



THE LATEST DEVELOPMENTS IN SUSTAINABLE AVIATION FUELS TECHNOLOGY

Abstract:

Over the last three decades, air travel has become more popular, increasing the amount of carbon emissions the aviation industry has released, pushing for further decarbonization [2]. Sustainable Aviation Fuels (SAFs) are the most realistic solution for decarbonization as they are made to be drop-in fuels and do not require design changes in the aircraft, as other alternatives might need [2], [3]. The American Society for Testing Materials (ASTM) has 11 approved SAF production pathways shown in Figure 2 [7], [8]. However, the only commercially competitive production pathway as of right now is the Hydroprocessed Ester and Fatty Acids Pathway (HEFA, ASTM D7566 Annex A2), which uses oil-based feedstocks and currently runs mainly on used cooking oil (UCO) imported from China [11], [12]. As this oil-based feedstock is also food grade, it is competitive with the food industry and therefore also unreliable in its availability. Developments have been made to use non-food-grade feedstocks and add a pretreatment step. Other processes in development but close to commercial maturity are the Alcohol-to-Jet Synthetic Paraffinic Kerosene pathway (ATJ-SPK, ASTM D7566 Annex A5) [7],[8] and Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK, ASTM D7566 Annex A1) [7], [28]. There is one ATJ plant in production, but it is not competitive with the production of SAF through HEFA [21]. As the main obstacle with these processes is feedstock, there must be more innovation done to find feasible solutions. Through organizations like the International Air Transit Association (IATA) and the International Civil Aviation Organization (ICAO), governments and airlines have been given incentives to invest in research and development that leads to decarbonization in aviation. The most recent developments have come in a new pathway to produce SAF: Power-to-Liquid (PtL) [32] where the feedstock comes from renewable resources like water, waste gas streams, or the air bypassing the challenges of feedstock availability [51].

Introduction:

In 2023, aviation accounted for 2.5% (950Mt) of global energy-related carbon dioxide (CO₂) emissions [1], [2]. Since 1990, aviation emissions have increased about 2.2% per year until 2019 when travel bans due to the Covid-19 pandemic caused air travel to plummet as seen in Figure 1 [2]. However, in 2023 aviation emissions rose back up reaching about 90% of their pre-pandemic peak [2]. Currently, Aviation accounts for 4% of all accumulated global warming to date and is only set to rise as other sectors decarbonize faster than aviation [3]. Improvements in energy intensity in aviation have historically not been enough to counterbalance the demand in recent years as seen in Figure 2 [2]. To decrease carbon emissions, there have been improvements made to infrastructure of an aircraft; however, the most effective changes can be made through alternative propulsion technologies [2], [3].

Various fuels have been investigated to replace or be combined with traditional jet kerosene. Hydrogen fuels are promising but require fuel storage systems and delivery methods requiring much change to aircraft infrastructure [2]. Electric propulsion is currently limited to small aircraft and requires design accommodations to incorporate the battery's energy density and weight [2]. The most realistic solution is sustainable aviation fuel (SAF) which is a form of biofuel that has similar properties to conventional jet fuel but with a smaller carbon footprint [2], [3]. Sustainable

Aviation Fuel contains the same hydrocarbon as fossil-based jet fuel but is made from bio-based feedstocks [3], [4]. It is designed to be a drop-in fuel to be combined with conventional jet fuel, allowing it to be incorporated without the need to alter established aircraft infrastructure [7]. Right now, SAFs are not developed enough to fuel aircraft as well as traditional jet kerosene by itself. Therefore, aviation fuel is dominated by jet kerosene while SAFs account for less than 0.4% of all aviation fuels consumed as seen in Figure 3 [2], [5]. With more support via government programs and incentives for aviation companies, there is greater motivation to further develop alternative fueling methods.

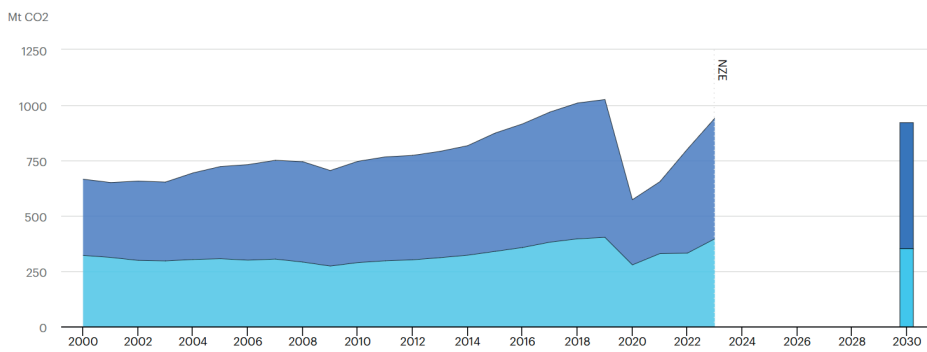


Figure 1: CO₂ emissions in Mt per year from 2000 with estimated emissions for 2030 [2].

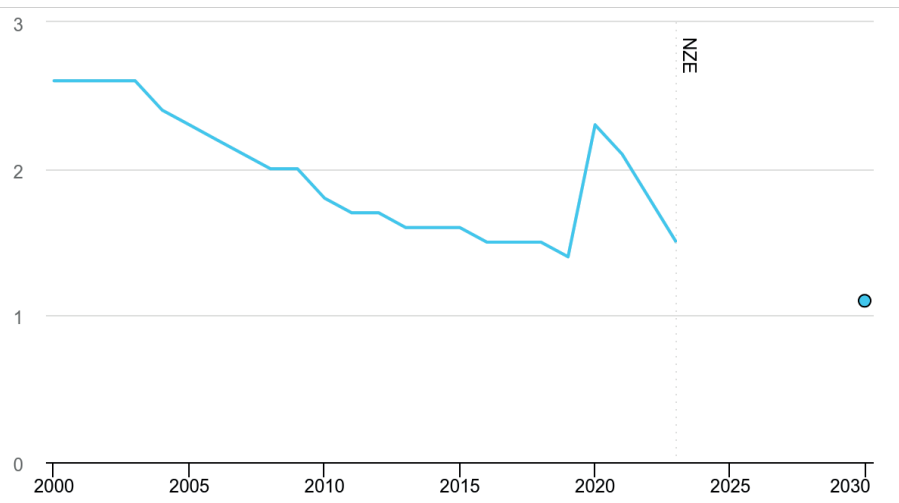


Figure 2: Energy Intensity of Commercial passenger aviation in the Net Zero Scenario [2].

Today, most biofuels are used only for cars and trucks, while providing less than 1% of global aviation demand as seen in Figure 3 [5]. There are 11 different pathways to produce SAFs approved by the American Society of Testing Materials (ASTM) but very few of them are available at commercial scale as seen in Figure 4 [6]. In 2024, SAF production reached 1 Mt, doubling the amount produced in 2023, adding up to 0.3% of global jet fuel use [6]. However, in total, the world produced 1400 terawatt-hours (TWh) of energy in the form of liquid biofuels for all sectors while just the aviation fleet consumed 2932 TWh of energy which means the total global biofuel

Less than 1% of the world’s liquid biofuels are used for aviation

Most of the world’s liquid biofuels are used for road transport, and most of the global aviation fleet still runs on fossil jet fuel.

