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Industry perspectives on advanced sustainable aviation fuel

What barriers remain for these technologies to scale?

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EXECUTIVE SUMMARY

Achieving emission reductions and sustainable aviation fuel (SAF) deployment goals in the European Union, United Kingdom, and United States will require rapidly expanding the production of low carbon intensity SAF. A limited supply of sustainable feedstock for currently commercialized SAF pathways means the majority of this production will rely on advanced technologies not yet deployed at commercial scale, namely those that use emerging technologies and scalable, non-food feedstocks.

To better understand the barriers to commercialization of these pathways, we surveyed technology providers and advanced SAF project developers on challenges related to technological readiness, feedstock availability, fuel demand, finance, and policy. We found that advanced SAF facility deployment faces three key challenges:

High capital costs. Establishing advanced SAF facilities at commercial scale is extremely capital-intensive; a single facility may represent a multi-billion-dollar investment. This contributes to an overall cost of production much higher than that of fossil jet fuel. Raising sufficient capital in most cases also requires debt financing, but debt providers are risk-averse and often unwilling to invest in pioneering facilities supplying an immature market.

First-of-a-kind technology deployment. The commercial-scale deployment of advanced SAF technologies is still in its infancy, making it difficult to accurately assess project economics. Funding the substantial cost of pre-final investment decision engineering work is a significant challenge for project developers, in part because of the uncertainty of overall production costs prior to conducting these detailed engineering studies. Engineering procurement and construction firms responsible for building these facilities may also be unwilling or unable to guarantee performance, increasing the risk to investors. Performance risks are highest for large-capacity facilities.

Offtake and price uncertainty. Because advanced SAF production is much more expensive than both fossil jet fuel and first-generation SAF, the success of advanced SAF projects relies heavily on policy-driven demand. Yet, because the market for policy-compliant fuel remains immature and the political resolve to maintain current mandates is unproven, the future trajectory of advanced SAF prices is highly uncertain. Project developers depend on binding, long-term offtake agreements with fuel users for this reason. Fuel users, though, are often reluctant to lock in long-term prices that may be disadvantageous if competitors can secure policy-compliant fuel at a lower cost in the future.

POLICY CONSIDERATIONS

Based on this feedback, we identified a two-stage policy framework that could be applied in the European Union, United Kingdom, and United States. During the initial “runway” phase of advanced SAF deployment, a government-backed revenue certainty mechanism could guarantee an offtake price for qualifying advanced fuel producers. This would eliminate the need for long-term purchase commitments from fuel users and provide assurance to investors, particularly providers of debt financing, that project returns are secure so long as fuel production is realized.

This revenue certainty mechanism could function in concert with a longer-term “takeoff” phase of advanced SAF deployment, in which a SAF mandate or comparable demand-side policies would promote a healthy and growing market for fuel. The key premise of this phase is that once the runway phase has enabled a certain level of advanced SAF deployment and a better understanding of technology costs and market dynamics, demand-side policies can support further investment in advanced SAF production.

The United Kingdom, European Union, and United States could each take steps to adapt existing policies to this framework:

United Kingdom. A recently finalized SAF mandate and upcoming revenue certainty mechanism in the United Kingdom are well aligned with the policy framework outlined in this paper. Looking ahead, key issues for UK policymakers will include ensuring the revenue certainty mechanism is established in a timely manner and that it sufficiently de-risks the financing of advanced SAF facilities. Due to high electricity prices, targeted measures may be required to support commercially viable UK-based power-to-liquids SAF production.

European Union. While ReFuelEU Aviation SAF mandates are aligned with the takeoff phase of the proposed policy framework, current EU policies are poorly suited to address the challenges experienced by first-mover advanced SAF project developers. Consequently, there is concern that 2030 synthetic SAF production will be insufficient to meet initial ReFuelEU sub-mandate. The development of an EU advanced SAF revenue certainty mechanism and possible deployment of targeted support from the Innovation Fund could address these challenges.

United States. An incentives-only approach to SAF policy in the United States has catalyzed some investments, but the long-term policy outlook is highly uncertain, as is the market demand toward 2030 and beyond. A national demand-side aviation fuel policy, such as a SAF mandate, complemented by a revenue certainty mechanism to support the initial deployment of advanced SAF facilities, could support future growth in U.S. advanced SAF production.

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INTRODUCTION

Meeting climate targets aligned with the Paris Agreement will require the widespread deployment of advanced sustainable aviation fuels (SAF) produced with emerging technologies and scalable, non-food feedstocks. These include SAF pathways that rely on solid waste or cellulosic feedstocks, alcohol from waste gas fermentation upgraded to jet fuel, and e-fuels produced via renewable electricity-powered electrolysis (Graver et al., 2022).

Advanced SAF pathways are required because lipid feedstocks for the commercially mature hydroprocessed esters and fatty acids (HEFA) SAF pathway are in limited supply, and further production using food- or feed-based feedstocks like soybean oil carries significant sustainability risks (Baldino & Mukhopadhaya, 2022; Rosales Calderon et al., 2024). However, advanced SAF production has not reached commercial scale.[1] Considering the rapid proliferation of low-carbon fuel production capacity anticipated by aviation decarbonization roadmaps in the European Union, the United Kingdom, and the United States, it is important to understand obstacles to the growth of such capacity in these markets.

A previous ICCT-commissioned report assessed barriers to several advanced fuel pathways, with a particular focus on cellulosic ethanol (Peters et al., 2016). That study, published in 2016, concluded that "capital costs are high, some technologies are not widely tested at commercial scale, and little certainty exists that produced fuels can be sold to the market at a sufficiently high price, as the regulatory climate to ensure long-term offtake has been lacking."

Since that time, much has changed. While cellulosic ethanol producers are still working to overcome technical challenges, rapid improvements in electric vehicles have bypassed the need for biofuels in the road sector. Meanwhile, ambitious climate targets have refocused attention on low-carbon fuels suitable for aviation and maritime applications—sectors where electrification is generally not an option. Moreover, as policymakers seek to marry decarbonization with industrial revitalization, the successful deployment of low-carbon fuels has become a cornerstone of green industrial policy.

In this report, we analyze barriers to advanced SAF deployment. We consider technologies that are expected to contribute to significant volumes of aviation fuel production within the next decade but are not yet fully commercialized, namely:

- Gasification;
- Alcohol-to-jet (ATJ);
- Electrolysis hydrogen from renewable electricity (renewable hydrogen);
- E-fuels; and
- Direct air capture (DAC).

To identify what has and has not changed since 2016, we conducted a survey of industry representatives from companies developing projects or equipment using these technologies. The survey was structured to assess barriers in technological readiness, feedstock, fuel offtake, policy, and finance.

This report first provides background on SAF technologies and relevant policies in the European Union, the United Kingdom, and the United States. We next summarize responses in each of the survey categories and discuss the overarching themes. The report concludes with considerations for policymakers in each market.

1 In this report, we define commercial scale as annual fuel production of 10,000 tonnes or more.

BACKGROUND

TECHNOLOGY OVERVIEW

Survey respondents were asked to comment on the following technologies. For a comprehensive review of advanced fuel pathways, see Baldino et al. (2019).

Gasification

During gasification, carbon-rich solids such as coal, municipal solid waste (MSW), or biomass are converted at high temperatures to an energy-rich syngas consisting of carbon monoxide, hydrogen, and carbon dioxide. Syngas is used as the feedstock for liquid fuel synthesis via the Fischer-Tropsch process or the production of ethanol via gas fermentation. Ethanol can subsequently be upgraded using ATJ technology. While gasification of coal to produce liquid hydrocarbons is a mature technology (Office of Air and Radiation, 2009), its application to biogenic feedstocks for liquid fuel synthesis has yet to be reliably achieved at a commercial scale (IEA Bioenergy, n.d.).

Alcohol-to-jet

ATJ technology uses hydrogenation to convert alcohols to a pure hydrocarbon liquid fuel suitable for use in jet engines. This technology can be applied to alcohol from the fermentation of first-generation crop-based feedstocks such as corn and sugar, as well as more sustainable second-generation feedstocks such as cellulosic residues or industrial gases. The only facility currently producing aviation fuel from a non-lipid feedstock at commercial scale is a first-of-a-kind facility employing ATJ technology to process corn- and sugarcane-derived ethanol (IEA Bioenergy, n.d.; Marsh et al., 2025).

Renewable hydrogen

For drop-in alternative fuels suitable for use in today's jet engines, hydrogen produced using renewable electricity with an electrolyzer can serve as an intermediate in power-to-liquids (PtL) fuel synthesis and can also play a role in lowering the greenhouse gas (GHG) intensity of other pathways that require a hydrogen input as part of their conversion process, such as enriched gasification Fischer-Tropsch and ATJ (Albrecht et al., 2017). While the technical feasibility of renewable hydrogen (also known as green hydrogen) production is fully established, the cost of large-scale production is still uncertain (Navarrete & Zhou, 2024). Hydrogen may also be used directly as a fuel, but at present hydrogen-powered aircraft are still under development (Mukhopadhaya & Rutherford, 2022).

