All Roads Leading to Sustainable Aviation Fuel

A Step Further Towards Sustainable Mobility

Despite the unprecedented drop in global air traffic due to the Covid-19 crisis in the past years, passengers number and cargo volumes are anticipated to increase in the coming decades. According to the IEA (International Energy Agency), the air passenger number is set to double other the next twenty years.

Greenhouse Gas (GHG) emissions from aviation industry contribute to 2% of total GHG emissions with just over 600 Mt of CO2 production in 2020. The International Civil Aviation Organization (ICAO) has enacted ambitious goals to reduce aviation GHG emissions and is targeting to reduce aviation net CO2 emissions by 50% compared to 2005 levels by 2050.

In addition, in 2021, the global air transport industry through the ATAG (Air Transport Action Group) adopted, a long-term climate goal of net-zero carbon emissions by 2050, confirming the commitment of the world's airlines, airports, air traffic management and the makers of aircraft and engines to reduce CO2 emissions in support of the Paris Agreement 1.5ºC objective.

A range of solutions including technical, behavioral and operational are not doubt required to reduce aviation emissions. This article will focus on the main technology options to transition from fossil-derived jet fuel to **Sustainable Aviation Fuel (SAF).**

What is Sustainable Aviation Fuel (SAF), its market perspectives, and how to produce it?

Sustainable aviation fuel (SAF) is an alternative to fossil jet fuel and a promising solution to decarbonize the aviation sector.

It is produced from either:

- Renewable or waste-derived biobased resources that meets sustainability criteria depending on the location, such as **renewables oils and fats, lignocellulosic biomass, wastes, low C-I inedible starches and sugars**
- Captured carbon dioxide converted with renewables hydrogen either produced from biomass or utilizing green electricity (so called e-fuel)

SAF is a drop-in fuel, meaning that it can be blended with traditional jet kerosene (currently up to 50% vol) and the blend does not require equipment change, special infrastructure or modification of the supply chain, therefore limiting supply-chain investment requirements.

According to the IEA, SAF currently accounts for less than 1% of the global jet fuel consumption.

The primary drivers for future SAF market development are listed below, resulting from the basic realization that producing SAF is currently more expensive than producing fossil-based jet fuel. A combination of consumer pricing, regulatory, and incentive programs is therefore required to expand SAF production, regardless of the pathway.

- Regulations:
  - World: In 2016, the International Civil Aviation Organization (ICAO) adopted a global market-based mechanism, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to address CO2 emissions from international aviation.

This program targets to freeze aviation CO2 emissions at 2020 level via three actions: increasing planes efficiency, improving operations efficiency, and expanding the use of biofuels (SAF).

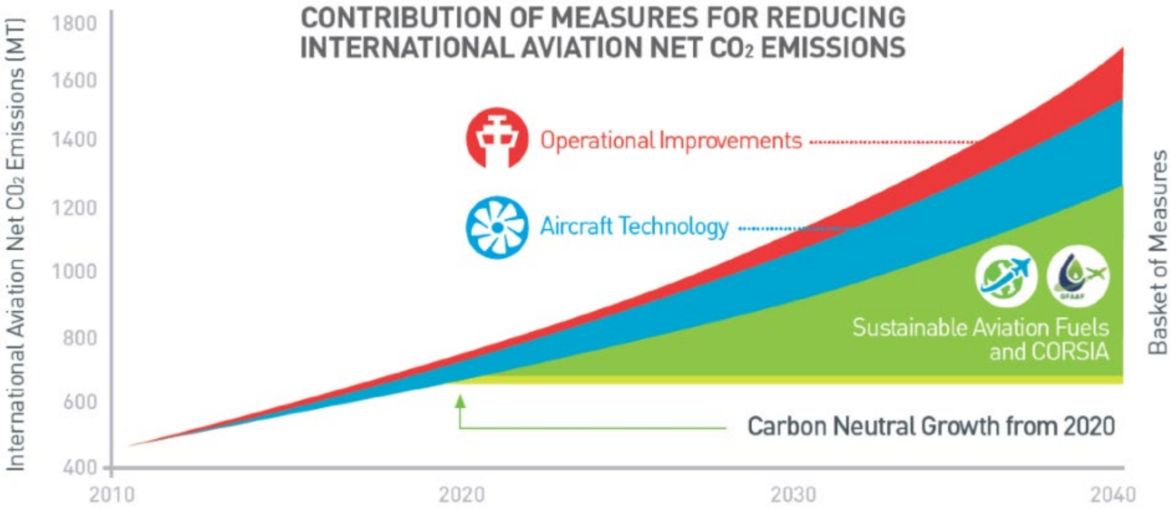


Figure 1: Contribution of measures for reducing international aviation net CO2 emissions (ref CORSIA)