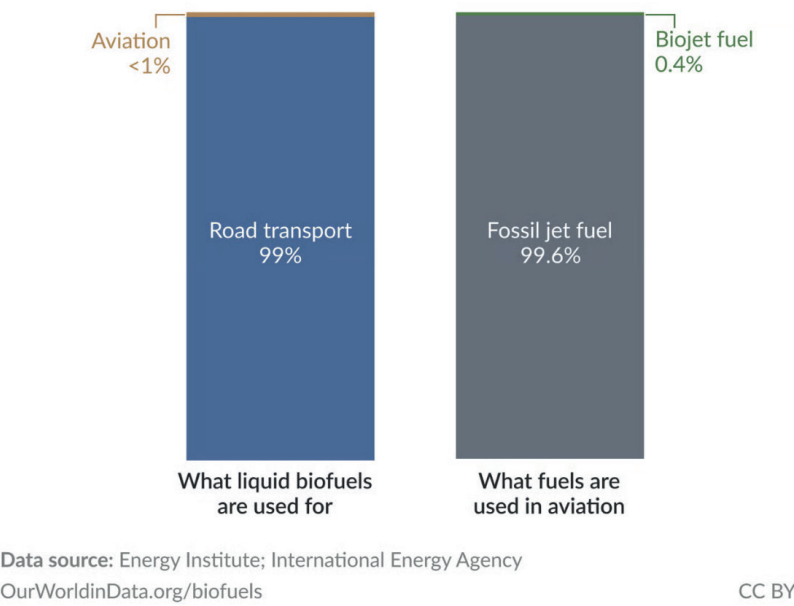


Figure 3: Aviation biofuels compared to biofuels used for road transport and bio jet fuel in comparison to fossil jet fuel [5].

production only meets 1/3 of the aviation fleets demand [5]. Therefore, biofuels can contribute to decarbonizing aviation but to only a limited extent [5]. Going into the future, SAF is estimated to contribute to 65% of the reduction in emissions needed by aviation to reach net zero CO₂ emissions by 2050 which is the goal set by the International Civil Aviation Organization (ICAO) [6]. As travel demands grow, biofuels, specifically SAFs derived from biomass, represent a promising pathway to reduce aviation emissions.

ASTM approved SAF pathways

SAF Pathway	Abbreviation	Blending Limit	Feedstock	Description
Fischer-Tropsch Syntehtic Paraffinic Kerosene	FT-SPK, ASTM D7566 Annex A1	50%	Woody biomass: MSW, agricultural wastes, forest wastes, wood, and energy crop	woody biomass converted to syngas using gasifaction which is then synthehsized through FT reaction to produce SAF
Hydroprocessed Esters and Faty Acids	HEFA, ASTM D7566 Annex A2	50%	oil-based feedstock	feedstock is hydroprocessed to break apart chain of fatty acids. Then Hydroisomerzation and hydrocracking occur to produce drop-in fuel
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins	HFS-SIP, ASTM D7566 Annex A3	10%	sugars	Microbial conversion of sugars to hydrocarbons. The feedstocs are pretreated to be eligible feedstocks.
FT-SPK with Aromatics	FT-SPK/A,ASTM D7566 Annex A4	50%	Woody biomass: MSW, agricultural wastes, forest wastes, wood, and energy crop	Similar to FT-SPK but with aromatic components
Alcohol-to-Jet Syntehtic Paraffinic Kerosene	ATJ-SPK, ASTM D7566 Annex A5	50%	cellulosic biomass	feedstock is converted through series of chemical reactions: dehydration, hydrogenation, oligomerization, and hydrotreatment.
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ, ASTM D7566 Annex A6	50%	Fatty acids, fatty acid esters, or lipids from fat oil greases: soybean oil, jatrophia oil, camelina oil, carinata oil, tung oil	fatty acid oil extracted from processing waste oils or energy oils and is combined with preheated feed water. That is then passed through a catalytic hydrothermolysis reactor
Hydrocarbon-Hydroprocessed Ester and Fatty Acids	HC-HEFA-SPK, ASTM D7566 Annex A7	10%	triglyceride oil: Algal oil	triglyceride oil is converted to jet fuel through fractionations.
Synthetic Paraffinic Kerosene with Aromatics	ATJ-SKA, ASTM D7566 Annex A8	50%	Sugars, starches, Lignocellulosic biomass, and alcohols	similar to ATJ-SPK but with aromatizaiton step.
Fats, oils, and grease Processing	FOG(CO), ASTM D1655 Annex A1	5%	Fats, oils, greases	FOG processed with petroleum intermediates.
FT Co-processing	ASTM D1655 Annex A1	5%	FT biocrude	FT syncrude processed alongside petroleum crude oil to produce SAF
Co-processing of HEFA	ASTM D1655 Annex A1	5%	Renewable lipids: vegetable oils, used cooking oils (UCO), or animal fats	Blending Renewable feedstocks with fossil-based feeds in existing HEFA process

Figure 4: 11 ASTM approved SAF pathways, abbreviation, ASTM certification, blending limit, feedstock, and brief description [7], [8].

1. SAF Production Pathways

There are 11 SAF pathways, certified by the American Society of Testing Materials (ASTM), a forum for industries and government stakeholders to create standards on products as seen in Figure 4 [4], [7], [8], [9]. ASTM D7566 is the classification used for aviation turbine fuel with synthesized hydrocarbons meant for non-petroleum-based jet fuel [7], [10]. ASTM D1566 is the standard specification for aviation turbine fuels which are allowed to be co-processed with biomass with biomass feedstock at a petroleum refinery [7], [10]. Out of the 11 approved pathways, there are three

pathways that are closest to commercial use: Hydrotreated Esters and Fatty Acids (HEFA), Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), And Alcohol-to-Jet (ATJ). HEFA is the leading pathway and the only one used commercially for SAF production [11]. However, it is still between 2 to 2.5 times more expensive than the development of any conventional aviation fuel with fossil fuel-based feedstock [11].

1.1 Hydroprocessed Ester and Fatty Acids Pathway

Hydroprocessed Ester and Fatty Acids Pathway (HEFA, ASTM D7566 Annex A2) is currently the most mature and developed process to create SAFs with Technology Readiness Level (TRL) level of 9 (it is tested and operational at scale) [11], [12]. HEFA is the most dominant SAF production pathway making up over 90% of the current or upcoming SAF capabilities [11]. This is expected to continue into the next decade, reaching up to 95% of the market [11]. It offers the lowest leveled cost compared to other SAF production pathways but is still more costly than traditional jet kerosene production [11]. HEFA pathways use oil-based feedstocks, making them susceptible to oxidative degradation and therefore requiring antioxidants or nitrogen blanketing in storage [12]. Food-grade vegetable oils are the optimal source for HEFA feedstocks but are expensive and compete with the food industry making their availability unreliable [4], [12]. To combat this issue, low value oils such as animal fats and used cooking oil (UCO) are utilized and must be pretreated to remove impurities that may increase corrosion or reduce catalyst life span and performance [12].

1.1.1 Pretreatment

HEFA feedstocks can be processed in SAF plants which take between 3 to 5 years to build, making it difficult to meet decarbonization goals [11], [12]. They can also be co-processed in existing refineries with very little modification [11]. In 2023, fractionation coprocessing was approved allowing up to 24% of previously hydroprocessed biomass to be blended with a petroleum stream in traditional refineries, generating jet fuel with 10% renewable hydrocarbons [12]. This is a more cost-effective method without the need for stand-alone facilities. However, the stand-alone facilities would provide more job opportunities [12].

Pretreatment traditionally involves filtration, degumming, adsorption or bleaching, and neutralization [12]. Filtration is used to remove insoluble impurities, degumming removes gum-like materials and bulk metals, while adsorption or bleaching utilizes activated clays to adsorb polar compounds. All these steps remove the impurities and lower the phosphorous levels. Further steps might be needed to remove high polyethylene often found in low-quality animal fats and mitigate the chloride content in used cooking oil (UCO) [12].

