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Clearing the Air:
*Sustainable Aviation Fuel
(SAF) for Transforming the
Aviation Industry*

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Glossary

ASTM	American Society for Testing and Materials
ATAG	Authoring Tool Accessibility Guidelines
ATJ	Alcohol to Jet Fuel
ATM	Air Transport Management
CH	Catalytic Hydro-thermolysis
CNS	Communication, Navigation, Surveillance
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
FT	Fisher Tropsch
FT-SPK/A	Fischer-Tropsch Synthetic Paraffinic Kerosene with aromatics
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
GHGs	Greenhouse gases
HEFA	Hydroprocessed Ester and Fatty Acids
HEFA-SPK	Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic
IATA	International Air Transport Association
MSW	Municipal Solid Waste
SAF	Sustainable Aviation Fuel
SIP-HFS	Synthetic Iso-paraffins Hydroprocessed Fermented Sugars
TRL/FRL	Technology Readiness Level / Fuel Readiness Level

Introduction



The aviation industry is projected to grow substantially, with an estimated 4 to 5% increase in air traffic annually. Some regions may experience higher growth rates, leading to more than 3 billion passengers travelling worldwide yearly. The aviation sector contributes significantly to the global economy, contributing approximately US\$2.2 trillion¹ to the GDP. However, it is essential to recognise the aviation industry's environmental impact. This industry is responsible for almost 2% of global greenhouse gas (GHG) emissions.

As the world continues to face climate change, global GHG emissions are expected to increase to over 3.0 billion tonnes by 2050. This figure is four times higher than the 2015 baseline of 0.78 billion tonnes, encompassing passenger and freight emissions. Therefore, it is apparent that the aviation sector's growth must be accompanied by sustainable practices and innovations to mitigate its carbon footprint.

Addressing the environmental impact of this industry is essential not only from an ethical standpoint but also for global efforts to combat climate change. The aviation sector must reconcile its growth ambitions with the need to reduce GHG emissions, making it imperative for stakeholders to explore cleaner and more efficient technologies and practices to ensure a sustainable future for air travel.

Currently, passenger and freight activities account for 2.5% of global CO₂ emissions², equivalent to 1.04 billion tonnes. This figure is projected to increase by 5% by the year 2050³. However, by 2050, the aviation industry is expected to contribute nearly 3 billion metric tons of CO₂ emissions globally⁴.

Air travel is also responsible for 1.9% of greenhouse gas emissions on a global scale⁵ and 3.5% of effective radiative forcing (RF), with positive RF contributing to warming and negative RF contributing to cooling.

Carbon emissions from the aviation sector in different parts of the world are shown in **Figure 1**.

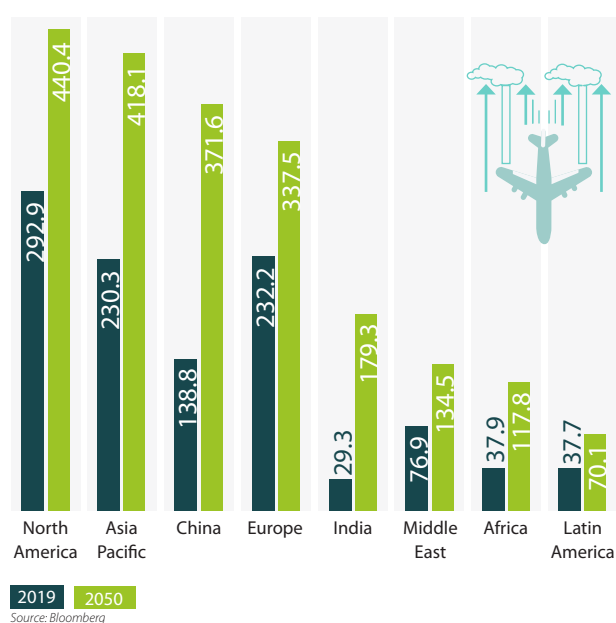


Figure 1: Carbon Emissions from Aviation by World Region (In Million Metric Tons CO₂ Equivalent)

The data, measured in million metric tons of CO₂ equivalent, is for 2019 and 2050. The findings indicate that India is projected to experience a significant increase in CO₂ emissions, estimated to grow about six times from 2019 to 2050. On the other hand, other regions show a relatively moderate increase in emissions by 2050 compared to 2019.

North America, Asia-Pacific, Europe, the Middle East, and Latin America are all expected to experience emissions ranging from 1.5 to 1.9 times more in 2050 compared to 2019. These findings highlight India's potential for a substantial increase in emissions in the aviation sector over the coming decades compared to other regions.

Air travel contributes to climate change through carbon dioxide emissions and other pollutants like nitrous gases, soot, sulphate particles, and particulate matter. These pollutants are often grouped under greenhouse gas emissions and collectively contribute to the environmental impact of air travel.

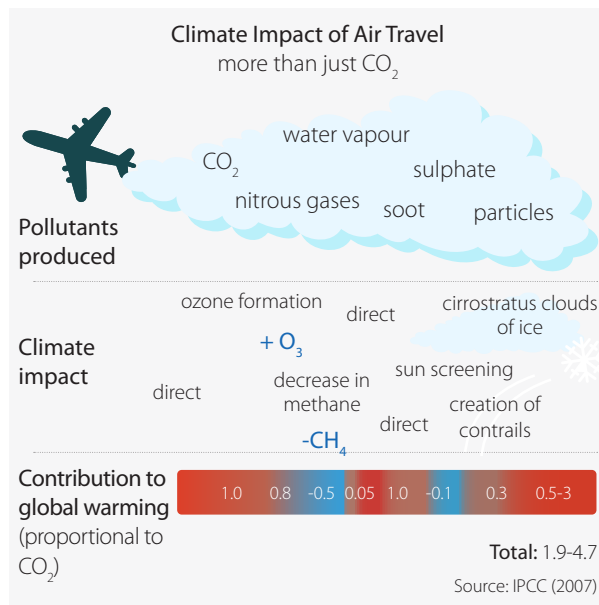


Figure 2: Climate Impact of Air Travel

While carbon dioxide is the most talked-about greenhouse gas emitted by aircraft, it's crucial to recognise the complex nature of aviation emissions and their implications for climate change and environmental health. **Figure 2** provides further insights into the climate impact of air travel through its greenhouse gas emissions.

The aviation industry came together in 2009 to establish the first-ever climate change objectives tailored to its sector⁶. These objectives include a 1.5% improvement in fuel efficiency from 2009 to 2020 and achieving carbon-neutral growth from 2020 onwards.

Additionally, the industry aims to reduce carbon emissions by 50% by 2050 compared to the baseline set 2005, as shown in **Figure 3**. The sector must widely adopt Sustainable Aviation Fuels (SAF) to reach this goal.

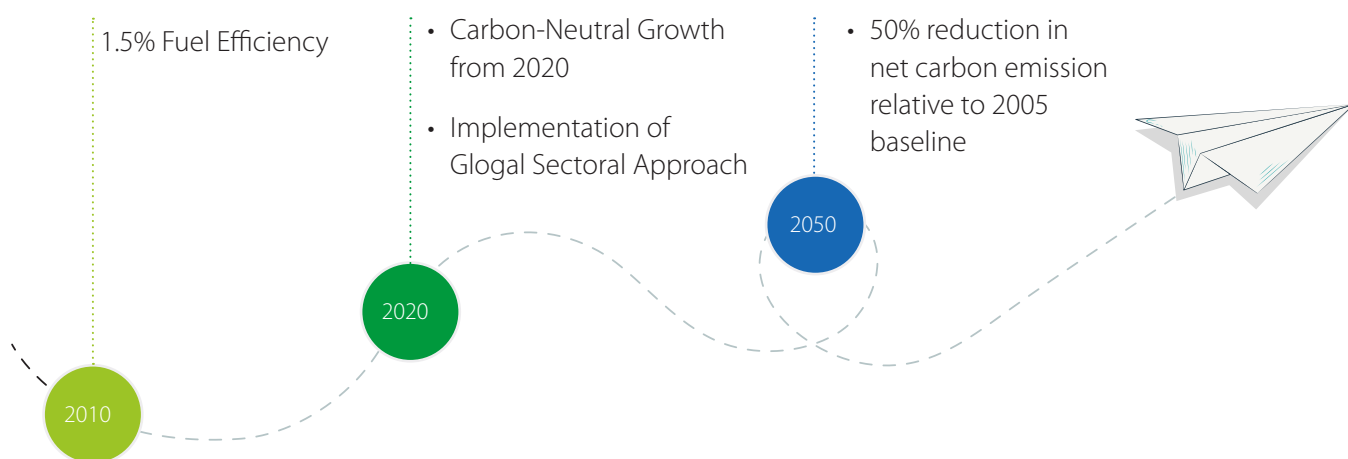


Figure 3: IATA Sustainable Aviation Fuel Roadmap

Commercial aviation, which relies on conventional fuel, faces multiple challenges, such as increasing fuel costs, environmental impact (including climate change), and energy security concerns. To overcome these challenges and achieve the goals set forth by IATA, the following actions have been proposed:

1. Development and implementation of Sustainable Aviation Fuel (SAF) - a sustainable, low-carbon alternative fuel.
2. Incorporating advanced, fuel-efficient technologies in existing aircraft to enhance their efficiency.
3. Developing zero-emission aircraft, including electric, hydrogen-powered, and hybrid-hydrogen aircraft.
4. Upgrading Communication, Navigation, and Surveillance (CNS) systems and Air Transport Management (ATM) to optimise air traffic management and infrastructure usage.
5. Implementing weight reduction strategies, aerodynamic enhancements, and efficient equipment to enhance operational efficiency.
6. Exploring and advocating for economic and market-based solutions to reduce emissions, such as emission trading, taxation, and offsetting, which are either cost-free or cost-effective.

These actions aim to address the challenges faced by commercial aviation and to ensure a sustainable and efficient aviation industry for the future.

Figure 4 illustrates the various technologies and strategies contributing to achieving net-zero emissions by 2050 within the aviation sector.

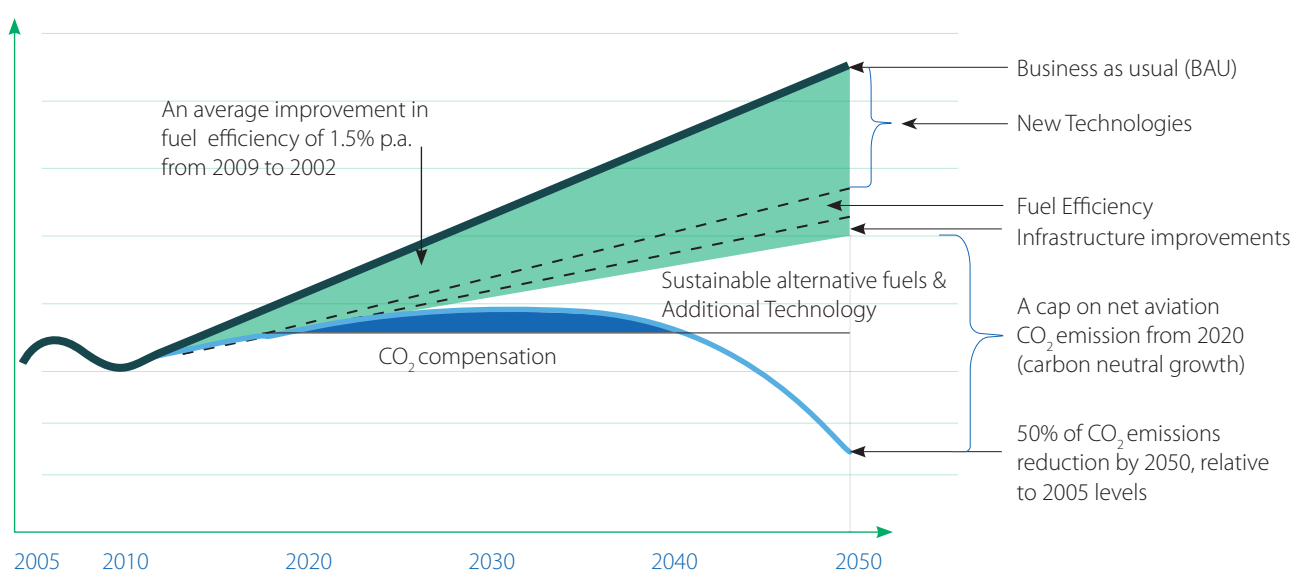


Figure 4: Conceptual Roadmap for Reducing CO₂ Emissions

These include Sustainable Aviation Fuel (SAF), emerging technologies like electric and hydrogen-powered aircraft, infrastructure improvements, operational efficiencies, offset programs, and carbon capture initiatives. The aviation industry collectively committed to reducing carbon emissions starting in 2009, and **Figure 5** presents the conceptual roadmap for this reduction. This roadmap relies on four key strategies:

1. Adopting new technologies
2. Enhancing fuel efficiency
3. Optimising infrastructure, and
4. Implementing sound economic policies

All of them are pivotal in reaching these sustainability goals. A few prominent considerations in the aviation sector are looking ahead to the emergence of fully electric aircraft with the capacity to transport more than 100 passengers in the coming decades. However, it is crucial to consider that, given the current state of battery technology, these aircraft would necessitate a significant battery weight.

Approximately 50 kilograms of batteries are needed for each kilogram of fossil fuel equivalent. Unlike fuel, the weight of batteries remains constant after energy consumption, necessitating their continued carriage by the aircraft.

Hydrogen fuel cell propulsion systems can eliminate CO₂ and NO_x emissions from aircraft exhaust. However, hydrogen as a fuel source presents significant challenges, encompassing hydrogen production and storage, aircraft and engine design considerations, and more. Realising hydrogen-powered air traffic for short distances (up to 2000 km) and long-haul flights (up to 10,000 km) may remain decades away.