E-fuels

PtL technology converts electrical energy into synthetic liquid fuels, commonly known as e-fuels or e-kerosene in the case of synthetic jet fuel. This is achieved by chemically combining renewable hydrogen with carbon dioxide (CO_2) to synthesize hydrocarbons via the Fischer-Tropsch process or similar chemical reactions (International Energy Agency, 2024). Because the production of e-fuels is primarily constrained by the availability of renewable electricity, these fuels are considered to be more scalable than biomass-based fuels (Breyer et al., 2022). A handful of demonstration-scale e-fuels facilities are operational or under construction, and construction of a commercial-scale facility has just begun in the United States (Infinium, 2025; Transport & Environment, 2024).

Direct air capture

There are two options for carbon capture for e-kerosene production: point source capture from an industrial source such as cement plants, or DAC, whereby CO_2 is removed directly from the air. Because the CO_2 fraction of air is only 0.04%, compared with 4%–98% for industrial sources, DAC entails much higher equipment costs and energy inputs than point source capture (International Energy Agency, 2022). In the case of liquid DAC, high-temperature heat is provided by natural gas combustion, with the resulting CO_2 sequestered alongside the CO_2 removed from the atmosphere. In contrast, solid DAC requires lower-grade heat, which could be provided by a variety of sources. In general, the current focus of DAC facilities is on CO_2 sequestration rather than utilization for fuel synthesis (1PointFive, 2023; Climeworks, n.d.).

POLICY LANDSCAPE

Since 2020, governments on both sides of the Atlantic have enacted policies intended to reduce aviation GHG emissions through the use of SAF. Here we provide a brief overview of SAF policy frameworks in the European Union, the United Kingdom, and the United States.

European Union

In the European Union, the ReFuelEU Aviation regulation sets mandatory blending levels for SAF use in aviation, with the share of SAF rising from 2% in 2025 to 70% in 2050 (Baldino, 2023; Regulation (EU) 2023/1804, 2023). A sub-mandate for synthetic PtL fuels increases from a minimum share of 0.7% in 2030 to 35% in 2050. Sustainable aviation fuels fulfilling the ReFuelEU mandate can also be used to help meet Renewable Energy Directive (RED) III targets for renewable energy use in the transport sector, which are implemented at the Member State level (Directive (EU) 2023/2413, 2023). These include a combined sub-target for advanced biofuels and e-fuels known as renewable fuels of non-biological origin (RFNBOs). The RED III also includes a minimum 1% RFNBO share for all energy supplied to transport in 2030.

Separately, revisions to the EU Emissions Trading System (ETS) require aircraft operators to purchase GHG emission allowances for all flights within the European Economic Area from 2026 onwards. The ETS revisions also created a re-investment mechanism that seeks to narrow the cost gap between SAF and fossil jet fuel with a focus on advanced fuels and RFNBOs (DG CLIMA B.4 & European Commission, 2023). The ETS-funded EU Innovation Fund can also provide financial support for SAF facilities, though to date there have been no SAF-specific requests for proposals (Commission Delegated Regulation (EU) 2019/856, 2019). Innovation Fund support for e-fuel production could also be channeled via the European Hydrogen Bank, which auctions support for RFNBO hydrogen production on a Euro per kilogram basis over a 10-year term (European Commission, 2023).

Further developments in EU SAF policy are anticipated. The Clean Industrial Deal initiative, launched in February 2025, mentions further rounds of European Hydrogen Bank support and promises a Sustainable Transport Investment Plan, which will include short- and medium-term measures to support low-carbon fuels for aviation (European Commission, 2025). As part of the investment plan, the European Commissioner for Sustainable Transport and Tourism has said the commissions will "look at new mechanisms to reduce the price gap for domestically produced synthetic fuels, and at a revenue guarantee for first movers" (Tzitzikostas, 2025).

United Kingdom

In the United Kingdom, the UK Department for Transport (2022) Jet Zero Strategy sets out a trajectory to achieve net-zero aviation emissions by 2050. Critical to achieving this ambition is a SAF mandate that obligates aviation fuel suppliers to blend a growing percentage of SAF into the UK aviation fuel market. Mandated blending levels increase from 2% in 2025 to 22% in 2040 (The Renewable Transport Fuel Obligations (Sustainable Aviation Fuel) Order 2024, 2024). In contrast to ReFuelEU, the mandate includes a cap on HEFA SAF. Like ReFuelEU, it includes a PtL sub-mandate, which increases from an initial 0.2% of the mandated volume in 2028 to 3.5% in 2040.

A revenue certainty mechanism intended to guarantee a fuel selling price to producers is also under development in the United Kingdom. A recent UK Department for Transport (2025a) consultation response outlines the future structure of the revenue certainty mechanism and promises implementation by the end of 2026. A further consultation response explains that a levy on fuel suppliers will be used to fund the revenue certainty mechanism, with the magnitude of the levy adjusting depending on the funding needs (UK Department for Transport, 2025b).

Additionally, the United Kingdom has made direct investments of £135 million in first-of-a-kind and demonstration-scale facilities through Advanced Fuel Fund grants, which cover pre-construction expenses associated with facility planning and engineering (UK Department for Transport, 2024a).

United States

In the United States, the SAF Grand Challenge, launched in 2021, set a non-binding target of 3 billion gallons of SAF production in 2030, increasing to 35 billion gallons in 2050 (U.S. Department of Energy et al., 2021). A number of incentive programs also support the use of SAF, and in many cases recipients can combine credits for qualifying fuels from multiple programs, a practice known as stacking. However, in contrast to Europe, SAF adoption in the United States is entirely voluntary; at present, the country has no penalties for aviation emissions and no requirements for SAF use.

At the federal level, support for SAF production includes section 45Z tax credits established under the Inflation Reduction Act (IRA), which offer up to $1.75 per gallon of fuel (Clean Fuel Production Credit, 2022). Opt-in crediting under the Renewable Fuel Standard (RFS) can also support biogenic SAF production (U.S. Environmental Protection Agency, 2010). The RFS requires gasoline and diesel producers to supply biofuels or purchase credits to meet their blending obligations, with cellulosic fuels commanding a higher value due to a cellulosic fuel sub-mandate. The IRA also supports renewable hydrogen production and carbon capture via 45V and 45Q tax credits, respectively (Inflation Reduction Act, 2022), though stacking with 45Z is not allowed. Additionally, the IRA included funding for Fueling Aviation's Sustainable Transition grants, administered by the Federal Aviation Administration, to support SAF production and infrastructure (U.S. Department of Transportation, 2024). New legislation enacted in July 2025, just prior to the publication of this study, made significant changes to IRA credits: 45V clean hydrogen credits now sunset in January 2028, while the 45Z clean fuel credit has been extended through December 2029, albeit with a reduced value of $1 per gallon for SAF (One Big Beautiful Bill Act, 2025).

Individual U.S. states also support SAF through opt-in inclusion in road sector-focused clean fuel standards such as the California Low Carbon Fuel Standard (LCFS) or state-specific SAF tax credits (Navarrete et al., 2024). Under the LCFS and similar programs in Oregon and Washington (with one currently under development in New Mexico), the value of credits for a given fuel depends on that specific fuel's carbon intensity and the market price of credits, which can vary based on the supply of alternative fuels to the road sector and other market factors.[2]

2 Carbon intensity is a measure of a fuel's life-cycle GHG emissions, frequently measured in g CO_2-equivalent per MJ.

SURVEY AND INTERVIEW RESPONSES

Between January and June 2024, we conducted surveys and interviews of industry representatives at companies developing projects or equipment using any of the five advanced fuel technologies discussed above. The written survey was conducted online using the Sogolytics platform (Sogolytics, 2024) and consisted of a mix of rating questions and open-ended responses. Interviews were conducted virtually. In some cases, respondents from a single company participated in both a survey and an interview. Table 1 summarizes responses received by technology. Overall, 70% of respondents commented on questions specific to either U.S. or EU policies, while only 40% commented on UK policy.

Table 1
Summary of respondents and technology focus of each company

Company	Written survey	Interview	Gasification	ATJ	Renewable hydrogen	E-fuels	DAC
A	●	●				●	
B	●	●				●	
C	●					●	
D		●	●				
E	●		●			●	
F	●				●		
G		●	●	●			
H	●					●	
I		●				●	
J	●	●					●

In this section, we provide summaries of responses to topics covered in the survey and interviews.

FACILITY DEPLOYMENT MILESTONES

To better understand the barriers to fuel facility deployment, our written survey included a section on project progression. Respondents were asked to identify key project milestones, specify the criteria necessary for advancing to subsequent stages, and indicate the stakeholders most critical to this advancement. Here we provide a summary of the stages identified by respondents.

Stage 1: Concept and screening. During this stage, project developers assess advanced fuel technology options with an emphasis on market readiness and scalability. If suitable technologies are available and financial modeling indicates that a facility will generate adequate financial returns, then a project will be initiated.