There have been alternative pretreatment technologies discovered improving the efficiency of pretreatment steps in the HEFA pathway [12]. The Applied Research Associate (ARA), an international research and engineering company, has patented the Hydrothermal Cleanup Technology (HCU) which is used to cleanup renewable or non-renewable organic feedstocks often used in the HEFA pathway [13], [14]. This process has a very short residence time, requires high-temperatures and pressure, and turbulent flow. This is an integrated vapor-liquid separation with a high-yield of oil product with significantly less concentrations of organic contaminants [14]. The equipment used has a smaller carbon footprint and can be used on the same plant as a conventional refinery [14]. It also eliminates the need for vacuum distillation, instead relying on a rectifying step [14]. HCU was launched at Montana Renewables in Great Falls, Montana in 2023 [13]. Furthermore, BioFlux has pretreatment technology with rapid deployment modular process units that can be operational in as little as 24 months compared to the traditional time frame extending as long as 5 years [15], [11]. This process has streamlined implementation, reducing operational disruption for existing facilities [15]. This is also a scalable technology with its flexible design that supports growth at any production scale allowing for the pretreatment process to keep up with the growth of the HEFA pathway.

1.1.2 Hydroprocessing

Hydroprocessing includes two main steps: hydrodeoxygenation and isomerization with a stabilization step in between as seen in Figure 5 [12], [16], [17]. The first step of hydrodeoxygenation or hydrotreatment is oxygen removal from triglycerides in the feed through hydrodeoxygenation, hydrodecarboxylation, or hydrodecarbonylation at high temeperatures and pressures [16], [17]. This process decreases the carbon atoms on the fatty acid chain resulting in straight chain paraffins while also releasing CO₂. [16], [17]. When straight chained, these paraffins make fuel less effective at cold temperatures requiring the isomerization step to meet cold flow property specification [16], [17]. Isomerization converts straight chained paraffins into branched isoparaffins often with the assistance of a catalyst [16], [17].

Hydroprocessing is usually a commercial process with steps that include commercial catalysts specific to the organization hydroprocessing the feeds [12], [16]. Chevron Lummus Global (CLG) uses their patented Isoterra process as an all-hydroprocessing route that can be operated to produce SAF [18]. Their process uses the EnHance™ catalyst during isomerization and ISOCRACKING® in the hydrocracking reactor [12], [16]. These catalysts help produce high quality base oils that meet industry standards and ASTM requirements [12], [16].

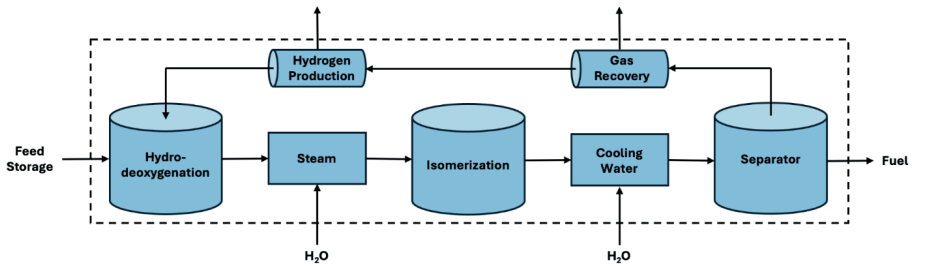


Figure 5: HEFA pathway schematic noting that the feed storage is after the pretreatment step [17].

1.1.3 SAF recovery

The final step in the HEFA pathway is fractionation or separation done in the separator as seen in Figure 5 [12], [17]. Multiple fuel products are created from the reactor effluent which also recovers gas. The HEFA pathway on its own is the dominant pathway to produce SAF and the only one that works at the commercial scale, but on its own it is unlikely to keep pace with the carbon emission goals of net zero carbon emissions by 2050 due to feedstock availability and up-front capital costs and time needed to create HEFA reactors [19]. However, with new technology like BioFlux's modular reactors costs and time required could be decreased [15]. To further decrease capital costs, HEFA feedstocks can be processed in SAF plants with some modifications to enhance the use of new catalysts and reactor designs being developed [11].

1.2 Alcohol-to-Jet Synthetic Paraffinic Kerosene Pathway

Newer, up-and-coming SAF production plants are utilizing the Alcohol-to-Jet Synthetic Paraffinic Kerosene pathway (ATJ-SPK, ASTM D7566 Annex A5) [7], [8]. It is the closest of the remaining SAF production pathways to commercialization with a TRL of 6 to 7 [20]. The first fully operational plant utilizing ATJ technology opened on November 13, 2025, in Soperton Georgia by LanzaJet, a sustainable fuels technology company [21]. ATJ must be investigated and developed as it addresses the challenges with feedstock availability that HEFA faces [19].

1.2.1 Feedstocks

ASTM has approved ethanol and isobutanol to produce jet fuel using the ATJ process which can be produced from cellulosic biomass through fermentation as seen in Figure 6 [8], [22], [20]. Bioethanol has traditionally been produced using edible feedstocks containing starch and sucrose like wheat, corn, and sugarcane which has the potential of reducing greenhouse gas emissions by 22% [23], [20]. Gevo Inc. partnered with Alaska airlines formed a corn sugar base ATJ where the patented Gevo fermentation Technology (GIFT) process is used to produce Isobutanol [10]. However, these food grade feedstocks face the same obstacles as HEFA feedstocks, competition with food grade crops. However, Gevo's ATJ-60 project announced in 2021, addresses this issue by utilizing regeneratively grown corn supply and focusing on a circular economy to increase efficiency as seen in Figure 7 [24]. The regeneratively grown feedstock is intended to put more focus on improving agriculture while putting nutrition into the food chain, this solution benefits local economies as well as farmers [24]. LanzaJet's ATJ plant is also designed to work with a wide range of feedstocks including agricultural residues, energy crops, and municipal solid waste (MSW) addressing the issues with feedstock availability facing HEFA pathways [21].

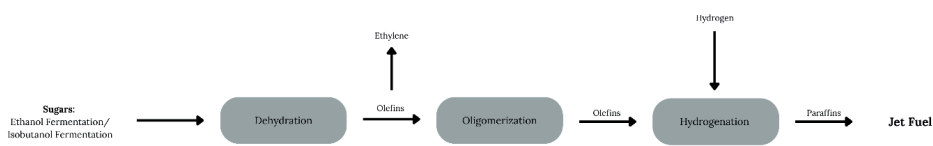


Figure 6: ATJ Process Schematic

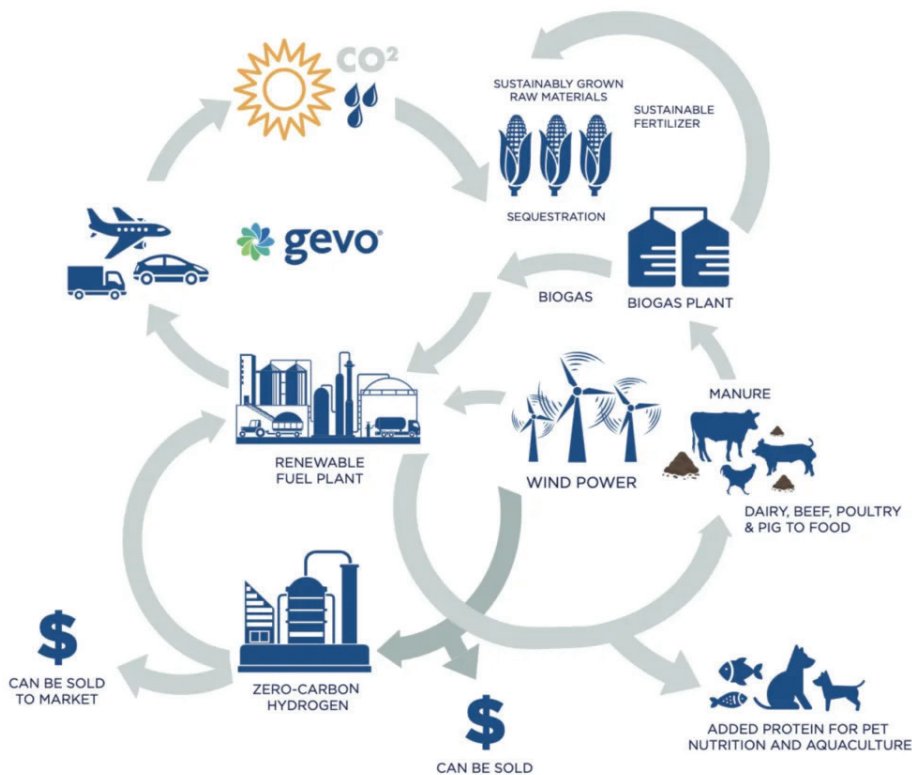


Figure 7: Gevo Inc.'s circular economy model [24].