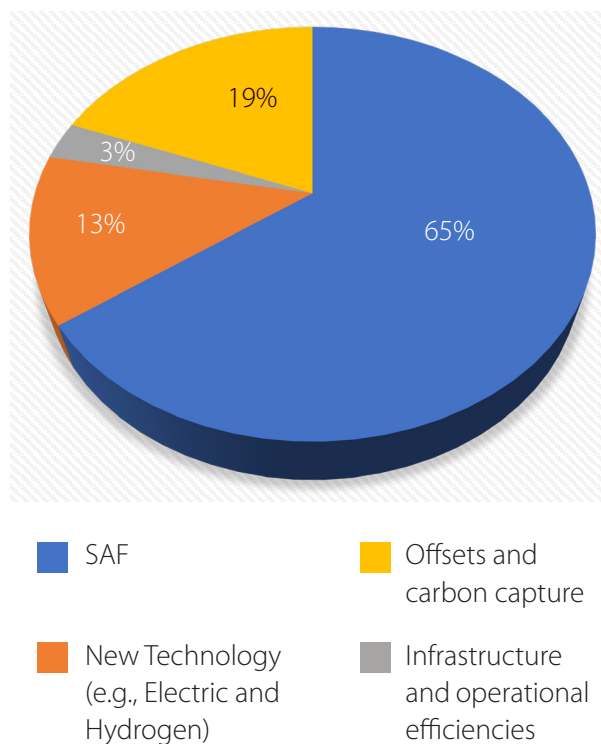
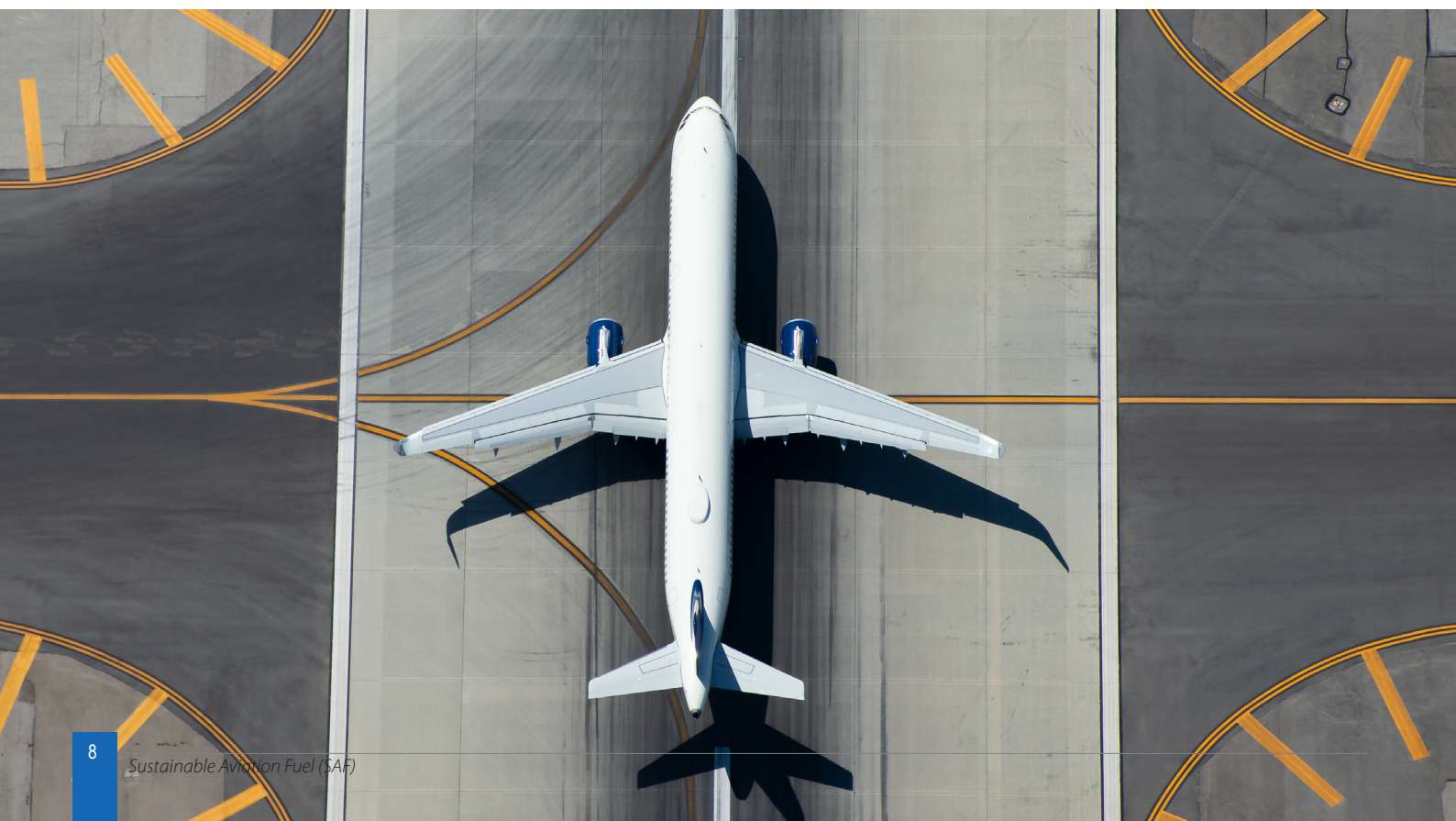


Figure 5: Approach to Achieving Net Zero Carbon in 2050



Short-range aircraft powered by hybrid H₂ propulsion

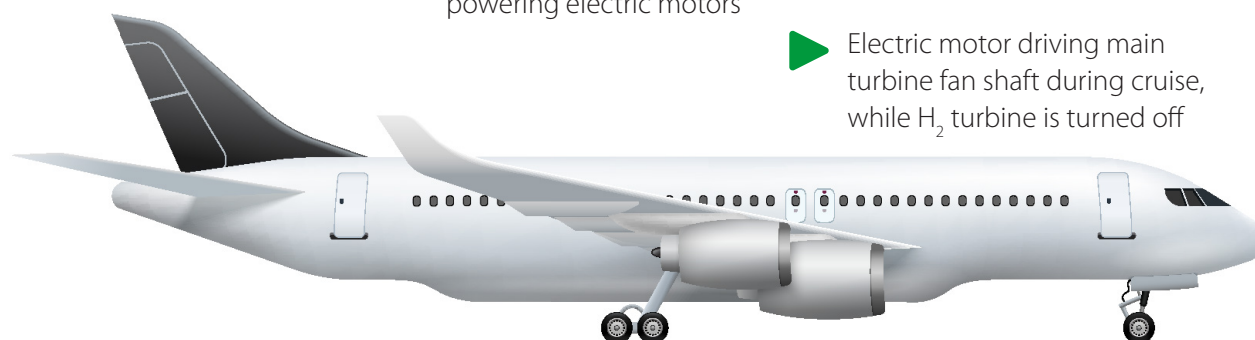
Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

▶ 2 LH₂ tanks behind PAX cabin-added weight: 4 tons

▶ Fuel cell system (11 MW) powering electric motors

▶ Electric motor driving main turbine fan shaft during cruise, while H₂ turbine is turned off



1. Major assumptions: 35% gravimetric index of LH₂ tank, 91% useable LH₂ fuel, FCS mass 2kw/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg. H₂ – turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

Energy demand ¹		-4%	Additional cost		20-30% CASK ²	Propulsion power		Hybrid
CO ₂ reduction		100%	Entry into service		15 years	MTOW ³		+14%
Climate impact reduction		70-80%						

Figure 6: H₂ Powered Aircraft up to 2000 km⁷

Figure 6 provides essential insights into short-range aircraft powered by hybrid hydrogen (H₂) propulsion. It is worth noting that liquefied hydrogen requires less storage space than traditional kerosene (due to its energy density) for passenger and cargo aviation, necessitating airport infrastructure upgrades to accommodate new hydrogen refuelling systems. The adoption of green hydrogen is essential to achieve the decarbonisation of the aviation sector.

However, in the context of short- and medium-haul operations, Sustainable Aviation Fuel (SAF) currently stands out as the most practical choice for reducing carbon emissions within air transport for the foreseeable future. Short-range aircraft incorporating hybrid hydrogen (H₂) propulsion systems are set to become feasible in the near future.

These hybrid H₂ propulsion systems are characterised by several key features, including a range of 2000 kilometres, the use of two LH₂ tanks, an 11 MW fuel cell, and additional equipment, such as an electric motor that drives the main turbine fan shaft during cruise, effectively allowing the H₂ turbine to be deactivated. Other details are depicted in **Figure 6**.

Electrified aircraft and hydrogen-powered aircraft using green hydrogen remain somewhat distant prospects. Consequently, SAF is the most viable and sustainable option for decarbonising the aviation industry. According to estimates by IATA, SAF has the potential to deliver a substantial portion of emissions reductions, ranging from 60% to 80%, necessary to attain net-zero emissions by 2050. As a result, this paper primarily focuses on developing and deploying SAF as a critical pathway towards a more sustainable aviation sector.

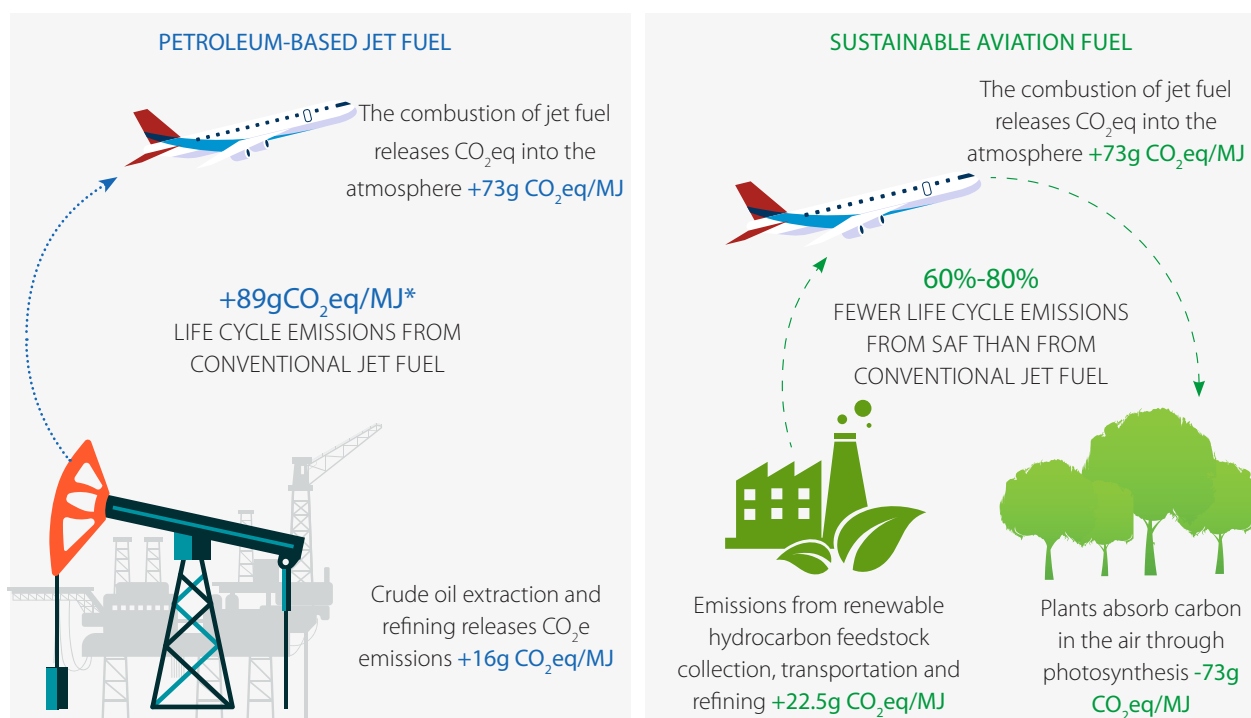


Figure 7: Comparison of Petroleum and Sustainable Based Fuel's Emission

Figure 7 illustrates two types of jet fuels like petroleum-based and sustainable-based. Emissions data are averages, based on estimates from LCA of current & future GHG emissions from Petroleum Jet Fuel Massachusetts Institute of Technology Laboratory. CO_2 eq per mega joule (MJ) is a measure of GHG emissions per unit of energy (DOE BETO Alternative Aviation Fuel Workshop Sep 2016). Petroleum-based jet fuel involves a process that emits 16 CO_2 eq (equivalent)/MJ during crude oil extraction and refining. When this fuel is burned, it releases 73g CO_2 eq/MJ into the atmosphere.

In contrast, sustainable-based jet fuel exhibits a lower environmental impact. It results in 22g CO_2 eq/MJ emissions, encompassing renewable hydrocarbon feedstock collection, transportation, and refining. When this sustainable jet fuel is combusted, it emits 73g CO_2 eq/MJ into the atmosphere.

One significant advantage of sustainable-based jet fuel is that the plants or crops used in their production absorb approximately 73g CO_2 eq/MJ of carbon dioxide from the air through photosynthesis. This natural process effectively reduces the overall carbon emissions throughout the fuel's lifecycle.

The information discussed above, includes aspects such as CO_2 reduction over the lifecycle, the medium to long-term adoption prospects of hydrogen-powered aircraft, and the current high cost of hydrogen production, which serves as a guiding framework for further research into Sustainable Aviation Fuels (SAF).

This data suggests that SAF may offer a more immediate and economically viable solution to reduce greenhouse gas emissions in the aviation industry, particularly compared to hydrogen-based alternatives.

In the context of short- and medium-haul operations, Sustainable Aviation Fuel (SAF) currently stands out as the most practical choice for reducing carbon emissions within air transport for the foreseeable future.

Sustainable Aviation Fuel (SAF)



SAF, often known as jet biofuel or aviation bio-kerosene, closely resembles the characteristics of conventional jet fuel⁸. However, SAF is derived from diverse and renewable biomass sources, including oil seeds, corn grain, animal fats, greases, algae, agricultural and forestry residues, wood mill by-products, municipal solid waste, and more, as shown in Figure 8.

The remarkable feature of SAF is its compatibility with existing infrastructure and aircraft engines, requiring no modifications to equipment such as engines and pipelines or infrastructure like distribution networks. This quality earns it the designation of “drop-in” fuel, signifying its seamless integration into current aviation systems.

The aviation sector has adopted safety guidelines and practises for blending SAF with regular fuel up to 50%. The two commonly used jet fuel types in passenger aircraft are “Jet A” and “Jet A-1”. The third type is “Jet B” (i.e., naphtha-kerosene), mainly used in military aircraft as per ASTM D1655 standard specifications.

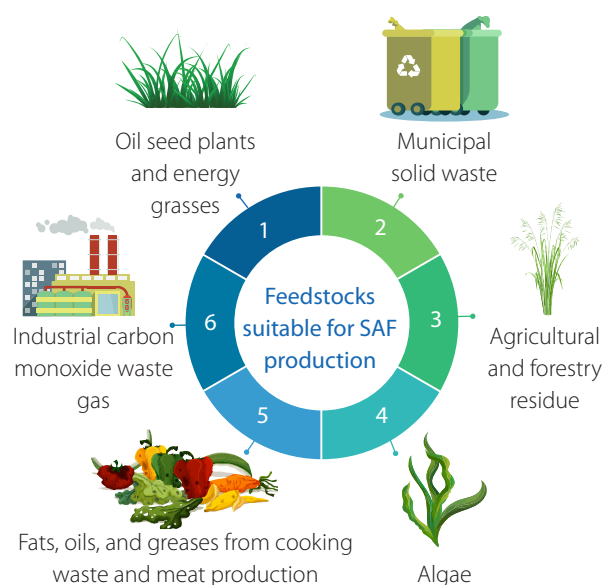


Figure 8: Feedstocks for SAF Production

The key features of jet fuel(s) are given below.

1. **Jet A** has a minimum flashpoint over 38.0°C and a maximum freeze point of (minus) - 40.0°C, density at 15°C of 775 – 840 kg/m³, maximum aromatic content of 25 vol %, viscosity of 8mm/sec @ -20°C, and maximum total sulphur content of 0.3 wt%.
2. **Jet A-1**, a kerosene-based aviation fuel, is suitable for various aircraft, including helicopter engines. Its properties are mentioned in **Table 1** below.
3. **Jet B** is a naphtha kerosene-based fuel used for operations in cold weather, as it has the lowest freezing point and a low flash point. It is used in some military aircraft and geographies with freezing weather conditions, such as Alaska, Northern Canada, and Russia.

The properties such as freezing point, energy density, and specific energy of these jet fuel A/A1 as per ASTM D1655 are given in **Table 1**.

Properties	Jet A	Jet A1
Specific energy, MJ/kg, (kWh/kg)	43.02, (11.95)	43.15, (11.99)
Freezing point, °C	- 40	-47
Energy density, MJ/L, (kWh/L)	35.3, (9.8)	34.7, (9.6)

Table 1: Typical Physical Properties of Jet A and Jet A-1

Life Cycle of SAF

Compared to conventional jet fuel, a pure SAF offers a remarkable reduction in carbon emissions of up to 80% over its entire lifecycle. The extent of this reduction depends on factors such as the sustainable feedstock used, the production methods employed, and the efficiency of the supply chain leading to the airport. SAF also generates fewer conventional pollutants, which can contribute to localised air quality concerns around airports. It emits lower sulfur oxides, particulates, carbon monoxide, and unburned hydrocarbons.

Furthermore, SAF reduces contrail formation due to the decreased presence of particulates in aircraft exhaust. Neste and Airbus have joined forces through a collaborative agreement to accelerate the adoption of 100% SAF within the aviation sector. This initiative encourages others and plays a crucial role in achieving the certification of 100% SAF usage by the end of the decade.

