Responsible Investing

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Sustainable Aviation Fuel

Sustainable aviation fuel (SAF) is an appropriate way to decarbonise a hard to abate sector.

SAF is the fastest pathway to reducing emissions from aviation and does not require new aircraft technology. For short haul flights, other technologies are being developed but are not yet commercialised. For long haul flights, currently there is no other option to reduce CO_2 emissions. Using SAF can reduce lifecycle emissions from aviation by up to 95%, with technology pathways and fuel eligibility approved for use.

There is long term structural demand for sustainable aviation fuel (SAF).

In 2023, about 0.2% (600m litres) of global jet fuel use was SAF. To achieve net-zero by 2050, it is estimated that SAF use could be as high as 449bn litres. We estimate legislated near term demand through to 2026 at ~1393m litres. This demand is supported by policy: examples include the US, EU, Singapore and Japan that either have SAF mandates or tax incentives to support SAF purchasing or SAF production.

SAF GHG reductions are calculated as lifecycle emissions.

When an aircraft uses SAF, it emits CO_2 in the same way as with traditional jet fuel. The GHG reductions come from the method in which the fuel was created. For example, as an oilseed plant grows it removes carbon from the atmosphere, and this is included in the lifecycle emissions of the SAF.

Supply is yet to come online, but estimates show feedstock is there.

Presently, most SAF comes from one technology pathway (called Hydroprocessed Esters and Fatty Acids, or HEFA) that uses vegetable oils, waste oils or fats as a feedstock.

This is the cheapest pathway, but has feedstock limitations. Other pathways, including those using synthetic feedstock, will come online over the coming years. The IATA estimate SAF demand in 2030 (~21.4 billion litres) can be met if 30% of renewable fuel production (~23.8 billion litres) is channelled towards SAF.

Not all SAF is the same.

To be used in aircraft, the American Society for Testing and Materials (ASTM) has to approve the technology. Within the list of approved ASTM processes, different feedstocks have different GHG reduction properties, and different hydrocarbon structures. The eligibility for SAF within certain regulatory regimes depends on the GHG reduction of the SAF: the EU has the strictest requirement for eligibility at 65% GHG reduction for the biofuels pathway.

SAF is a drop in fuel.

Once created, SAF replaces traditional jet fuel up to a maximum of 50% as allowed by the ASTM. We expect this to increase as SAF supply chains and products improve. Limitations at the moment are not due to engineering (a flight using 100% SAF flew across the Atlantic in Nov 2023). However, specific properties of traditional jet fuel are required to maintain rubber sealing integrity in the fuel system and ASTM approved SAF does not generally have these required properties.

SAF costs about ~2x-4.5x more than traditional jet fuel.

Use has been constrained by airlines because the price of SAF is significantly higher than traditional jet fuel. Tax incentives and legislated mandates will drive demand and supply growth initially (we estimate to at least 2030). While it is difficult to estimate long term SAF prices in light of supply increases, as policy globally becomes more restrictive with respect to carbon emissions, we expect legislated incentives for SAF buying to continue.

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Aviation emissions

Proportion of global emissions

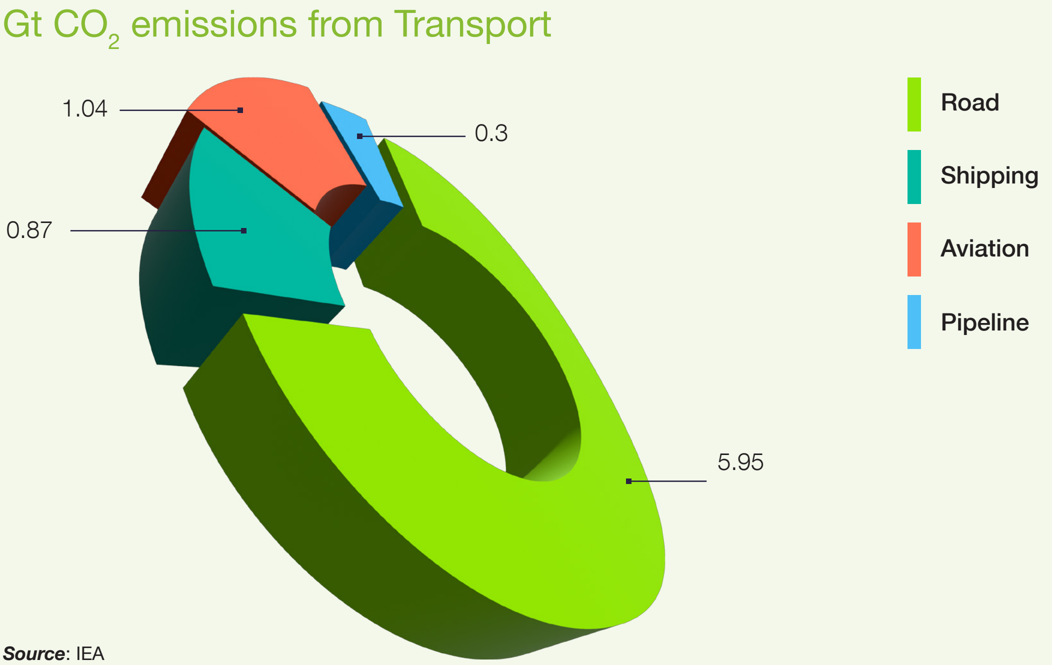
The world emits approximately 55Gt of greenhouse gas (GHG) per year. GHG emissions are measured in carbon dioxide equivalents (CO_2-e) over a 100 year timescale, which captures the natural attrition of greenhouse gases into the ecosystem.

