Navigating Early-Stage Barriers to Accelerate Sustainable Aviation Fuel (SAF) Projects

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Synopsis: The increasing efforts to decarbonize the various modes of transport for cargo and commercial flights have had a strong impact in the airline industry. Demand for biokerosene/low carbon kerosene is growing rapidly and airlines are committing to off-take agreements to thereby increase their consumption of Sustainable Aviation Fuel (SAF) as a contribution towards achieving these goals. However, there are challenges that may slow down the deployment of SAF production projects such as but not limited to; technology, location-related factors, resource availability, financing, regulations and others.

1. Introduction: SAF to decarbonize Air Transport

The aviation industry contributes approximately 2-3% of global CO2 emissions and is one of the fastest-growing sources of greenhouse gases. To meet global climate targets, notably those under the Paris Agreement and the International Civil Aviation Organization's (ICAO) decarbonizing air transport is essential.
One of the most promising lever is the development and deployment of Sustainable Aviation Fuel (SAF).

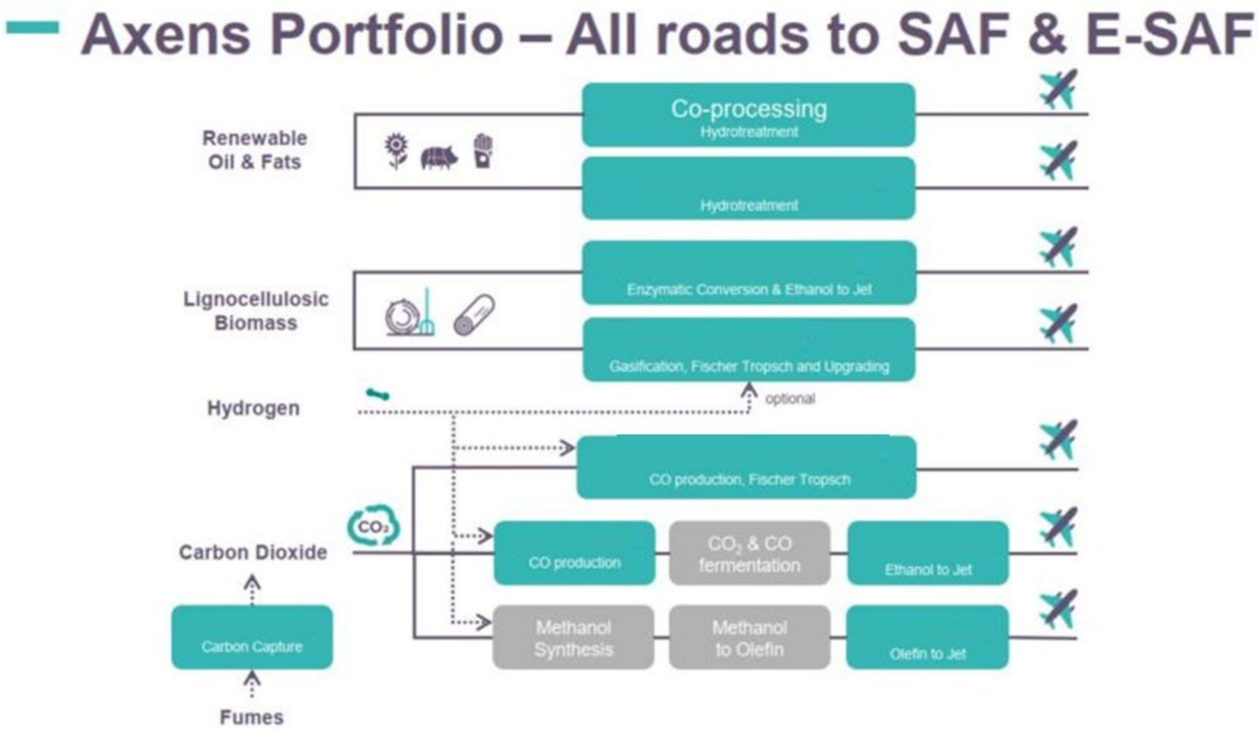
2. SAF: Sustainable Aviation Fuel & So Amazing Fuel

Sustainable Aviation Fuel (SAF) is an advanced type of jet fuel derived from renewable resources and waste materials rather than fossil crude oil. It is designed to reduce the overall carbon footprint of the fuel, a hard to abate sectors due to its reliance on liquid hydrocarbon fuels with high energy density and the long haul flights where electrification is not possible or use of hydrogen is not yet ready.
SAF is a “drop-in” fuel, meaning it can be blended with conventional jet fuel in varying proportions (up to 50% today depending on SAF type, with ongoing research to increase this) without requiring any changes to aircraft engines, fuel infrastructure, or operations. This compatibility makes SAF an immediately deployable solution .
It is produced from a variety of sustainable feedstocks, such as waste oils like used cooking oils, animal fats, agricultural and wood residues, municipal solid waste, captured CO2 combined with low carbon hydrogen and even Algae and other advanced biological resources.
The carbon footprint of the SAF can be reduced by up to 80% or more compared to fossil jet fuel, depending on the feedstock and production pathway. The life cycle analysis is calculated by external parties, which includes emissions from cultivation or collection of raw materials, processing, transportation, and combustion of the final fuel. Besides GHG reductions, SAF also tends to produce fewer particulates and sulfur oxides, contributing to improved air quality near airports.

3. Approved Production Pathways: where we are in 2025?

The production of Sustainable Aviation Fuel involves diverse technological pathways, each leveraging different feedstocks and conversion processes. The selection of a pathway often depends on feedstock availability, technological maturity, economic viability, and desired environmental outcomes. Currently, several key pathways are certified and commercially available or nearing commercialization, with others in earlier stages of development.

Here below are shown the main technology pathways to produce SAF:



3.1. HEFA (Hydroprocessed Esters and Fatty Acids)

<u>Description:</u> HEFA, also known as HVO (Hydrotreated Vegetable Oil) when referring to diesel, is currently the most mature and widely adopted SAF production pathway. It involves the hydroprocessing of waste oils and fats to produce paraffinic hydrocarbons suitable for jet fuel. The process typically includes hydrogenation, isomerization, and hydrocracking steps:
* Hydrogenation: Adds hydrogen to the unsaturated fatty acids to saturate them.
* Isomerization: Rearranges the molecular structure to improve cold flow properties.
* Hydrocracking: Breaks down larger hydrocarbon chains into the desired jet fuel range molecules.