Stage 2: Feasibility. During this stage, developers conduct a more detailed analysis of project costs and schedules. From this stage onward, buy-in from external stakeholders is necessary. Outcomes required for moving the project forward are:

» Favorable feedstock availability and cost estimates;

» Favorable assessment of the policy environment, including applicable subsidies supporting an adequate return on investment;

» Securing a non-binding offtake agreement;[3] and

» Securing additional developmental capital to fund a Front-End Engineering Design (FEED) study and land acquisition.

Stage 3: FEED study. During this stage, detailed engineering is conducted to enable plant construction and add certainty to the cost and performance estimates from stages 1 and 2. According to respondents, the cost of a FEED study is generally on the order of 10% of the capital cost of a completed facility. To proceed toward construction, FEED study cost and performance estimates must align with the price specified in offtake agreements.

Also during stage 3, the groundwork is established for any binding contracts that must be in place before beginning construction. This includes securing land, feedstock, and an equipment procurement and construction technology provider, as well as applying for necessary permits.

Stage 4: Final investment decision. Assuming the FEED study confirms the economic viability of a project, the developer must then secure commitments from stakeholders before making a final investment decision and commencing construction. For a positive final investment decision, the following elements must be in place:

» A binding "take-or-pay" offtake agreement for fuel produced at the facility;

» Binding long-term supply agreements for relevant feedstocks;

» Completed construction permits;

» Binding debt and equity commitments; and

» An agreement with an equipment procurement and construction technology provider for facility construction, which includes a guarantee of technology performance.

TECHNOLOGY AND FEEDSTOCK

Given the central role of technology underperformance in the failure of several previous advanced fuel production facilities (Bettenhausen, 2022; Lane, 2015; Witcover, 2021), we solicited a candid assessment of technological readiness from respondents. We focused on the likelihood that a commercial-scale plant would be able to achieve its designed production capacity within a given time frame. We also asked which technological components contribute the most to fuel costs and offer the greatest opportunities for reducing overall production cost. We additionally asked respondents to describe any concerns related to the acquisition of feedstock for each process.

Gasification

In assessing the overall technological readiness of gasification, respondents indicated that while fuel production at a commercial scale is feasible, successful operation will depend on matching the right gasifier technology (e.g., fixed bed, fluidized bed, or entrained bed) with the specific feedstock supplied to a facility. Respondents also suggested that while immediate operation at full capacity should not be expected, sufficient planning and investment can help avoid the more severe start-up difficulties experienced by past gasification projects.

3 An offtake agreement is an arrangement in which a buyer agrees to purchase a specified quantity of fuel from a producer at predetermined terms, typically to secure supply and support project financing. Binding "take-or-pay" contracts create a legal obligation to purchase the fuel. In contrast, a non-binding offtake agreement consists of a memorandum of understanding that demonstrates an intent to enter into a binding contract in the future.

One respondent also noted that the methodical scaling and refinement of coal gasification, which enabled reliable operation at commercial-scale coal-to-liquids facilities, has not yet occurred for biogenic feedstocks. The respondent attributed the recent failure of the Fulcrum gasification facility (Wallace, 2023) in part to a failure to validate the chosen gasification technology on the plant's MSW feedstock at a more limited scale before attempting a commercial/first-of-a-kind scale implementation. The respondent also noted that gasifiers that have dealt successfully with biogenic feedstocks, have generally worked at atmospheric pressure, but that pressurized systems better prepare syngas for downstream fuel synthesis.

Cellulosic and MSW feedstocks face distinct challenges. An existing waste collection system and potential revenue from waste management were cited as advantages for MSW, with the primary challenge being processing highly heterogeneous MSW into a consistent feedstock. Respondents noted that municipal waste sorting in European material recovery facilities is more advanced than standard practice in the United States, and that transfer of this technology could facilitate U.S. production of MSW-based fuels. Regarding cellulosic feedstocks such as crop or forest residues, respondents cited high feedstock costs, the absence of existing supply chains, and reluctance of feedstock suppliers to commit to long-term contracts as significant barriers. Seasonal variation in quality and moisture content was cited as an important but secondary concern.

From a cost reduction standpoint, respondents noted that gasifier and syngas purification equipment are the most expensive components of a facility, but that the gasifier and feed system represented the most likely opportunities for cost reduction. Respondents also noted the potential for cost reductions from centralizing fuel production at large-scale facilities while drawing feedstock from a wide geography. We note, however, that the challenge of transporting low-density MSW and cellulosic feedstocks in a cost-effective manner has been a consistent theme in academic assessments of MSW and cellulosic pathways (Balan, 2014; Montoya Sánchez et al., 2023).

For MSW feedstocks, capturing some portion of the value of waste disposal (known in some regions as a "tipping fee") was cited as an important means of reducing the overall cost of fuel production; in other words, avoided tipping fees could result in a low or negative-cost feedstock. Respondents suggested that a commercial-scale MSW-based fuel facility receiving a tipping fee for feedstock disposal could approach cost parity with fossil fuel production, a view that was not expressed for other fuel pathways in our survey.

Alcohol-to-jet

Respondents described ATJ technology as needing only a brief period of validation before entering commercial operation and noted that this technology has recently been deployed at a commercial-scale facility. Ethanol derived from sugarcane and from industrial flue gas were cited as important for near term ATJ production. We note that while corn-grain ethanol supply chains are fully established in the United States, the International Civil Aviation Organization (2019) has assessed that SAF produced from U.S. corn ethanol has life-cycle emissions comparable to conventional aviation fuel.

The need for complementary technologies to reduce the carbon intensity of alcohol feedstocks was cited as the biggest technical barrier to ATJ deployment. For example, the development of gasification technology to enable alcohol production via gas fermentation of second-generation non-crop feedstocks and the application of carbon capture technology to ethanol production in the United Sates were both cited as less mature technologies important for the expansion of low-carbon ATJ production. The implementation of a hybrid PtL and ATJ pathway involving the fermentation of syngas derived from renewable hydrogen and captured CO_2 was also cited as a possibility, contingent on the availability of low-cost renewable hydrogen.

Renewable hydrogen

A single respondent commented on the technological challenges to renewable electricity-based hydrogen production. The electrolyzer itself was cited as offering the greatest opportunity for cost reduction, but the respondent also noted that the balance of plant (i.e., the non-electrolyzer components of a built-out renewable hydrogen facility) is a significant source of cost, especially for smaller-scale projects.

Meeting customer requirements for a steady supply of hydrogen was also cited as a challenge, especially for projects using a direct “behind-the-meter” connection to renewables or those relying on renewable electricity that would otherwise be curtailed. The respondent cited batteries, hydrogen storage, and novel electrolyzer designs incorporating energy storage as possible solutions. Beginning in 2030, both EU and U.S. policies will require hydrogen producers to match their electricity use with renewable energy production on an hourly basis; in the United Kingdom, half-hourly matching is already required for renewable hydrogen used in transport (Commission Delegated Regulation (EU) 2023/1185, 2023; Credit for Production of Clean Hydrogen and Energy Credit, 2025; UK Department for Transport, 2024b).

E-fuels

Respondents varied in their assessment of PtL technology readiness. This may reflect PtL’s reliance on a suite of technologies that are considered relatively mature in isolation but have yet to be fully integrated at a commercial scale (International Energy Agency, 2024). Indeed, one respondent noted that while electrolysis and gas-to-liquids technology (e.g., Fischer-Tropsch synthesis) are both proven, the construction and operation of a fully electrified fuel synthesis facility incorporating these components is still a challenge. Overall, the conversion of CO_2 to carbon monoxide (CO) was cited as the least-proven part of the PtL process.[4]

Respondents were unanimous in reporting that high capital costs are a major barrier to the commercialization of e-fuels, with one respondent benchmarking capital costs at $1–$2 billion depending on the size of facility. In addition to electrolyzer costs, reactors for converting CO_2 to CO were cited as high-cost components for PtL facilities with potential for cost reduction. To reduce overall production costs, greater process efficiency and lower capital costs were also considered important. Respondents noted that co-electrolysis to produce syngas directly from water and CO_2 without the need for a separate reverse water gas shift reactor is not ready for commercial deployment but may be used in the future.[5] Other suggested opportunities for cost reduction included low-cost electricity storage to manage renewable intermittency and research and development into improved chemical catalysts for the Fischer-Tropsch reaction. Attempting to scale up too quickly at initial PtL facilities was cited as the most likely cause of underperformance.

The ability to access low-cost renewable electricity supplied by the grid was cited as critical for commercially viable e-fuel production. Asked to identify something that policymakers misunderstand, one respondent noted, “it is more practical and lower cost to source electricity from the grid than co-locate with renewable energy production facilities.” Respondents referenced the large differential between the levelized cost of renewable electricity and the delivered cost as a significant barrier in all regions, noting

4 The Fischer-Tropsch reaction requires a CO-containing syngas input, which can be produced by applying a reverse water gas shift reaction to hydrogen and CO_2. This step is not required in existing gas-to-liquids and coal-to-liquids Fischer-Tropsch facilities.