Figure 9 illustrates the lifecycle of SAF. Carbon dioxide (CO₂) emitted by aircraft or any other process is absorbed by plants during biomass growth. Consequently, SAF can be considered approximately carbon neutral over its lifecycle, effectively “de-fossilizing” the fuel by utilising carbon already in the biosphere.

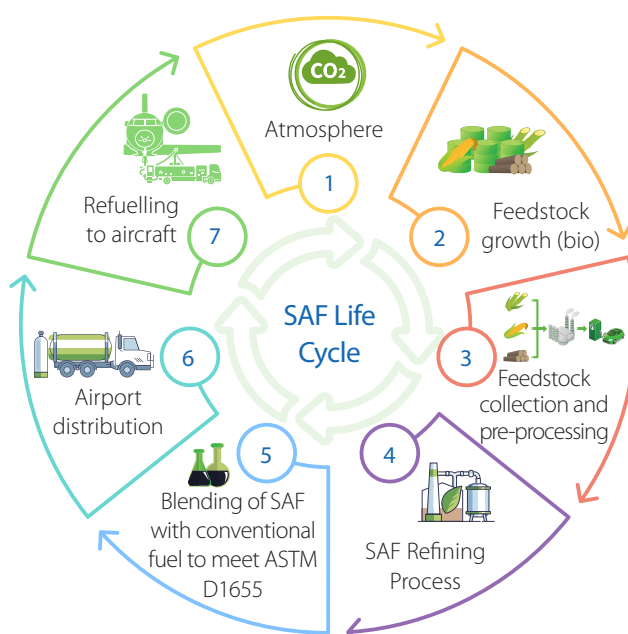


Figure 9: Life Cycle of SAF

However, emissions are produced during the SAF manufacturing process, transportation of raw materials, fuel refinement, etc. When all of these factors are considered, SAF has shown an overall reduction in CO₂ lifecycle emissions compared to fossil fuels. Furthermore, SAF has less sulphur and other impurities, which means lower sulphur dioxide and particulate matter emissions than conventional fuel. In the case of SAF produced from municipal solid waste (MSW), it would generate power for a commercial aircraft and eliminate the use of petroleum fuel in developing the SAF and conventional fuel used in powering the aircraft.

Key Driver(s) and Limitation(s)

The following vital drivers and limitations enable and hamper SAF development, as shown in **Table 2**.

Drivers	Limitations
Reducing GHG emissions is imperative to preserve biodiversity, enhance public health, strengthen the local economy, and mitigate the impacts of global climate change.	Feedstock supply readiness encompasses fuel quality, infrastructure & consistency, including a robust supply chain.
The volatility of oil and natural gas prices leads to fuel insecurity due to demand and supply fluctuations, production costs, and political instability.	Limited diversity in feedstock sources and production technologies.
Implementation of carbon pricing or taxation.	High feedstock processing costs can be approximately 3 to 5 times more expensive than conventional jet fuel.
Emergence of a new growth market for SAF or biofuels.	The necessity for clear policies and related incentives to stimulate SAF production. There needs to be a policy in the current situation.
It has the potential to boost agriculture and create numerous job opportunities.	Policy to create a level playing field with conventional fuel
A 50% blend can decrease emissions by 40%.	

Table 2: Key Drivers and Limitations of SAF Development

This paper investigates the market prospects and expansion of SAF, examining production technologies, the readiness level of this technology and the role of engineering consulting in decarbonising the aviation sector. This discussion is framed within the context of India, considering both energy security and environmental sustainability.

The remarkable feature of SAF is its compatibility with existing infrastructure and aircraft engines, requiring no modifications to equipment such as engines and pipelines or infrastructure like distribution networks. This quality earns it the designation of “drop-in” fuel, signifying its seamless integration into current aviation systems.

Market Potential - India Perspective



The challenging situation in India due to the COVID-19 pandemic and the ongoing Ukraine war has forced us to review critically the development of cleaner, affordable and renewable energy to resist global shocks. To achieve the 50% carbon reduction goal by 2050, a blend of fossil jet fuel and lower carbon SAF will be needed. This is also reflected in the IEA's Sustainable Development Scenario (SDS), which expects 10% and 20% biofuels or SAF mix to meet the aviation fuel demand by 2030 and 2040, respectively.

In this ambitious journey of sustainability, approx. 8 billion litres of SAF would be needed by 2025 and 449 billion litres by 2050 for net zero emissions. **Figure 10** depicts the global expected SAF production from 2025 to 2050⁹.

India has a unique opportunity to emerge as a global leader in producing and using SAF. India also has a strategic advantage to impact SAF production significantly. As per the McKinsey report¹⁰, "more than 80 private and public-sector organisations that make up the Clean Skies for Tomorrow Alliance, around 20 are from India".

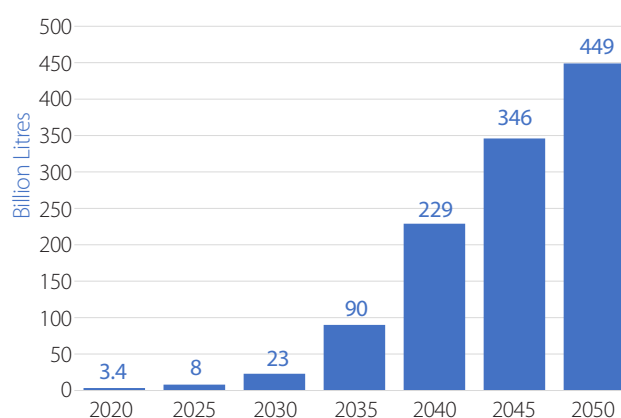


Figure 10: Global Expected SAF Production

India also has excellent potential to generate SAF feedstock (approximately 166 million tons per year, which can produce 22 to 24 million tons of SAF currently) in abundance, such as agricultural waste (husks, chaff, etc), used cooking oil, and other solid waste. Further, India has the advantage of low-cost renewable energy sources and the required technology to produce SAF.

As reported by the Indian Sugar Mills Association, Indian sugar production in FY 22 was 358 lakh tons and is expected to reach 365 lakh tons in FY 23. However, the domestic consumption is only 260 lakh tons, resulting in a substantial carry-over sugar stock within the mills. To find a long-term solution to the problem of excess sugar, the Government of India (GoI) is encouraging sugar mills to produce less sugar and divert excess sugarcane to ethanol.

GoI has mandated to blend 20% fuel-grade ethanol with petrol by 2025. In any integrated sugar plant, an essential by-product is Ethanol. When the E-20 programme is completed, the ethanol production requirement will be around 1,500 crore litres. India had imported over 180 million tonnes of petroleum in FY21, spending \$551 billion. India can save over Rs. 30,000 crores a year through the E20 programme because transportation is the country's leading consumer of petroleum products.

Currently, the aviation sector in India contributes to less than 1% of all emissions in the country. It might rise because of the ongoing expansion of air travel. At COP26 Glasgow in 2021, the Indian Prime Minister announced that the nation will achieve net zero by 2070, which requires a reduction of CO₂ emissions by approximately 20 million tonnes per year¹¹. According to the Clean Skies for Tomorrow (CST) research from the World Economic Forum study, India needs 360,000 metric tonnes of SAF to accomplish its goal of transporting 100 million domestic passengers on a 10% SAF blend by 2030 and close to 20% by 2040 in line with IEA's Sustainable Development Scenario (SDS).

The encouraging fact is that today, technologies to produce SAF exist. Aviation emissions and waste are two significant issues that must be resolved in the coming years, and SAF provides an opportunity to address them both.

SpiceJet operated India's first domestic biofuel test flight on a 25% blend of SAF in 2018. India's Centre for Military Airworthiness and Certification (CEMILAC) piloted SAF use across the Indian Air Force's AN-32 fleet as a milestone towards expanded use in India¹².

To become a worldwide leader in the infrastructure and manufacturing of SAF, India must make quick decisions and develop and implement clear policies to create level playing fields. India is poised to become a "Green Revolution" leader.

Advantage of Using SAF in India

To sustain this growth in future, India needs to reduce its dependency on using its natural resources and, at the same time, maximise the use of renewable resources.

It is possible to meet the UN's Sustainable Development Goals (3, 7, 8, 9, 13 and 17) with this SAF shift. **Figure 11** gives the significant benefits of SAF other than CO₂ reduction.



Figure 11: Socio-economic Benefits That Can be Derived by Using SAF¹³

Targets on SAF Blending



As shown below, several countries and regions have announced SAF blending targets and established roadmaps for incorporating SAF into their aviation sectors.

- **European Union:** The European Union has outlined a roadmap in its “Flightpath 2050” initiative, with targets for increasing SAF use in aviation. The European Commission has proposed SAF blending targets of 2% by 2025, 5% by 2030, and 63% by 2050.
- **Canada:** Canada has established goals for SAF use in aviation, with a target of 2% SAF by 2025 and 10% SAF by 2030.
- **Australia:** The Australian government has set targets to achieve a 10% SAF mandate for domestic flights by 2030.
- **Singapore:** Singapore aims to have SAF make up at least 2% of jet fuel used in the country by 2030 and 5% by 2035.
- **United Arab Emirates:** The UAE is working on introducing SAF into its aviation sector, with plans to achieve a 2% blending target by 2025
- **Norway:** Norway has set a target for SAF to make up 30% of aviation fuel by 2030.
- **Finland:** Finland has announced its goal to achieve a 30% SAF blending target for aviation by 2035.
- **Netherlands:** The Netherlands has a roadmap to introduce SAF into aviation, aiming for a 14% SAF mandate by 2030.
- **France:** France aims to incorporate 50% SAF in aviation by 2050.

These targets and roadmaps represent global efforts to reduce aviation’s carbon footprint by increasing the use of sustainable aviation fuels.

India Market for SAF

In 2021, India's consumption of aviation turbine fuel (ATF) consumed approximately 8 million tons, resulting in emissions of roughly 21.95 million tons of CO₂. India's ATF consumption has increased to 8.61 million tons, associated with a higher CO₂ emission of 27.2 million tons in 2023. This growth in ATF demand is calculated as a compound annual growth rate (CAGR) of approximately 5.8%.

Figure 12 illustrates this data clearly and indicates the projected trajectory of ATF demand and its corresponding CO₂ emissions. This data attributes the ongoing growth in India's aviation sector to its environmental impact in terms of carbon emissions. India must continue monitoring and implementing measures to address the environmental consequences of increased air travel and the use of conventional aviation fuels.

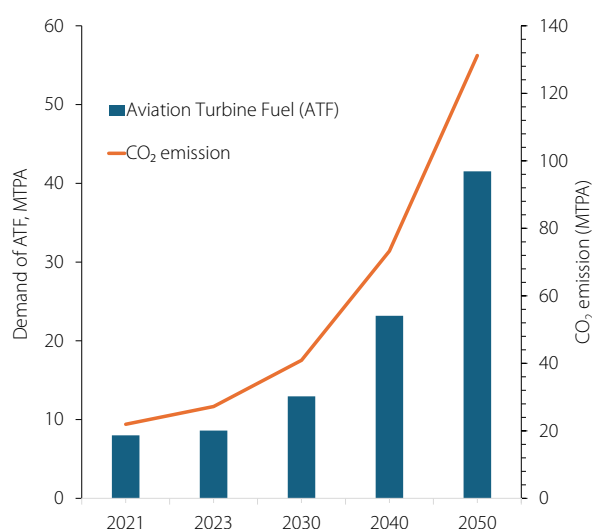


Figure 12: Demand of aviation turbine fuel and their CO₂ emission

In addressing this challenge, SAF is key in reducing carbon emissions throughout the entire fuel lifecycle. India is actively working toward a mandatory proposed policy of blending 1% SAF into all domestic commercial flights within the next two years, aiming for full implementation by 2025. According to the Ministry of Petroleum & Natural Gas, a 1% SAF blending target for Jet fuel by 2025 would necessitate the production of approximately 14 crore litres (0.1 million tons) of SAF per annum. In an even more ambitious scenario, where the goal is to achieve a 5% SAF blend, India would require a substantial production of approximately 70 crore litres (0.48 million tons) of SAF per annum.

Assumption(s)

This study incorporates an in-depth analysis of two distinct scenarios regarding the integration of SAF within the aviation sector.

- **Optimistic Scenario:** It aligns with the Government of India's (GOI) perspective. This implies a trajectory corresponding to the government's view on SAF adoption and its gradual penetration into the aviation industry.
- **Ambitious Scenario:** It envisions a more accelerated uptake of SAF driven by private sector initiatives to capture carbon emissions and transform them into valuable SAF products. This broader perspective acknowledges the role of industries like steel production, where CO₂ emissions are harnessed to generate SAF, contributing significantly to its adoption within the aviation sector. The ambitious scenario emphasises innovative and proactive efforts from the private sector to push SAF integration forward.

Table 3 shows the penetration of SAF in the aviation sector in two scenarios based on assumption.

Scenario	2023	2025	2030	2040	2050
Optimistic	0	1%	5%	10%	20%
Ambitious	0	2%	10%	20%	40%

Table 3: Assumption for SAF penetration

India must continue monitoring and implementing measures to address the environmental consequences of increased air travel and the use of conventional aviation fuels

Figure 13 shows the SAF demand based on optimistic and ambitious scenarios from 2025 to 2050. The demand for SAF varies depending on the aviation sector's penetration level. To provide a clearer picture, let's elaborate on the quantities required for different penetration rates:

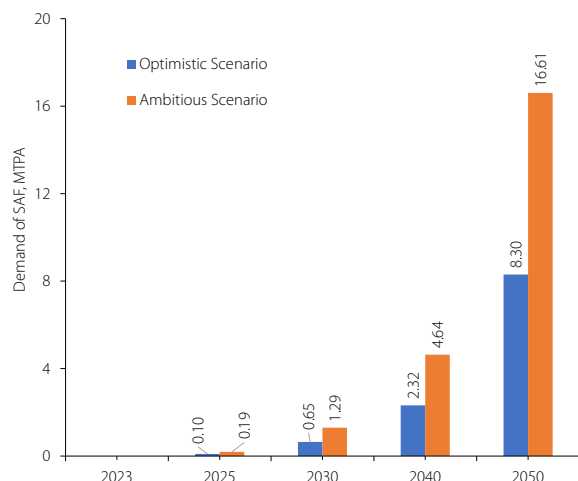


Figure 13: Demands of SAF

To achieve a 1% penetration rate in India, the aviation industry would require approximately 0.1 million metric tons (MT) of SAF. For the optimistic scenario, this amount is roughly equivalent to around 14 crore litres of SAF. This demand projection is crucial when considering the anticipated aviation turbine fuel requirements, which are expected to reach 9.6 million metric tons per annum (MTPA) by 2025. This emphasises the importance of developing a robust and sustainable SAF infrastructure to meet the growing demand while reducing the aviation industry's carbon footprint.

In an ambitious scenario, to attain a 2% penetration rate in India, the aviation sector would need approximately 0.19 million metric tons (MT) of SAF. This quantity is roughly equivalent to around 28 crore litres of SAF under the optimistic scenario. This projection is of utmost significance when considering the anticipated demand for aviation turbine fuel, which is projected to reach 9.6 million metric tons per annum (MTPA) by 2025. This highlights the pressing need to establish a robust and sustainable infrastructure for SAF. Such an infrastructure is pivotal for meeting the increasing demand for aviation fuels while mitigating the industry's carbon footprint.

These figures emphasise the substantial growth in SAF demand as the aviation sector increasingly

integrates sustainable aviation fuels, reflecting the potential scale of SAF production and usage in India's aviation industry. India has the necessary feedstock resources to produce a remarkable annual output of SAF ranging from 19 to 24 million tons. This situation highlights India's substantial potential for SAF production, far exceeding the immediate demand projections. As the aviation industry progresses toward greater SAF integration and sustainable practices, India stands in a favourable position to not only meet domestic requirements but also explore export opportunities and contribute to the global effort to reduce carbon emissions from aviation.