- Europe: In 2021, under the Fit for 55 initiative, EU regulation defined a road map and mandates for SAF, which are also agreed by the ATAG: from 2% in 2025, 5% by 2030 all the way up to 63% in 2050. According to the ATAG, it is likely that the aviation sector will need around 450-500 million tons of SAF per year by 2050. Europe regulations are promoting advanced biofuels, or those derived from feedstocks not in direct nor indirect competition with food resources.

- US: Many US fuel purchasers are considering carbon-intensity-based metrics to evaluate fuel sustainability, utilizing such tools as the GREET model developed by Argonne National lab. Such models do not group feedstocks or processes by category, but rather scientifically calculate the overall GHG emission profile of a given feed considering its feedstock production, transportation, processing, and utilization. The resulting scientifically-based, quantified Carbon Intensity (CI) score can then be utilized to both (1) determine the sustainability of a given fuel compared to fossil baselines and (2) provide regulatory and credit structures that incentivize CI reductions across the entire SAF value chain.

- Market price:
  - Consumers may also play a role in growing SAF production. Programs exist today from many of the major carriers, allowing private passengers to pay a ticket premium that is then transferred down through the airline procurement chain to ensure SAF blending.
  - On the corporate level, major organizations are now actively trading air travel emission credits and maturing dialogues with their air transportation partners to formulate actionable, mid and long-term SAF strategies driven by an increasing

societal demand, which, when combined with the lack of SAF production, has led to SAF prices in excess of 3,000$/t FOB Rotterdam in early 2022.

- Project Development Support:
    - Major corporate organizations are in some cases partnering with airlines and migrating upstream in the SAF supply chain to inject capital, offtake commitments, and other support directly at the project-development level, helping to reduce risk, offset project development costs, and catalyze SAF supply market growth

SAF processes review

Among the seven pathways currently certified under the ASTM D-7566 specification for synthetic kerosene to be blended into Jet A1 pool, Axens is uniquely positioned, providing de-risked technology for the three main pathways. The **Fischer-Tropsch** pathway was the first process to be certified in 2009, followed by the **hydrotreatment of esters and fatty acids** in 2011. The **Alcohol to Jet** process was certified in 2018 for SAF production.

Each of those pathways can significantly reduce fuel lifecycle GHG when compared to fossil baselines, with reductions well over 90% possible when utilizing advanced, cellulosic feedstocks and / or green power.

The following section will give more details on the certified SAF pathways licenced by Axens and shown on figure 2.