1.2.2 Dehydration

Once the feedstock has been treated to be pure ethanol or isobutanol, it can go through the process to be converted to jet fuel. There are three main catalytic reactions that make up the reactor: alcohol dehydration, olefin (alkene) oligomerization, and hydrogenation as seen in Figure 6 [10]. The first reaction, alcohol dehydration, is the conversion of renewable ethanol into ethylene which is a process that dates to the 1960s [10]. Ethanol dehydration has been explored thoroughly with various catalysts leading to about 2% mixed hydrocarbons as impurities [10].

SynDol is the commercially available catalyst often used for this reaction [10], [25]. The catalyst

is absorbed on a porous granular catalyst support like carbon or charcoal [25]. The dehydration reaction removes a hydroxyl group generating water [10]. SynDol's hydrophobic groups adhere to the catalyst to support better in the presence of water [25]. Furthermore, SynDol can be used alongside an auxiliary phosphoric acid catalyst to reduce costs [25]. This auxiliary catalyst will gradually be reduced through contact with a solution of phosphoric acid or polyphosphoric acid. Therefore, the auxiliary catalyst is a replaceable component of the reaction [25]. Overall, with the assistance of these catalysts, the dehydration reaction yields conversion efficiencies between 95 to 100% [25]. They also prevent oligomerization from starting prematurely as it is the following step as seen in Figure 6.

1.2.3 Oligomerization

Olefin oligomerization must result in a desired distribution of hydrocarbon chain lengths; therefore, the reactor is carefully designed to achieve the necessary yield in the desired range [10]. Ethylene oligomerization processes have been using commercial processes to produce yields centered around 10 and 12 carbons with chains ranging around four and more than 20 carbons [10]. For the patented commercial process, the molar ratio of feed between isoparaffins to ethylene is less than 0.1 [26]. Then the feed is charged with an ionic liquid catalyst alongside a co-catalyst with a halide [26]. Finally, the oligomerization process in the reactor produces hydrocarbon product as seen in Figure 8 [26].

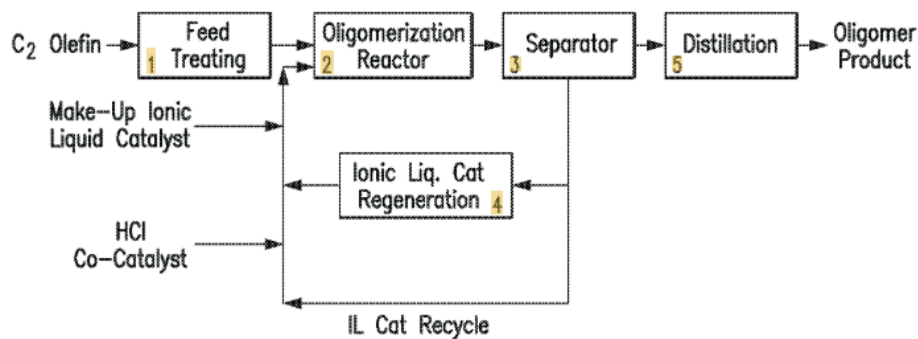


Figure 8: Patented Oligomerization process in the ATJ pathway [26].

1.2.4 End of pathway

The last of the three catalytic processes is hydrogenation where the remaining double bonds of the olefins are saturated after oligomerization [10]. It is important to saturate the product to make sure that there is low reactivity of the fuel. A solid catalyst is used for this process along with hydrogen gas in excess which is fed into the reactor as seen in Figure 6 to make sure that the conversion occurs to completion [10]. After, fractionation of the synthetic paraffin product occurs as the result of hydrogenation is a mixture of synthetic paraffins in the kerosene range. It is separated into viable blend stock, and the remaining is used for products in naphtha and diesel [10].

There must be more investigation done into the conversion of isobutanol into jet fuel. Currently, most processes rely on ethanol. However, isobutanol and isobutylene are more favorable due to their thermodynamic properties leading to lower capital costs for dehydration, oligomerization, and separation. The ethanol pathway requires additional gas [10].

There is only one working ATJ-SPK pathway plant in commercial use making it far less developed than the commercially available HEFA pathway; however, it is currently approaching commercialization. Another approach that will assist ATJ towards this goal is the addition of alcohol to upgrade ethanol production which allows for identical carbon yield but improves the jet fuel yield [10]. There are also further innovations being made to catalysts used in the three processes that make up the core of this pathway. On January 14, 2026, Gevo, Inc was awarded a patent that broadens protections for different catalysts for the Ethanol to Olefins (ETO) technology used to produce fuels [27]. The patented process produces light olefins from ethanol and can then convert those olefins into SAF using commercially available ATJ technologies [27]. Even with developments being made to ATJ technology it is still a more expensive pathway than HEFA [19]. ATJ has the advantage of utilizing a wider range of less competitive feedstocks than HEFA making the ATJ pathway a reliable prospect for SAF production going into the future [19].

1.3 Fischer-Tropsch Synthetic Paraffinic Kerosene Pathway

1.3.1 Pretreatment: Syngas production

Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK, ASTM D7566 Annex A1) process is still in development, with a demand to meet emission goals [7], [28]. The Fischer-Tropsch process was developed by Franz Fischer and Hans Tropsch in the 1920s [29]. The process starts with gasification, a thermochemical process that converts the solid biomass feedstock into syngas rich in Hydrogen (H_2) and carbon monoxide (CO) [30], [29]. Traditionally syngas is produced with coal as feedstock, but more renewable options include woody biomass like invasive alien plants (IAPs), MSW, sugarcane molasses, and industrial waste gases reducing greenhouse gas emissions [31].

The process starts with gasification where the feedstock is broken into individual parts that then form synthetic gas (syngas) which is the feedstock for the FT-SPK pathway. Gasification utilizes a plasma gasifier which produces an electric arc turning feedstock into syngas as seen in Figure 9. The waste initially in the waste storage is inserted into the inlet of the furnace at high temperatures where it is turned into gas [32]. The incombustible materials go down and melt in the furnace. The gas generated in the gasifying layer of the furnace is collected in the upper levels. The steam from the boiler helps to power the steam turbine to generate the electricity needed to power the furnace [32].

Catalysts can also be used in the production of syngas which are often small amounts of char and tar [29]. However, tar can clog the gasifier pipes leading to safety issues [29]. With the assistance of a catalyst syngas, less tar is formed at low reaction temperatures [33]. Repanga et al. tested several different kinds of catalysts in producing H₂ from biomass [33]. They discovered that tri-metallic

perovskite catalysts prepared with a sol-gel technique and characterized in relation to their structure [34]. $\text{LaNi}_{0.3}\text{Fe}_{0.7}\text{O}_3$ had the best activity at the temperature and concentration often encountered in a gasification reactor. Furthermore, the addition of a hydrogen stream allows for better control of the degree of reduction of catalysts preventing oxidation of the metallic Ni sites [34]. Ni-based catalysts are often used in gasification, tar conversion, and reforming light hydrocarbons [33]. Jiang et al. prepared a Ni-based catalysts meant for producing hydrogen-rich syngas from straw biomass which is abundant in China [33]. This group found max yield of hydrogen with a 7.5% Ni/ $\gamma\text{-Al}_2\text{O}_3$ catalyst. With the addition MgO , there is an increase in H_2 yield and a decrease in the CO content in the syngas as seen in Figure 10 [33].