Life Cycle CO₂ Reduction

The utilisation of SAF in the aviation sector substantially reduces life cycle carbon dioxide (CO₂) emissions, as shown in Figure 14. SAF is often derived from renewable feedstocks or innovative carbon capture technologies. Unlike conventional fossil-based aviation fuels, SAF sources tend to be more environmentally friendly, emitting fewer greenhouse gases when burned. Additionally, the potential for carbon-neutral or even carbon-negative production processes further highlights the life cycle benefits of SAF.

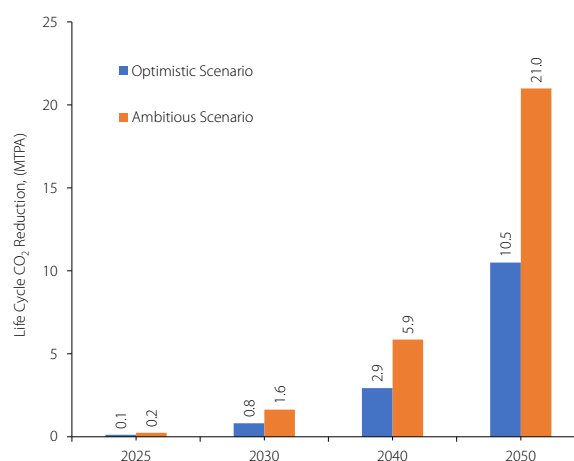


Figure 14: Life Cycle CO₂ Reduction

This transition to SAF mitigates emissions and contributes to the broader goal of making the aviation industry more sustainable. These life cycle CO₂ emissions reductions are particularly crucial in combating climate change and adhering to global emissions reduction targets, making SAF a key player in the mission for a greener, more eco-friendly aviation sector.

SAF Technologies



The SAF production processes are changing rapidly with the commercialisation of emerging new technologies. Several ASTM-approved technology pathways are available for SAF production from various types of feedstock, as shown in Figure 15.

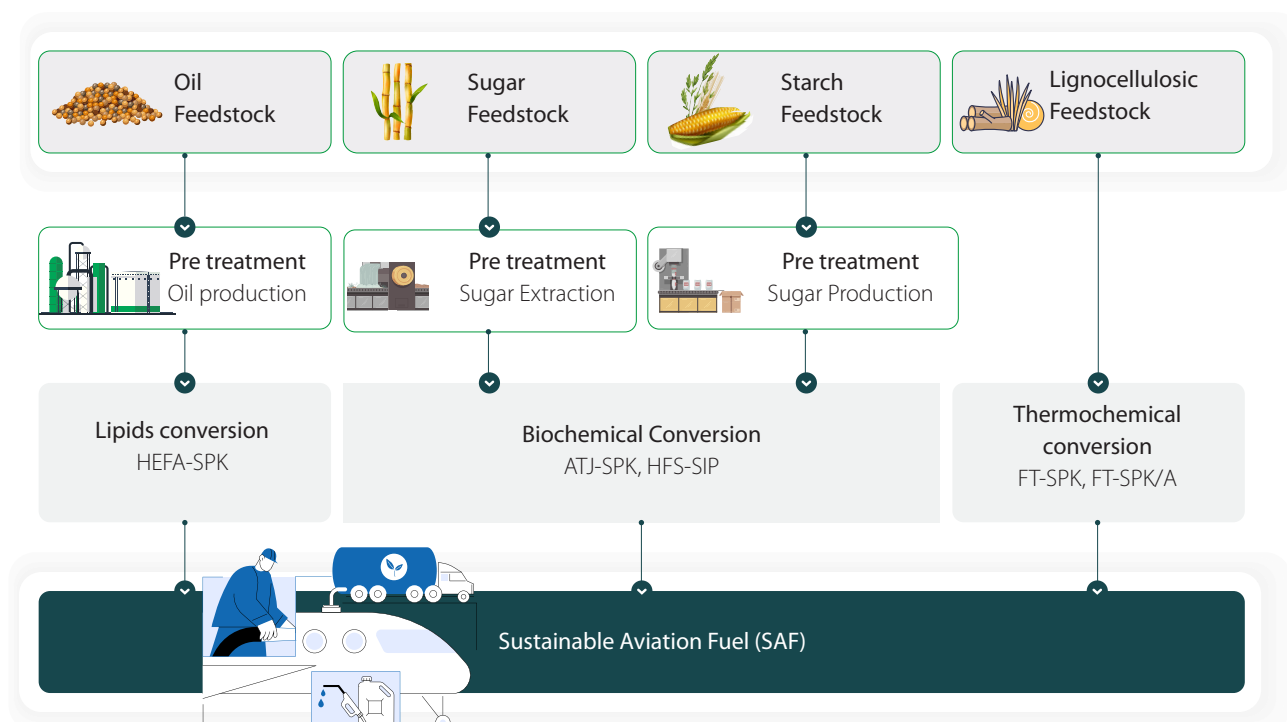


Figure 15: SAF Production Routes

1. Hydro-processed Esters and Fatty Acids (HEFA) to Synthesized Paraffinic Kerosene (SPK) – HEFA-SPK.
2. Catalytic- Hydrothermolysis (CH)
3. Gasification/ Fischer-Tropsch synthesis to SPK – (FT-SPK)
4. Gasification/ Fischer-Tropsch synthesis with rich aromatic content – (FT-SPK/A)
5. Alcohol to Jet fuel – ATJ
6. Synthesized iso-paraffins produced from hydro-processed fermented sugars – (SIP-HFS)

Table 4 shows the status of ASTM-certified (ASTM D7566-19a certification) SAF-producing pathways and their process characteristics with a maximum blending (in specified volume per cent) ratio of conventional jet fuel. ASTM prescribes limits to the amount of SAF mixed with traditional jet fuel due to its aromatic content, mainly depending on the production pathways' maturity.

S. No	Methods	Process	Feedstocks	Description	Max Blending Ratio by Vol
1	Oil to Jet fuel	HEFA-SPK	Lipids (i.e., Fats, Oils, Greases)	Deoxygenation of oils and fats ---> hydro processing.	50%
2	Oil to Jet fuel	CH	Lipids (i.e., Fats, Oils, Greases)	Dehydration or decarboxylation ---> hydrothermolysis ---> Hydro processing.	50%
3	Gas to Jet fuel	FT- SPK	Biomass, waste (MSW), sawdust, natural gas, coal	Biomass gasification ---> FT ---> Hydro processing.	50%
4	Gas to Jet fuel	FT - SPK/A	Biomass, waste (MSW), sawdust, coal, natural gas,	Biomass gasification ---> FT ---> hydroprocessing ---> enhance aromatics content	50%
5	Alcohol to Jet Fuel (e.g., Isobutanol & Ethanol)	ATJ- SPK	Sugarcane, sugar beet, sawdust, lignocellulosic residues (straw)	Hydrolysis of biomass ---> Fermentation of sugar to alcohol ---> Dehydration ---> Oligomerisation ---> Hydrogenation ---> Fractionation	50%
6	Sugar to Jet fuel	SIP-HFS	Sugarcane, sugar beet	fermentation of sugars ---> hydrocarbon molecule (farnesene) ---> Hydroprocessing ---> fractionation	10%

Table 4: Status of ASTM-certified SAF Production Routes

Figure 16 represents an overview of the techno-economic analysis while selecting appropriate SAF production pathways. The SAF process technology generally becomes more complex for processing waste and residues than lignocellulosic, sugar, starches and oils. However, oil feedstock is more expensive than lignocellulosic, sugar, and starches, whereas waste and residues are the least costly feedstocks. The level of technical effort required increases depending on the type of feedstock, which can include waste and residues, lignocellulosic materials, sugars, and starches.

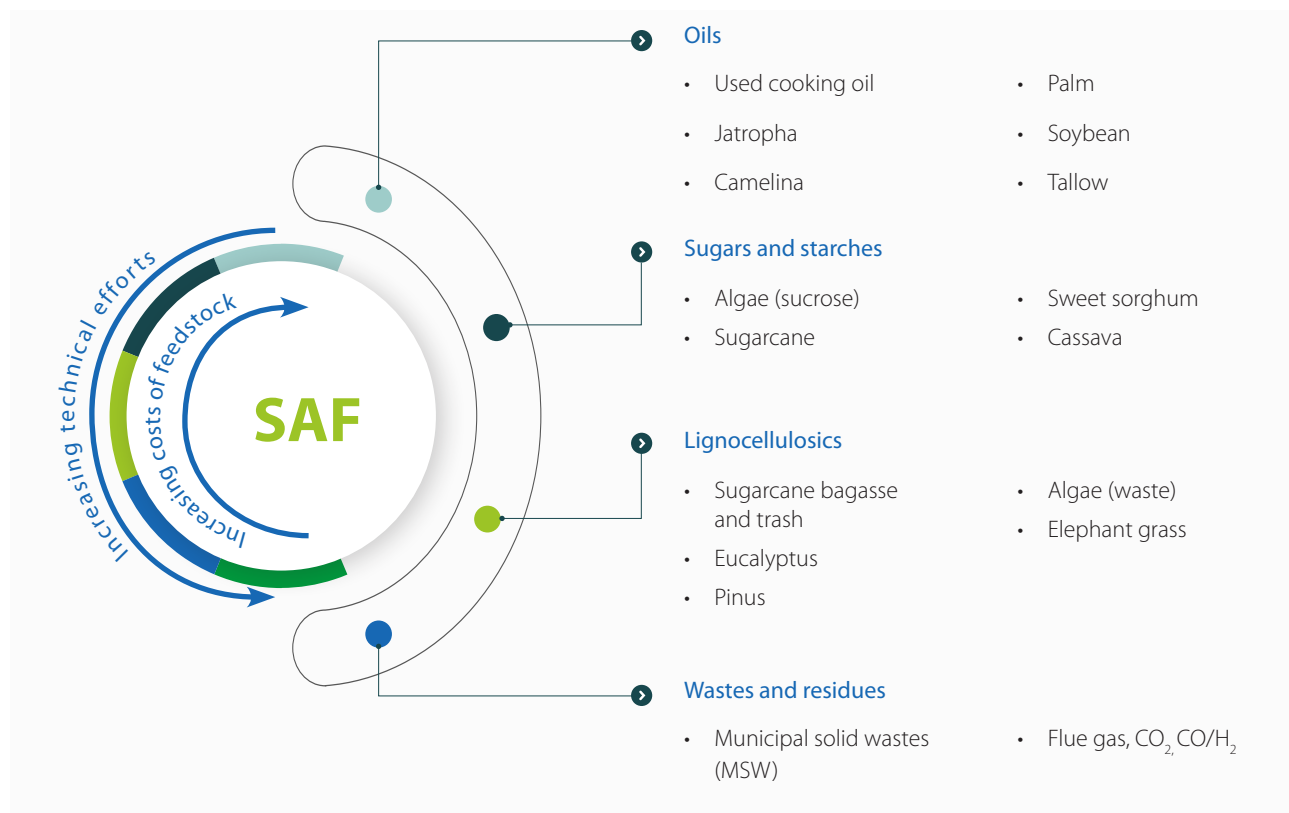


Figure 16: Cost of Feedstock and Processing Effort for SAF Production



HEFA – SPK

HEFA fuel exhibits properties similar to traditional petroleum-based fuels but offers advantages such as a higher cetane number, reduced sulfur and aromatic content, and lower greenhouse gas emissions. Commercially available hydro-processing conversion technologies with a high level of maturity are used in this process.

Figure 17 illustrates the schematic diagram of the HEFA production process. In this process, unsaturated fatty acids (glycerides) in liquid form are converted into saturated ones through catalytic hydrogenation, utilising hydrogen. Free Fatty Acids (FFAs) are obtained from a propane cleave unit and then undergo either hydrodeoxygenation or decarboxylation processes to eliminate oxygen, resulting in the production of octadecane (C₁₈H₃₈) and heptadecane (C₁₇H₃₆), respectively.

The typical paraffin generated through deoxygenation needs to undergo hydrocracking and hydro isomerisation to produce a Synthetic Paraffinic Kerosene (SPK) product that meets the requirements for jet fuel. These reactions of cracking and isomerisation may occur either simultaneously or sequentially. Exothermic hydrocracking reactions yield lighter fluids and gaseous products, followed by a fractionation process that separates these into paraffinic diesel, paraffinic kerosene, naphtha, and light gases.

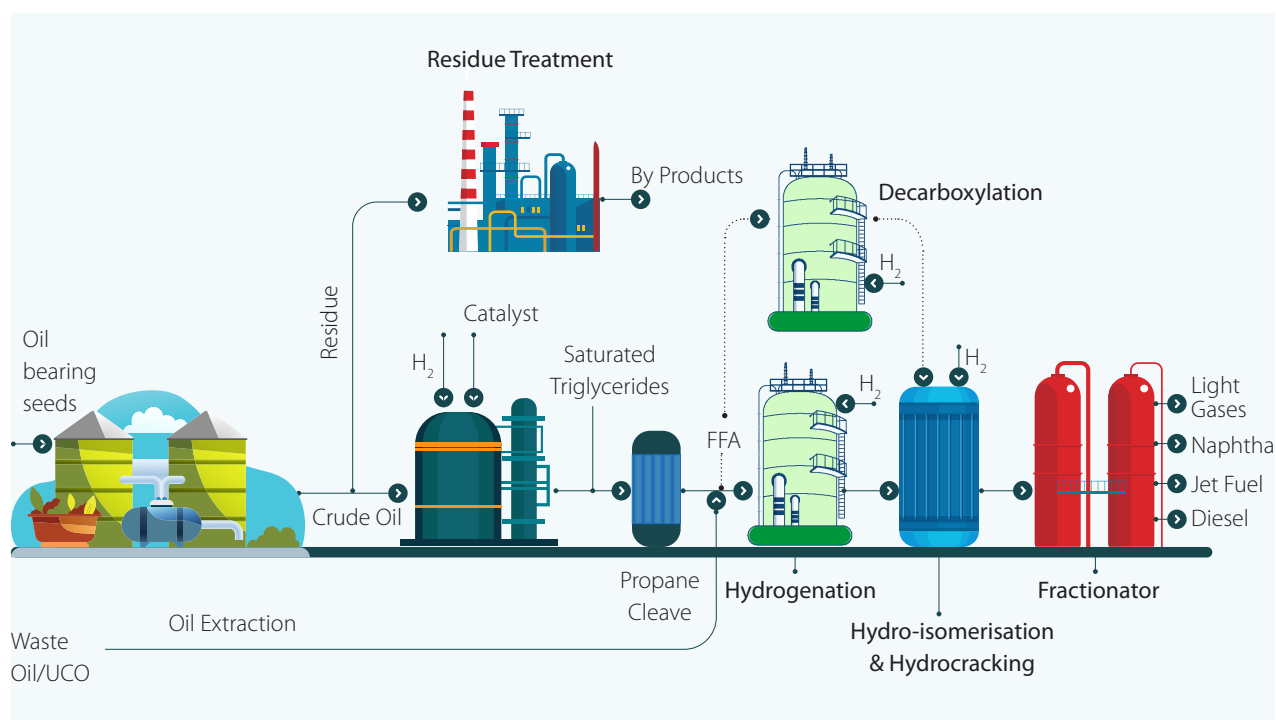


Figure 17: Schematic - HEFA Process

Table 5 presents a well-to-wake comparison between SAF and traditional jet fuel. Compared to other oils such as Oilseed rape, Soy oil, Jatropha oil, and Camelina oil, used cooking oil stands out as a more environmentally friendly option, contributing to carbon reduction.