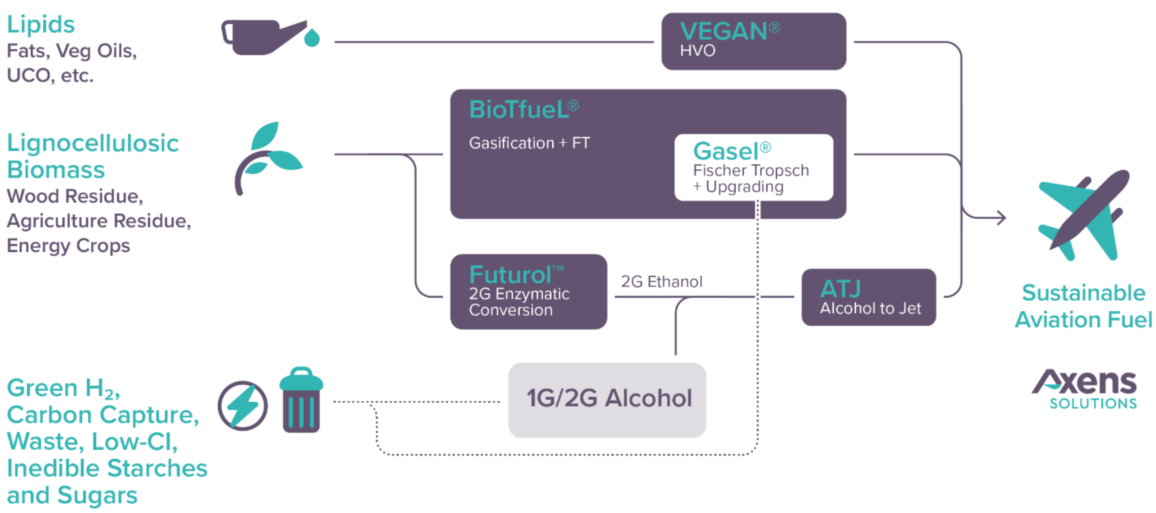


Figure 2: Main Sustainable Aviation Fuel Pathways

Vegan®: Hydroprocessed Esters and Fatty Acids (HEFA) pathway

Vegan® is a flexible solution to produce renewable diesel and SAF through the hydrotreatment of a wide range of lipids (renewable vegetable oils and animal fats). This technology allows producers to effectively address environmental regulations, sustainability targets, and secure energy diversification with drop-in premium quality products. Vegan® technology includes:

- A **Hydrotreatment (HDT) section** in order to deoxygenate and remove contaminants from renewable lipids in the presence of hydrogen to produce linear paraffins.
- A **Hydroisomerization (HDI) section** in order to upgrade the linear paraffins produced in the previous step into real drop-in middle distillate biofuels. The hydroisomerization section can be tuned to produce different grades of jet fuel or diesel fuel, according to market needs, with the ability to produce anywhere from 0 to 100% of the middle distillate product as SAF.

HEFA pathway can be a low investment solution as it offers the possibility to revamp some hydrotreatment units and turn them into HEFA units to produce SAF.

Gasel®: Fischer Tropsch (FT) pathway

Gasel® technology converts synthesis gas (H2+CO) from various origins - biomass, captured carbon oxides - into a flexible slate of ultra-clean liquid fuels (XTL), including SAF. This Fischer Tropsch route is commonly accepted as one of the most promising mid-term solutions for the production of alternative fuels and petrochemicals, including Biomass-to-liquids (BTL) and e-fuels:

- **Syngas Purification**: If required, this step aims at ensuring a syngas purity suitable for the FT catalyst. It can treat syngas from any conventional acid gas removal process.
- **Fischer-Tropsch Synthesis:** The reaction takes place in a three-phase slurry bubble column (SBC) reactor where syngas is brought into contact with the solid FT-catalyst to produce long chained liquid hydrocarbons. The liquid products are recovered in L/S and G/L separators and sent to the upgrading section.
- **FT Product Upgrading:** The raw FT liquid product is stabilized, hydrotreated (olefins & oxygenates), hydrocracked & isomerized. The fully converted product is then separated and it offers flexibility towards different production modes (max kerosene or max middle distillates/diesel with a small production of naphtha).

BioTfueL®: Gasification pathway

BioTfueL® [(1)] technology unlocks Sustainable Aviation Fuel and advanced biofuels production from energy crops, agricultural and forestry residues (including wood industry residues) via a thermochemical pathway. This technology enables the access to a wide range of biomass and positions itself as a sustainable alternative to vegetable oil and food-based biofuels, and is the only technology that offers the complete BTL chain backed by one licensor.

- **Pre-treatment**: Biomass is conditioned with drying and torrefaction. These steps homogenize feedstock quality, facilitate the grinding and increase both storage stability and biomass energy density. Flexible process conditions allow to adapt to changes in biomass quality and supply strategy.
- **Gasification:** The applied Uhde® entrained-flow gasification Process with Direct Quench (PDQ) is a high pressure and high temperature partial oxidation converting carbonaceous material into tar free syngas.
- **Syngas Conditioning:** Syngas is conditioned to Fischer-Tropsch requirement by adjusting the H_2/CO ratio via a Water Gas Shift reaction, followed by acid gas removal and a final purification.

- **Fischer-Tropsch Synthesis and Upgrading:** see description of Gasel® technology hereabove.

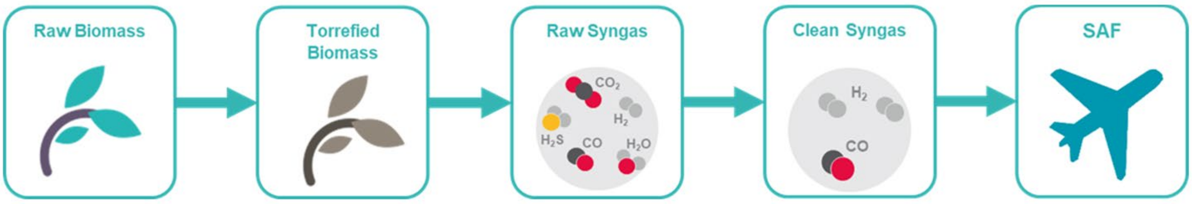


Figure 3: Gasification Pathway

(1) BioTfuel Project partners: Avril, Axens, CEA, Total, IFP Energies nouvelles and ThyssenKrupp Industrial Solutions.

