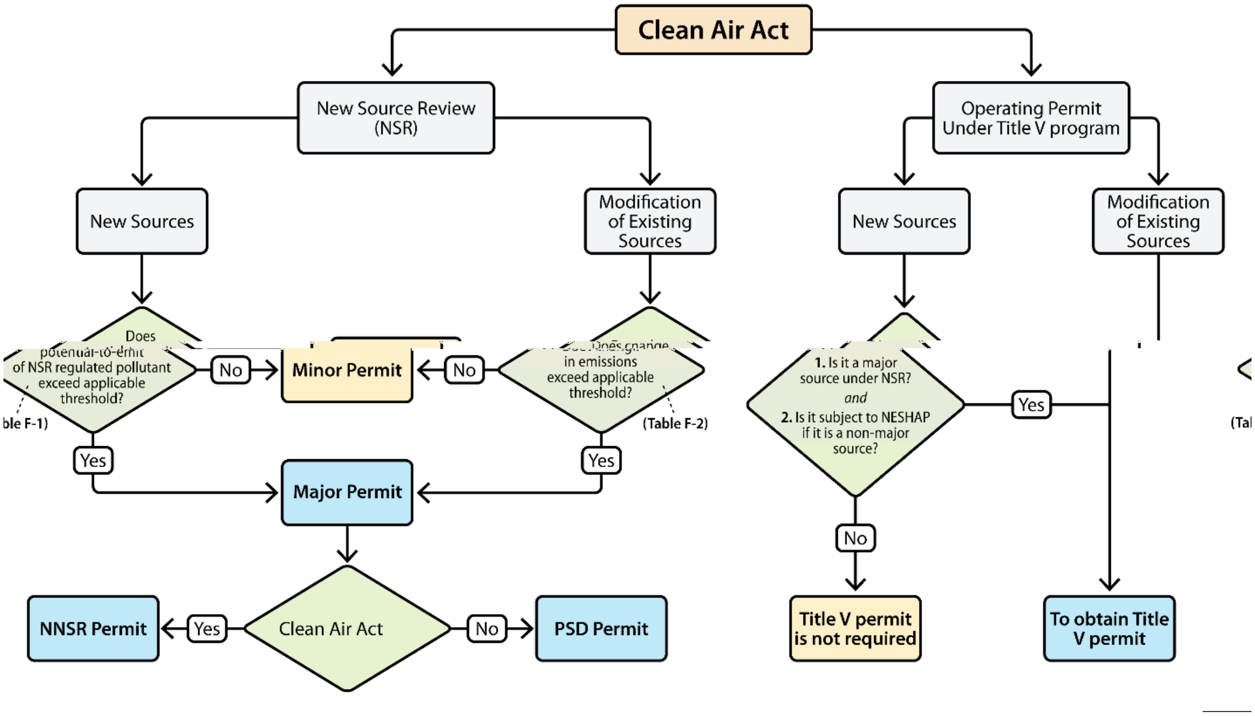

Figure F-1. Simplified flow diagram of the air permitting process for SAF facilities in the United States: PSD, NNSR, and National Emission Standards for Hazardous Air Pollutants.

* Existing sources are assumed to be U.S. petroleum refineries.

¥ https://www.epa.gov/title-v-operating-permits/who-has-obtain-title-v-permit.

Permitting for New Major Sources (Greenfield SAF Facilities)

- A primary factor in determining which permitting requirements will apply to a new source is the quantity of regulated pollutants that the source will emit from its operation after commissioning. As shown in Figure F-1, if a facility's potential to emit for one or more pollutants is at or above the applicable major source thresholds, it would be considered major. There are two sets of major NSR permitting provisions that can apply to major NSR sources: PSD and NNSR. PSD requirements can apply to any NSR-regulated pollutants except for nonattainment pollutants in the area where the new source is to be located. NNSR applies when a new source meets two criteria: (1) the source is to be constructed in a nonattainment area and (2) the source is major for the nonattainment pollutant.
- **If a new SAF facility is required to obtain a PSD** permit, the permitting process could be more time-consuming when compared to that for a minor source because the PSD requires (1) installation of best available control technology, which is an emissions limitation; (2) an air quality analysis; (3) an additional impacts analysis that assesses the impacts on soils, vegetation, and visibility caused by an increase in emissions from the source; and (4) public involvement [137].
- **If a new SAF biorefinery is subject to NNSR**, the permitting requirements are more stringent and will require (1) installation of the lowest achievable emissions rate, which is the most stringent emissions limitation; (2) emissions offsets, generally obtained from