Figure 9: plasma gasifier used to generate syngas feedstock for FT-SPK [32]

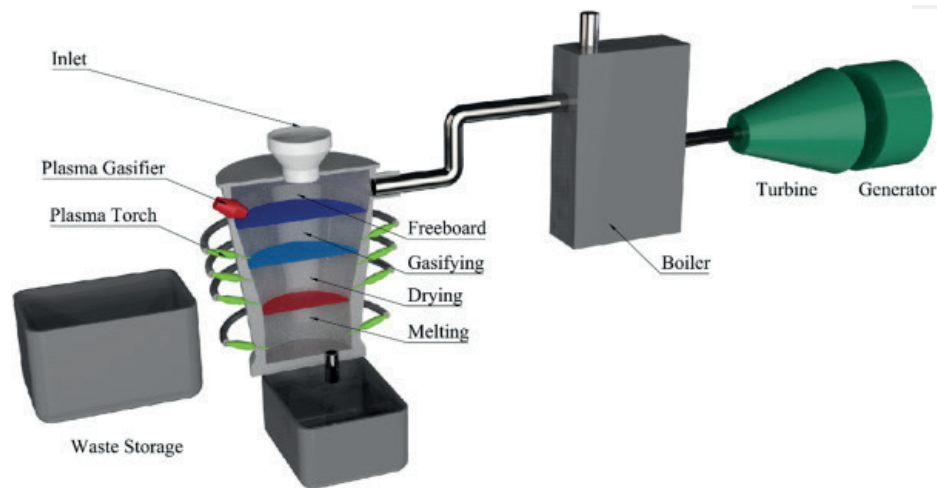
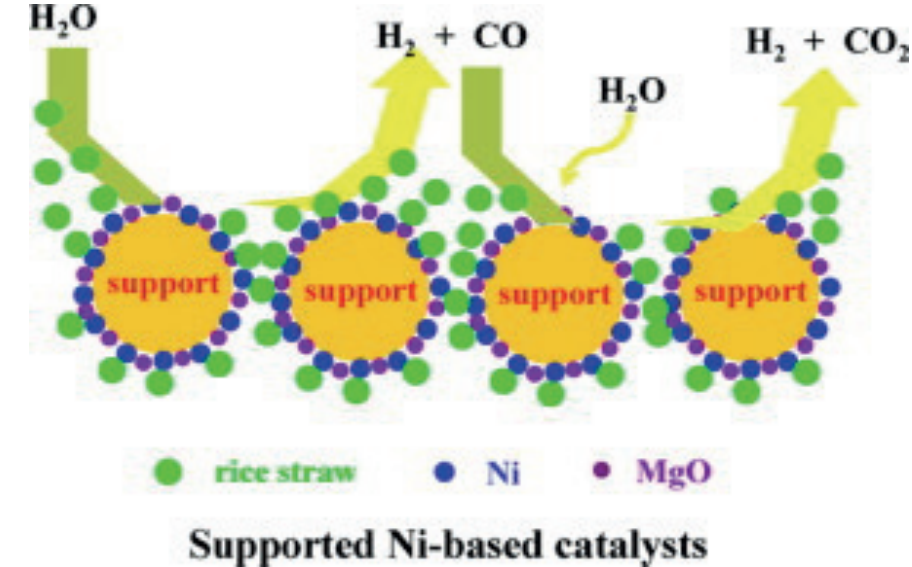


Figure 10: Reaction of Ni-based catalyst with MgO [33].



1.3.2 FT-Reactor

Once the syngas is produced through a pathway developed by Sasol, a South African company, which can be seen in Figure 11 [35]. Like most other FT processes, the Sasol pathway is a gas to liquid technology with three major steps: Syngas production, FT conversion, and then fractionation [36]. A schematic of the reaction can be seen in Figure 11 [36]. Once syngas is produced as described in the previous section, the FT reactor converts feedstock to fuel with iron or cobalt catalysts, creating a synthetic crude (syncrude) product [31]. With a cobalt catalyst, the temperature range is decreased, often less than 240°C compared to an iron catalyzed process which ranges from 220°C to 340°C [31], [35]. The syncrude is a mixture of light gases like methane and long chain hydrocarbons [37].

Once the syncrude is created, it is separated and refined to produce the desired product. Refinery processes include distillation, hydrogenation, hydrocracking, and hydroisomerization to produce hydrocarbons [35]. The syncrude is separated into three different liquid streams: liquid wax fraction which includes the long-chain hydrocarbons, hot condensate, and cold condensate. The wax fraction is a liquid under the operating conditions and therefore can be easily separated from the gaseous product stream. In the refining process, as seen in Figure 12 starts with the wax fraction of the syncrude mixing with hot condensate and hydrogen to be heated and fed to the hydrocracking reactor [37]. The products are saturated hydrocarbons within a downstream rectification column; the heavier components are recycled back into the reactor [37]. The hydrocarbons extracted from the process are used to produce SAF.

1.3.3 Fischer-Tropsch Synthetic Paraffinic Kerosene Aromatic Pathway

The Fischer-Tropsch Synthetic Paraffinic Kerosene Aromatic Pathway (FT-SPK/A, ASTM D7566 Annex A4) is like the FT-SPK pathway with the addition of aromatics [7], [8]. Aromatics are derived from crude oil and have a distinctive smell. Aromatic synthesis has been shown to increase SAF yield while reducing production costs and is more suited for standalone syncrude refinery [35]. The higher the temperature of the reactor, the more aromatics are produced [35]. Aromatics are needed to maintain seal compatibility; they promote seal swelling and without them seal shrinkage occurs leading to fuel leakage [38]. A primary refining step includes oligomerization with an aromatic feed which allows for alkene oligomerization and Friedel-Crafts alkene-aromatic alkylation over the same catalyst [35].

1.3.4 Outlook for the FT-SPK Pathway

There are no large-scale FT-SPK plants that can keep up with the demand for SAF production. However, compared to other ASTM SAF approved pathways, it is the closest to being commercialized. It would be widely beneficial as the FT-SPK pathway utilizes a variety of feedstocks including MSW and waste gas [39]. This process is also often powered by renewable energy sources like wind and solar reducing its carbon footprint compared to traditional fossil fuels. This process also has a lower sulfur content, reducing the risk for corrosion and increasing thermal stability [28]. However, there are challenges with the FT reactor design including hotspot formation due to exothermic reactions, catalyst fouling, and catalyst-wax separation difficulties, and a large carbon footprint and complexity at the commercial scale [40].

There are designs that have been developed of FT-SPK reactors that address these challenges and help move the FT-SPK pathway towards commercialization. Velocys has developed a Microchannel Fischer-Tropsch reactor which has thousands of small, parallel flow channels enhancing heat and mass transfer addressing issues with poor heat transfer that lead to catalyst deactivation. This reactor is easier to scale up by simply numbering up the reactor units [40]. This reactor also makes it easier to control the highly exothermic FT reaction as well as reducing the thermal gradients and hot spots further reducing the chances of catalyst degradation [40].