Carbon dioxide is defined as having a global warming potential (GWP) of 1, with other gases then referenced to this measure. Methane has a GWP of 28, because while it lasts less time in the atmosphere than CO_2, it absorbs more energy, and so has a larger effect on global warming.

Of the 55Gt CO_2-e, approximately 74.4% is carbon dioxide (CO_2), 17.3% is methane (CH_4), 6.2% is nitrous oxide (N_2O), and 2.1% is F-gases (HFCs, CFCs, SF_6). By sector, Energy (57%) is the largest contributor to GHG emissions, which consists of buildings (17.5%), industry (24.5%), agriculture and fishing (1.7%) and unallocated and fugitive emissions (13.6%).

Using 2019 data, the International Energy Agency (IEA) estimates that transport emits 8Gt CO_2, with most coming from road travel.

Exhibit 1: Distribution of CO_2 emissions from transport



Source: IEA

Progressing towards net zero emissions (NZE) requires transport emissions to fall by ~25% to 6Gt by 2030 (IEA, 2024). At present, all forms of transport continue to rely on oil products for ~91% of its energy.

The IEA estimate that in 2019 aviation accounted for 1.04Gt CO_2, which is 1.9% of global CO_2-e GHG emissions.

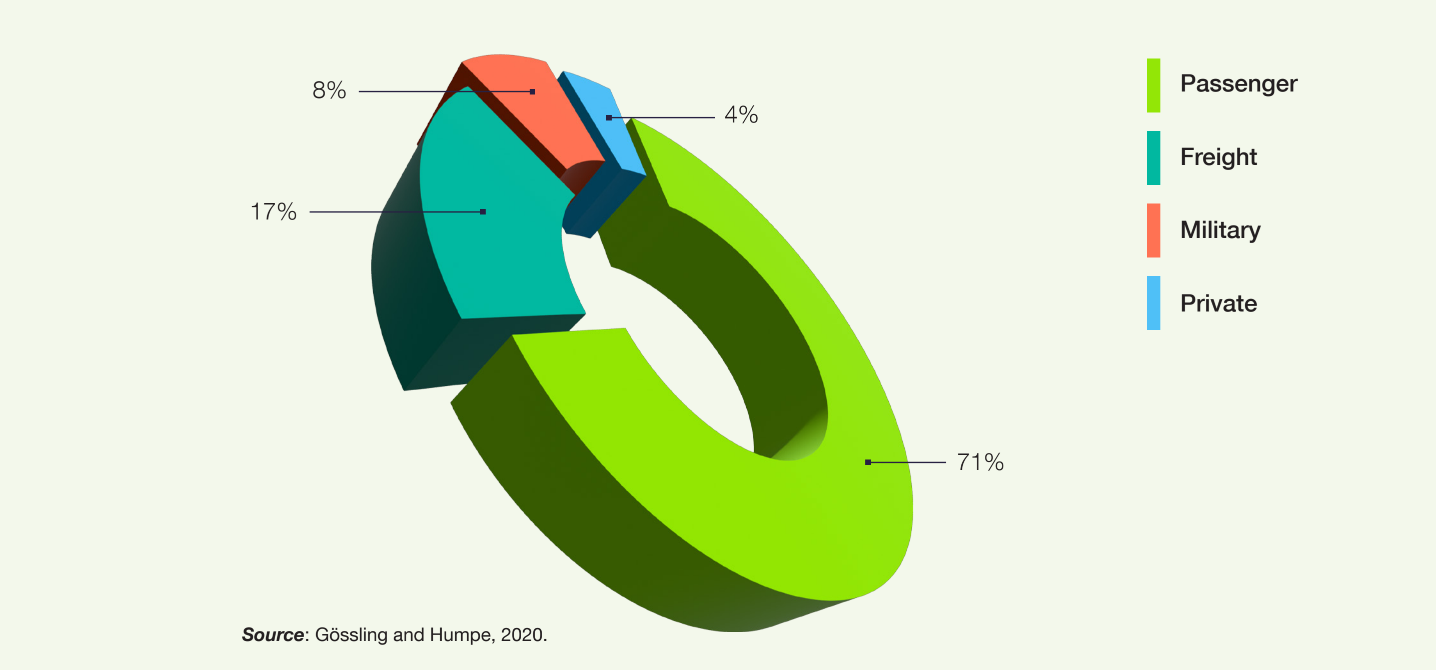
When including the warming impacts of non-CO_2 effects from airline emissions, for example, the radiative forcing effects of nitrous oxides and water vapour this becomes about 3.12Gt CO_2-e (Lee et al., 2021).