Feedstock	Bio - Jet GHG gCO ₂ _{eq} /MJ	Fossil Jet, gCO ₂ _{eq} /MJ	Savings CO ₂ _{eq} %
Oilseed rape, Soy	40-108	87.5	20-54
Jatropha oil	55		37
Camelina	47		46
Used Cooking Oil (UCO)	27		69

Table 5: Well Wake Emission Comparison of SAF or Bio-jet Fuel to Conventional Jet Fuel¹⁴

Table 6 displays some information about newly constructed SAF production units. Honeywell Universal Oil Products (UOP), Neste (NexBTL), Pertamina, World Energy, Dynamic Fuels, and EERC are some of the top producers of aviation biofuels under HEFA. These methods use a variety of oil-based feedstocks, including camelina, algae, jatropha, and yellow grease.

Description	M/S. World Energy	M/S. Total	M/S. Sinopec
Capacity	10 million gal of SAF	170 million gallons -total	33 million gallons -total
Start production	SAF	Diesel in 2019 and SAF in 2020	TBD
Other products	HRD, naphtha	Diesel, Naphtha	Diesel, Naphtha
Blending capacity	Yes	Yes	Yes
Location	Los Angeles, US	La Mede, France	Ningbo, China
Main feedstocks	UCO, Tallow	Mix of animal fats and vegetable oils	Combination of animal fats and vegetable oils
Airline offtake	United Airlines, KLM	NA	NA
Technology	HEFA	HEFA	HEFA

Table 6: *New Build SAF Suppliers SAF Producers by HEFA Technology¹⁵*

The HEFA technique presents advantages and challenges in producing Sustainable Aviation Fuels. It is a well-established commercial process characterised by simplicity and scalability (capable of accommodating extensive facilities producing over 1 billion litres annually). Typically, the HEFA process yields a bio-jet portion of 15-20%, while the remaining 80% takes the form of diesel, also known as renewable diesel.

Bio-jet fuel production often necessitates additional processing steps like hydrocracking and isomerisation, leading most producers to focus on diesel rather than bio-jet fuel distribution. Feedstock costs and potential sustainability concerns are the primary obstacles to employing HEFA for SAF or bio-jet fuel development.

To illustrate, the CSIR-IIP in Dehradun recently engineered a high-pressure fixed-bed hydroprocessing pilot plant for converting used oil into jet fuel using HEFA. This innovative facility successfully produced 15 litres of bio-jet fuel daily and boasted a feed capacity of 100 kg per day. The produced fuel was delivered to an industrial collaboration involving HPCL and IOCL.



Catalytic Hydro-thermolysis

Triglycerides undergo a hydrothermal process, resulting in a mixture of straight-chain, branched-chain, and cyclic hydrocarbons through a series of transformations involving cracking, hydrolysis, decarboxylation, isomerisation, and cyclisation, as illustrated in **Figure 18**.

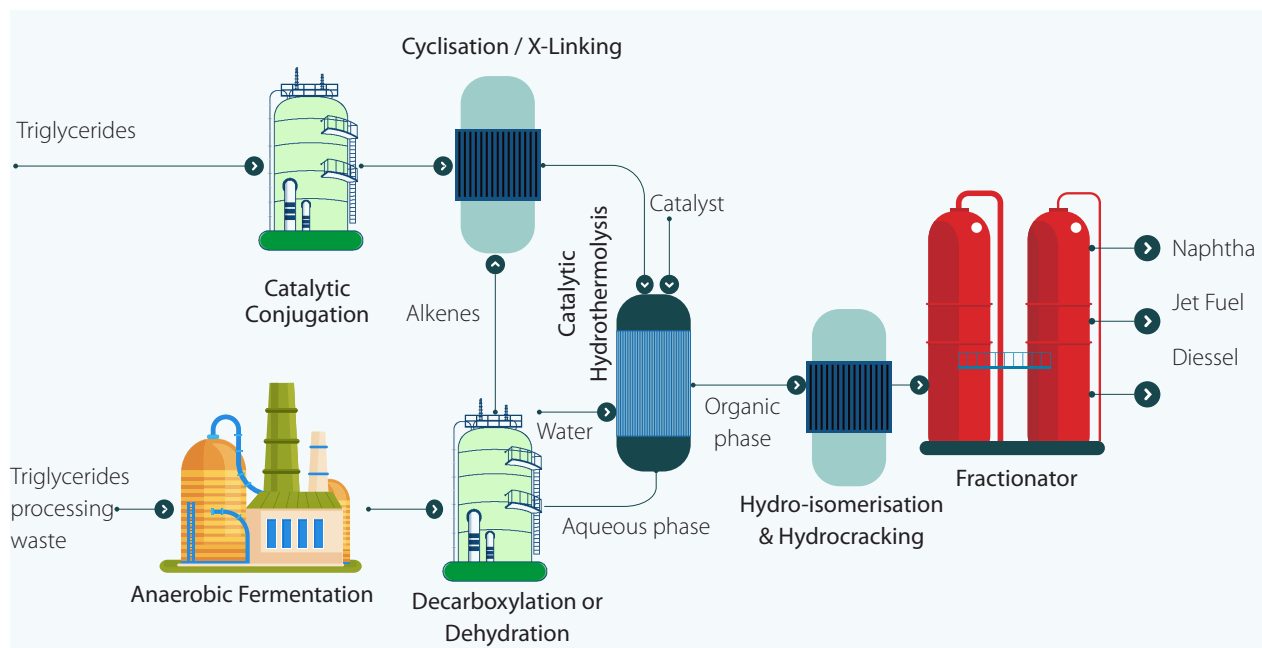


Figure 18: Schematic Diagram of Catalytic Hydro-thermolysis (CH)

The hydrothermal process (CH reaction) occurs in water, with or without a catalyst, at pressures of 210 bars and temperatures ranging from 450°C to 475°C. The resulting organic phase, often called bio-crude, undergoes decarboxylation and hydrotreating, yielding carbon compounds spanning the range of 6 to 28, including aromatics, n-alkanes, iso-alkanes, and cyclo-alkanes¹⁶.

A fractionation process separates these components into naphtha, jet fuel, and diesel fuel. Jet fuel produced through the CH method meets stringent ASTM and military (MIL) standards and exhibits stability and impressive cold-flow properties. Extensive research has shown that the CH process can convert various triglyceride-based feedstocks, such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil, into biojet fuels.



FT-SPK

Fischer-Tropsch (FT) technology can be combined with various biomass conversion techniques to generate synthetic fuels, including gasification, pyrolysis, and liquefaction. Gasification, which involves high temperatures (typically exceeding 1000°C), transforms carbonaceous resources like biomass into syngas, primarily composed of CO and H₂, essential components for synthesising FT liquid fuels. **Figure 19** illustrates the integration of FT synthesis and refining with biomass gasification to produce high-quality jet fuel.

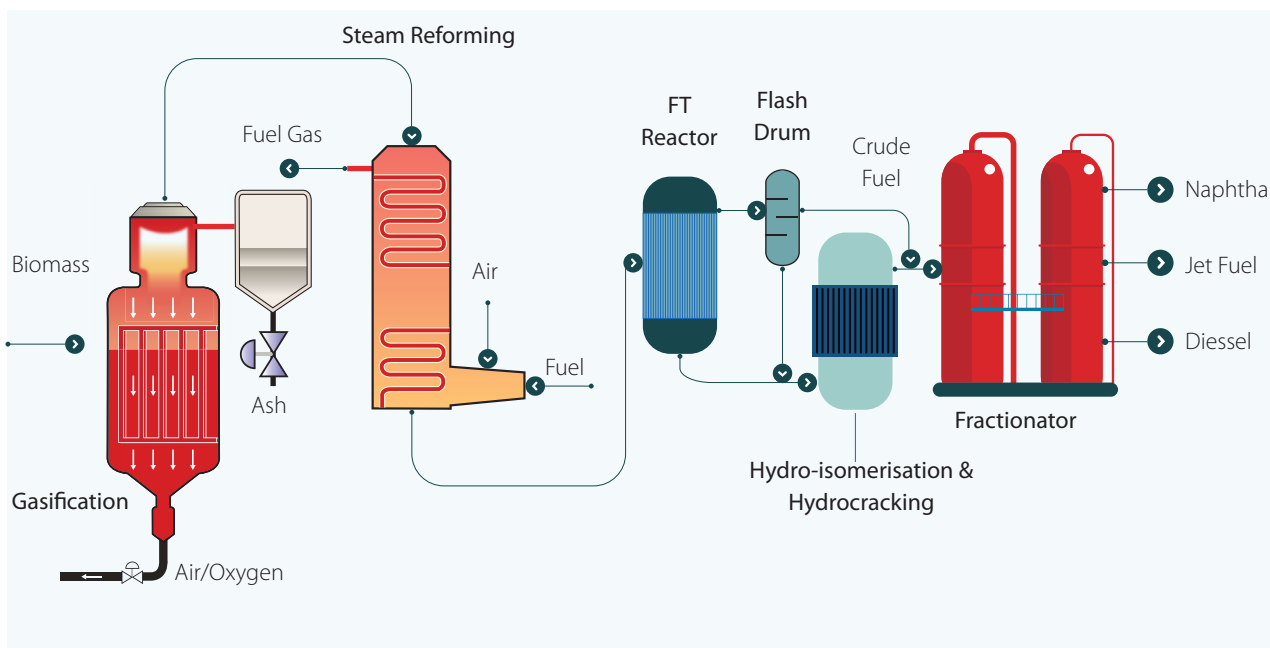


Figure 19: Schematic Diagram of FT-SPK Process

Typically, it takes approximately 5–6 tonnes of biomass to produce one ton of FT liquid fuel¹⁷. The FT process yields various hydrocarbons. Notably, FT-derived fuels contain fewer sulfur and aromatics than conventional fossil fuels (such as petrol and diesel), reducing carbon emissions.

The FT process generates a range of hydrocarbon products, including light hydrocarbons, naphtha, kerosene, distillate, and waxes, each with distinct carbon chain lengths and associated energy applications, as detailed in **Table 7**.

Type of Hydrocarbon	Carbon Length	Uses
Light hydrocarbons	C1-C4	Generate heat and power via a gas turbine or refined into LPG.
Naptha	C5-C10	mixed with gasoline and jet fuel
Kerosene	C10-C16	mixed with gasoline and jet fuel
Distillate	C16-C20	processed into diesel
Waxes	C20+	processed into diesel

Table 7: Carbon Length and Uses

Shell has successfully employed coal-based syngas for commercial FT synthesis in Bintulu, Malaysia, Qatar, and Sasol, South Africa. Currently, gasification of biomass and FT technology is undergoing pilot phases in projects like Total's BioTfuel project in France, Velocys/Red Rock Biofuels in Austria and the United States, and CEA/Air Liquide's Syndièse-BtS project in France. **Table 8** provides information about newly constructed Sustainable Aviation Fuel (SAF) production units¹⁸.

Description	M/S. Fulcrum	M/S. Red Rock
Capacity	10 million gallons total	6 million gallons SAF
Other products	Diesel, naphtha	Diesel, naphtha
Location	Reno, Nevada, US	Lakeview, Oregon, US
Main feedstocks	MSW	Forestry residues
Airline offtake	United Airlines, Cathay Pacific	Southwest FedEx
Technology	FT-SPK	FT-SPK

Table 8: New Build SAF Suppliers SAF Producers by FT-SPK Technology

FT-SPK/A

Aromatic-rich jet fuel can be synthesised by combining FT with an alkylation unit. Alkylation units typically produce light aromatics, such as benzene, necessitating the use of elastomer seals in aircraft components to prevent fuel leakage. FT-SPK/A facilitates a shift from paraffin toward fuels encompassing a broader spectrum of molecules resembling conventional fossil jet fuel.

The primary feedstock for this process is synthesis gas (H_2 and CO), typically derived from the gasification of carbon-rich sources such as municipal solid waste, agricultural waste, jungle waste, timber, biofuel crops, natural gas, and coal. Gasification involves high temperatures (ranging from 1200 to 1600°C) to break down the feedstock into CO , H_2 , CO_2 , and some ash.

The syngas, produced from this gaseous mixture through separation, are subsequently employed in the FT synthesis process to generate long carbon chain waxes¹⁹.

Alcohol to Jet Fuel

The ATJ process effectively converts shorter-chain alcohols such as methanol, ethanol, and butanol into longer-chain hydrocarbons, specifically C8-C16 alkanes.

There are two primary processing methods for producing jet fuel from alcohol:

- a) **"Methanol-to-Olefins (MTO) followed by Mobil's Olefin-to Gasoline / Distillate (MOGD)"**: This process involves the conversion of methanol into jet fuel. Methanol is first processed in a fluidised bed reactor of MTO, operating at 482°C under 1 bar pressure, using a Zeolite Socony Mobil (ZSM) catalyst.

This yields methane, paraffins, olefins, and gasoline. The olefins are treated in a fixed bed reactor (FBR) at 1 bar and 400°C with a ZSM catalyst in the MOGD unit, producing light gases, gasoline, and distillate. Fractionation of these products results in light gases, gasoline, jet fuel/kerosene, and diesel.

- b) **"Ethanol/isobutanol/butanol/other alcohols processing via dehydration, oligomerisation, and hydrogenation"**: This method involves transforming alcohols (such as ethanol, n-butanol, iso-butanol, and higher alcohols) into jet fuel through well-established chemical industry processes, including dehydration, oligomerisation, and hydrogenation²⁰.

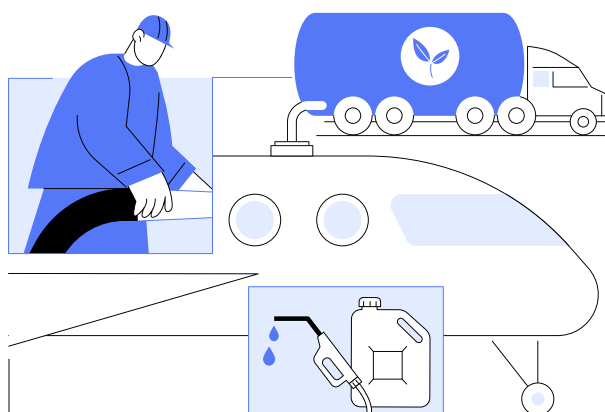


Figure 20 Provides a conceptual schematic diagram of the alcohol-to-jet fuel production process.