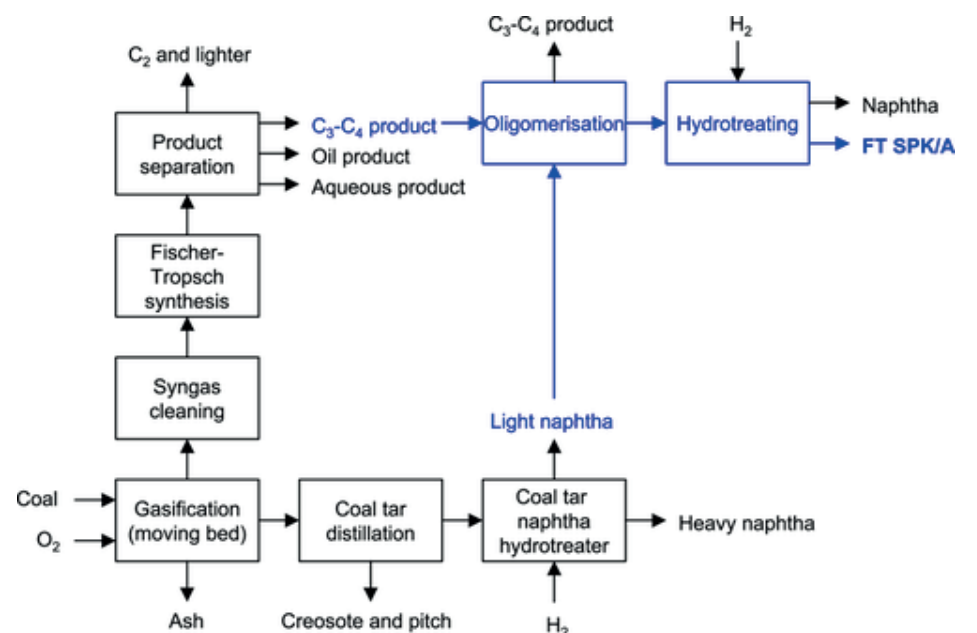


Figure 11: Sasol FT Pathway [35]

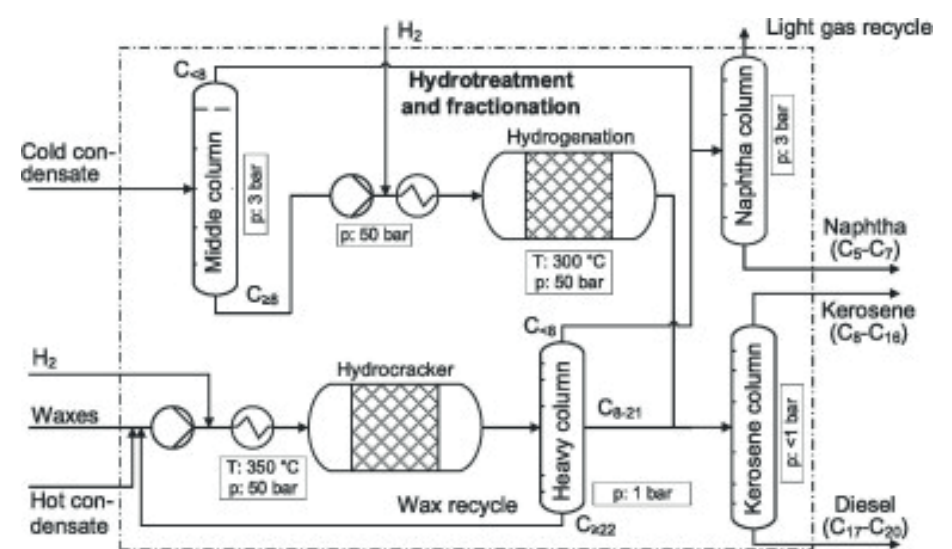


Figure 12: Syncrude refining flow sheet [37].

2. Industry Progress, Commercialization, and Future Outlook

2.1 SAF production feedstock

One of the main focuses when discussing SAF reliability and production is feedstocks based on the requirements of each specific pathway as seen in Figure 13. There are four different categories of biofuels characterized by their feedstock and biosynthetic platform, three of which can be seen in Figure 14 [23]. First generation biofuels are bioethanol and biodiesel which are produced based on microbial fermentation of edible feedstocks which are rich in starch and sugar as seen in the traditional HEFA and ATJ pathways [23], [12]. These feedstocks include vegetable oils, canola, soybean and palm [23], [11]. First generation feedstocks are technologically mature and cost-effective and can be used on a commercial scale mainly for the road sector but is limited due to the concern over high demand for land use [11]. Many crops would be needed to supply only a fraction of the fuel needed for aviation [23]. This method also raises concerns over competition with the food supply chain leading to land use and deforestation [11], [41].

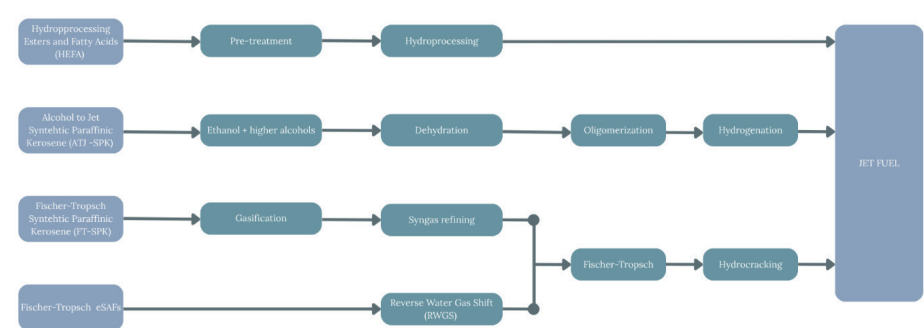


Figure 13: Schematic with feedstock and ASTM certified pathway taken to produce SAFs [23].

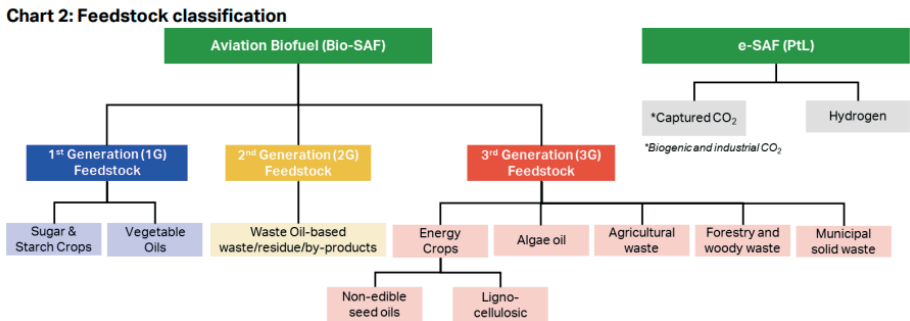


Figure 14: Feedstock classification for first, second, and third generation of biofuel feedstock and e-SAF PtL. [11].

Second generation biofuel and e-kerosene are more commonly used in the production of aviation fuel as the feedstocks are lignocellulosic biomass which can come from woodland residues and other waste streams [23]. Feedstocks that come from waste have an inelastic supply and no economic value [42]. They are non-food cellulosic materials which require less land and do not compete with food resources. Due to the impurities in the waste, pretreatment steps are required as seen in the HEFA pathway pretreatment process, this leads to greater process time and costs [23],[41]. Wastes are more sustainable compared to first-generation feedstocks due to the higher potential for greenhouse gas emission reduction by reusing waste that would otherwise contaminate environments [11]. Used cooking oil (UCO) is the feedstock that is most frequently used for the HEFA process which is currently the only commercially available SAF production process [43].UCO is primarily imported to the United States and Europe from China, but with tariffs and new SAF mandates, the feedstock is facing global constraints [43]. However, second generation bio-SAF is one of the most sustainable and reliable options to produce aviation fuels [41]. To avoid increasing prices for feedstock and availability imbalance, alternative oily feedstock options should be explored.