Emissions are expected to grow

Using 2018 data, the share of the world's population travelling by air is ~11%, with ~4% flying internationally. The percentile of the most frequent fliers (at most 1% of the world's population) accounts for more than 50% of emissions from passenger air travel (Gössling and Humpe, 2020).

Aviation emissions are projected to reach 1.9Gt CO_2 by 2050, or 3.4Gt CO_2-e as the world becomes wealthier (Bergero et. al., 2023).

Exhibit 2: Distribution of aviation use by type



Source: Gössling and Humpe, 2020.

In 2019, passenger demand was for ~8,700 billion passenger-kilometres (pkm) and freight demand was for 225,000 million-ton per km (ICAO).

Demand varies regionally, with 38%, 24% and 23% of pkm attributed to the Asia-Pacific, Europe, and North America respectively (Bergero et. al., 2023).

Demand in the Middle East (9%), Latin America and the Caribbean (5%) and Africa (2%) is lower, but increasing.

Demand is growing while flying has become more efficient

Comparing passenger-kilometres (pkm), in 1990 one pkm used 2.9MJ of energy which by 2019 had reduced to 1.3MJ pkm. This has come from engineering improvements, larger planes that can carry more passengers, and from optimising seat occupancy.

Note that the carbon intensity of that fuel has not changed during that period: jet fuel remains a hydrocarbon. Over the same period, demand rose ~4x, meaning the total emissions from aviation doubled from 1990 to 2019 (Ritchie, 2024).

Demand is expected to continue to grow. The Airports Council International (ACI) estimates that from 2023 to 2042, global passenger traffic will grow at 4.3% CAGR, which includes a post-COVID recovery of 9.1% CAGR for 2023 to 2026 and a convergence to pre-COVID growth rate of 3.6% CAGR from 2026. Boeing estimates freight will grow at 4.1% CAGR to 2041, similar to passenger demand.

Demand is increasing, and at present, hydrocarbons are the only energy source that provides the necessary energy densities required for long haul air travel.

Direct climate impact of aircraft

The climate impact of aircraft is larger than the direct CO_2 emissions. An example of a non-CO_2 effect is the warming impact of aircraft contrails, which are the clouds that form when water vapour condenses and freezes around aerosols in aircraft exhaust.

Exhibit 3: Climate impact of air travel

Pollutants	CO_2	Water Vapour	Nitrous gases	Soot	Sulphate	Particles
Climate impact	Direct	Direct	Ozone formation & decrease methane	Direct	Sun screening	Creation of contrails and cirrostratus clouds of ice
Climate impact	~70%	~29%	<1%	<1%	<1%	Derivative
Contribution to global warming (proportional to CO_2)	1	0.05	0.3	0.1	-0.1	0.5-3

Source: Environmental and Energy Study Institute.

The total warming contribution of airplane emissions is ~1.85-4.7x the emitted CO_2. Lee et al. estimate that non-CO_2 impacts comprise ~2/3 of net radiative forcing, and that based on global warming potentials (GWPs) aviation emission are warming the climate at ~3x the rate associated with CO_2 emissions alone.

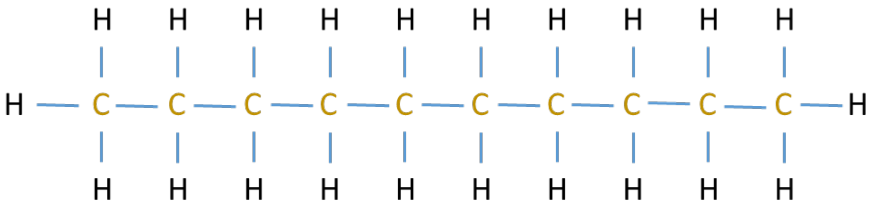
This impact could be reduced using other techniques. Research completed by Google and Breakthrough Energy in collaboration with American Airlines used artificial intelligence to predict contrail formation and then alter a flight path in real time to reduce contrails by 54%, reducing the GWP from emissions. Note that in order to reduce contrails, there would be a ~2% fuel cost for an individual flight. However, not all flights need to be adjusted, so Google and Breakthrough estimate the total cost to the industry of reducing contrails at cost ~US$5-25 ton CO_2-e.

Sustainable Aviation Fuel

Jet fuel chemistry

Jet fuel consists of organic molecules consisting of carbon and hydrogen atoms, called hydrocarbons.