existing sources located in the vicinity of a proposed source, to offset emissions increases and to achieve a net air quality benefit; and (3) public involvement [138].

- **A new SAF facility is also subject to the Title V permit requirement**, known as an operating permit (shown in Figure F-1) if it is subject to PSD and/or NNSR. The Title V permit program also addresses hazardous air pollutants and pollutants included in Section 112(r) of the Clean Air Act. For Title V permitting, a SAF facility will be subject to major source permitting requirement if it emits 10 tons per year for a single hazardous air pollutant or 25 tons per year for any combination of all hazardous air pollutants.

Table F-1 displays the major source thresholds for new facilities. Depending on the location of the facility (e.g., whether it is in a nonattainment area for a given pollutant), a new SAF facility would be subject to a major source permit prior to the construction of the project if it has the potential to emit a pollutant at or above any one of the applicable thresholds (refer to [136]).

Table F-1. Major Source Thresholds Prescribed by the NSR

For NSR permits, the major source thresholds depend on the attainment status of the area in which the new facility will be located, PSD, and NNSR.

Pollutant	**NSR Program**		
	PSD permit for attainment pollutants [a]	*NNSR permit for nonattainment pollutants* [a]	
	Major source threshold for chemical plants (tons per year)	Nonattainment classification [b]	Major source threshold (tons per year)
CO	100	Moderate	100
		Serious	50
Volatile organic compounds or NO_x regulated for ozone National Ambient Air Quality Standards	100	Marginal	100
		Moderate	100
		Serious	50
		Severe	25
		Extreme	10
PM_{10}	100	Moderate	100
		Serious	70
$PM_{2.5}$	100	Only one classification	100
NO_x	100	Only one classification	100
SO_2	100	Only one classification	100

[a] Attainment or nonattainment pollutants refer to air pollutant emissions in a particular area that either comply or do not comply, respectively, with the National Ambient Air Quality Standards.

[b] The severity of the nonattainment classification (e.g., moderate, severe) is evaluated by the EPA according to the local pollutant concentration and varies by pollutant.

Permitting for Existing Sources (Repurposing Existing Petroleum Refineries)

Because some developers have been or are converting existing petroleum refineries (repurposing) or part of the petroleum refineries to produce SAF, we briefly discuss the permitting requirements for modifications of petroleum refineries.

- **The EPA has determined that all petroleum refineries in the U.S. are major sources of hazardous air pollutants** and subject to the National Emission Standards for Hazardous Air Pollutants [139]. Because all refineries are major sources, they are required to have a Title V permit. If a petroleum refinery is modified to produce SAF, it will **have to revise its current Title V permit** to incorporate all compliance requirements in air standards that apply to the facility modifications for SAF production, as well as any requirements contained in an NSR permit authorizing the facility modifications.
- **Modifications at a petroleum refinery will trigger the need to apply for and acquire an NSR permit.** If emissions of regulated pollutants are increased by amounts lower than the significant emissions rates (Table F-2), a minor permit would be required. If emissions are increased by more than the significant emissions rate for any pollutant, then the changes would be considered a major modification. If it is determined that the net emissions increase is greater than the significant emissions rate for one or more pollutants, PSD permitting and/or a major modification NNSR permit would apply.
- **A major modification NNSR permit would apply only if the facility is located in a nonattainment area and the emissions increase of a nonattainment pollutant is above the significant emissions rate**.
- **Criteria to determine collocation: If a SAF project considers being collocated with an existing source (e.g., petroleum refinery), the determination of whether two sources are collocated under either Title V or NSR permitting is on a case-by-case basis depending on individual circumstances surrounding the design and operation of the processes.**