Third and fourth generation biofuels are less commonly used to produce aviation fuels because technology is still in development. Third generation biofuels are derived from biological and agricultural waste from degraded land; they have high potential for emissions reductions and are more abundantly available [11]. Feedstocks include MSW, agricultural and forestry residues, and algae that were seen in the production of SAF through the more developed ATJ and FT-SPK pathways [31], [8]. Currently, research is being carried out to utilize microalgae as a feedstock as it is faster and abundant. However, due to the CO₂ needed for photosynthesis this feedstock could lead to a negative carbon footprint [23]. Fourth generation biofuels use genetic engineering and multiple types of sugars with challenges of toxicity [23].

HEFA is the only commercially mature and available production pathway for SAF production. However, there is no diversity in feedstock being used, HEFA is reliant on oil-based feedstock with current infrastructure with the primary feedstock being UCO. This leads to feedstock shortages; therefore a infrastructure needs to be established to diversify feedstocks [11], [43]. The feedstock supply chain must be streamlined, particularly, the availability of waste oils and animal fats which face challenges in aggregation [11]. It is essential to develop new scalable feedstock sources to support long-term growth for the HEFA pathway

ATJ and FT pathways and even HEFA with developed pretreatment processes can use a wider range of feedstocks like MSW and agricultural residues [11]. The cost for any SAF pathway is currently more expensive than the traditional petroleum-based fuel production pathways so the diversification of feedstock could reduce the cost disparity and encourage airlines to use more SAFs [30]. Municipal Solid Waste (MSW) is abundant and a low-cost feedstock that can be used to produce SAF [11]. MSW FT through gasification has a TRL between 7 and 8 so using MSW for SAF production helps diversify feedstocks for SAF production as well as supporting waste management goals [11]. However, due to the impurities a pretreatment process must be used leading to technical complication [11]. This requires organizations and companies to invest in renewable energy and carbon capture research and development.

2.2 Biomass Feedstock Future Outlook

There are various industries currently using about 60% of total biomass resources which means less than 35% is expected to be available for bioenergy and biofuels at around 4200 Mt in 2050 [11]. There are discrepancies of feedstocks around the world leading to hotspots for biomass feedstocks concentrating in the United States, Brazil, Europe, and India consisting of 50% of the global total availability [11]. There is expected to be an increase in biomass feedstocks through 2050 stemming from an increase in agricultural residues due to crop production and improved yields as seen in Figure 15 [11]. Some regions will benefit more from sugar and starch-based ethanol being allocated to the SAF market while others will not [11].

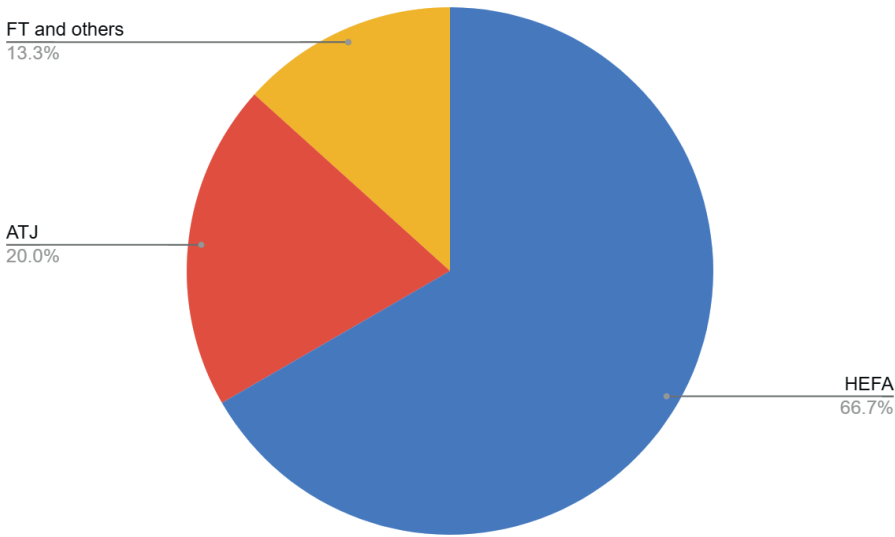


Figure 15: Chart of SAF production pathways by expected performance in 2030 [49]

Most technologies are expected to increase ambitiously except for MSW FT and HEFA routes. The HEFA routes are commercially scaled already and do not require a growth phase while MSW has scale-up challenges with FT [11]. However, the HEFA routes that rely on UCO are not consistently reliable as the dominant feedstock of UCO faces global supply constraints due to new tariffs on the primary importer, China [35]. It is necessary to explore alternative oily feedstocks including more research into waste and byproduct feedstocks that have low life cycle greenhouse gas emissions [35]. Biomass feedstock is available but not all of it could be used for SAF production therefore, action is needed to establish global, liquid, and transparent SAF [11].

Chart 7: Regional potential availability of biomass feedstock for SAF in 2030 and 2050

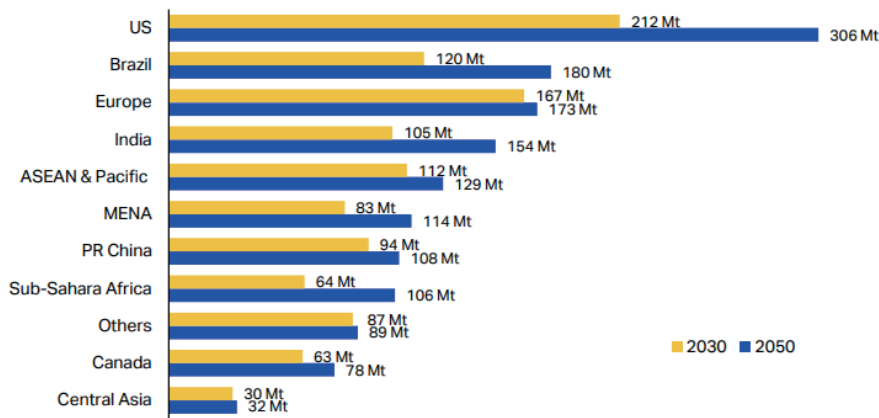


Figure 16: Regional potential availability of biomass feedstock for SAF in 2030 and 2050 [11].

2.3 Commercialization

2.3.1 Incentives

SAFs are one of the main routes to decarbonization in the aviation sector, however, it is not an attractive option for a lot of airlines. SAF is currently 2 to 4 times more expensive than standard jet fuel [44]. SAF credits and government incentives are crucial to bridging the cost gap and further accelerating SAF development and adoption [44]. This begins with setting goals for decarbonization for governments to work towards. International organizations like the ICAO and IATA provide a forum for governments to agree on goals. Member states of the ICAO and IATA have pledged to reach net zero emissions by 2050 under the Net Zero Initiative [2]. In Late 2022, counties also agreed on a new baseline for the Carbon offsetting and Reduction Scheme for International Aviation (CORSIA) at 85% of the 2019 emissions level of international aviation [2]. These goals allow countries to create their own road maps and incentives for the private sector to increase SAF production and use.

Different countries have established their own initiatives to meet the net zero emissions goal. In Europe the ReFuelEU from the European Commission which sets up a trading system to phase out allowance given to the aviation industry [2], [44]. In 2022, France and Norway set their own blending mandates [2]. In the United States, the US Department of Energy (US DOE), Department of Transportation (DOT), The Department of Agriculture (USDA), and other federal government agencies developed a strategy for scaling up new SAF technologies titled, the Sustainable Aviation Fuel Grand Challenge [45]. The roadmap involves 3 billion gallons per year of domestic SAF by 2030, and 35 billion gallons of SAF to fulfill 100% of domestic demand by 2050 [45]. In South America, Brazil announced their Fuel of The Future requiring airlines to reduce domestic flight greenhouse gas emissions by 10% in 2037 with the use of SAFs [2]. In the Asia Pacific Region, Japan and China have proposed legislation to lower GHG emissions with their own individual roadmaps [2]. To achieve the goals, various governments have set mandates that the fuel industry must meet but to further encourage the private sector and airlines to focus on SAF technology, incentives are essential.