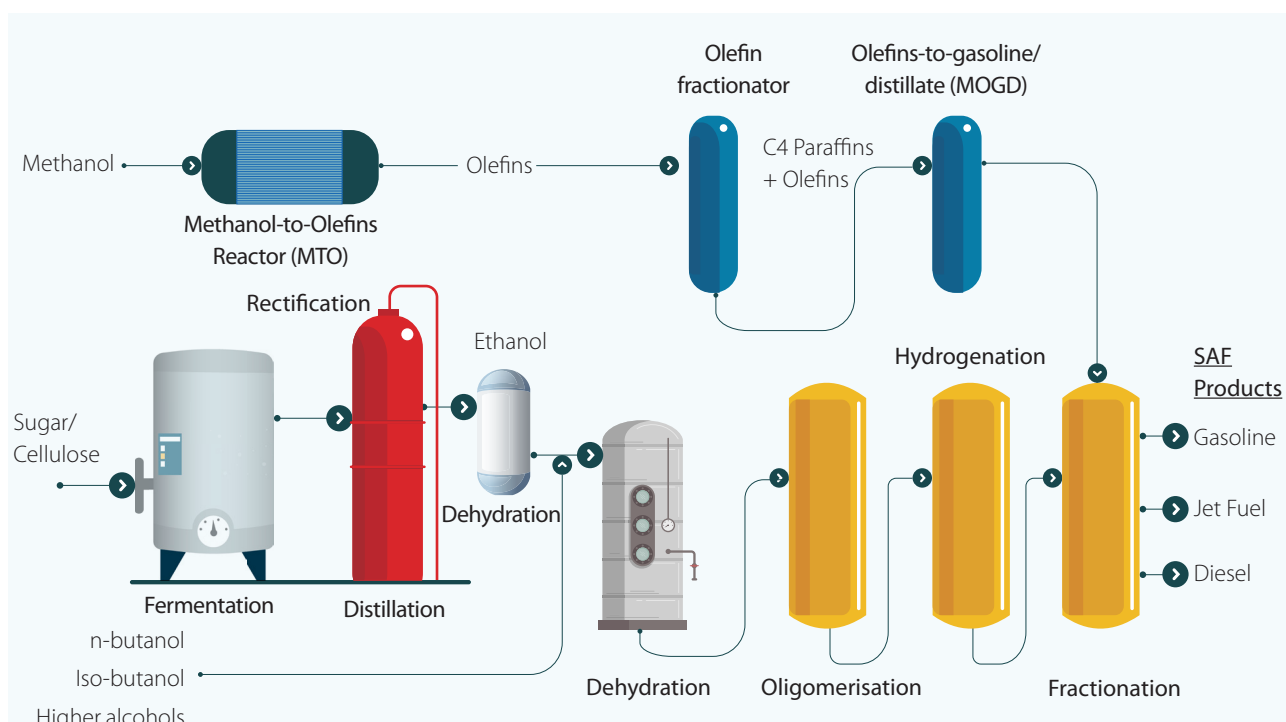


Figure 20: Schematic Diagram of SAF Production from Methanol and Ethanol Route

Synthetic Iso-Paraffins - Hydroprocessing of Fermented Sugars (SIP-HFS)

Figure 21 illustrates the biological conversion pathway of biomass into synthetic iso-paraffins (SIP), also known as “direct sugars-to-hydrocarbon” (DSHC), through the hydroprocessing of fermented sugars (HFS). The process involves the following steps:

- Separation of Sugars from Lignin:** In this initial stage, sugars are extracted and separated from lignin, a complex structural component of biomass.
- Conversion of Sugar to Farnesene (C₁₅H₂₄):** The separated sugars are then converted into Farnesene (C₁₅H₂₄) through a process of enzymatic hydrolysis and fermentation. Enzymes play a crucial role in breaking down the sugars into farnesene, which serves as an intermediate compound.
- Hydroprocessing of Farnesene into SIP:** Farnesene is further subjected to hydroprocessing, producing synthetic iso-paraffins (SIP). These SIPs can be used as sustainable aviation fuel (SAF) or bio-jet fuel.

This bioconversion process relies on utilising a specific yeast strain, *S. cerevisiae* strain (PE-2), during fermentation. Companies like Amyris and Total have successfully commercialised this technology, making it a viable and sustainable pathway for producing bio-jet fuel from biomass-derived sugars.

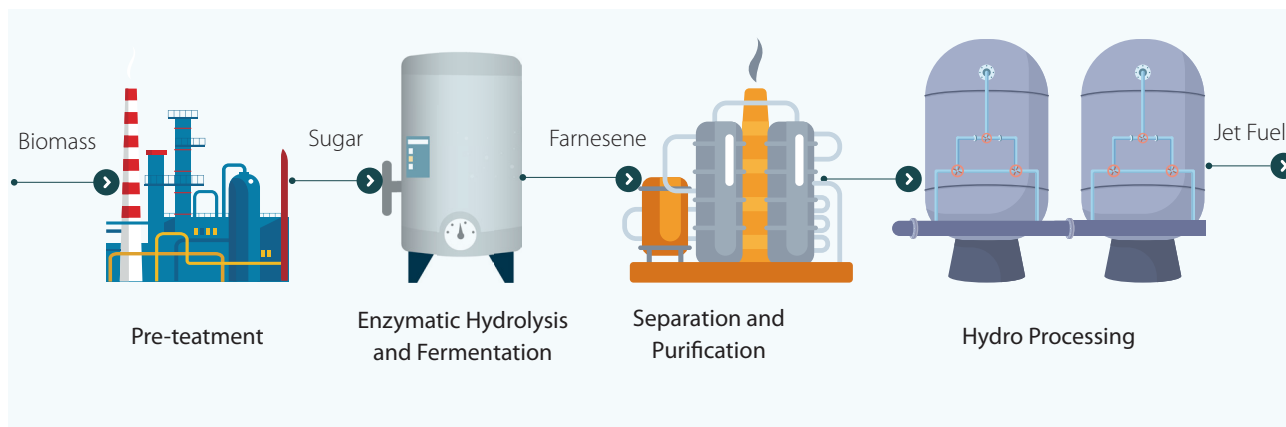


Figure 21: Schematic Diagram of SIP-HFS

Why Not 100% of SAF

Stringent safety requirements are essential for airline operations. Jet fuel is categorised based on physical and chemical properties, including boiling point, viscosity, cetane number, range, aromatic content, freezing point, autoignition temperature, and flash point. The specific characteristics and behaviours of jet fuel are as follows:

- a) **n-Alkanes:** These compounds have limited blending potential due to their suboptimal fluidity properties.
- b) **iso-Alkanes:** iso-Alkanes offer higher specific energy, improved thermal stability, and a lower freezing point than n-alkanes.
- c) **Cycloalkanes:** Cycloalkanes outperform iso-alkanes and provide functional advantages by enabling fuels to meet density and seal-swelling capacity requirements.
- d) **Aromatics:** Aromatics have lower specific energy than alkanes and tend to burn less cleanly, increasing particle emissions.

The specifications outlined in ASTM D7566 for various ASTM-approved Sustainable Aviation Fuel (SAF) types may vary from the overall SAF specifications outlined in ASTM D1655 before blending.

However, the resulting fuel must adhere to ASTM D1655 standards once agreed. **Table 9** illustrates the variations for blended fuels according to ASTM D7566 for different SAF production pathways.

Parameters	Standard	HEFA-SPK	CH	FT-SPK	FT-SPK/A	AJT-SPK	SIP-HFS
Density (kg/m ³)	775-840	730-770	NA	730-770	755-800	730-770	765-780
Max freeze point (°C)	- 47	- 40 (Max)	NA	- 40	- 40 (Max)	- 40	- 60
Aromatics, (% mass)	8.4-26.5% Vol.	0.5	20	0.5	20	0.5	0.5
Thermal Stability	260	325	NA	325	325	325	355

Table 9: Variation for the blended fuel with ASTM D7566

Nitrogen, Cycloparaffins, Paraffins and Olefins have yet to be proposed for the jet fuel blend, but these are mentioned in the Annexes of ASTM D7566. The details are given below.

1. **FT and HEFA-SPK:** 15 wt% of maximum cycloparaffin
2. **SIP:** 300 mg (Br)/100g of maximum olefin mass content
3. **SPK/A:** 15% of maximum cycloparaffin content
4. **ATJ:** 15% of maximum cycloparaffin content
5. **Nitrogen:** 2mg/kg (Maximum)

The following components are part of standard specification in the Annexes of ASTM for the SAF,

6. **Water:** 75 mg/kg (maximum)
7. **Halogens:** 1 mg/kg (maximum)
8. **Metals:** 0.1 mg/kg (maximum) per metal
9. **Flashpoint:** Min 38 °C for most all pathways, except SIP – 100 °C
10. **FAME- HEFA-SPK:** <5 ppm.

The aromatic content of SAF has constrained its blending potential in existing fuel. Recent industry observations indicate that the aromatic content typically falls within the range of 8% (minimum) to 25% (maximum) for synthetic jet fuel; these levels are considered suitable for aviation use. Standard aromatic components in jet fuel include alkylbenzenes, di-aromatics, and cyclo-aromatics, known contributors to smoke and emissions.

FT-SPK, HEFA, SIP-HFS and ATJ-SPK produce SAF with a maximum aromatic content of 0.5% per the ASTM International D7566 standard. SAF, Produced via other technologies such as FT-SPK/A and CHJ, has a maximum aromatic content of 20%, which could be used in commercial aircraft. SAF production methods like FT-SPK, HEFA, SIP-HFS, and ATJ-SPK adhere to the ASTM International D7566 standard, ensuring a maximum aromatic content of 0.5%. On the other hand, SAF produced through alternative technologies such as FT-SPK/A and CHJ may contain a higher aromatic content, up to 20%, suitable for use in commercial aircraft.

Emission Reduction

More than 80% of carbon emissions result from the combustion of petroleum-based jet fuel, with approximately 20% originating from fuel production. Sustainable Aviation Fuels (SAF), produced using biobased feedstock that absorbs CO₂ during their lifecycle, can be mainly considered carbon-neutral (ATAG, 2009).

A report by European Aviation Environmental (2019) revealed that SAF manufactured through FT technology can reduce carbon emissions by up to 68% when using municipal solid waste and up to 94% with agricultural residues, compared to conventional fossil aviation fuels²¹. However, the extent of carbon emission reduction depends on the feedstock type and production process. Various processes yield different reductions in carbon emissions with specific feedstocks:

- a) **HEFA Technology:** HEFA technology can decrease CO₂ emissions by approximately 30% when using palm oil and up to 85% when using cooking oil (UCO), compared to conventional aviation fuel.
- b) **SIP-HFS:** SIP-HFS can reduce CO₂ emissions by about 60% with sugarcane and 65% using sugar beet as feedstock.

- c) **ATJ (Ethanol) to Jet Fuel:** The ATJ process can reduce carbon emissions by 25% using corn grain and up to 70% using sugarcane.
- d) **ATJ (Iso-Butanol) to Jet Fuel:** Utilising corn grain, the ATJ process can reduce carbon emissions by up to 55%, and with forestry residues, it can achieve a reduction of 75%.

Figure 22 provides an overview of potential carbon emission reductions based on various feedstocks and pathways (Doliente et al., 2020)²². SAF also holds the potential to lower particulate matter emissions, both volatile and non-volatile, compared to traditional aviation fuels.

A study by Moore et al. (2017)²³ demonstrated nearly a 50% reduction in particulate matter emissions when using a blend of 50% HEFA fuel and 50% conventional low-sulfur Jet A fuel. Volatile and non-volatile particle emissions were reduced by 50% to 70% compared to pure fossil fuel. Lobo et al. (2015) also found that the average reduction in non-volatile particulate emissions was approximately 35%. It was about 60% for particulate matter when using HEFA produced from UCO in blends with conventional Jet A-1 fuel.

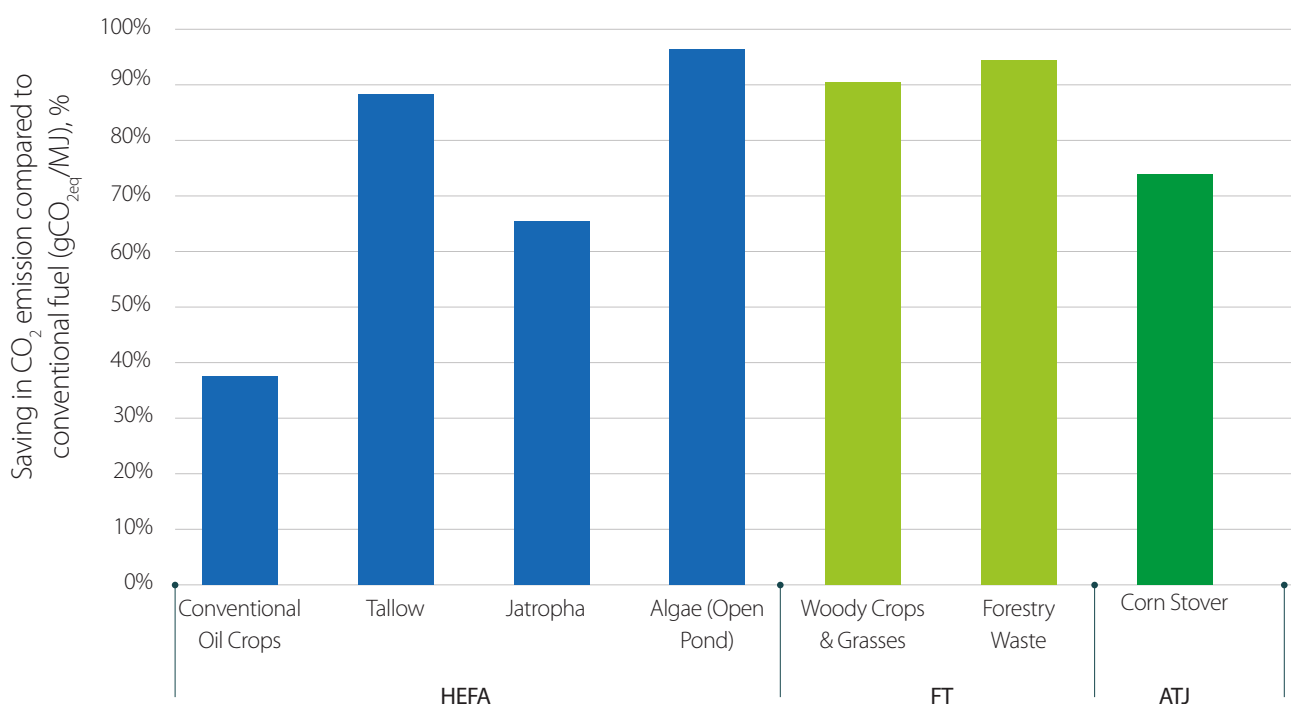


Figure 22: Potential Emission Saving from Using Different Feedstock and Production Pathways

Technology or Fuel Readiness Level



The advancement of new technologies can be achieved through a gradual scale-up process, encompassing bench or laboratory testing, pilot, demonstration, and commercial stages.

Technologies or Fuel Readiness Levels (TRL/FRL) 3, 6, and 7 often encounter bottlenecks requiring additional research funding for progression. To reach TRL 4, further research funding is needed, while TRLs 5 and 7 demand significant financial investment and commercial interest. **Figure 23** illustrates the current status of Sustainable Aviation Fuel (SAF) production technologies and their corresponding Fuel Readiness Levels (FRL).

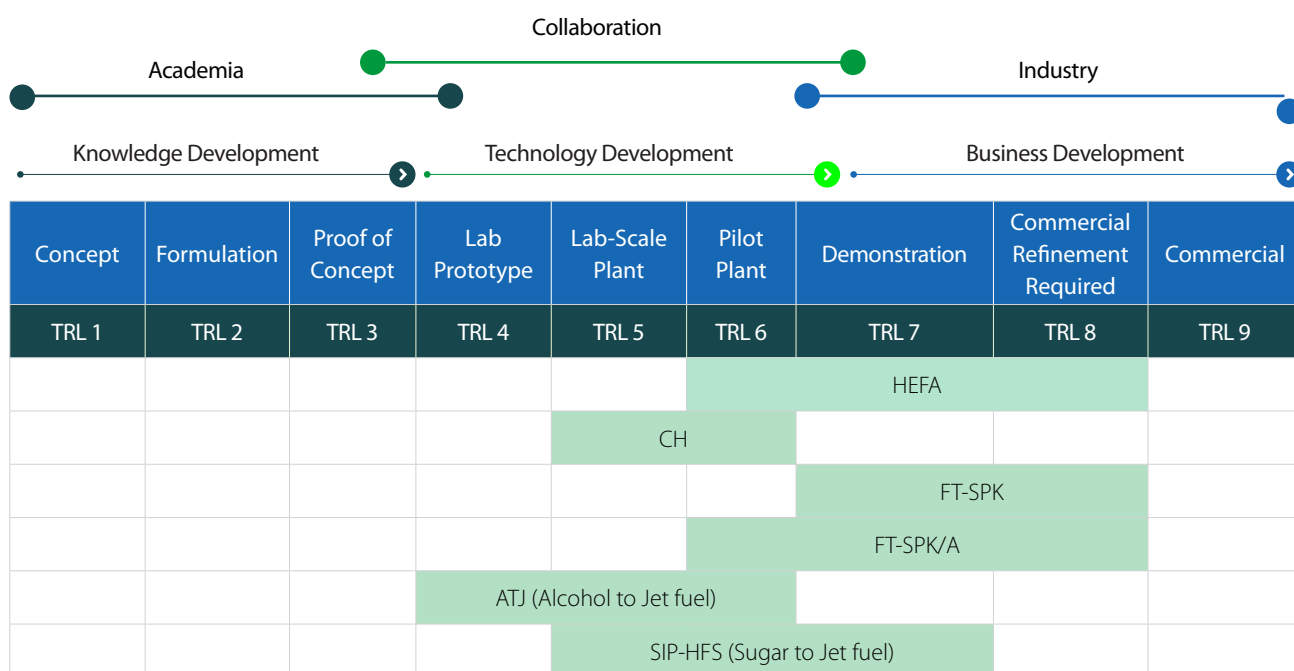


Figure 23: Fuel Readiness Level

HEFA: Hydrotreatment and isomerisation are integrated into HEFA technology to convert triglycerides or oil into paraffinic kerosene (PK) or iso-paraffinic kerosene within the jet fuel range (C9-C16). HEFA is a well-established and widely used method for SAF production. Numerous SAF production facilities are planned and operational worldwide. Companies such as Honeywell UOP, Neste (NexBTL), Sinopec, Pertamina, World Energy, Dynamic Fuels, and EERC have successfully deployed HEFA technology²⁴.