<u>Feedstocks:</u> The primary feedstocks for HEFA are oleaginous materials, including:
* Used Cooking Oil (UCO): A major waste stream suitable for conversion without impacting food systems.
* Animal Fats (Tallow, Poultry Fat): Abundant in the meat industry; high in saturated fats which process well.
* Technical Corn Oil from ethanol production: this residue is not suitable for human consumption.
* Vegetable Oils (Soybean, Rapeseed, Camelina, Jatropha…): Available in large volumes but might become subject to land-use change risks.
* Algal Oils or Other Advanced Lipids (less common in current use)

All feedstocks must comply with sustainability certification schemes (e.g., ISCC, RSB) to qualify for SAF production under international standards.

Advantages:
* High Maturity: The technology is well-established, building on existing hydrotreating capabilities in refineries.
* High Yield: Relatively high conversion efficiency from feedstock to fuel since the amount of carbon of the waste oil is similar to the kerosene / SAF
* Proven Performance: HEFA-SAF has been used in numerous commercial flights, is being traded in the market, and is widely certified (ASTM D7566 Annex A2).
* Significant GHG Reduction: Offers substantial lifecycle GHG reductions (typically 50-80%) vcompared to fossil jet fuel, depending on the specific feedstock.

Challenges:
* Feedstock Availability: The primary limitation is the finite quantity of waste oils and fats. Scaling up significantly beyond current levels could put pressure on food supply chains or lead to indirect land-use change (ILUC) issues.
* Cost: While being the most mature technology, the cost of HEFA-SAF is still significantly higher than fossil jet fuel, largely due to feedstock costs.
* Purity Requirements: Feedstocks need to be pre-treated to remove impurities, adding to process complexity and cost.

3.2 Coprocessing for SAF Production

Among various production pathways, coprocessing stands out for its ability to integrate renewable feedstocks into existing fossil fuel refineries. This approach enables rapid deployment of SAF technologies by leveraging established infrastructure.

Process Description: Coprocessing involves the simultaneous treatment of fossil-based feedstocks and bio-based feedstocks in conventional petroleum refinery units, typically hydrotreaters or hydrocrackers. The blended feed enters a hydrotreatment unit, where it undergoes chemical reactions in the presence of hydrogen and catalysts. These reactions remove heteroatoms (oxygen, sulfur, nitrogen) and adjust hydrocarbon structures to meet jet fuel specifications. The product stream is then fractionated to isolate jet-range hydrocarbons (C8–C16) suitable for aviation use. A portion of this stream, typically up to 5–10%, can be classified as SAF if it meets stringent technical and sustainability standards, such as ASTM D7566 Annex A5, which defines specifications for HEFA-SPK (Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene).

Feedstocks Used in Coprocessing are the same as the one used for HEFA: refer to chapter 3.1 above.

Advantages of Coprocessing: Coprocessing offers several economic, technical, and environmental benefits:
* Use of Existing Infrastructure: Reduces capital expenditure compared to building standalone/grassroot SAF biorefineries.
* Drop-in Compatibility: Produces SAF molecules chemically identical to fossil jet fuel; no aircraft or airport modifications needed.

* Fast Deployment: Allows near-term SAF volumes by retrofitting current assets.
* Carbon Footprint Reduction: Depending on feedstock and hydrogen source, can achieve up to 60–80% lifecycle GHG savings.
* Operational Synergies: Blending with crude can help stabilize process conditions in refinery operations.

Challenges and Limitations: Despite its promise, coprocessing has several constraints that limit its widespread use:
* Blending Limitations: The share of biogenic input is typically capped at 5–10% due to process and certification limits.
*Product Traceability: Once processed, it's difficult to isolate the SAF fraction from the rest of the fuel stream, complicating emissions accounting and regulatory compliance.
* Certification Complexity: Requires detailed mass balance tracking and approval under standards like ASTM D7566, which can be time-consuming.
* Feedstock Variability: Inconsistent feedstock quality or supply can affect refinery operations and fuel properties.
* Hydrogen Source Matters: If fossil hydrogen is used (common in refineries), the carbon footprint of the SAF is higher. Use of low GHG emissions hydrogen (green/renewable hydrogen) is preferred but currently costly.
Role in Global and Regional SAF Strategy: Coprocessing is recognized in international aviation decarbonization roadmaps (e.g., ICAO, IATA) as a transitional SAF pathway, especially valuable in regions with mature refinery infrastructure but limited investment capacity for greenfield biorefineries. In Latin America for example, where countries like Brazil, Argentina, and Colombia have abundant lipid feedstocks and existing refineries, coprocessing offers an effective early-stage solution to SAF deployment, while full-scale HEFA, ATJ, or FT-SPK plants are under development.

Future Outlook: As SAF demand grows, coprocessing may serve as a bridge technology, allowing rapid ramp-up of SAF volumes while more advanced and scalable pathways (e.g., e-SAF, ATJ, FT) mature. Improving the traceability of SAF fractions, increasing the allowable bio-blend ratios, and deploying low-carbon hydrogen will be key to enhancing its impact.

3.3. Alcohol-to-Jet (ATJ)

Description: The Alcohol-to-Jet (ATJ) pathway converts alcohols (ethanol or isobutanol) into jet fuel. The process typically involves dehydration of the alcohol to form olefins, followed by oligomerization (joining smaller molecules to form larger ones) and then hydrogenation to produce paraffinic hydrocarbons/jet fuel blendstock.

Feedstocks: The alcohols used as feedstocks can be produced from:
* Sugar and Starch Crops: (e.g., corn, sugarcane - though sustainability concerns exist due to potential food competition).
* lignoCellulosic Biomass: (e.g., agricultural residues, forestry waste) through biochemical conversion (e.g., fermentation).
* Renewable Electricity + Captured CO2: conversion of Industrial Waste Gases with CO2/CO fermentation into ethanol),

Advantages:
* Feedstock Diversity: Can utilize various bio-alcohols, including those from advanced cellulosic sources, expanding feedstock options.
* Existing Alcohol Production Infrastructure: Leverages some aspects of the mature ethanol production industry.