Exhibit 4: Example chemical structure of hydrocarbon where C represents a Carbon atom and H represents a Hydrogen atom. The lines represent covalent bonds, with a single line representing one pair of shared electrons. The carbon chain length shown is called C10 (ten carbon atoms)



Source: *Platypus*

Specifically, jet fuel is a refined kerosene based liquid. Unrefined kerosene consists of about 10 different hydrocarbons, each containing 10 to 16 carbon atoms per molecule. Within kerosene, the main constituents are straight-chain (Exhibit 4) paraffins, branched-chain paraffins, and other shaped paraffins (paraffin here refers to a group of hydrocarbon compounds derived from petroleum). Kerosene is refined into jet fuel using a variety of processes that include distillation, caustic treatment, hydrotreating, and hydrocracking (White, 1999).

Constituents

There are two types of organic compounds that are important for jet fuel: aromatic and aliphatic. To be classified as aromatic, the molecular structure of the compound must meet specific criteria, one of which includes at least one ring (as opposed to a linear structure shown in Exhibit 4) made from connected carbon atoms.

Aliphatic hydrocarbons are the primary hydrocarbon components (81%) of jet fuel, and exhibit a broad range of carbon chain length (9% C8–C9, 65% C10–C14, and 7% C15–C17). The remainder are aromatic compounds.

For most transportation fuels, aromatics are viewed as a source of pollution, so are removed as much as possible. However, for jet fuel, aromatics play an important role. They are still hydrocarbons, but the specific molecular structure means the fuel has a different impact on the aircraft fuel infrastructure than aliphatic hydrocarbons. The aromatic compounds interact with elastomers (rubber O rings and hydraulic lines) in such a way as to cause them to expand, creating tightness in the seals in the fuel system. This is important for aged seals and for this reason, aromatics are not removed from jet fuel (Chong and Ng, 2021).

This matters for sustainable aviation fuel, which at present either contain no or few aromatic compounds. This is why present jet fuel standards limit the proportion of sustainable aviation fuel used in aircraft.

Jet fuel standards

The American Society for Testing and Materials (ASTM), an international body, has created the **ASTM D1655** standard specification for aviation turbine fuel. There are two main types: Jet A and Jet A-1 that are commonly used in commercial passenger aircraft. Jet A is primarily used in the United States while Jet A-1 is primarily used elsewhere.

Jet A: must have a freeze point of < -40°C, and does not typically contain static dissipator additive.

Jet A-1: must have a freeze point of < -47°C, and normally contains static dissipator additive.

Static dissipators are added to improve the conductivity properties of the fuel, minimising the hazardous effects of static charges that build up during movement of jet fuels.

There are other industry specifications (namely the Canadian CGSB 3.23 and the U.K. DEF STAN 91-091) that are also used. Fuel providers create products that meet multiple standards.

Exhibit 5: Industry specifications for ExxonMobil jet fuel

	Jet A	Jet B
ASTM D1655	√	√
CGSB 3.23	√	√
U.K. DEF STAN 91-091	X	√

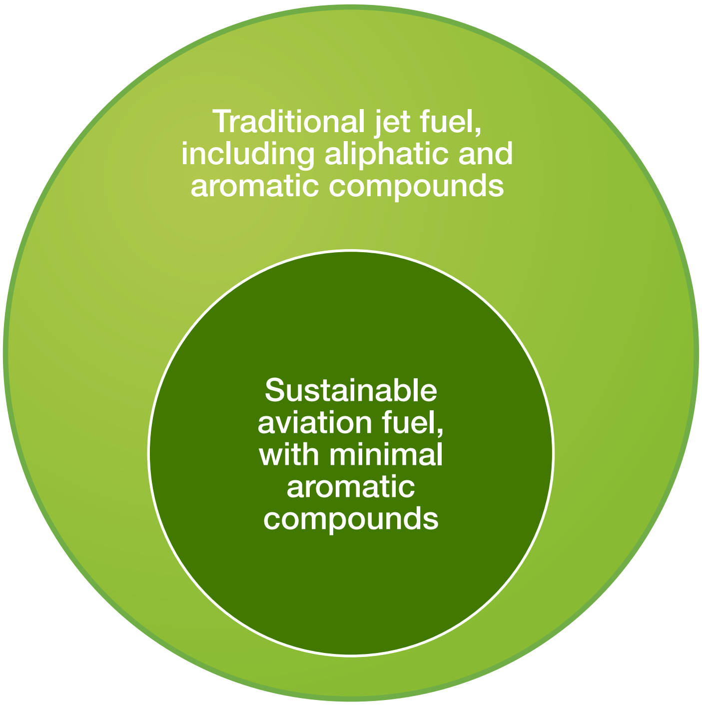
Source: *Platypus*

The ASTM D1655 limits the proportion of aromatic hydrocarbons to between 8% and 25%. The lower limit is needed to prevent the shrinkage of elastomer seals (Chong and Ng, 2021), and the upper limit results from environmental and safety concerns.