Additionally, non-edible crops like jatropha and camelina, as well as oils from algae, are utilised as feedstock for this process to produce SAF. Common feedstocks include used cooking oil (UCO), recycled oils, and animal fats, compliant with ASTM D7566 Annex 2. This standard certifies blending up to 50% SAF with conventional jet fuel. However, HEFA needs help with the availability and cost of triglyceride feedstocks. This technology is evaluated as FRL 6-8.

Globally, various types of lipid feedstocks, including Used Cooking Oil (UCO), palm oil mill effluent (POME), animal fats, and palm fatty acid distillate (PFAD), among others, are commonly utilised as feedstock for the Hydroprocessed Esters and Fatty Acids to Synthesized Paraffinic Kerosene (HEFA) process. India's palm oil refining industry is expanding, but additional research must assess its sustainability.

Given that India is the world's largest consumer of edible oil annually, UCO, despite being frequently reused, holds significant potential as a valuable feedstock. However, there is a need to strengthen the collection of UCO, mainly since the current group primarily focuses on critical industrial sources. Additionally, there is a high demand for animal fats and tallow in India, driven by the large-scale export of meat products. India annually produces a substantial quantity of tallow, approximately 360,000 tons, which finds applications in soap production, oleochemicals, and exports.

Although an estimated 2-5 million tons of UCO are available in India, its accessibility is hindered by issues within the collection system and supply chain. To fully harness the considerable potential of the HEFA pathway in India, there is a critical need to upgrade and enhance the UCO supply chain.

Establishing an effective UCO collection system presents various challenges, as UCO producers encompass households, food factories, and petrochemical companies. Currently, the UCO collection primarily focuses on industries and nearby cities, but it should be expanded to encompass a broader range of UCO producers. Offering reasonable incentives for UCO collection will incentivise players in the food industry to participate in the supply chain, further bolstering its effectiveness.

CH: Catalytic hydrothermolysis (CH), also known as hydrothermal liquefaction (HTL), is strong enough to handle species with lower lipid content and is primarily developed for algae as a SAF feedstock. Applied Research Associates (ARA) and Blue Sun Energy are developing this technology on a trial scale. ASTM D7566 Annex 6 certifies the blending of CH products up to 50% for SAF production. The process utilises subcritical water to refine aromatic, cyclo-paraffinic, and isoparaffinic hydrocarbons from wet biomass and carbon-rich bio-crude.

This technology has been assigned FRL 5-6. This process uses free fatty acid (FFA) oil derived from refining crude oil, algae, or synthetic oils as feedstock. However, this technology faces significant challenges related to the availability of feedstock and the necessary infrastructure for collection, segregation, and storage. From an Indian perspective, this technology may not be viable for Sustainable Aviation Fuel (SAF) production. It is still evolving and presents engineering challenges that need to be addressed.

FT-SPK: The FT synthesis pathway synthesises Most jet fuel using natural gas and coal as feedstock. It is certified by ASTM D7666 for blending up to 50% with fossil jet fuel. Renewable biomass sources such as agricultural wastes, municipal solid waste (MSW), wood waste, and bioenergy crops can also be used as feedstocks. The Fischer-Tropsch (FT) route combines biomass gasification, FT synthesis, and catalytic cracking to produce SPK.

This technology is fully commercialised, with ongoing research and development efforts to enhance catalyst performance. Companies such as Sasol, Shell, Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, and Syntroleum are actively involved in commercialisation efforts²⁵. This technology is evaluated as FRL 7-8.

The FT-SPK chemical synthesis process holds the potential to produce Sustainable Aviation Fuel from municipal solid waste (MSW). This technology is advancing rapidly and is on the verge of commercialisation. A comprehensive waste-processing supply chain would be essential to make this a reality, encompassing collection, segregation, sorting, and transportation. Collaboration with local governments is crucial for the success of this endeavour.

As India engages in revenue-sharing agreements with private MSW suppliers like 'Eco Green and Rollz India Waste Management in Gurgaon', it becomes imperative to define a viable, long-term business model for MSW management. This model would require infrastructure across the supply chain to segregate valuable feedstock elements from impurities. While efforts can be made to enhance segregation at the source through initiatives like the "Swachh Bharat Abhiyan" campaign (with Bhopal serving as a model), additional infrastructure is needed to maximise reuse and minimise landfill volumes²⁶.

FT- SPK/A: Synthesized kerosene is produced through the FT-alkylation process, certified by ASTM D7566 Annex 4 for blending up to 50% SAF with conventional jet fuel. This high-quality liquid fuel made from biomass, known as SPK, can substitute regular kerosene jet fuel. It is evaluated as FRL 6-8.

Currently, crop residues serve as valuable feedstock in bioethanol refineries, a practice employed by fuel producers. Within the framework of the Sustainable Alternative Towards Affordable Transportation (SATAT) initiative, there is a demand for 35 to 40 kilotons of agricultural feedstock, including sugarcane bagasse and municipal solid waste (MSW), for biogas production.

Coal plants also rely on 10% agricultural residue, requiring an annual feedstock supply of 70 to 75 million metric tonnes (MTPA). Shortly, it is anticipated that some 2G-ethanol refineries, expected to be operational by fiscal year 2024, will utilise over 2.0 million tonnes of feedstock annually. This pathway can produce about 8 million tonnes of Sustainable Aviation Fuel using agricultural residue in India.

However, realising this potential necessitates the development of efficient infrastructure for collecting, segregating, and transporting feedstock, which would also create additional job opportunities.

Establishing the infrastructure for agricultural residue collection, including supply chains, will need to address various challenges, such as high costs associated with bulk material transportation, seasonal variations in crop production, and coordination among farmers nationwide. Given the high flammability of agricultural residue, storage infrastructure is crucial to maintaining feedstock quality while adhering to safety standards.

Moreover, feedstock collection should consider location-specific challenges, including shorter harvest seasons and multiple single-crop harvests. The feedstock collection system should align with the National Policy for Crop Residue Management, encouraging farmers to sell agricultural residue rather than burning it, thus contributing to a more sustainable and environmentally responsible approach.

ATJ: The Alcohol-to-Jet (ATJ) pathway involves converting alcohols into hydrocarbon fuel through dehydration, oligomerisation, and hydrogenation or MOGD. These processes are well-established in commercial petrochemical applications. ATJ feedstock-to-jet fuel process chains are in pilot and demonstration stages, with companies like Gevo, Swedish Biofuels, Cobalt, LanzaTech, Honeywell UOP, and Byogy executing ATJ commercialisation proposals and projects. This technology is evaluated as FRL 4-6 and is certified by ASTM D7566 Annex 5 for blending up to 50% SAF with conventional jet fuel.

Bioethanol can be produced through three primary methods:

- From sugar, starch, and cellulose sources
- From hemicelluloses, which often contain significant starch levels, and
- From non-molasses sources like agricultural residues. The selection of ethanol feedstock depends on regional variations in soil and climate.

In India, widely available feedstocks for bioethanol production include rice straw and sugarcane molasses. Additionally, efforts are underway to produce ethanol from bamboo feedstock, with the northeastern part of India being a significant source of bamboo, accounting for over 60% of the country's bamboo production. India presently produces approximately 1400 million litres of ethanol annually, expected to triple in the coming years. An essential factor for the successful commercialisation of SAF in India is the availability of sustainable feedstock at a lower cost.

The abundance of feedstock resources makes SAF production via the Alcohol-to-Jet (ATJ) route a viable option in India. The country generates approximately 500 million tonnes of agricultural residues each year, with a significant portion being burnt, leading to severe air pollution, health risks, and adverse effects on agricultural yields. India has the potential to produce 4 million tons of SAF using its 66 million tonnes of agricultural residue.

ATJ production from agricultural residue, similar to Fischer-Tropsch Synthesized Paraffinic Kerosene (FT-SPK), is still in its early stages but is expected to mature for commercialisation rapidly. Furthermore, sugarcane juice, equivalent to 3 to 5 million tons of sugar, can produce 1 to 1.5 million tons of SAF annually. Existing 1G bioethanol plants can be retrofitted with an additional module for Isobutanol Alcohol recovery (IBA) instead of constructing entirely new SAF facilities. Similarly, ongoing installations of 2G bioethanol plants can explore conversion options to produce IBA. The key challenges to overcome in scaling up SAF production include feedstock supply consistency, technological viability and selection, and managing feedstock costs.

Approximately 11 litres of ethanol can be produced from one tonne of sugarcane. Presently, India is producing 465 crore litres of ethanol per year. The Government's 'National Policy on Biofuels' 2018 set an indicative target of achieving a 20% ethanol blending in petrol by 2030. India has reached the 10% ethanol blending goal by November 2022, five months before the deadline.

This accomplishment has not only bolstered India's energy security but has also had significant economic and environmental benefits, with a forex impact of over Rs. 41,500 crores and a reduction of 27 lakh MT in greenhouse gas emissions. After completing the E-20 program, the ethanol requirement will reach around 1,500 crore litres. Typically, it takes 28 to 30 kilograms of ethanol to produce 1 kilogram of jet fuel. This pathway offers a cleaner alternative to fossil fuels, achieving up to an 80% reduction in greenhouse gas emissions over the fuel's lifecycle compared to conventional fossil jet fuel. Sugarcane ethanol, a clean, affordable, and low-carbon biofuel, has emerged as an attractive feedstock for producing SAF.

SIP-HFS: The Direct Sugar to Synthesized iso-paraffins (SIP-HFS) or DSHC route converts sugar via anaerobic fermentation into alkane-type fuels without an alcohol intermediate product. Recent research focuses on simple hexoses (sugars) from sweet sorghum, sugarcane, and maize due to their ease of fermentation. A joint venture between Amyris and Total is developing SIP-HFS, certified by ASTM D7566 Annex 3, for blending up to 10% SAF with fossil jet fuel. This technology is evaluated as FRL 5-7.

One significant advantage of sustainable-based jet fuel is that the plants or crops used in their production absorb approximately 73g CO₂ eq/MJ of carbon dioxide from the air through photosynthesis. This natural process effectively reduces the overall carbon emissions throughout the fuel's lifecycle.

Technology Licensor / Producer

Table 10 presents technology providers for SAF production, highlights the specific SAF production technologies they offer, information about the feedstock they use, and remarkable global projects.

Process	Producer	Feedstocks	Projects
HEFA	Neste	SAF is made from 100% renewable waste and residue raw materials, such as used cooking oil.	Neste is the world's leading producer of SAF, with a current production capability of 1 million tons per annum (in Finland and Singapore). This will grow to 1.5 million tons annually by the beginning of 2024.
HEFA	Honeywell UOP	HEFA process uses hydrogen to refine vegetable oils, waste oils, or fats, tallow, non-edible corn oil, and non-edible vegetable oils into SAF.	Honeywell UOP's Ecofining process technology is licensed for use at 35 plants globally with a combined production capacity of 400,000 barrels of SAF per day. BP has selected this technology for five of its production facilities.
HEFA	Sinopec	Used Cooking Oil (UCO)	Sinopec has an HEFA SAF plant with an annual production capacity of 100,000 tons. The plant is located in the Zhenhai District of Ningbo, Zhejiang province. It was the first RSB-certified SAF production unit in Asia.
HEFA	Pertamina (Indonesia)	Refine vegetable oils, palm oil, waste oils, or fats.	Pertamina produces HEFA at two refineries: - Cilacap Refinery: Can produce up to 3,000 barrels per day and is targeting to increase to 6,000 barrels per day in 2026. - BioRefinery Dumai: Can produce up to 1,000 barrels per day.
HEFA	EERC	Refine vegetable oils, palm oil, waste oils, or fats.	EERC's HEFA production capacity is 75 million gallons per year. The projected production capacity of HEFA-based SAF is 4.2 million tonnes by 2025.
HEFA	Red Rock Biofuels	Woody biomass	- First SAF plants in North America are designed to produce approximately 20 million gallons per year. - The facility will use a Fischer-Tropsch process to convert 175,000 tons of forestry waste into biofuels.
HEFA	Sundrop Fuels, Inc.	Woody biomass	The plant was to have a capacity of 50 million gallons and produce green gasoline.
HEFA	Preem (Sweden)	Tallow, Raw, tall diesel Crude tall oil from the forest industry, Animal fats from the food industry, Rapeseed oil from the agricultural industry	- The unit has a capacity of 6,600 barrels per day. - Unit can co-process 85% renewable feedstock using Topsoe's HydroFlex™ technology. - Total production capacity of renewable fuels at the Gothenburg refinery will be around 1.6 million m3 by 2030.
ATJ	LanzaTech	Its gas fermentation technology can convert carbon-rich gases into sustainable fuels, including jet fuel.	The plant is expected to be operational in 2023 and produce 10 million gallons of SAF and renewable diesel annually.
ATJ	Axens (Jetanol™)	Ethanol or iso-butanol	Axens' ATJ technology is being used in five industrial-scale projects. These projects are in the advanced stages of engineering or early construction phases. They have a cumulative SAF production capacity of over 1.4 MMtpy (460 MMgpy).

Process	Producer	Feedstocks	Projects
ATJ	Gevo	Isobutanol, Ethanol Cane molasses and cane syrup	- Praj has partnered with Gevo to produce SAF using bio-based feedstock. Praj and Gevo completed a commercial flight between Pune and New Delhi. - Praj has also partnered with Axens. - IOCL aims to establish several production facilities in India to generate 400–500 tons of SAF daily by 2030. - The facilities will use sustainable feedstocks such as cane molasses and cane syrup.
ATJ	Amyris	Sugars into a hydrocarbon molecule (i.e., Farnesene)	- Amyris and Total are preparing to market a drop-in jet fuel that contains up to 10 per cent blends of renewable farnesane. - Amyris has two plants with a total capacity of 150 million litres. - The plant in São Paulo state has a production capacity of 50 million litres annually. - The Amyris/Total production plant in Brotas, Brazil, has a production capability of 40 kt/y of farnesene.
FT-SPK	Fulcrum BioEnergy	Municipal solid waste	Fulcrum NorthPoint: We anticipate an output of 100 million litres of sustainable aviation fuel (SAF). Sierra BioFuels Plant: Situated near Reno, Nevada, this facility will annually yield 11 million gallons of renewable, low-carbon syncrude from 175,000 tons of landfill waste.
FT-SPK	AltAir Fuels	Agricultural and forest residues	The facility has a total refining capacity of 40 million gallons per year, including renewable jet fuel capacity.
FT-SPK	Velocys	Residual commercial and Municipal solid waste	Southwest Airlines has a 15-year agreement with Velocys. The agreement could produce the equivalent of 575 million gallons of net-zero fuel and avoid 6.5 million metric tons of CO ₂ over the term of the agreement.
FT-SPK	Shell	Shell has been involved in SAF production and distribution, focusing on biomass and gas-to-liquids (GTL) technology.	- Shell aims to produce 2 million metric tons of SAF annually by 2025. By 2030, Shell aims to have at least 10% of its global aviation fuel sales as SAF. - Shell is building a biofuels facility in Rotterdam, the Netherlands. The facility will produce 820,000 tonnes of SAF and renewable diesel per year. Shell expects to start production in 2025.
FT-SPK	Johnson Matthey	CO ₂ , Hydrogen (HyCOgen™ + FT CANS™)	HyCOgen and FT CANS* (*jointly developed with bp) are being selected for plants across the world, such as in a new Repsol and Aramco synthetic fuel plant in Bilbao, Spain, which uses renewable hydrogen and CO ₂ as its only raw materials

Table 10: List of Licensor/Producer

Case Study

The following industries are known for being significant carbon dioxide (CO₂) emitters, and their approximate CO₂ emissions per ton of product can vary based on different factors such as technology, location, and operational practices.