5 See Zong et al. (2024) for a recent review of co-electrolysis technology.

that relief from grid tariffs or access to wholesale power pricing could significantly improve the prospects for e-fuel production. Access to electricity at a cost no greater than ~$40 per MWh delivered was cited as necessary for economic viability. Respondents identified several ways to improve the power system to benefit e-fuel production. These included investments in grid infrastructure to enable access to renewable electricity produced in multiple regions, measures to accelerate the interconnection process for renewable energy in the United States, and enhanced transparency in power markets and power-purchase agreement pricing across all regions.

Respondents expressed confidence that biogenic point sources would be sufficient to supply near-term e-fuel facility deployments. However, respondents also highlighted the challenge of aggregating CO_2 to sites supplied with low-cost renewable electricity, particularly over the long term. Respondents noted that restrictions on the use of fossil CO_2 sources beyond 2040 under EU law would prevent investment in facilities relying on these sources but that fossil CO_2 sources may be used for e-fuel production in other regions.[6] Respondents from companies focused on e-fuels were unanimous in the opinion that direct air capture is currently too expensive and lacks the technological maturity for consideration as a CO_2 source in near-term PtL facilities.

Direct air capture

We received a response from a single company focused on DAC. Respondents from this company noted that while a commercial-scale facility can be built using today's DAC technology, optimization will be required to achieve consistent operation at full capacity. The biggest barrier cited was high overall costs, with a carbon price in the range of $200–$500 per ton needed to offset the cost of CO_2 capture. The respondents cited efficiency improvements (i.e., increasing the amount of CO_2 captured per unit of energy input) as important for lowering costs and noted that fundamental changes in DAC technology from today's systems are possible but difficult to predict.

Respondents emphasized that early DAC projects will primarily generate revenue from carbon removal credits rather than from supplying CO_2 to fuel producers, meaning the speed of DAC deployment is sensitive to credit values. They also highlighted the challenge of competing with cheaper but potentially lower-quality nature-based credits like those for reforestation; while initial facilities have depended on a few technology-minded credit buyers, widespread DAC expansion will require establishing a premium for DAC carbon removal in broader carbon markets. Additionally, respondents noted that natural gas supplies with low upstream leakage rates are important for DAC facilities that use natural gas for heating; compensating for upstream emissions requires additional CO_2 removal, significantly increasing overall cost (McQueen et al., 2021).

OFFTAKE, FINANCE, AND POLICY

Even when technology and feedstock barriers are surmounted, the higher cost of advanced SAF relative to conventional and HEFA fuels means that successful production does not guarantee economic viability. Instead, a mixture of policy measures and voluntary purchase commitments known as offtake agreements underpin project economics, and these factors are key drivers of investment decisions. To deepen our understanding of the challenges facing advanced fuel projects, we asked respondents to describe their outlook on offtake commitments, construction financing, and policies supporting SAF uptake in each of the three markets assessed.

6 EU regulations state that for RFNBOs and recycled-carbon fuels, the use of CO_2 from fossil fuel combustion to produce electricity will no longer be considered as avoided emissions after 2035; for other uses, the avoided emissions designation lasts until 2040 (Commission Delegated Regulation (EU) 2023/1185, 2023).

Fuel offtake

Offtake agreements, which define the terms for purchasing fuel at a specific price, help ensure producers can sell their product profitably.[7] However, the reliability of these agreements varies. Long-term, binding "take-or-pay" contracts require purchasers to pay for fuel at a negotiated price even if it is not used, so long as the fuel is produced by a specified date and meets previously agreed upon criteria. These types of contracts provide the greatest certainty. Contracts used to help secure debt financing also require that purchasers have a high credit rating and enough financial capital to guarantee purchases. Given that the production costs of advanced fuels exceed those of fossil fuels (International Civil Aviation Organization, 2022), policy measures are a key driver of advanced fuel purchases. For instance, mandates or performance standards may obligate the use of alternative fuels, while other policies may offset costs through subsidies.

Opinions were mixed on whether current policies in any of the three markets are sufficient to guarantee offtake at prices supporting investments in production facilities. Respondents also cited the absence of an established market price for advanced fuels as a driver of offtake uncertainty, noting that without an active market, offtake agreements are the only way to determine the value of future fuel production.

Multiple respondents cited EU mandates as critical for driving offtake, with one respondent noting that mandates in the European Union could enable a "cost plus" pricing model in which fuel is sold at the cost of production plus a margin for the fuel producer, thereby guaranteeing returns. Respondents also noted that EU SAF mandates facilitate a "green premium" (i.e., a higher selling price for low-carbon fuels compared with fossil) by forcing SAF purchases. However, while the SAF premium is important for the economics of advanced fuel production, respondents cited the uncertain future value of this premium as a risk both to airlines signing long-term contracts and investors in production facilities. Most respondents agreed that some form of government backstop guaranteeing an offtake price, either through regulation or revenue certainty mechanisms such as contract for difference arrangements, could be helpful for the deployment of advanced fuel production facilities.[8]

Respondents noted that offtake agreements are considered important for the financing and construction of production facilities but can also be a source of difficulty. Specifically, offtake agreements are needed to convince investors to finance engineering studies, but airlines are hesitant to make firm commitments to projects at such an early stage. Respondents also assessed that binding agreements entail significant risks to airlines that are not addressed under current policy frameworks. Airline concerns about future market prices and changes to the policy environment were cited as major barriers to obtaining quality offtake agreements, with respondents noting that if high fuel prices are locked in by a binding contract, this can put an airline at a competitive disadvantage. One respondent summarized the issue by noting:

> *The main issues in obtaining offtake agreements is the price uncertainty and the long time frame involved. Airlines are willing to sign offtakes but are uncomfortable committing for so many years. This is understandable. In addition, offtake*

7 Offtake contracts generally do not include the sale of policy credits such as RFS or LCFS credits in the United States or credits derived from Member State RED implementation in the European Union. This means that offtake contracts do not insulate producers from changes in credit values or underlying policies. For a sample contract, see https://www.sec.gov/Archives/edgar/data/1843724/000110465922129481/tm225496d16_ex10-43.htm.

8 A contract for difference offsets the difference between a realized market-determined selling price and the guaranteed "strike price" set out in a long-term contract. This form of revenue certainty mechanism has been used to support investment in low-carbon electricity generation, particularly in the United Kingdom. See UK Department for Transport (2024a) for a discussion of contract for difference mechanics.

agreements are new and vary greatly from how airlines currently purchase fuel. There is a learning curve for all stakeholders.

Finance

The majority of respondents indicated that high capital costs are the greatest barrier to facility deployment, highlighting the importance of access to financial capital. For capital-intensive projects, the cost of capital (i.e., the rate of return required by investors) significantly impacts production costs (Brown et al., 2020). High capital costs also increase risk; large upfront investments and longer payback periods increase exposure to changing market and policy conditions over a facility's lifetime.

This contrasts with HEFA SAF production, which is dominated by feedstock costs and often requires only modest capital expenditures to modify existing facilities (Rosales Calderon et al., 2024). Respondents highlighted that growing investments in HEFA capacity should not be taken as evidence that financing is readily available for advanced SAF projects. Instead, respondents indicated that securing capital for advanced fuel facilities remains challenging and often requires assembling funds from diverse sources. In describing these sources, a respondent noted:

Many different entities make up the capital stack. Each one is needed for different stages of the project. In the initial stages (feasibility study and initial engineering) government and public funding is crucial. Once proof of concept through a pilot plant is achieved, offtake contracts and funding from organizations such as Breakthrough Energy are critical. Once a financial investment decision has been made, investors for the capital markets are needed. This can be supplemented by contributions from technological partners. Governments have a role to play in all stages through policies such as incentives, mandates and de-risking mechanisms.

Financing facility design and construction poses significant challenges at two key stages, according to respondents. The first is securing funding for FEED studies, described by one as a "valley of death" for projects. Advanced fuel technologies are not yet widely deployed, meaning total construction costs are uncertain until a FEED study is completed. This uncertainty makes investors hesitant to take on the risk, and government support for FEED studies is limited. One respondent highlighted this dilemma: "To get funding for a capital project, we must complete a FEED study, but to complete a FEED study, we need funding." They suggested that government policies to mitigate the risk of unsuccessful FEED studies could help address this situation.

Multiple respondents offered estimates of costs prior to a final investment decision, with one estimating costs between $40 and $70 million and another citing expenditures exceeding $30 million for the FEED study and other planning efforts. One respondent cited the backing of an established energy company as essential to financing the pre-construction stage of a project. This respondent also noted that equipment procurement and construction providers, which contribute to FEED studies and take on substantial risk when committing resources to a project, are more comfortable partnering with companies experienced in oil and gas project development.