Using established technology under present regulations, SAF can be thought of as a subset of traditional jet fuel (Exhibit 6). Note that there are researchers investigating how to create aromatic SAF products (Stone et al., 2022), so this understanding will evolve as science progresses.

Some manufacturers are preparing for increased SAF use. For example, Airbus has the ambition to achieve 100% certification unblended SAF by 2030.

Exhibit 6: Schematic of aviation fuel with respect to traditional jet fuel



Source: *Platypus*

Sustainable aviation fuel (SAF) best near-term option

On a broad level, sustainable aviation fuel (SAF) seems to be the best near term option for reducing the carbon emissions of aviation (ICAO, 2022). It does not require new aircraft or battery technology.

SAF is created using various different products (e.g., waste oils and fats, municipal and forestry waste, non-food crops). It works as a 'drop-in' solution - traditional jet fuel is mixed with a sustainable alternative before being used by the aircraft. SAF can be integrated into existing fuelling systems, with the engineering impacts well understood.

There are three classes of feedstock currently used to develop SAF:

- Biomass (biogenic waste, e.g., used cooking oil);
- Non-biogenic waste (unrecycled plastics or waste fossil gases);
- E-kerosene (synthetic fuel generated through a reaction between hydrogen derived from electrolysed water and CO_2).

The first transatlantic SAF flight was conducted using a Virgin Atlantic Boeing 747 in 2008 and in November 2023, the same consortium flew a test transatlantic flight using 100% SAF that consisted of 88% aliphatic and 12% aromatic SAF (not ASTM approved at the time of writing).

While the CO_2 emissions and the non-CO_2 warming effects of contrails are not reduced, the lifecycle emissions can be up to 94% less than traditional jet fuel if 100% SAF is used. SAF feedstock has removed carbon from the atmosphere before being used in the aircraft - it is the CO_2 lifecycle that is important.

SAF in the supply chain

SAF is blended with Jet A/Jet A-1 before being used in the aircraft.

SAF could be co-processed at an existing refinery, then the blended fuel would flow through the supply chain in the same way as traditional jet fuel. SAF can also be blended at a fuel terminal, entering the supply chain at this point. There would be no change to fuel operations at the airport. While possible to blend fuels at the airport, there are potentially more costs with this approach.

The global standard regulating SAF is the **ASTM D7566**. This standard defines the required characteristics of any SAF. Once the SAF is blended with Jet A/Jet A-1, then the blended fuel is certified to ASTM D1655 and is regarded as equivalent to Jet A/Jet A-1. So, it really is 'drop-in'.

Put simply, the SAF molecule replaces the hydrocarbons at a certain chain length.

Regulatory landscape

Non-governmental organisations

There are two main non-government organisations: the International Air Transport Association (IATA) and the International Civil Aviation Organisation (ICAO).

The IATA is a trade association of the world's airlines with 320 members from 120 nations.

> Sustainability is one of IATAs five priorities, and in 2021 at the 77th IATA Annual General Meeting a resolution was passed by IATA members committing to net-zero from operations by 2050, bringing air transport in line with the 2015 Paris Agreement. To achieve net-zero, 65% reduction will be from SAF, 13% from new technology, 3% from operational efficiencies, and 19% from offsets and carbon capture. Additionally, the IATA are aiming for 50% reduction of absolute emissions from 2005 levels by 2050.

The ICAO is a United Nations agency which aims to achieve the sustainable growth of the global civil aviation system.

> One of five strategic objectives of ICAO is Environmental Protection. Within this, member states have agreed to concentrate on three areas: climate change and aviation emissions, aircraft noise, and local air quality. In October 2022, members agreed to a long-term aspirational goal of net-zero CO_2 emissions from aviation by 2050. ICAO modelling for three different scenarios has SAF playing a significant role in emission reductions. For more ambitious emission reductions, more SAF is required.

ICAO Third Conference on Aviation Alternative Fuels (called CAAF/3)