To further encourage the private sector and airlines to focus more on SAF technology, investments from governments is essential. The Swedish government has announced that it is aiming to annually invest 15 million Swedish Kroner (1.6 million USD) to support research and development of SAF [2]. The United States has fuel credit for Sustainable Aviation under the inflation reduction act of 2022 where 1.25 USD is credited for each gallon of SAF and supplemental credit of 0.01 USD for

each percent that the reduction exceeds 50% [46]. To meet mandates, in the private sector, airlines are moving towards offtake agreements with fuel suppliers to supply SAFs. The IATA launched an SAF registry through the Civil Aviation Decarbonization Organization (CADO) which tracks SAF purchases between airlines, corporate customers, fuel producers, and regulatory bodies as seen in Figure 16 [6], [47], [48]. This helps to determine SAF use and GHG emission reduction so that SAF use can be credited. With governments reallocating support from fossil fuels in favor of renewable energy production, there is an added incentive for the private sector to keep pursuing research and development in the area [47]. As policy support accelerates in the 2030s, there is expected to an increase in reduction in emissions.

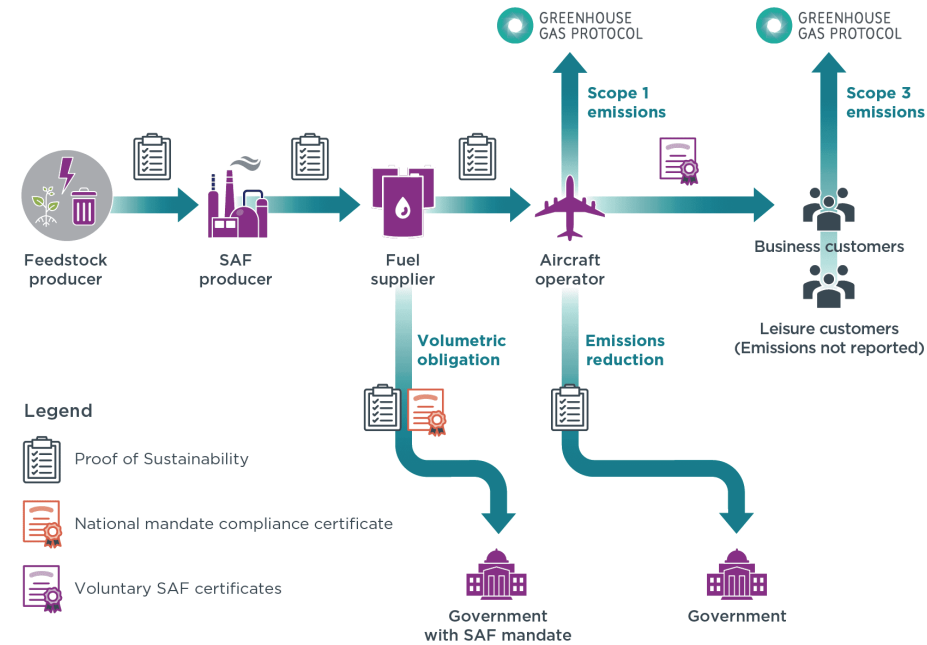


Figure 17: Infographic showing pathways of SAF production and distribution and where mandates are monitored [48]

2.3.2 Outlook

There are 11 different ASTM approved avenues to create SAFs as seen in Figure 2 but there are only a few that have been developed close to commercial maturity as seen in Figure 8. Scaling is the challenge inhibiting the further development of this technology. As of 2024, the SAF market is less than 0.5% of the global jet fuel consumption at around 1.1 million mt [49]. To meet the goals of net zero emissions by 2050, 80 million mt of SAF are required [49]. HEFA is expected to have a capacity of 25.3 million mt by 2030 amounting to two-thirds of the total SAF production while one-fifth (8.4 million mt) of the capacity is expected to rely on the ATJ pathway, and the remaining will be reliant on FT, methanol to jet, and other pathways as seen in Figure 15 [49]. There is not one SAF production pathway that is sufficient to meet the future demand for SAF. With further developments to SAF production infrastructure and feedstock diversification, the combination of these different paths can be the solution [50].

2.4 Innovation – Power-to-liquid (PtL)

As feedstock availability and cost efficiency of the processes have led to obstacles in the development of more SAF production, there has been a lot of attention on research being done on eSAFs. With air travel becoming more popular and an increase in passengers every year, to keep up with the emissions, SAF production must also increase [49]. In the last year, SAF capacity has slowed down along with investments into developing the technology [49]. To ramp up SAF production, more costly but efficient technologies like power-to-liquid (PtL) will be needed [49].

The HEFA, ATJ, and FT processes discussed in Section 1 are kerosene-based fuels which are made up of hydrocarbons and deal with challenges of limited feedstock availability [51]. PtL requires a feedstock with carbon dioxide (CO₂) and like the other pathways can get it from biomasses or industrial waste. What makes PtL different is that it can also use captured air combined with green hydrogen as a feedstock or other renewable energy sources like water [51], [52]. PtL produces eSAF from the feedstock through processes like FT to convert the produced syngas into liquid products [39]. which is not made from biomass but instead is derived from CO₂ through an electrochemical process as seen in Figure 17 [52], [53].

The production of PtL has a favorable greenhouse gas balance and represents an emissions reduction of up to 90% while using 30 times less land and 1000 times less water than biofuels [51], [53]. Currently, waste gases and biogenic industrial sources like ethanol production [53]. Like the ATJ and FT pathways, PtL struggles to reach commercial production without significant policy incentives [52]. To keep SAFs commercially viable for large airlines, it is important to keep exploring and researching alternative pathways which can be done through government incentives which also encourage the private sector to invest in PtL pathway development.

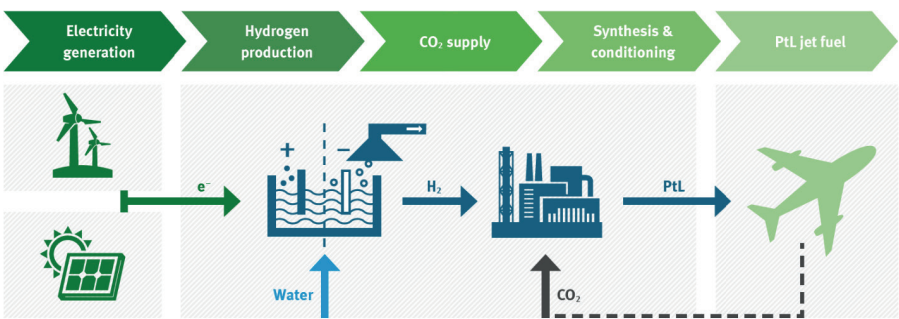


Figure 18: Electrochemical processes used during the PtL process.

Conclusion

With air travel becoming more popular, it is crucial to emphasize the importance of decarbonization in the aviation industry as it contributes to a significant portion of carbon emissions. SAF production pathways are the most practical way to reach the net zero emissions by 2050 that the IATA has set [4]. HEFA is the leading pathway but has reached a plateau in improvements while facing challenges facing feedstock availability. With slow progress being made in other ASTM approved pathways FT and ATJ are the closest to commercialization. To meet the 2050 net zero goal, a combination of different pathways must be used and that can be done with further research and development. The money needed for that comes from airlines and governments investing in research which they have been encouraged to do through incentives from the ICAO, IATA, and programs like ReFuelEU and the IRA. Looking into the future, innovation is necessary to develop and find new solutions like Power-to-liquid where the feedstocks are renewable resources, and the process is powered by renewable energy reducing greenhouse gas emissions.

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