Respondents indicated that even after a FEED study has been completed, achieving a final investment decision to begin construction is extremely challenging. Inherent to this challenge is balancing risk between stakeholders, such that a project is bankable from a financing perspective. As one respondent stated:

Most important in the process for projects of scale: infrastructure funds and debt guarantee providers. These investors have a low appetite for risk and the energy transition is inherently new and riskier. Policy ambiguity and the market doubt that *mandates will remain in place increases risk profile of projects. Recent evidence: removal of biodiesel mandate in Sweden.*[9]

In addition to policy risk, an inability to satisfactorily mitigate technology and offtake risk was also cited as a barrier to construction financing. Respondents noted that, in many cases, equipment procurement and construction providers are unwilling or unable to financially backstop the performance of nascent technologies, exposing debt providers to the risk of technology failure or underperformance. Additionally, as previously described, offtakers such as airlines may be unwilling to commit to binding long-term contracts that might lock in above-market fuel prices, but without these contracts facility construction cannot be financed.

We also surveyed respondents on which policy mechanisms most effectively provide the financial confidence needed to enable the construction of first-of-a-kind or pilot facilities unable to compete in commodity fuel markets. Respondents noted that grants and government tenders are likely to be most reliable, but that other mechanisms may be effective given the right conditions. In particular, respondents noted that mandates or revenue certainty mechanisms can be successful in driving this type of investment if they include narrowly cast advanced fuel targets or sub-targets. In contrast, technology-neutral policies like the California LCFS, which incentivizes many types of fuel in multiple sectors, were seen as poorly suited to driving investment in pilot facilities. Respondents also pointed to impact-focused investment programs such as Breakthrough Energy Catalyst as enabling the construction of pilot projects.

Policy

Our survey also queried respondents on whether current SAF policies are sufficient to drive the deployment of advanced aviation fuel production facilities. Respondents were asked to comment on the impact of specific SAF policies in each market and whether policy uncertainty or ambiguity is hindering investments. We also asked respondents to rank the usefulness of different policy types such as mandates and tax credits in supporting investment.

Regarding the overall policy environment, respondents were unanimous in citing the ReFuelEU Aviation SAF mandate as critical to driving investments in advanced fuel production capacity in Europe, especially for fuels qualifying for the synthetic fuel sub-mandate. This was attributed to the growing demand created by the mandate, which ensures a market for SAF through 2050. In contrast, tax credits and the opt-in inclusion of SAF in U.S. fuel policies, while welcomed, were considered less effective at driving investments in fuel facilities because these mechanisms do not guarantee future demand. Respondents suggested that a combined mandate and revenue certainty mechanism in the United Kingdom could be very effective at driving investment. However, they noted that investors would likely disregard these policies until they are formally adopted.

European Union

Respondents noted that while ReFuelEU ensures a future market for SAF, uncertainty about the price of advanced fuel in this market makes it difficult to secure binding offtake agreements and debt financing for construction. The availability of first-generation SAF produced using HEFA technology contributes to this uncertainty; if overall ReFuelEU-mandated volumes can be met by lower-cost HEFA SAF, then the market for advanced fuels outside the synthetic SAF sub-mandate will be limited. Some

9 Infrastructure funds are used to finance durable assets in sectors such as energy, electricity, telecommunications, and waste management. Debt guarantee providers offer financial protection against project risks, for example by guaranteeing that a contractor will perform the work as specified. If the contractor fails to do so, the debt guarantee provider would compensate the project owner.

also observed that in the absence of subsidies or incentives it is likely that fuel needed to meet ReFuelEU volumes can be produced at a lower cost outside the European Union, creating further uncertainty for investors in European SAF facilities.

Even in the case of e-fuels qualifying for the synthetic fuel sub-mandate, one respondent expressed that offtakers are not currently motivated to commit to large volumes of e-fuel offtake at a price that supports production. According to this respondent, incumbent fossil jet fuel suppliers who must meet ReFuelEU blending levels or face penalties have expressed a belief that the synthetic fuel sub-mandate will be revised downwards in response to an absence of e-fuel production; in their experience, suppliers are also unwilling to commit to purchasing fuel unless a "one-to-one" contract is in place that guarantees subsequent purchase of the fuel by an end user such as an airline. The respondent noted that additional measures to incentivize obligated suppliers to engage with advanced fuel producers in anticipation of the synthetic fuel sub-mandate going into effect could be very helpful to e-fuel producers. This respondent also noted that although the European Union has set aside allowances from the ETS to help airlines cover the price gap between conventional and low-carbon fuels, these allowances will likely be used up by HEFA SAF production, and as a result will not be helpful in establishing revenue certainty for advanced SAF producers (Sandford & Malins, 2025).

Multiple respondents expressed that EU requirements for fuel feedstocks, including carbon and electricity, are complex and sometimes ambiguous, creating a situation in which each potential feedstock source has to be carefully evaluated for compliance. One respondent noted that an inability to confirm eligibility prior to a facility becoming operational is a barrier to investment. Respondents also noted that the 2041 cutoff for non-biogenic point source CO_2 will prevent these sources from being used in fuel production, as the expected production lifetime of facilities entering construction in the next few years will extend beyond this deadline. In contrast to other views, one respondent reported that "we see EU policy as written today as favorable because it includes robust detail on feedstock and power sourcing scenarios."

United Kingdom

Limited comments were received on UK policies but, in general, respondents were optimistic about the coupling of mandates and a revenue certainty mechanism as envisioned in the Jet Zero proposal. Respondents suggested that this combination, insofar as it would guarantee both a market and a clearing price for fuels, could be very effective in enabling facility deployment. As described in the introduction, the SAF mandate has since gone into effect and the implementation of the revenue certainty mechanism is set for 2026.

Commenting on potential deficiencies in UK policies, one respondent expressed concerns that demand for the non-HEFA, non-PtL advanced fuels required under the policy in the near term could be insufficient to provide the offtake certainty for projects of this type. Another respondent expressed that the proposed PtL buyout price, which is the price that obligated parties could pay in lieu of meeting the mandate, may be lower than the domestic cost of e-kerosene production, which they largely attributed to the high cost of electricity stemming in part from high transmission and distribution charges.[10] Respondents noted the importance of the Advanced Fuel Fund in attracting interest in project development within the United Kingdom and advancing those projects that have received funding.

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10 The PtL buyout price is £5 per liter.

United States

In the United States, the lack of a mandate guaranteeing future SAF demand was cited as a significant barrier to investment. One respondent noted that under the current framework it will only be possible to assess the market for advanced fuels purchases once the supply of lower-cost HEFA SAF has been exhausted. The respondent also noted that while, in their view, the intention of IRA tax credits is to support nascent technologies, the inability to guarantee eligibility prior to a final investment decision and the impending expiration of 45Z credits in 2028 make IRA support more useful to producers using established technologies. In their opinion, these credits have not been effective at improving the bankability of advanced fuel facilities.

Respondents noted that the performance-based structure of the California LCFS, which rewards greater GHG reductions, is helpful for advanced fuels, but that the inclusion of multiple sectors (i.e., both road and aviation fuels) within a single policy is detrimental to the market confidence required by investors. One producer also noted that, in their experience, lenders assign zero value to LCFS and RFS credits when evaluating the cashflows of advanced fuel projects.

The 45V hydrogen and 45Q e-fuels tax credits in the IRA were cited as extremely important for driving e-fuel investments within the United States. Respondents viewed the ability to lock in 10 to 12 years of credit eligibility when beginning construction as more effective than the annually applied 45Z fuels credits. Nevertheless, several respondents noted that uncertainty about the final rules for 45V has made it difficult for projects to move forward.[11] One respondent also noted that the greater credit value for sequestration rather than utilization of CO_2 in 45Q credits is a barrier to fuel producers incorporating point source CO_2 into projects.[12]

Respondents also noted that while grants and loans from the Department of Energy and other agencies have been critical to the development of individual projects, these programs are limited and will be unable to support a widespread buildout of advanced fuel production capacity.

11 45V rules were finalized in January 2025. In July 2025, legislation was enacted discontinuing 45V credits for projects entering construction after December 2027 (One Big Beautiful Bill Act, 2025).

12 At the time of the survey, 45Q credits for point source capture were $85 per ton for sequestration and $60 per ton for use. DAC credits were $180 and $130 per ton, respectively. Legislation enacted in July 2025 made the value of utilization credits equal to that of sequestration credits (One Big Beautiful Bill Act, 2025).

DISCUSSION

Based on the survey responses, issues related to high capital costs, first-of-a-kind technology deployment, and offtake uncertainty may have been partially mitigated by policy and technology developments over the last decade but have not been fully eliminated. What follows is a review of these barriers, a possible framework to address them, and market-specific policy considerations.