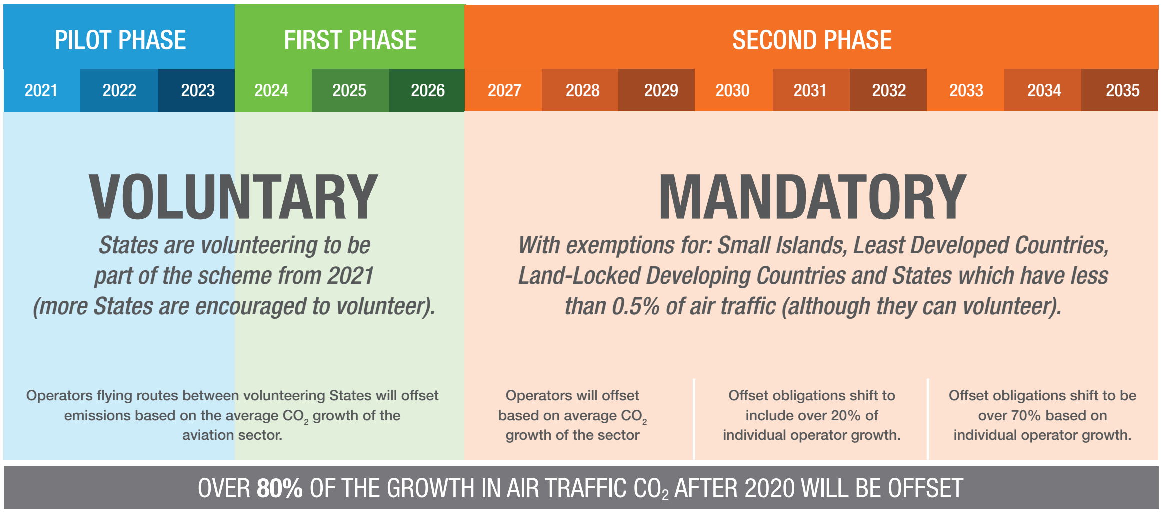
Held in November 2023, this conference set the Global Vision for 2030:

- 5% CO_2 emissions reduction in international aviation by 2030. Emission estimates for 2030 are 682Mt CO_2, which should be reduced by 34Mt through SAF, corresponding to 17.5 billion litres of SAF use in 2030.
- Supporting this are three measures:
    1. A global policy framework will be developed to promote SAF production;
    2. Capacity will be supported via the ICAO Finvest Hub;
    3. SAF accounting methods will be standardised, ensuring environmental integrity.

To achieve net-zero, carbon offsets will be required, and so the ICAO have implemented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). As well as setting the baseline (emissions in 2035 will be 85% of 2019 emissions), this established an international standard for eligible carbon offsets for aviation. Under CORSIA, flights under the scheme reduce emissions by buying and then cancelling offsets. CORSIA classifies an airline operator as: one providing international flights with maximum take-off mass > 5,700kg and annual CO_2 emissions > 10kt.

Offsets are monitored under the IATA, and under the criteria are based on principles commonly applied under existing carbon offset mechanisms. SAF can be used as an alternative to offsets to meet CORSIA requirements.

Exhibit 7: CORSIA offsetting demand



States are volunteering to be part of the scheme from 2021 (more States are encouraged to volunteer).

With exemptions for: Small Islands, Least Developed Countries, Land-Locked Developing Countries and States which have less than 0.5% of air traffic (although they can volunteer).

Operators flying routes between volunteering States will offset emissions based on the average CO_2 growth of the aviation sector.

Operators will offset based on average CO_2 growth of the sector

Offset obligations shift to include over 20% of individual operator growth.

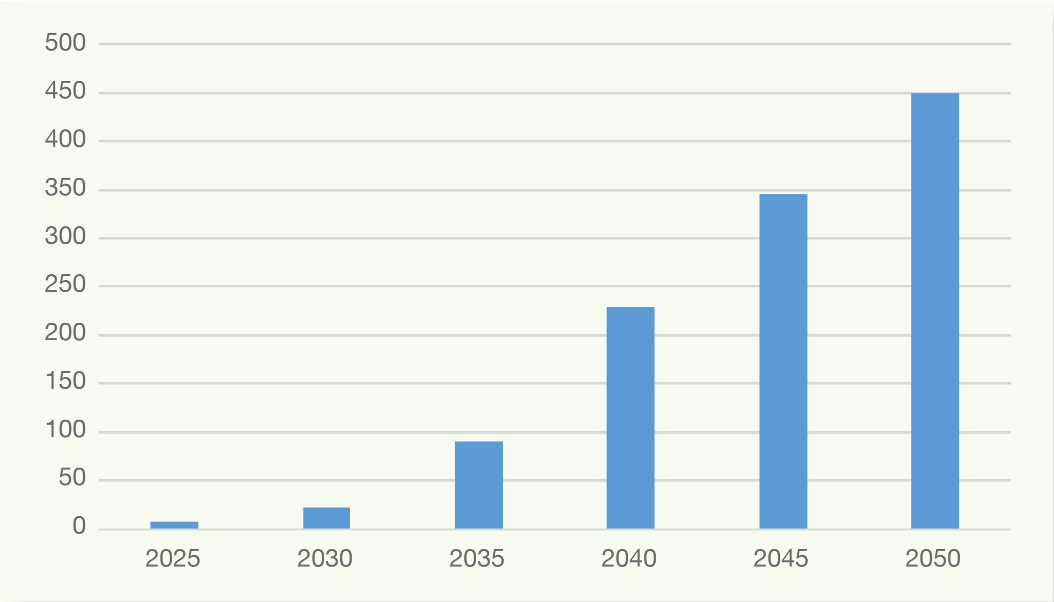
Offset obligations shift to be over 70% based on individual operator growth.