Challenges:
* Ethanol's Energy Density: Ethanol has lower energy density than hydrocarbons, meaning more feedstock is needed per unit of jet fuel.
* Sustainability of 1st Generation Alcohols: Use of food-competing crops (e.g., corn ethanol) raises sustainability concerns. Focus is on advanced cellulosic alcohols.
* Maturity: Technology bricks are commercial already, taken one by one, but the integration from the ethanol to the SAF still needs to be proven

3.4. FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene)

Description: The Fischer-Tropsch (FT) process is a well-established technology for converting syngas (a mixture of hydrogen and carbon monoxide produced generally from natural gas) into liquid hydrocarbons with commercial plant in operation. For SAF production, syngas shall be produced from non fossil feedstocks, such as biomass gasification, or low carbon CO2 and H2 which is the novelty. Waxes are produced after the Fischer Tropsch reaction, which then needs to be upgraded (e.g., hydrotreating, hydrocracking, isomerization) to meet jet fuel specifications.

Feedstocks: FT-SPK offers significant feedstock flexibility, including:
* Biomass: Agricultural residues, forestry waste, dedicated energy crops.
* Municipal Solid Waste (MSW): Non-recyclable waste.
* Industrial Waste Gases: (e.g., steel mill gases).
* Renewable or low carbon Electricity (Renewable Hydrogen)
* Captured CO2: (as part of Power-to-Liquid, see 3.6).

Advantages:
* Feedstock Flexibility: Can utilize a wide range of abundant feedstocks (ie lignocellulosic biomass) and waste streams.
* High Scalability Potential: The large availability of diverse feedstocks makes it highly scalable in the long term.
* High Carbon Reduction Potential: Can achieve high GHG reductions (60-90% or more), with an even lower carbon footprint by using biogenic CO2 and renewable electricity (ie green H2); when using DAC CO_2 and green H_2, the overall lifecycle emissions of SAF can be significantly reduced or even net-zero.

* Co-production: other valuable products like renewable diesel, naphtha can be produced as co-products.

Challenges:

* Capital Intensive: FT plants require significant upfront capital investment due to the complexity of the gasification and FT synthesis units.
* Operating Costs: Energy intensity and catalyst costs can be high.
* Lower Maturity than HEFA: While the FT process is mature, its application to SAF from diverse biomass/waste feedstocks still needs to be demonstrated at large scale.

3.5 Methanol To Jet (MtJ)

The Methanol-to-Jet (MtJ) process is an emerging route for producing Sustainable Aviation Fuel (SAF) by converting methanol - either derived from renewable sources or from captured carbon - into synthetic hydrocarbons suitable for use in aviation turbines. This pathway belongs to the broader category of power-to-liquid (PtL) or e-fuel technologies when methanol is synthesized from green hydrogen and captured CO_2.

<u>Description:</u> The MtJ process typically consists of three main stages:
1. Methanol Synthesis, from low carbon CO2 and hydrogen sources.
2. Methanol-to-olefins (MTO) conversion, often catalyzed by zeolites.
3. Oligomerization and hydroprocessing, which convert light olefins into longer-chain hydrocarbons in the jet fuel range (C8–C16), followed by isomerization and hydrogenation steps to meet jet fuel specifications.

<u>Feedstocks:</u> The MtJ pathway relies on methanol as an intermediate, which can be produced from the same feedstocks as FT-SPK pathway opresented in the above chapter 3.4.

<u>Advantages:</u> The MtJ pathway offers several important advantages for sustainable aviation:
* Feedstock flexibility: Methanol can be produced from a broad range of renewable sources, including biogenic CO_2, green H_2, biomass, and waste materials.
* Infrastructure compatibility: Existing methanol infrastructure (shipping, storage, handling) can be leveraged, reducing the need for entirely new logistics networks.
* Potential for carbon circularity: Especially when using DAC CO_2 and green H_2, the overall lifecycle emissions of SAF via MtJ can be significantly reduced or even net-zero.

<u>Challenges:</u> Despite its promise, the MtJ pathway still faces several technical, economic, and regulatory challenges:
* Technology maturity: While methanol synthesis and MTO processes are well-known (MTO is already used to produce gasoline for example), the full MtJ chain is not yet commercially deployed at scale for SAF production
* Catalyst development: To be further developed to ensure a selective conversion of methanol to jet-range hydrocarbons
* Capital and operational costs: High capital investment is needed for integrated MtJ facilities, particularly when green hydrogen is used.

3.6. Use of Hydrogen with CO2 (Power to liquid – PTL) or with biomass Gasification

<u>Description:</u> Power-to-Liquid (PtL), also known as e-fuel or synthetic fuel, is a cutting-edge pathway that offers the potential for very high GHG emissions reduction. It involves combining captured carbon dioxide (CO2) with green hydrogen (produced via electrolysis using renewable electricity) to synthesize liquid

hydrocarbons. The primary routes for PtL involve either direct synthesis (e.g., reverse water-gas shift followed by FT synthesis) or indirect synthesis (e.g., conversion to methanol or other intermediate chemicals, then to jet fuel).

Feedstocks:
* Green Hydrogen: Produced from water electrolysis powered by renewable electricity (solar, wind, hydro).
* Carbon Dioxide (CO_2): Sourced from industrial point sources (e.g., cement, steel, ethanol plants) or Direct Air Capture (DAC) technology.

Advantages:
* Highest GHG Reduction Potential: it can achieve near 100% or even net-negative lifecycle emissions by using DAC,.
* Feedstock Abundance: Water and CO_2 are abundant, making it highly scalable in the long term, limited mainly by renewable electricity availability.
* No Land-Use Change Issues: Avoids competition for land or water resources associated with biomass feedstocks.
* Energy Storage Medium: Converts intermittent renewable electricity into a stable, energy-dense liquid fuel that can be stored and transported.

Challenges:
* High Energy Demand: Electrolysis and CO_2 capture are very energy-intensive processes, requiring vast amounts of affordable renewable electricity.
* High Capital Costs: Complex facilities for electrolysis, CO_2 capture, and synthesis require significant upfront investment.
* Lower Technological Maturity (for large-scale commercial plants): While components are known, integrating them into large-scale, cost-competitive PtL facilities is still nascent. Several demonstration projects are underway.
* Certification: Currently certified for FT-SPK (ASTM D7566 Annex A1) and ATJ (ASTM D7566 Annex A5/A6) pathways, which can be part of a PtL concept. A dedicated PtL annex is under development.