HIGH CAPITAL COSTS

The high capital costs for the construction of advanced fuel facilities were cited as the most important overall barrier by respondents. These high costs also imply that the cost of producing advanced fuel will likely exceed that of fossil jet fuel for facilities built within the next 5 to 10 years. This is consistent with estimates that current ATJ production costs are approximately 3 to 4 times higher than fossil jet fuel (Adamson et al., 2024), while e-kerosene costs are 4 to 6 times higher (International Energy Agency, 2024; Zhou et al., 2022). The European Aviation Safety Agency (2025) has estimated average synthetic aviation fuel costs at €7,695 per tonne and advanced biofuels at €2,715 compared with only €734 per tonne for conventional jet fuel.

Respondents also assessed that a carbon price alone would not drive the use of advanced fuels in the near term, as the required price would far exceed the historical and expected per-ton value of CO_2 under programs like the EU ETS (BloombergNEF, 2024); at the current ETS price of €65, the total penalty for conventional jet fuel emissions would be €250 per tonne of fuel.[13] Instead, measures requiring the use of advanced fuels would be needed to justify investments in production. Based on the responses we received, such measures could include the creation of ring-fenced markets ensuring demand and isolating advanced SAFs from direct competition with fossil jet and lower-cost first-generation SAFs.

High capital costs also mean risk-averse debt financing is generally needed for facility construction, and respondents identified risk mitigation as a significant gap in current policies. At present, the level of risk associated with financing advanced fuel production plants is unacceptable to debt capital providers. One respondent summarized the issue, stating,

> *The industry understands the difference between a balance sheet (i.e., equity investor) financed project and a project (i.e., debt) financed project, but the policies do not seem to align. What seems to be lost in policy conversations is the risk mitigation that is required from offtakers and investors to finance a project.*

This emphasis on risk mitigation was echoed by others, who noted that attracting debt financing for advanced SAF plants requires a risk-reward profile that competes favorably with alternatives like renewable power projects. To address this challenge, respondents suggested that policy adjustments will be needed to reduce risk and make advanced fuel projects more appealing to providers of debt capital.

FIRST-OF-A-KIND TECHNOLOGY DEPLOYMENT

Despite technological progress, advanced fuel facilities remain unproven at scale, raising additional barriers to facility deployment. For example, accurately estimating the final cost of fuel production requires a detailed and expensive FEED study. This creates a risk to early investors that an initially promising project may prove uneconomical. Respondents emphasized that the high cost and difficulty of funding FEED studies often prevent projects from moving forward. The unwillingness of

13 This value assumes the ETS is applied to well-to-wake emissions of 89 g CO_2e/MJ.

equipment procurement and construction providers to guarantee construction cost and performance for unfamiliar technologies was also cited as a significant barrier.

Experience has also shown that construction, permitting, and ramp-up times at first-of-a-kind projects are often longer than expected (Rubin et al., 2021), which likely contributes to the perception among investors that advanced SAF projects carry significant risk. Taken together, while the technologies underlying advanced fuel production are sound, the challenge of engineering a cost-effective commercial-scale facility should not be discounted. For this reason, the continued application of programs such as the UK Advanced Fuels Fund (UK Department for Transport, 2024a) and the U.S. Federal Aviation Administration's Fueling Aviation's Sustainable Transition grants (U.S. Department of Transportation, 2024), which offset the cost of project development, may be required until more experience is gained with construction and operation of advanced fuel facilities.

Another possible risk to the progress of advanced fuel technologies is the concentration of capacity in a few very large projects that seek to immediately scale today's technology by several orders of magnitude. For both PtL and gasification, respondents expressed that the most likely cause of project failure would be construction of excessively large facilities without intermediate scale technology validation. These concerns echo the history of cellulosic ethanol, in which "insufficient experience with the technology at a medium scale…that would uncover technical glitches associated with scale up from demonstration plants, and allow for learning by doing and innovation" was cited among the key factors hindering development of this technology in a National Center for Sustainable Transportation study (Witcover, 2021). We can conclude that policy frameworks that inadvertently favor the construction of a few very large facilities carry greater risk, as large projects are more likely to encounter unforeseen challenges and costly delays than facilities operating at a modest commercial scale.

OFFTAKE AND PRICE UNCERTAINTY

Although mandates in the European Union and United Kingdom may ensure future demand for SAF, uncertainty about the market price of advanced fuel remains a critical barrier to investment. This issue is reflected in our survey and in recent setbacks to advanced fuel projects. As described by respondents, obtaining binding, creditworthy offtake agreements at prices supporting project economics is particularly challenging, but without these agreements, most projects will not move forward. The cancellation of the FlagshipONE e-fuels project after a positive final investment decision due to a lack of offtake demand (Parkes, 2024) and Shell's withdrawal from the HySkies e-SAF facility (Vattenfall, 2024) despite an award from the EU Innovation Fund underscore this point. These cases highlight that current policies are likely insufficient to secure binding commitments from fuel users.

Additionally, as noted by respondents, offtake agreements with airlines can have two critical flaws. First, the risk that the market price for mandated eligible fuel drops below the cost of production at pioneering facilities is not eliminated by offtake contracts, but rather transferred to airlines. Airlines signing these agreements are subject to the possibility of a first-mover disadvantage: For instance, if an airline commits to buying SAF at $6 per gallon through an offtake agreement but the market price of SAF drops to $5.50 per gallon, the airline is locked into a higher price compared with what is paid by competitors. As described by one respondent, "the biggest fear of airlines is to be put at a competitive disadvantage if they pay a green premium and other airlines do not." This risk creates a strong disincentive for airlines to sign binding contracts.

Second, respondents noted that, from the perspective of financial institutions, airlines are not always regarded as creditworthy counterparties due to the volatility of the aviation industry. This means that even a binding "take-or-pay" offtake agreement may not be sufficient to secure debt financing. Without price certainty outside the context of an offtake agreement there is a concern from financiers that fuel produced at a high cost may not find alternative buyers. In this case, a project would not be able to cover the debt used to finance its construction. The risk of such an unrecoverable loss is unacceptable to providers of debt capital, but an advanced fuel market could solve this issue. As described by one respondent, "once we have a market price, then the need for individual offtake contracts is eliminated."

A FRAMEWORK FOR PROGRESS

Addressing revenue uncertainty and establishing a guaranteed and growing market for advanced SAF could help to overcome the barriers cited by our survey respondents. A two-phase approach—consisting of a "runway" focused on technology de-risking and the establishment of a robust market for advanced fuels followed by a "takeoff" characterized by the continued deployment of sustainable low-carbon fuel capacity—could place the aviation sector on a stable trajectory towards decarbonization. Figure 1 outline the goals of this framework.

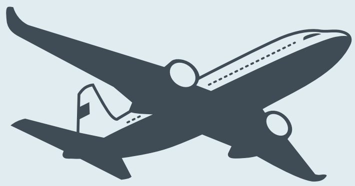
Figure 1
Proposed advanced SAF policy framework

RUNWAY

Advanced SAF revenue certainty

- Enables debt financing of facility construction
- De-risks technologies
- Allows for price discovery
- Ensures initial advanced fuel targets can be met

TAKEOFF



Long-term SAF mandate

- Provides certainty to all stakeholders
- Enables market-led expansion of capacity
- Supports in-sector financing of decarbonization
- Maintains environmental integrity

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Phase I: Runway revenue certainty mechanism

A revenue certainty mechanism could be used to establish offtake price certainty at the earliest possible stage of project development, enabling access to the development and debt capital needed to fund an initial wave of advanced fuel facilities. As described above, under the current policy framework, uncertainty about the future price of advanced fuels is preventing project developers from securing funding and achieving positive final investment decisions. Multiple respondents pointed to a revenue certainty mechanism as a straightforward way to reduce the financial risks for all parties engaged in advanced fuel project deployment.

This finding is consistent with the results of a consultation by the UK Department for Transport (New, 2023; Rigby, 2021), which determined that a revenue certainty mechanism guaranteeing offtake at a predetermined price would be the most effective policy option for promoting advanced SAF production within the United Kingdom. The Department for Transport (2024c) later conducted a detailed exploration of possible revenue certainty frameworks, laying the groundwork for the development of these policies within the sector. As noted above, the UK revenue certainty mechanism is scheduled to take effect in 2026.

The success of a revenue certainty mechanism can be measured by the degree to which two outcomes are achieved. The first is whether it enables the demonstration of advanced fuel technologies at a commercial scale, lowering the cost of future facilities through gains in experience while mitigating technology risk. The second is whether it allows a sufficient volume of advanced fuel production to become available for purchase such that real-world production costs can be determined and a market for fuel is established, enabling price discovery. This is of particular importance when advanced fuel mandates, such as the RefuelEU synthetic SAF sub-mandate, are accompanied by significant penalties for non-compliance. If these fuels are not produced and a market is not established, it is possible that the enforcement of sub-mandate non-compliance penalties becomes politically challenging. One respondent stated that at least one major fuel provider has privately expressed confidence that the RefuelEU synthetic fuel sub-mandate will be eliminated for this reason.