OVER **80%** OF THE GROWTH IN AIR TRAFFIC CO_2 AFTER 2020 WILL BE OFFSET

Source: *Aviation Benefits Beyond Borders*

The IATA estimate that in 2023, about 0.2% of global jet fuel use was SAF, which is ~600m litres of a 300bn litre market. While this proportion has tripled from 2022, SAF use remains at the beginning of its growth curve. To achieve net-zero by 2050, the IATA estimate that SAF use at 70% of jet fuel could be as high as 449bn litres by 2050 (Exhibit 8).

Exhibit 8: IATA SAF demand estimates under net-zero 2050



Source: *IATA*

Governing organisations

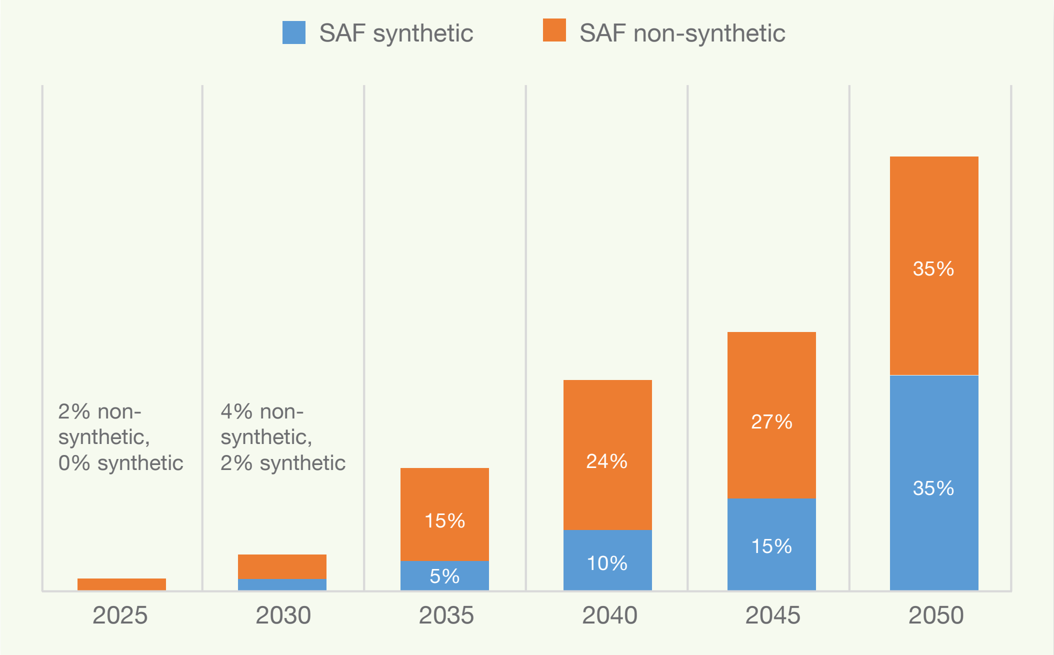
European Union

In July 2021, the European Commission proposed the ‘Fit for 55’ package, consisting of a group of proposals for EU wide policies that will enable the EU to reduce GHG emissions by 55% by 2030, compared to a 1990 baseline. The Fit for 55 package included a proposal called ReFuelEU, which aims to level the playing field for sustainable air transport.

The Council of the European Union adopted the ReFuelEU in October 2023, legislating SAF demand out to 2050. The demand is split into synthetic (produced using renewable energy, water and CO_2) and non-synthetic SAF (produced from biogenic sources). To help put this demand into context:

- We estimate that EU jet fuel consumption at ~1m barrels per day equivalent, or 158.6 million litres per day, equating to ~57.9 billion litres per year;
- Under ReFuelEU, in 2025 2% of jet fuel is expected to be non-synthetic SAF;
- So, in 2025 the 27 member states in the EU will require ~1.16 billion litres of SAF. For context, the IATA estimates global SAF production will triple to 1.875 billion litres in 2024.

Exhibit 9: Regulated SAF demand for EU, split into synthetic and non-synthetic feedstocks



Source: *Official Journal of the European Union*

In terms of eligible feedstocks for SAF within the EU, the fuels need to comply with the sustainability criteria set out in the Renewable Energy Directive:

- The average annual expansion of the global production area of the feedstock is > 1% and affects more than 100,000 hectares after 2008;
- The share of such expansion into land with high-carbon stock[1] is higher than 10%, according to a formula that accounts for different types of land and crop productivity.

If both of these criteria apply to the feedstock, it is not eligible to be used as SAF within the EU. Palm oil SAF is not eligible under this criteria, and soy-bean derived SAF at present meets the first criteria, but not the second. To be eligible as a feedstock, GHG emission reductions have to be at least 65% for biofuels and 70% for Power-to-Liquids (described later) technologies across the lifecycle compared to fossil fuels.