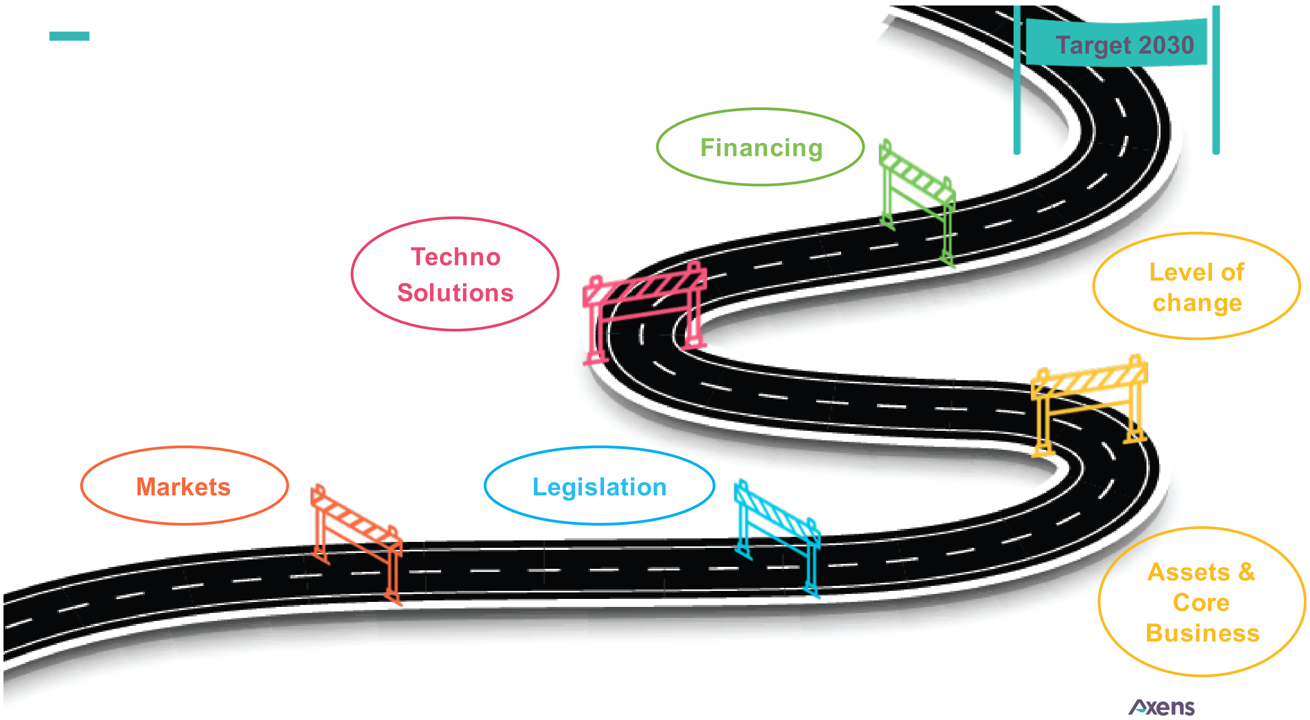
3.7 Technology readiness Level:

The ASTM has approved or is in way of approving eight routes to produce synthetic paraffinic kerosene (SPK) or sustainable aviation fuel (SAF), as shown in below table, which includes the level of technological readiness of these routes, with the TRL of 9 being the most technologically mature:

Pathway	Full Name	Short Process Description	Feedstock	Product	ASTM Status	TRL
HEFA-SPK	Hydroprocessed Esters and Fatty Acids – Synthetic Paraffinic Kerosene	Hydrotreatment of plant oils or animal fats to produce paraffinic kerosene.	Vegetable oils, used cooking oil, animal fats	Synthetic paraffinic kerosene (SPK)	Approved (up to 50%)	TRL 9
FT-SPK	Fischer–Tropsch Synthetic Paraffinic Kerosene	Gasification followed by Fischer–Tropsch synthesis and hydrocracking.	Biomass, municipal solid waste, or natural gas	Synthetic paraffinic kerosene (SPK)	Approved (up to 50%)	TRL 8–9
ATJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene	Dehydration and oligomerization of alcohols (e.g., ethanol, butanol).	Ethanol, butanol, other alcohols from biomass	Synthetic paraffinic kerosene (SPK)	Approved (up to 50%)	TRL 7–8
HC-HEFA-SPK	Hydroprocessed Esters and Fatty Acids from Hydrocarbon feedstocks – Synthetic Paraffinic Kerosene	Hydroprocessing of algae oils, waxes or similar hydrocarbon feedstocks.	Algae oils, waxes, other advanced hydrocarbons	Synthetic paraffinic kerosene (SPK)	Approved (up to 50%)	TRL 7–8
SIP	Synthesized Iso-Paraffins	Fermentation of sugars to farnesene, then hydrogenation to farnesane.	Sugars from biomass (e.g. sugarcane, corn stover)	Farnesane (iso-paraffinic hydrocarbon)	Approved (up to 10%)	TRL 7–8
CHJ	Catalytic Hydrothermolysis Jet	Hydrothermal conversion of lipids to jet-range hydrocarbons using catalysts.	Plant oils, animal fats, waste lipids	Jet-range hydrocarbons	Approved (up to 50%)	TRL 7–8
SPK/A	Synthetic Paraffinic Kerosene with Aromatics	SPK with added synthetic aromatics to ensure seal compatibility.	SPK base plus synthetic aromatic compounds	SPK with synthetic aromatics (SPK/A)	In certification / experimental	TRL 6–7
ATJ-SKA	Alcohol-to-Jet Synthetic Kerosene with Aromatics	Same as ATJ-SPK with added aromatics for full fuel compatibility.	Ethanol, butanol + aromatic additives	Synthetic kerosene with aromatics (SKA)	In certification / toward 100%	TRL 6–7
Coprocessing	Coprocessing of Renewable Feedstocks in Fossil Refineries	Co-refining of renewable oils (e.g. vegetable oils, fats) with petroleum in existing refinery hydrotreaters or FCC units.	Vegetable oils, animal fats, used cooking oil	Drop-in hydrocarbon fuels (incl. jet fuel fraction)	Partially approved (under evaluation for wider use)	TRL 6–7
MtJ	Methanol-to-Jet	Conversion of methanol to olefins, followed by oligomerization and hydroprocessing to produce jet fuel range hydrocarbons.	Methanol (fossil-based or renewable)	Synthetic kerosene (SPK) or SKA	In certification / experimental	TRL 5–6

4. SAF Projects: What early-stage barriers?

The transition from niche to mainstream sustainable aviation fuels faces significant industry barriers, including technological, economic, infrastructure, and regulatory challenges.