To maximize the benefits of a runway revenue certainty mechanism, policymakers may consider a few key elements:

» **Limited scope**: To enable a smooth transition to private sector-led growth, the revenue certainty mechanism can be sized such that a “first-wave” of technology deployment can occur without long-term industry reliance on prices guaranteed by the government; designing the program to support a transition to market pricing can help to avoid such reliance.

» **Cap on the size of eligible facilities**: This can assist in maximizing technological progress while avoiding costly failures.[14]

» **Polluter pays**: Financial support for the program can be derived from penalties levied on the supply of fossil jet fuel. Given the limited scale of advanced fuel production relative to fossil jet consumption, modest penalties on fossil jet fuel could provide revenue certainty for each gallon of advanced fuel produced under the runway program.

» **Require proof of scalability**: Limiting eligibility to technologies that demonstrate a feasible pathway to sustainable large-scale production could ensure that the revenue certainty mechanism enables future growth. Criteria to be considered include feedstock availability and evidence that cost can be reduced through technological improvements.

Phase II: Takeoff of the advanced SAF market

The goal of the takeoff phase is to ensure growing demand for advanced low-carbon SAF consistent with aviation decarbonization roadmaps, as well as to create the conditions necessary for continued deployment of advanced fuel projects. Important to this outcome is ensuring that advanced fuels projects maintain bankability, enabling access to low-cost debt financing for facility construction. This will require the establishment of a market for advanced SAF such that the value of the fuel is not tied to specific offtake contracts.

14 For example, a 150 kilotonne per year cap on revenue certainty mechanism-supported SAF at a single facility could ensure that multiple facilities would be needed to meet 2035 synthetic SAF sub-mandate for the combined EU and UK market.

A mandate requiring the use of advanced SAF at an increasing rate or an equivalent mechanism guaranteeing demand can signal that growing volumes of advanced SAF will be required, which is a baseline condition for continued investment in SAF facilities. Complementary demand-side measures can include policies to encourage the involvement of stakeholders who are necessary for the development of advanced fuel projects but for whom such projects may not be a primary focus. For example, tax relief targeted at debt providers financing advanced fuel projects or grants to equipment procurement and construction providers for expenses related to working on new technologies might encourage participation in advanced fuel projects. Meanwhile, proceeds from the application of carbon pricing mechanisms such as the ETS to aviation emissions can continue to support cutting-edge advanced fuel technologies.

We note that robust life-cycle assessment and sustainability rules can protect the environmental integrity of SAF production, encourage public confidence in SAF policies, and help to create a reliable environment for investment. Without stable rules, investors cannot be certain of which pathways deserve investment and which should be avoided. Overly permissive rules that are later tightened risk souring investor support for the deployment of policy-dependent infrastructure. Conversely, the perception that safeguards may be removed in the future can delay investments in high-quality projects, lest competitors subsequently take advantage of looser regulations.

Based on the responses we received, achieving a stable growth trajectory for low-carbon SAF will likely require the following policy ingredients:

- **Mandates or other demand-side mechanisms** supporting predictable, structural increases in advanced SAF demand.
- **Stringent but transparent life-cycle assessment and sustainability criteria** for mandate-eligible fuel production that can be relied upon by project developers at early stages of project conception.
- **Stringent penalties for non-compliance**, particularly on fossil fuel providers. The enforcement of such measures can serve to encourage strategic investments by current industry participants.
- **A balance of carrots and sticks** to maintain alignment between the interests of critical stakeholders (e.g., airlines, equipment procurement and construction providers, financiers, and incumbent fuel providers) and continued facility deployment.

MARKET-SPECIFIC CONSIDERATIONS

Based on this framework, the market-specific responses we received from industry officials, and the ICCT's prior work on aviation decarbonization, this section presents policy considerations specific to each market aimed at facilitating the achievement of SAF deployment targets.

UNITED KINGDOM

Among the three markets addressed in this report, the United Kingdom—with its combination of a revenue certainty mechanism and SAF mandate—is most aligned with the policy framework outlined above (UK Department for Transport & Haigh, 2024). This is unsurprising, as the UK government solicited extensive industry feedback in designing its policies. Consultant reports commissioned by the UK Department for Transport (Rigby, 2021; New, 2023) have pointed to a revenue certainty mechanism as key to enabling debt financing of SAF facilities and noted the potential synergy between such a mechanism and a mandate for SAF utilization.

While expressing optimism that policies proposed in the United Kingdom would be effective in spurring the deployment of advanced fuels projects, survey respondents also emphasized that, until UK SAF policies are enacted in law, the outlook for investment would remain uncertain. After the completion of the survey, the UK SAF Mandate was adopted by Parliament and is now binding (The Renewable Transport Fuel Obligations (Sustainable Aviation Fuel) Order 2024, 2024). Efforts to design the revenue certainty mechanism have also moved forward and the Department for Transport (2025a) expects all required legislation to be in place by the end of 2026. The revenue certainty mechanism will be funded through a levy on fossil jet fuel suppliers (UK Department for Transport, 2025b).

For PtL fuels, respondents expressed concern that the buyout price is too low to encourage domestic production, particularly given the high cost of electricity within the United Kingdom. In the absence of this production, either large-scale buyout or PtL imports would be required. While proposed reforms to the UK electricity market (UK Department for Energy Security and Net Zero, 2022) could lower the cost of renewable power in some regions of the country, targeted measures might be required to ensure the viability of projects currently under development. The Department for Transport's (2025b) recent consultation response acknowledges this challenge and promises future engagement with stakeholders on this issue.

Based on the feedback to our survey, UK policymakers could consider:

- **Implementing a revenue certainty mechanism as soon as feasible.** This would complement the significant momentum generated via the Advanced Fuels Fund for domestic advanced SAF production within the United Kingdom. A key theme from the responses to our survey and the reports commissioned in the United Kingdom is the importance of risk-mitigation measures specifically designed to enable debt finance to the construction of advanced SAF facilities. The success of a UK SAF revenue certainty mechanism can be primarily measured by the degree to which it achieves this goal.
- **Improving access to low-cost renewable electricity to enable domestic PtL SAF production**. Power prices are the largest overall determinant of PtL production costs. It is apparent both from the responses we received and from UK consultant reports that the high delivered cost of renewables is a significant barrier to the viability of this pathway within the United Kingdom. Under current electricity prices, the PtL buyout price may be too low to support domestic production, a situation that could be addressed with targeted measures prior to electricity market reforms.

EUROPEAN UNION

Based on our survey, the ReFuelEU SAF mandate has served as an effective signal that a regulated market for advanced fuels will exist within the European Union. Nevertheless, the feedback we received indicated that current EU measures do not fully address challenges faced by first-mover facilities, which will necessarily produce fuels at a high cost for a market that does not yet exist. Specifically, the ReFuelEU SAF mandate is not considered sufficient to establish the bankability of advanced SAF projects.

ETS allowances intended to bridge the cost gap between fossil fuels and SAF (DG CLIMA B.4 & European Commission, 2023) have so far fallen short of enabling the binding offtake agreements required for investment. This may partly reflect a timing issue; under ordinary circumstances, a FEED study might be initiated 5 years before the start of fuel production, (Rahbar & Avalon, n.d.), but under the current framework, ETS aviation allowances can only be claimed by airlines after the purchase and uplift of fuel. Respondents noted that the finite number of allowances allocated on a first-come, first-served basis creates a situation in which these credits may be exhausted by HEFA SAF use before advanced SAF production can be brought online. Thus, the current system is not well aligned with project development timelines, making producers unlikely to consider ETS allowances for SAF when assessing project economics.

To resolve this dilemma and support initial advanced fuel facilities, EU policymakers could consider developing a revenue certainty mechanism, potentially supported by a further allocation of ETS allowances. Under this framework, long-term fixed-price contracts with a government-backed entity could allow qualifying advanced SAF facilities to guarantee offtake at a set price prior to taking final investment decisions. The produced SAF would then be available for purchase under shorter-term contracts. If the short-term market price were to fall below the guaranteed long-term offtake price, revenue from the sale of ETS allowances to fossil jet users could be used to cover the gap. This would ensure that funding for the revenue certainty mechanism is contained within the aviation sector. For maximum effect, it is important that projects be able to establish revenue certainty mechanism eligibility at an early stage of development; an auction could be helpful for determining which projects receive revenue certainty contracts (Lambert et al., 2024).

Based on the feedback we received, a revenue certainty mechanism is also likely to be more effective than a Hydrogen Bank-style mechanism, where producers bid for subsidies that only partially cover the cost of production (European Commission, 2023). The more limited guarantee offered by the Hydrogen Bank is considered disadvantageous for three reasons:

1. Because winning the Hydrogen Bank auction requires bidding for a smaller subsidy than competitors, there is a danger that producers bid for subsidy values that are too small to guarantee project economics. In this case, auction winners may ultimately fail to achieve a final investment decision, a concern expressed by some market analysts (Lambert et al., 2024). The withdrawal of one of the initial Hydrogen Bank winners just months after the pilot auction illustrates this risk (Collins, 2024).
2. Hydrogen Bank-style subsidies do not eliminate the need for binding long-term offtake contracts with fuel users, a key barrier identified by respondents, because only a portion of the overall cost of fuel production is covered by the subsidy. Although such subsidies can improve project economics, the price risks faced by offtakers are not eliminated, so securing these contracts may still be difficult.