Ethanol to Jet pathway

Ethanol to Jet (ETJ) is the process by which 1G or advanced bioethanol (2G) is converted to SAF via different steps.

- **Dehydration**: First, polymer grade ethylene is produced by ethanol dehydration (Atol®).
- **Dimerisation**: The ethylene is then oligomerized at close to ambient temperature with a high selectivity towards Butenes, utilizing a liquid phase, homogeneous Ziegler type catalytic system based upon a transition metal derivative, nickel, activated by an alkylaluminium reduction compound. The catalytic system is called homogeneous because the reactants, the products and the catalysts form a single liquid phase (Dimersol™).
- **Oligomerisation**: The produced butenes and hexenes are converted into SAF via heterogeneous oligomerization (Polynaphtha™), utilizing a robust, environmentally friendly and regenerable catalyst, which ensures long cycles and long catalyst life.
- **Upgrading**: A last step of hydrogenation is necessary to reduce the olefin content of the product in order to fulfil the final products ASTM specification.

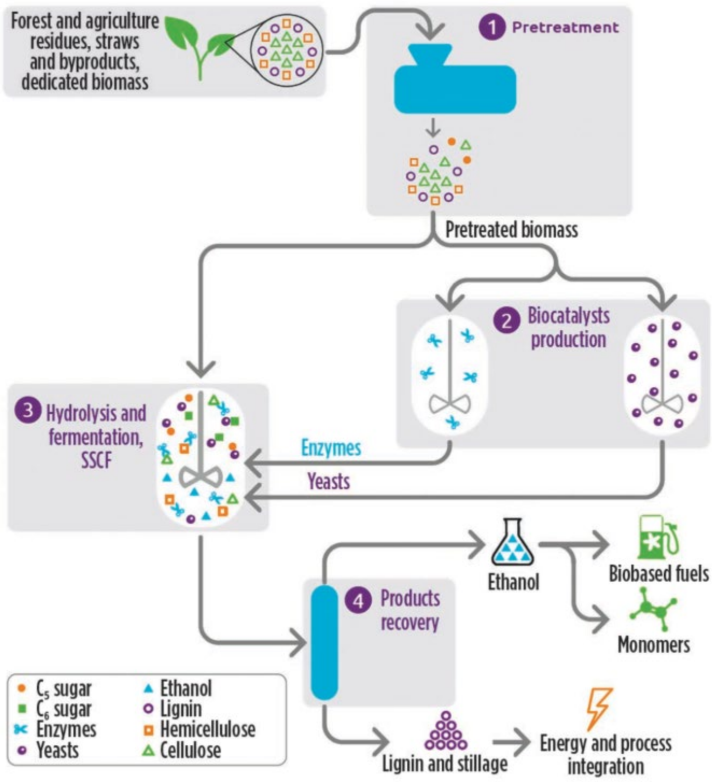
This differentiating technology bundle approach utilizes already commercially-proven processes, with over 100 homogeneous and heterogeneous reference units.

Futurol™: Enzymatic conversion pathway

Futurol™ converts lignocellulosic biomass from various origins into cellulosic ethanol (advanced bioethanol). (figure 4). This cellulosic ethanol can then be converted to SAF with ATJ process described above.

- **Pre-treatment:** An energy-efficient, single-train, continuous technology was selected and optimized for converting biomass feedstock such as energy crops, agricultural and wood residues to a standardized pre-treated substrate, highly digestible and with low moisture. High hemicellulose conversion is attained, while product degradation is minimized.

- **Biocatalysts Production**: Inhibitors resistant tailor-made biocatalysts (enzymes and yeasts) were designed, adapted and improved to optimize process performances. Futurol™ offers on-site enzyme production and yeast propagation using lignocellulosic substrate, which strongly contributes to ethanol production cost reduction.
- **Hydrolysis and Fermentation**: Enzymatic hydrolysis of biomass and co-fermentation of C5 and C6 sugars take place simultaneously in the same vessel ("one-pot" process). This process configuration capitalizes on a unique synergy between biocatalysts and allows for both CAPEX and OPEX minimization while achieving high ethanol yield through full conversion of C5 and C6 sugars.
- **Products Recovery**: State of the art distillation and dehydration allow recovery of advanced bioethanol suitable for biofuel applications or for further processing in chemical production. Lignin and stillage are recovered and routed to energy production while water is recycled.