4.1. Technological Barriers:

* Feedstock Diversification and Sustainability: While various feedstocks exist, consistently sourcing large volumes of truly sustainable, non-food competing feedstocks (e.g., advanced biomass, municipal waste, algae) remains a challenge. Research is ongoing to improve yields and optimize conversion processes for a wider variety of waste streams and dedicated non-food energy crops.

* Conversion Efficiency and Yield: Optimizing the efficiency of converting diverse feedstocks into SAF is critical. Some pathways, especially those dealing with complex biomass or waste, still face challenges in maximizing fuel yield and minimizing by-products.

* Process Integration and Optimization: For advanced pathways like FT-SPK and Gasification+PtL, integrating multiple steps (e.g., gasification, syngas clean-up, synthesis, upgrading) into a single, efficient, and reliable commercial-scale operation is key to enhance production cost.

* Technological Maturity and Scale-up: HEFA is mature, other promising pathways like PtL and advanced biomass-to-liquid have been demonstrated at demonstration scale with some commercial projects being under design.

* Catalyst Development: Efficient and robust catalysts are essential for many SAF conversion processes. Developing catalysts that are highly selective, durable, and cost-effective under demanding industrial conditions have been developed to take up these challenges.

4.2. Economic Barriers:

* Cost Premium: The most noticeable barrier is the significant cost premium of SAF over conventional jet fuel. SAF can be two to ten times more expensive, largely due to:

* Higher Feedstock Costs: Sustainable feedstocks are more expensive to collect, transport, and process than crude oil.

* Higher Production Costs: The feedstock being more complex or with a smaller number of carbons, forming a fuel requires sometime more steps than in standard refining business. The Capex is not higher than a refinery, but the amount of fuel produced is lower resulting in a higher levelized cost of product

* Lack of Scale: The nascent industry lacks the economies of scale enjoyed by fossil fuel production, which has centuries of development and optimization.

* Profitability and long term:. Longer payback periods are expected while uncertainties regarding future policy stability and demand are not clear.

* Financing Challenges: Investors may be hesitant to commit large sums due to the perceived risks of new technologies, volatile feedstock prices, regulatory uncertainty,

* Price Volatility: SAF feedstocks prices & Fossil-jet fuels prices are volatile, making long-term financial planning for SAF producers challenging.

4.3. Infrastructure Barriers:

* Feedstock Supply Chain: Developing robust and efficient supply chains for diverse and often distributed feedstocks (e.g., agricultural waste, municipal solid waste) is a major challenge. This includes collection, pre-treatment, and transportation infrastructure.

* Blending and Distribution: While SAF is a "drop-in" fuel, the existing aviation fuel supply chain is highly optimized for fossil fuels. Integrating different types of SAF (biofuels, efuels, HEFA etc.), particularly at higher blend ratios, requires adaptations in logistics, storage, and blending facilities at refineries and airports.

* Limited Production Capacity: Current global SAF production capacity is small (less than 1Mt in 2024) compared to global jet fuel demand, which limits SAF immediate availability.

* Regional Imbalances: Production facilities tend to be concentrated in specific regions (e.g., Europe, North America), leading to high transportation costs if SAF needs to be shipped long distances to airports. One solution to tackle this, would be the book and claim adoption.

4.4. Regulatory Barriers:

* Lack of Harmonized Global Policies: The absence of consistent, harmonized global policies and mandates creates market uncertainty for SAF producers and airlines. Different regional regulations can complicate investment decisions and cross-border operations.

* Certification Process: While pathways are certified, the process for new pathways or higher blend ratios is rigorous, costly, and time-consuming (e.g., ASTM standards)which slowsdown innovation and market entry.

* Sustainability Criteria Development: Establishing clear, robust, and globally accepted sustainability criteria for SAF feedstocks and production is complex. Ambiguity can hinder investment and public acceptance, transparency is needed

* Incentive Mechanisms: While some countries offer incentives (e.g., tax credits, blending mandates), they are often insufficient to close the cost gap with fossil fuels or they lack the long-term stability needed to de-risk investments.

* GHG Accounting and Reporting: Developing standardized and transparent methodologies for calculating and reporting lifecycle GHG emissions from SAF is crucial for accurate claims and for integrating SAF into carbon reduction schemes (e.g., CORSIA).

Overcoming these interconnected barriers requires concerted efforts from governments, industry, investors, and researchers. A multi-pronged approach involving policy support, technological innovation, strategic infrastructure development, and strong financial commitments is essential to accelerate SAF deployment.

5. Levers to De-risk and Accelerate Deployment

Accelerating the deployment of Sustainable Aviation Fuel requires a concerted effort to mitigate the inherent risks and overcome the significant industrial barriers. A combination of strategic levers, encompassing policy, innovation, certification, and demand-side mechanisms, will be necessary to achieve the ambitious scale-up targets.

5.1. Policy and Regulation

Effective and stable policy frameworks are arguably the most crucial levers for de-risking investments and stimulating SAF production and uptake. Here below some examples of regulatory levers that could facilitate the development of the SAF market.

<u>Blending Mandates/Quotas:</u> Establishing clear, escalating blending mandates for SAF (e.g., "X% SAF by Year Y") provides long-term market certainty for producers and off-takers. Examples include the EU's ReFuelEU Aviation initiative and mandates in individual states/countries. These create guaranteed demand.

<u>Production Incentives and Subsidies:</u>

* Tax Credits: Investment tax credits for SAF production facilities or production tax credits per gallon/liter of SAF produced help offset high capital and operating costs (e.g., US SAF tax credit in the Inflation Reduction Act).

* Grants and Loans: Government grants for R&D and demonstration projects, and low-interest loans or loan guarantees for commercial-scale facilities, can significantly de-risk early investments.