Modifications at a petroleum refinery will trigger the need to apply for and acquire an NSR permit. EPA uses significant emissions rate thresholds to determine when NSR requirements apply to modification of existing facilities and whether it is considered a major modification and therefore requires the facility to obtain permits [140]. If emissions of regulated pollutants are increased by amounts lower than the significant emissions rates, a minor modification permit would be required. If emissions are increased by more than the significant emissions rate for any pollutant, then the changes could be considered a major modification. If it is determined that the net emissions increase is greater than the significant emissions rate for one or more pollutants, PSD permitting and/or a major modification NNSR permit would apply. A major modification NNSR permit would apply only if the facility were located in a nonattainment area and the emissions increase of a nonattainment pollutant is above the significant emissions rate (Table F-2).

Table F-2. PSD and NNSR Major Modification Thresholds

Pollutants	PSD Significant Emissions Rate for Attainment Areas (tons per year)	Nonattainment Area Classification	NNSR Significant Emissions Rate for Nonattainment areas (tons per year)
PM	25	n/a	n/a
PM_{10}	15	Serious, Moderate	15
$PM_{2.5}$	10	Serious, Moderate	10
Ozone (regulated through its precursors, i.e., volatile organic compounds and NO_x)	40 (volatile organic compounds or NO_x)	Moderate, Marginal	40
		Severe, Serious	25
		Extreme	Any increase in actual emissions
CO	100	Serious	50
SO_2	40	Nonattainment	40
Pb	0.6	Nonattainment	0.6

Certain collocated operations at a commercial or industrial site could be determined to be separate facilities, and the emissions from each facility would be assessed separately to determine if it is a major source. Conversely, under the source definitions in the rules, certain operations that are not physically collocated could be determined to be part of a single facility, and the collective emissions would be added together to determine if the major source threshold is exceeded. **All the operations would be subject to permitting as one source.** Two or more sources could be considered one facility if all three of the following criteria are met:

- The sources must be under **common ownership or common control**
- The sources must belong to the **same industrial grouping**
- The sources must be located on **contiguous or adjacent properties.**

Factors Influencing Air Permitting Processes and Timelines

It has long been recognized that the permitting process is critical to the success of a project. A project could be delayed or even canceled if it cannot obtain the required permit(s) prior to its construction or modifications. During discussions with SAF developers, some of them expressed concerns and dissatisfaction due to the challenges (e.g., lack of clear guidance, length it takes to get a permit), holdups, and hinderances they faced in obtaining the necessary permits. While each project is unique, there are several key factors that can impact the efficiency of the permitting process:

- **Geographic locations.** States regulate stationary sources of criteria pollutants (such as SAF facilities) through their permitting program to ensure attainment and/or maintenance of the National Ambient Air Quality Standards. Since air permits are issued by local permitting authorities (e.g., state, district), the permitting requirements and timelines vary by location. For example, if a project is located in a nonattainment area and emits a pollutant for which the area is in noncompliance, the permitting process could be considerably more stringent and complex compared to a similar projected located in an attainment area. In addition, a source would be subject to applicable local air regulations, which also differ by location.

- **Magnitude of emissions.** If a source emits regulated pollutants at or above the applicable thresholds it will be considered a major source or major modification. The additional permitting requirements a major source will need to meet typically imply a longer timeline compared to a minor source. It is worth noting that although larger projects/facilities enjoy the benefits of economies of scale, these projects/facilities may need to consider the trade-offs in (total) air emissions and delays they may experience in obtaining permits.
- **Project complexity.** It takes longer to review complex processes/projects by permitting authorities. This is particularly true when reviewers have not previously encountered similar designs that have new unit operations for which established emission factors are not readily available.
- **Other project characteristics.** In addition to the size and complexity of the project process, studies also find that the social, economic, and environmental impacts of a project could influence the length and efficiency of the permitting process [141]. For example, negative impacts such as traffic noise, impact on visibility, and decreased water quality could lead to distrust among stakeholders and communities and thus cause longer-than-expected public review/involvement periods.