3. Due to the prevailing need for long-term offtake contracts, fuel supported by Hydrogen Bank-style subsidies would likely not be available for purchase via short-term contracts, delaying the establishment of a market price for advanced SAF. As noted above, a market price for mandate-eligible advanced fuels is essential for the subsequent takeoff phase of advanced SAF deployment. For this reason, a revenue certainty mechanism that does not require long-term contracts with fuel users is preferable.

For projects currently in development, time is of the essence (Project SkyPower, 2024; Transport & Environment, 2024). If the implementation of a revenue certainty mechanism within 1 to 2 years is infeasible, other stopgap measures may be applied to help make SAF available to meet the synthetic fuel sub-mandate in 2030. One option would be to open a round of Innovation Fund support specifically for advanced or synthetic SAF to help ensure that some portion of the facilities now in development reach a positive final investment decision and begin construction.

Based on the feedback from our survey, EU policymakers could consider:

- **Establishing a revenue certainty mechanism for an initial wave of advanced fuel projects,** with a focus on projects contributing to meeting the ReFuelEU synthetic fuel sub-mandate. Under current policies, it is apparent that the offtake price certainty required to take a final investment decision for advanced fuel projects has not been established, creating a risk that compliant fuel will not be available to meet the 2030 sub-mandate. Quickly establishing an advanced fuel revenue certainty mechanism could avoid this outcome.
- **Leveraging the ETS to support a revenue certainty mechanism.** Aviation ETS credit obligations can serve as an in-sector source of funding to support advanced SAF projects. Better alignment between the allocation of allowances and the development timelines for SAF projects could greatly improve the effectiveness of SAF ETS allowances in meeting ReFuelEU requirements.
- **Enacting measures to support a favorable risk-reward proposition for stakeholders involved in advanced fuel deployment**. As noted by respondents, the risk-reward calculus of critical stakeholders such as equipment procurement and construction providers, project financiers, airlines, and feedstock providers is not always favorable to the construction of advanced fuel facilities. Policies such as tax breaks connected to work on ReFuelEU-eligible projects could lead to greater stakeholder interest in advanced fuel projects. To maintain in-sector funding and revenue neutrality, these tax incentives could be offset by fossil jet fuel taxes.
- **Reaffirming the synthetic fuel sub-mandate and disclosing details on penalty administration.** Incumbent jet fuel providers are the obligated parties under ReFuelEU. These companies also have significant financial capacity and expertise in project development but have so far committed only limited resources to the deployment of advanced fuel facilities. A clear signal that the legislated ReFuelEU synthetic fuel sub-mandate will not be removed following the 2027 impact assessment could motivate obligated fuel providers to secure access to qualifying synthetic fuels rather than face penalties. Disclosure of penalty administration details by Member States would likewise ensure that obligated parties account for these penalties in their corporate strategies.

UNITED STATES

Based on the responses we received, while the combination of incentives and programs offered under the IRA and Department of Energy may be sufficient to enable a limited buildout of advanced fuel facilities, the absence of policies intended to ensure future demand for low-carbon SAF is a significant barrier to achieving the production growth outlined in the SAF Grand Challenge. Current SAF policies in the United States are most applicable to production using more established but supply-limited HEFA technology, which requires significantly less upfront investment. To remedy this situation, a long-term aviation fuel policy along the lines of ReFuelEU or the UK SAF mandate would likely be required.

Existing road-sector fuel policies in the United States can offer useful templates. One possibility is an aviation-specific LCFS implemented at the federal level requiring a continuously decreasing overall carbon intensity for aviation fuel used within the country. Previous ICCT research has shown that a national aviation LCFS could drive significant demand for advanced fuels under scenarios in which elevated credit values and tax incentives offset the high costs of fuel production (Pavlenko & Zheng, 2024).

However, the responses analyzed in this paper raise doubts about whether these measures would enable debt financing for SAF projects. Specifically, the unpredictability of future LCFS credit prices and vulnerability of tax credits to changing political priorities could hinder projects from achieving the offtake price certainty needed to secure debt financing. And while advanced fuel projects currently under development in the United States have been able to attract significant equity investment (Infinium, 2024; Twelve Catalyst, 2024), it is generally understood that the total pool of capital available for impact-focused “catalytic capital” and large ($200 million or greater) equity investments is limited (Cohen & Yeh, 2024).

To enable debt financing, a runway-style revenue certainty mechanism could be incorporated into an aviation LCFS. This mechanism could serve not only to offset the additional cost of advanced SAF production but also to reduce the “certainty gap” created by a mismatch between the unpredictable value of SAF credits and the price certainty required for debt financing. Funding for the program could come from a pool of credits set aside for that purpose, and access to the revenue certainty mechanism could be limited to advanced SAF projects entering operation before a certain date. While the sale of set-aside credits could be used to fund this mechanism, it would be preferable for the mechanism to guarantee a fixed offtake price to producers that does not depend on the current market value of credits.

As an alternative to an aviation LCFS, binding SAF obligations like those employed in the European Union could be also considered. This approach would be similar to that of the RFS, which sets mandatory targets for biofuel supplied to the road sector. If this style of policy is considered, it would be critical not to repeat the mistakes of the RFS program, which was unable to achieve the expected deployment of advanced biofuel and cellulosic ethanol production capacity (Witcover, 2021). In particular, establishing realistic but stable targets for advanced fuels may send a more effective policy signal than an ambitious mandate that is revised downward, as occurred under the RFS (U.S. Energy Information Administration, 2018). As with an aviation LCFS, a revenue certainty mechanism could be incorporated into an RFS-style mandate. To fund this mechanism, a pool of advanced fuel credits could be set aside and sold to meet the blending obligations of fossil jet providers. Incorporating this mechanism from the outset could help ensure that initial advanced fuel volume targets are met.

Based on the feedback from our survey, U.S. policymakers could consider:

» **Establishing a national SAF policy that ensures growing demand for advanced SAF in line with SAF Grand Challenge targets.** Based on the results of our survey, policies that create long-term demand certainty are likely to be most effective in stimulating the continuous deployment of advanced fuel facilities. Establishing either a national aviation LCFS or a long-term mandate for SAF utilization could provide the demand certainty to underpin investments in advanced SAF.

- **Including HEFA caps and/or synthetic fuel sub-mandates under a potential SAF mandate.** Such measures in the United Kingdom and European Union were put in place to avoid HEFA being the only fuel purchased to meet SAF mandates. To enable advanced fuel deployment in the United States, a similar measure will likely be required.
- **Establishing a revenue certainty mechanism aligned with the runway framework presented above,** possibly funded through the aggregation of credit purchase obligations generated by fossil jet fuel consumption. The absence of a market price for advanced fuel offtake is a critical barrier to attracting financing, but price discovery cannot take place without supply. Pooling credits under a national LCFS or an alternative aviation decarbonization policy to fund a revenue certainty mechanism could enable investments in advanced fuel facilities that would otherwise be considered too risky due to credit and fuel price uncertainty.
- **Prioritizing moderate-scale commercial facilities employing technologies with the possibility of future cost reductions.** As described by respondents, the risk of technological failure is elevated for projects attempting to deploy nascent technologies at an excessive scale.

CONCLUSIONS

Based on the responses to our survey, while mandates in the European Union and the United Kingdom and subsidies in the United States have generated significant interest in advanced SAF projects, the barriers associated with high capital costs, implementation of emerging technologies, and price uncertainty persist. For developers of pioneering first-of-a-kind advanced SAF facilities, the combination of these obstacles may endanger the ambitious SAF deployment targets set forth by policymakers and the aviation industry.

Addressing these challenges will likely require a two-pronged approach, consisting of a revenue certainty mechanism supporting the initial deployment of advanced SAF facilities coupled with mandates or other policies intended to guarantee long-term growth in demand for low-carbon SAF. Under this framework, once advanced SAF technologies have been proven at scale and a market price for fuel established, demand-side policies should be sufficient to drive a steady expansion of capacity.

Among the markets considered in this study, the United Kingdom, with its SAF mandate and promised revenue certainty mechanism, is currently best aligned with this approach. In contrast, EU support mechanisms may be poorly suited to the challenges facing the developers of pioneering SAF projects, creating a risk that the availability of synthetic SAF in 2030 may be insufficient to meet the ReFuelEU synthetic fuel sub-mandate. The rapid implementation of a revenue certainty mechanism could address this issue. Targeted support for projects currently under development may also be warranted given the limited time before the synthetic fuel sub-mandate goes into effect. Meanwhile, in the United States, an incentives-only approach to SAF policy makes for an uncertain future. To ensure steady advanced SAF deployment in the United States, a national demand-side policy will likely be required.

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