* Carbon Pricing/Credits: Integrating SAF into carbon pricing mechanisms or generating tradable carbon credits for its use provides an economic incentive for airlines to choose SAF over conventional fuels, and corporate to lower down their scope 3 emission or any other actors in the aviation sector willing to reduce its scope 1 emission.

R&D Funding: Public funding for fundamental and applied research into novel SAF feedstocks, conversion technologies, and efficiency improvements can accelerate technological maturation and cost reduction.

Regulatory Streamlining: Expediting the certification process for new SAF feedstocks origins and higher blend ratios, while maintaining safety standards, can reduce time-to-market.

5.2. Innovation and Investment

Continuous innovation and substantial financial investment are vital to improve SAF economics and expand its production capabilities.

* Technology Development and Scale-up: Investing in R&D for next-generation SAF technologies, particularly Power-to-Liquid (PtL) and advanced biomass pathways, aims to improve conversion efficiency, reduce costs, and broaden feedstock flexibility.

* Venture Capital and Private Equity: Attracting private investment into SAF start-ups and scale-ups is crucial. This requires demonstrating viable business cases, aided by supportive policy environments.

* Strategic Partnerships: Collaborations between airlines, fuel producers, technology providers, and feedstock suppliers can pool resources, share risks, and accelerate commercialization. Examples include off-take agreements between airlines and SAF producers that provide long-term revenue certainty.

* Feedstock Security and Supply Chain Development: Establishing dedicated feedstock supply chains through long-term contracts or vertical integration helps ensure reliable raw material access. Some SAF producers are investing directly in feedstock production or processing to secure supply chains and capture additional value. Development of new feedstock sources, including purpose-grown energy crops and waste streams, can expand available raw materials while reducing competition with existing uses. Municipal solid waste, , and algae represent potentially abundant feedstock sources that require continued development. Regional feedstock aggregation and preprocessing centers can help consolidate smaller sources into viable commercial volumes while reducing transportation costs. These facilities can also standardize feedstock quality and provide buffer storage.

* Infrastructure Investment: Investment in infrastructure for feedstock collection, processing, and distribution, as well as modifications to existing airport fuel systems for higher SAF blends, is necessary.

5.3. Certification and Scaling

Ensuring SAF meets stringent safety and performance standards while facilitating rapid scale-up is a delicate balance.

* Capacity Building: Investing in the necessary technical expertise, skilled labor, and supply chain management capabilities required for large-scale SAF production.

* Modularization and Distributed Production: Exploring modular production facilities that can be deployed closer to feedstock sources might reduce transportation costs and facilitate quicker scale-up.

5.4. Demand-Side Mechanisms

Creating and sustaining robust demand for SAF is essential to incentivize production and investment.

* Airline Off-take Agreements: Long-term purchase agreements by airlines provide financial certainty to SAF producers, enabling them to secure financing for new facilities. These agreements are often crucial for de-risking initial investments but are also a difficult engagement for airlines which are not used to such long duration. .

* Corporate Programs: Engaging corporate customers (e.g., through corporate SAF programs) who are willing to reduce their scope 3 emission by buying SAF attributes to offset their business travel carbon footprint

* Voluntary Targets and Commitments: Airlines setting ambitious voluntary SAF uptake targets (e.g., IATA's 2050 net-zero target, specific airline commitments) signals strong demand to the market.

* Green Procurement Policies: Governments and public sector entities can adopt policies to procure SAF for their own travel, creating a foundational demand.

* Consumer Awareness and Education: Increasing public awareness about the benefits of SAF and its role in sustainable travel can foster broader acceptance and even willingness to pay a small premium.

5.5. Feasibility Study to derisk the SAF Projects

The SAF projects' feasibility and viability are strongly depending on three key parameters: Profitability, Carbon Footprint, and Legislation.
Projects for SAF production could be prepared and should be derisked through upfront complete Feasibility Studies in order to foresee and leverage all aspects of the projects: Technology review and selection, calculation of all economical aspects and overall project's execution challenges (logistics, storage, strategy, feed availability, offtake contracts etc…), risks identification, project execution plans. Moreover, that kind

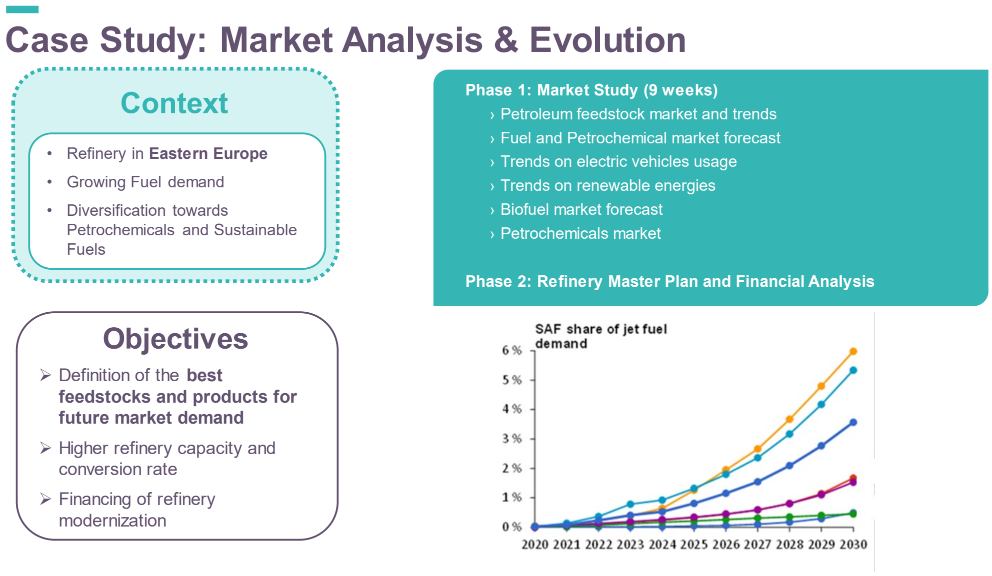
of complete Feasibility Study shall be performed by Consultancy specialists that have a deep background and knowledge of the market, as well as the technologies to bring reliable data to the Project Team:

- The Consultancy specialists shall be able to develop high quality Market and Economical studies to foresee the Project Business Model and its main parameters, including Discounted cash flow rate-of-return, NPV, IRR, levelized cost of production, selling prices etc.
- A deep knowledge of the technologies of SAF production:
    - Reliability and confidence on provided data like reactions' yield and feedstocks consumption because the profitability is generally driven by optimal use of feedstock towards valuable products.
    - Possible ways of by-products valorization like LPG/Naphtha/Diesel production to increase the project economic performance
    - Optimization of required resources (energy, water, existing assets, plot area), whether it is a greenfield project or smart integration in an existing plant
    - Ability to accurately define the optimal technico-economic strategy for a SAF production project, considering its integration into the foreseen ecosystem (grassroot, network).
- Environmental impact & Legislation knowledge are crucial for product validation and financial viability:
    - While regulations vary by country, they all aim to reduce greenhouse gases (GHG). In some cases, optimizing the Carbon Index (CI) is essential for maximizing profitability, but success hinges on connecting with an experienced and reliable partner that understands the intricacies of SAF production from a technical and regulatory point of view.
    - Using proven de-risked technologies, the Consultancy specialists ensure products meet ASTM standards and complies with regulations. They go further by optimizing Carbon Footprint for profitability gains, covering the complete project scope (feedstocks, core of the process, utilities).
    - Finally, with in-depth knowledge of local regulations, they adapt selected solutions to effectively engage with stakeholders, both regulatory and financial.

6. Case studies

We will present in this section some Case studies illustrating the ways to leverage the barriers on SAF Projects, brought through collaboration with a Consultant being part of a Technology Supplier Company.

6.1. Case Study 1:



<u>Context:</u> Refinery in Eastern Europe:

(i) Seeks to increase its capacity and crude conversion to respond to the increase in fuel demand.

(ii) Questions the benefits of diversifying towards petrochemicals and/or sustainable fuels.

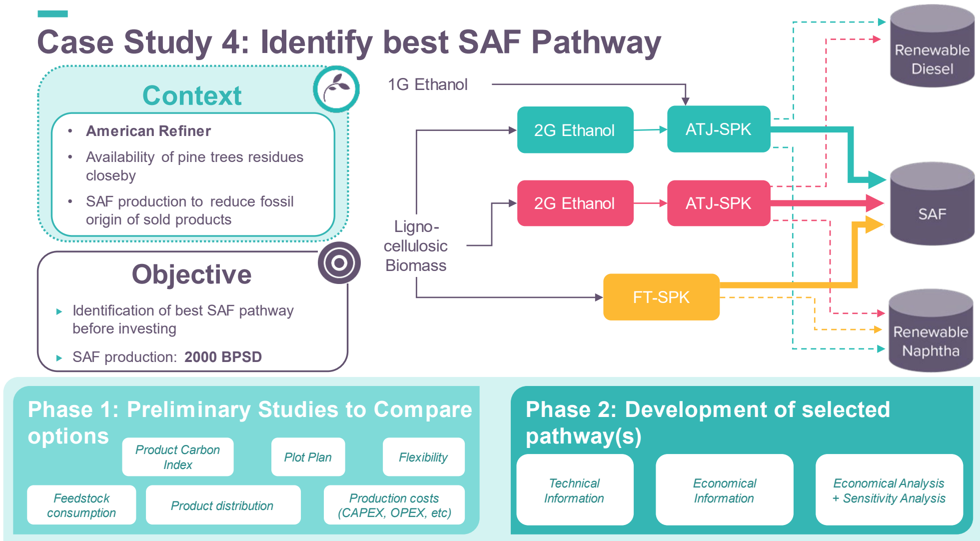
(iii) Seeks to improve its Business Case to consider the evolution of future markets, including traditional and new products. Thus, adapting the refinery for future demands and securing financing for refinery.

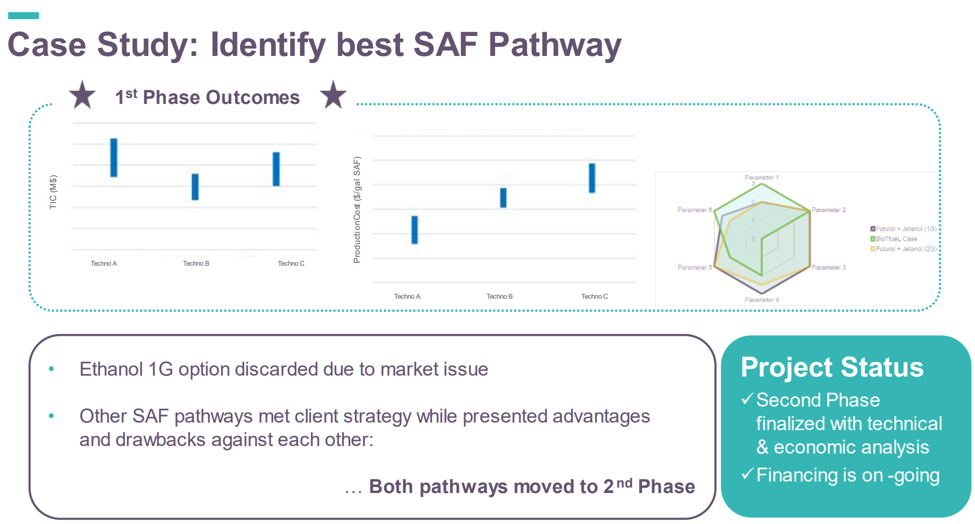
<u>Activities & Main outcomes of the Feasibility Study developed by the Consultant:</u>

With the help of its partners, the Consultant developed a Market Study to analyze the different markets of interest like Naphtha, Diesel or those they might be interested to enter like renewable fuels (SAF), petrochemicals (Aromatics) and Used Cooking Oils.

This deep knowledge of the market and its potential openings helped the client to decide on which products to focus for its refinery upgrade.