- **Steel Production:** Steel production is another heavy carbon emitter. It typically emits around 1.8 to 2.3 tons of CO₂ for each ton of steel produced.
- **Power Generation (Coal-Fired Power Plants):** Coal-fired power plants emit significant amounts of CO₂. They emit about 2.2 to 2.7 tons of CO₂ per megawatt-hour of electricity generated.
- On average, natural gas power plants emit approximately 0.4 to 0.6 metric tons of CO₂ per MWh of electricity generated. These power plants are considered one of the cleaner options for electricity generation in terms of CO₂ emissions compared to coal-fired power plants, which emit significantly more CO₂ per MWh.
- **Petroleum Refining:** The petroleum refining industry releases substantial CO₂ emissions, and the emissions per ton of product vary depending on the specific refining processes. On average, it can range from 2 to 4 tons of CO₂ per ton of product.
- **Cement Production:** The cement industry is one of the largest sources of CO₂ emissions. It can emit approximately 0.8 to 1 ton of CO₂ for every ton of cement produced.

The integrated steel mill process is the predominant method for global steel production, accounting for approximately 74.3% of total output. This process begins with converting iron ore into crude iron within a blast furnace (BF), where coke is a reducing agent. Then, the crude iron is melted into steel within a basic oxygen furnace (BOF). The electric arc furnace (EAF) method is the second most established after the integrated steel mill process. This technique involves melting scrap metal and pig iron to yield the final steel product.

This case study focuses on steel plants, where the carbon emissions range from 1.8 to 2.3 tons of CO₂ per ton of steel produced. Furthermore, the global

iron and steel industry contributes roughly 5% of worldwide CO₂ emissions. The energy and heat required for these processes predominantly derive from fossil fuels, with coal being the primary source. One notable aspect is that the flue gas produced by steel plants contains a relatively higher concentration of CO₂, typically falling within the range of 15–20%. This elevated CO₂ concentration presents a valuable advantage for separation technologies, making capturing and managing carbon emissions in these industrial processes more feasible and efficient.

A steel mill produces three distinct types of gases: blast furnace gas (BFG), basic oxygen furnace gas (BOFG), and coke oven gas (COG), and their composition is detailed in **Table 11**.

Mole Composition (%)	BFG	BOFG	COG
CO	23.5	54	4.1
CO ₂	21.6	20	1.2
H ₂	3.7	3.2	60.7
CH ₄	0	0	22
C _x H _y	0	0	2
N ₂	46.6	18.1	5.9
H ₂ O	4	4	4
Ar + O ₂	0.6	0.7	0.2
Flow Rate, (Nm ³ /h)	730000	35000	40
LHV, (kJ/Nm ³)	3365	7163	15660
LHV, (kCal/Nm ³)	804	1712	3743
Thermal Power (MJ)	682	70	174

Table 11: *Composition of Steel Mill Gases*

At present, steel mill gases are typically managed through either combustion for electricity heat generation or flaring, resulting in significant greenhouse gas (GHG) emissions. An alternative approach that could prove more economically advantageous involves extracting valuable components, such as carbon monoxide (CO) and hydrogen (H₂), from steel mill gas.

This strategy may offer greater cost-effectiveness when obtaining these components from traditional fossil fuel sources or low-carbon alternatives, even after factoring in the value these gases provide to the steel mill regarding heat and electricity generation. Notably, adopting this approach is also conducive to reducing the overall emissions of the steel mill. This reduction in emissions is particularly significant, as the combustion of steel mill gas for electricity production tends to have a relatively high emissions intensity, often ranging from 0.64 to 0.82 tons of carbon dioxide equivalent per ton of steel mill gas combusted. In addition, CO and H₂, once extracted, can be combined to create syngas, a versatile feedstock that can produce various fuels through a Fischer-Tropsch (FT) reaction.

Source of CO ₂	CO ₂ Partial pressure (kph)	Gas Partial pressure (kpa)
Smelting Process	32 - 35	Atmospheric
Hot Stove	24 - 28	Atmospheric
Lime Calcining	7.1 – 8.1	Atmospheric
Sinter Plant	3.7 – 4.2	Atmospheric

Table 12: *Source of CO₂ emission and partial pressure in Steel plant*

Table 12 presents the sources of CO₂ emissions and their partial pressure for a steel plant. Flue gas streams, generated in various industrial processes, typically operate at or near atmospheric pressure of approximately 100 kilopascals (kPa). The concentration of carbon dioxide (CO₂) in these flue gases can vary widely, ranging from as low as 1 volume per cent (in cases such as aluminium smelting) to as high as 35 volume per cent (in processes like the Corex smelting reduction process within steel plants).

This diversity in CO₂ concentration levels results in relatively low CO₂ partial pressures within these flue gas streams, usually measuring below 40 kPa. Partial pressure is the pressure exerted by an individual gas component within a mixture. In this context, the CO₂ partial pressure, despite variations in concentration, remains relatively modest, emphasising the importance of managing and reducing emissions in these industrial processes to mitigate their environmental impact. The partial pressure of CO₂ plays a pivotal role in various

aspects of carbon capture processes, influencing the sizing of process equipment, the energy needs of capture plants, and the choice of applicable capture technologies. These factors collectively determine the overall cost associated with CO₂ capture. When the CO₂ partial pressure is higher, it signifies that CO₂ molecules will transfer more rapidly from the source gas to the capturing medium, such as a solvent or adsorbent. This heightened transfer rate has a significant advantage - it allows for the design of smaller and more compact capture equipment, reducing its capital cost. Moreover, elevated total gas pressures also lead to a reduction in the gas volume per tonne of CO₂ captured, further contributing to a decrease in equipment size and, consequently, a reduction in capital costs.

In this case study, the authors have investigated the production of SAF derived from the carbon dioxide emissions from steel mills. As part of their analysis, they have made certain assumptions. Specifically, it is assumed that for every million tons of steel produced, it is feasible to generate 44 tons of SAF, 22 tons of naphtha and 11 tons of gas oil. This innovative approach of deriving SAF from the emissions of steel mills signifies a significant synergy between industrial processes. It highlights the potential for repurposing and converting some CO₂ emissions from steel production into valuable, environmentally friendly aviation fuel. The precise ratios of SAF, naphtha, and gas oil obtained per one million tons of steel demonstrate the promising possibilities for reducing carbon footprints within the steel industry while contributing to the aviation sector's sustainability efforts. **Table 13** outlines the specific assumptions made for this analysis.

Description	Value	UOM
Assumed Steel production capacity	1	MTPA
Plant operating hours	8300	h
CO ₂ Generation	2.2	t-CO ₂ /t-steel
CO ₂ available flow rate	265	t/ h
SAF	44	t/ h
Naphtha	22	t/ h
Gas Oil	11	t/ h

Table 13: *SAF from 1 MTPA of Steel Plant*

In a similar approach, it is observed that each one-million-ton facility in the cement, ammonia, and aluminium industries has the potential to yield a combination of SAF, naphtha, and gas oil, as depicted in **Figure 24**. This observation underscores the versatile approach of these industries in not only addressing their specific production requirements and contributing to sustainable practices and the broader goal of aviation fuel production. It highlights the synergy between different sectors and the potential for harnessing diverse industrial processes to produce SAF, naphtha, and gas oil, which can positively impact aviation sustainability.

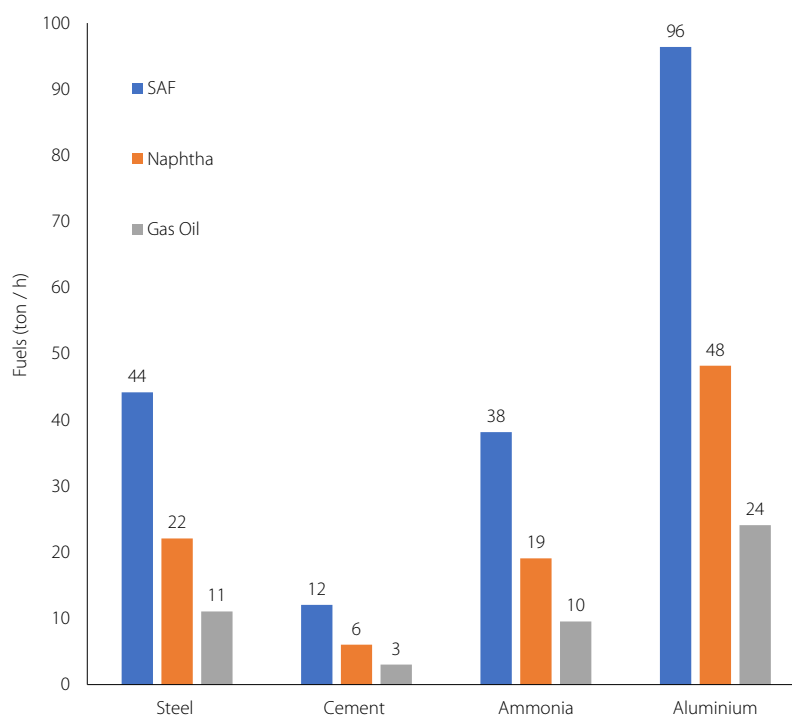


Figure 24: Fuel Obtained from one MTPA of Steel, Cement, NH_3 , Al.

The aluminium industry holds the distinction of being the highest SAF producer per unit of aluminium output. According to the latest data, global aluminium production reached 69 million metric tons (MT). From this volume of aluminium production, it is estimated that the industry has the potential to generate approximately 55.2 million tons of SAF. This is a significant contribution toward sustainable aviation.

When we examine the world's crude steel production in 2022, the scale of potential SAF production is considerably larger. Global crude steel production reached a substantial 1878.5 million tons (Mt). The industry can produce approximately 689 million tons of SAF from this impressive steel output. This underlines the significant potential for the steel sector to contribute to the large-scale production of SAF. It also emphasises the importance of further exploring ways to harness CO_2 emissions from steel production to fuel the aviation industry's sustainability goals. India's crude steel production reached a substantial 120 Mt. From this remarkable steel output; the industry can produce approximately 44 million tons of SAF.

Figure 25 shows the production of methanol (in ton per hour) from one million tons per annum of steel, cement, ammonia, and aluminum plant.

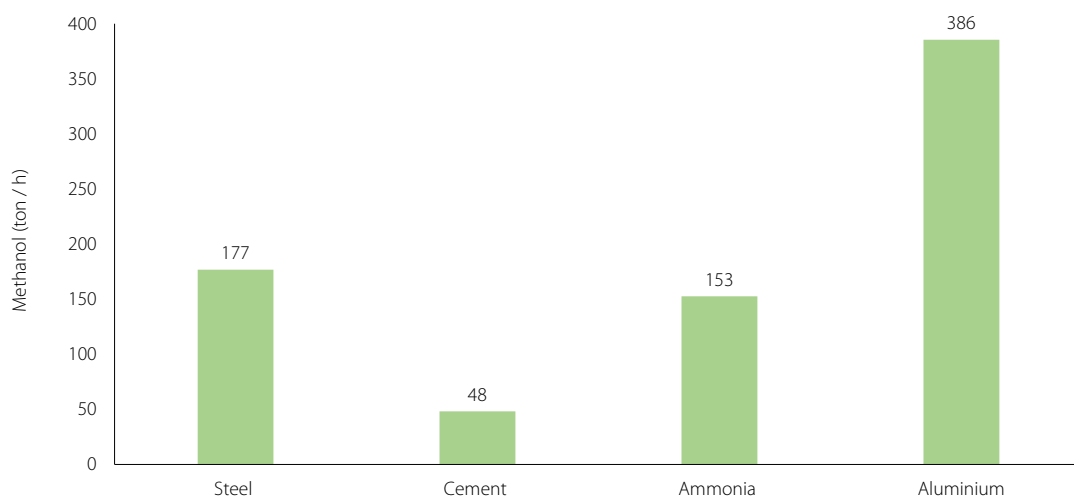


Figure 25: Methanol Production from one MTPA of Steel, Cement, NH_3 , Al

Conclusion

SAF has an exceptional ability to decrease carbon emissions compared to conventional fossil jet fuels. Another key driver is SAF's contribution to supporting energy security within the aviation sector. SAF mitigates the industry's reliance on volatile oil markets, thus enhancing resilience and energy security by diversifying energy sources through a more comprehensive array of feedstocks.

The increasing demand for SAF, driven by airlines and countries committed to carbon emission reduction, has fuelled substantial investments and advancements in SAF production technologies. This growth underlines SAF's economic potential and creates fresh opportunities in the aviation and biofuel industries. Additionally, regulatory support from governments worldwide is on the rise, with incentives, mandates, and tax benefits introduced to encourage SAF production and utilisation, further strengthening its role as an indispensable asset in the aviation industry's sustainability journey. The market potential for SAF is substantial, both in India and globally.

With growing awareness of climate change and the need for sustainable practices, the demand for SAF is expected to increase significantly. With its growing aviation sector, India presents a substantial growth opportunity for SAF adoption, and policy support can play a pivotal role in fostering its development. Given its abundant natural resources and wealth of bio-based feedstocks, India is strategically positioned to emerge as a global leader in SAF production. Critical factors for success on India's SAF journey include the identification of suitable feedstock and corresponding technology, early decisions regarding establishing and implementing a national policy

framework, developing a robust supply chain and infrastructure, and active participation by corporations and financial institutions.

These elements will be instrumental in driving India's progress towards sustainable aviation and reducing its carbon footprint in the sector. The various SAF technologies, including HEFA, Catalytic Hydrothermolysis, FT-SPK, FT-SPK/A, Alcohol to Jet fuel, and Synthetic Iso-Paraffins, offer unique advantages and challenges. Each technology must be evaluated based on feedstock availability, production costs, and emission reduction potential. While 100% SAF usage in aircraft engines may not be feasible soon, SAF's integration into aviation fuel blends is a critical step toward achieving substantial emission reductions.

In summary, SAF is crucial to the aviation industry's strategy to reduce emissions and promote sustainability. As technology readiness levels continue to advance and market demand grows, SAF is poised to play a pivotal role in shaping the future of aviation, mitigating environmental impact, and meeting global climate goals. Collaboration, innovation, and policy support will be instrumental in realising the full potential of Sustainable Aviation Fuel.



Tata Consulting Engineers (TCE)



Tata Consulting Engineers Limited (TCE) is the largest private sector engineering and project consultancy in India and is an emerging global leader in providing integrated engineering solutions. TCE has a presence in over 60 countries and has completed over 11,000 projects.

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- a) Establishing manufacturing infrastructure for new facilities or expanding existing ones in jet fuel production and SAF storage and distribution.
- b) Conducting environmental assessments and assisting in regulatory framework and policy formulation.
- c) Designing utilities or balance of plant (BOP) systems for small, medium, and large-scale operations.
- d) Collaborating with regulatory bodies to establish norms and acceptance criteria.
- e) Implementing digitalisation throughout the entire SAF value chain.

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