<u>**Figure 4: Enzymatic Conversion Pathway for Ethanol Production**</u>

Combination of Enzymatic conversion + Alcohol to Jet pathways:

By combining Futurol™ and the Alcohol to Jet processes (figure 5) provides the possibility of producing ultra-low CI – or even carbon-neutral, advanced SAF from lignocellulosic biomass. This chain has many advantages including (1) a two-stage investment plan to either produce advanced bioethanol first (with Futurol™), then subsequently build an alcohol to Jet block, (2) to produce SAF from low-CI 1G ethanol (with ATJ) the decarbonize the SAF over time with the introduction of advanced bioethanol, or (3) to utilizing a "hub and spoke" approach by building multiple small Futurol™ plants near feedstock sources that all feed a centralize ATJ plant that captures economies of scale. These advantages make the ATJ pathway unique in today's continuously evolving environment.

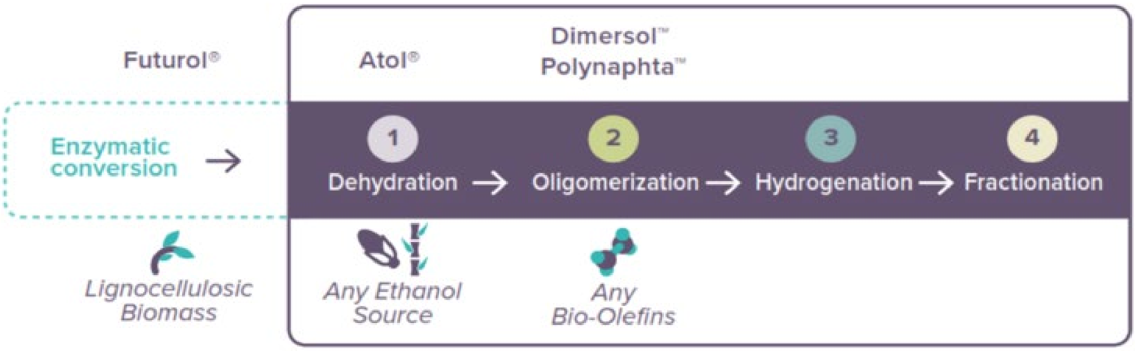


Figure 5: Alcohol to Jet Pathway

TAKEAWAYS

Sustainable Aviation Fuel will be an essential lever in the near future to decarbonize the aviation sector, along with increased aircraft efficiency and behavioral adaptations. Consensus forecasts predict exponential growth in SAF capacity to meet the regulatory and market-driven demand.

As previously exposed, many different types of technologies and pathways are now available to produce SAF and Axens is uniquely positioned to bring de-risked technologies to three of the primary pathways (HEFA, ATJ, and Biomass to Liquids via Gasification and Fischer-Tropsch). Each pathway has distinct regional, feedstock-specific, economies of scale, and techno-economic advantages, with each one having a role to play depending on individual project context; meeting the demands of the aviation sector will likely require implementation of multiple project pathways including those listed here.

The common threads running through these technologies are flexibility, reliability and the realization of decades of technology development, demonstrating that Axens is rising to meet the challenges of scaling-up of SAF capacity in the coming years.

Authors: Yvon Bernard, Dave Schwalje

Co-author: Carine Leclercq

About Axens

Axens Group provides a complete range of solutions for the conversion of oil and biomass to cleaner fuels, the chemical recycling of plastics, the production and purification of major petrochemical intermediates as well as all of natural gas treatment and conversion options. The integrated offer includes technologies, equipment, furnaces, modular units, catalysts, adsorbents and related services, commercialized under "Axens Solutions", "Heurtey Petrochem Solutions" and "Axens Horizon" brands. Axens is ideally positioned to cover the entire value chain, from feasibility study to unit start-up and follow-up throughout the entire unit life cycle. This unique position ensures the highest level of performance with a reduced environmental footprint.

Summary of Abbreviations :

ATAG: Air Transport Action Group

ATJ : Alcohol to jet

BtL: Biomass-to-liquid

CI: Carbon Intensity

ETJ: Ethanol to jet

EU: Europe

FT: Fischer-Tropsch

GHG: Greenhouse Gas

HEFA: Hydroprocessed Esters and Fatty Acids

H2+CO: synthetic gas

HDT: Hydrotreatment

HDI: Hydroisomerization

ICAO : International Civil Aviation Organization

IEA : International Energy Agency

PDQ: Process with Direct Quench

SAF: Sustainable Aviation Fuel