6.2. Case Study 2:





Context: North American Refiner:

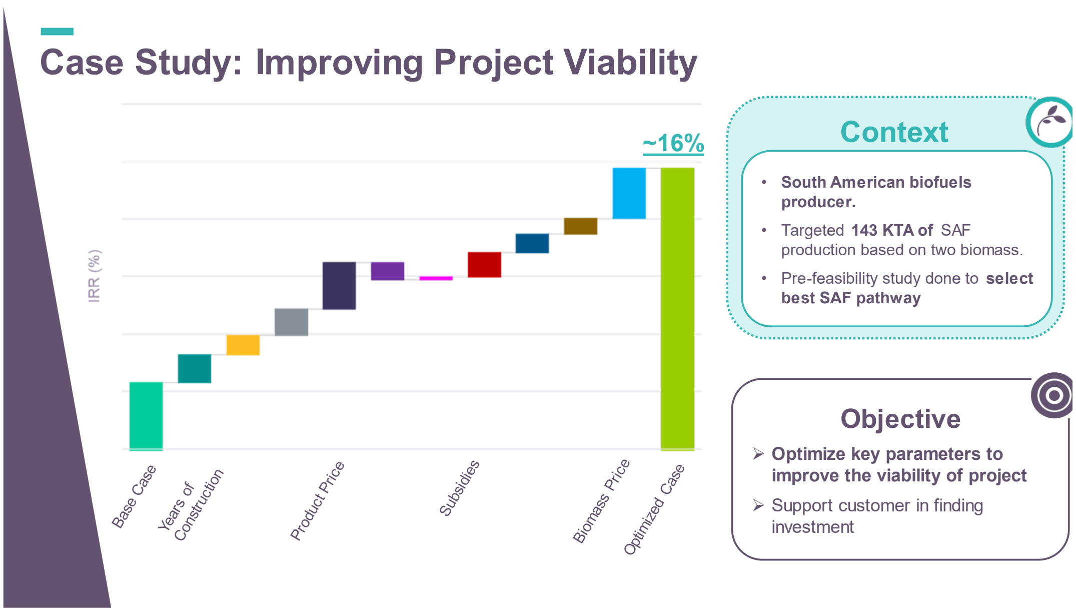
(i) Availability of high volumes of pine trees closeby
(ii) Seeks to reduce the carbon footpring of sold products
(iii) Seeks to define the optimum pathway to produce SAF among two main pathways: Biomass to 2nd Generation ATJ-SPK, or Biomass to FT-SPK

Activities & Main outcomes of the Feasibility Study developed by the Consultant:

(i) Complete technico-economic studies of both pathways have been performed, enabling to conduct a detailed and fair comparison between those two ways
(ii) Optimum pathway for SAF production has been clearly identified and selected

(iii) Project is now moving forward with the development of Basic Engineering (Process Books), Financing is on-going & Land to install the project has been identified and secured.

6.3. Case Study 3:



<u>Context:</u> Client was considering two pathways to produce 50 Million US Gallons of SAF per Year from different cellulosic feedstocks. The objective of the Feasibility Study was to compare two potential SAF technology routes:

- FT-SPK (Feed Pre-treatment, Gasification, Fischer-Tropsch, Upgrading) Technology
- Ethanol-To-Jet technology: 2G Ethanol & ATK SPK

Activities & Main outcomes of the Feasibility Study developed by the Consultant:

(i) Complete technico-economic studies of both pathways have been performed, enabling to conduct a detailed and fair comparison between those two ways
(ii) Optimum pathway for SAF production has been clearly identified and selected
(iii) Some of the main levers to improve project financing have been identified during that project feasibility study:
   a. Improve selectivity via process optimization,
   b. Optimize price structure (biomass, main and secondary products),
   c. Efficient project management to reduce time and years of construction
   d. Apply for incentives including funding & government aids

7. Conclusion

The successful industrialization of sustainable aviation fuel requires coordinated action across multiple stakeholders, including governments, airlines, fuel producers, technology developers, and financial institutions. By implementing comprehensive risk mitigation strategies and supportive policy frameworks, the aviation industry can accelerate the transition to sustainable fuels while maintaining operational efficiency and economic viability. Projects for SAF production could be prepared and should be derisked through upfront complete Feasibility Studies to foresee and leverage all aspects of the projects: technology review and selection, calculation of carbon footprint scenario and all economic aspects, and overall project's execution challenges (logistics, storage, execution strategy, feed availability, offtake contracts, scheduling etc…).

Bibliography: Information contained in this article is based on Axens internal and external articles, brochures and presentations.

Authors:

- **Mustapha TEBBANI**, Project Manager on Decarbonization & Consulting Studies, Axens

Experienced Process Engineer and Project Manager with over 15 years in the chemical and energy industries. Professional Experience:

- 2010: AkerSolutions, Process engineer on Natural GAs Dehydration Unit
- 2011-2014: Air Liquide, Process & Proposal Engineer on Helium & Syngas Purification Units
- 2014-2025: Axens, Process engineer & Technologist on Aromatics Units (2014-2019); Project Manager on Decarbonization & Consulting Studies (2020-2025)

- **Jordi Pinent-Armengol** – Decarbonization & Consulting Business Development Manager, Axens

After graduating from ENSIGC-Tarragona (Spain) as chemical engineer, Mr Pinent-Armengol followed IFP school program to specialize in oil refining.

He started his career with Spie Oil & Gas Services in 2004 as process engineer and was involved in Detailed Engineering projects.
He joined the Process Licensing Department of Axens in 2006 and was in charge of the Basic Design of numerous process units in the field of hydrotreatment and reforming. He was assigned Project Manager for several multiple-units large projects such as new Venezuelan Upgrader.
He moved to Axens Horizon as Project Manager in 2013 where he has been in charge of numerous Feasibility studies for new and revamped refining and petrochemical complexes and has managed several Energy Efficiency Audits and Margin Improvements Programs.
Since 2019 he has been appointed Consulting Sales Manager then Business Development Manager.

- **Leandro LABANCA** - Business Development Manager Decarbonization and Consulting, Axens

As a Business Development Manager, Leandro focuses on helping & accompanying customers transform and optimize their sites including defining their pathways for decarbonizing their sites. The wide spectrum of support covers from the energy improvement of existing sites, the evaluation and implementation of the latest technologies in decarbonization of either brownfield or greenfield ones up to the repurposing of assets.

Before, he was responsible for the design and optimization of several Aromatics Complexes including the development of different schemes for a wide range of feedstock looking to minimize energy consumption and feedstock needs.

Prior to joining Axens, Leandro worked as Business Development Team Manager for Process Integration Ltd, a consultancy focused on Energy Efficiency and Process Optimization to improve the margins of the oil and gas companies.

Leandro holds a Master degree in Chemical Engineering from the University of Buenos Aires and a MSc in Advanced Process Design for Energy from the University of Manchester.