Fines apply for non-compliance, but are limited to twice the amount of the price difference between SAF and traditional jet fuel.

At present, jet fuel is not taxed within the EU. Member states are presently negotiating introducing a tax that would apply from 2028 and gradually increase. Current at February 2024, negotiations are focused on reducing the tax for island nations and territories within the EU.

UK In April 2024, the UK government confirmed a SAF mandate of 2% in 2025 rising to 10% of all jet fuel in flights taking off from the UK by 2030. By 2040, this will increase to 22%. This was constructed under the Jet Zero strategy, which aims for net zero aviation by 2050.

SAF feedstocks will be required to have a minimum GHG savings of 40% compared to fossil jet fuel.

Current SAF usage in the UK is ~1% of fossil-based jet fuel, and in 2025 this will lift to 2%, which is ~310 million litres. All else being equal, this will 1.55bn litres by 2030.

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[1] High carbon stock refers to high concentrations of carbon contained in the vegetation and soils of high carbon stock forests (using industry definitions).

The UK has put a cap on the hydroprocessed esters and fatty acids (HEFA) feedstock, allowing HEFA to contribute 100% of SAF demand in 2025 and 2026, then decreasing to 71% of total SAF by 2030 and 35% by 2040. The mandate requires Power-to-Liquids to be 0.2% of jet fuel demand in 2028 rising to 3.5% by 2040.

The UK government has implemented a reference carbon intensity of SAF at a reduction of 70% to fossil jet fuel, with more emission reductions beyond this rewarded under the scheme. SAF fuels will have to save at a minimum of 40% of GHG emissions compared to fossil kerosene (SAF fuel will have a maximum lifecycle emissions of 54.3gCO_2-e/MJ).

The SAF mandate will include a certificate trading scheme. For airlines not meeting their SAF requirements, they can buy out their obligations at GBP4.70 per litre (GBP5 per litre for Power-to-Liquids), estimated at more than 2x the production cost of SAF. For airlines that buy more SAF than legislation requires, they will be able to sell their SAF obligation to those airlines that have a shortfall at the market price. As at May 2024, traditional jet fuel in the UK was trading at GBP1.05 per litre. At present, fossil-based jet fuel is not taxed in the UK and SAF will come under this umbrella.

The UK is supporting SAF supply through grant funding (GBP135m to support domestic SAF projects) and the introduction of a revenue certainty mechanism for SAF producers by the end of 2026.

US Announced in 2021, the Biden administration announced the Sustainable Aviation Fuel Grand Challenge (SAFGC) that brings together multiple federal agencies to support SAF.

The aim is to expand domestic consumption to 11.36 billion litres by 2030 and 132.5 billion litres by 2050. Eligible SAF products have to achieve at least 50% reduction in GHG emissions. The SAFGC provides funding opportunities to support SAF projects and producers with up to US$4.3 billion.

The U.S. Departments of Energy, Transportation, Agriculture in collaboration with the U.S. Environmental Protection Agency released the SAF Grand Challenge Roadmap in 2022. This laid out six action areas: i) feedstock innovation, ii) conversion technology innovation, iii) supply chains, iv) policy, v) end use, and vi) communication progress. The document highlights the use of public-private partnerships to aid implementation. This a common theme with SAF – the emerging supply chain requires both private and public money.

For SAF, the Inflation Reduction Act (IRA) included the following:

- a two year tax credit for those who blend SAF;
- a subsequent three-year tax credit for those who produce SAF;
- a grant program of US$290 million over four years to carry out projects that produce, transport, blend, or store SAF, or develop, demonstrate, or apply low-emission aviation technologies.

To be eligible, the SAF must reduce GHG emissions by 50% compared with fossil based jet fuel.

The tax credit starts at US$1.25/gallon for neat SAF and increases with every percentage point of improvement in life cycle emissions performance up to US$1.75/gallon. The IRA allows tax credits to be stackable, so SAF credits can be combined with clean electricity credits, manufacturing credits, carbon capture, utilisation and storage credits, and hydrogen production credits (for some feedstocks).

While demand in the US has not been mandated for commercial aviation, the recently introduced Sustainable Aviation Fuel Act includes a 10% SAF mandate for the Department of Defence for fuel for operational purposes. The bill has been sponsored by Representative Julia Brownley and as at May 2024 is yet to pass the House.

Singapore

In 2024, the Civil Aviation Authority of Singapore (CAAS) will aim for a SAF target of 1% from 2026, moving towards 3-5% by 2030.

In 2019, Singapore used 10.6 billion litres of jet fuel, so if demand returns to pre-COVID levels, this will account for 106 million litres in 2026.

Airlines will be charged a SAF levy that will be based on the volume of SAF needed to achieve 1% and the SAF price at that point. Estimates are for the levy for economy class for flights from Singapore to Bangkok, Tokyo and London are S$3, S$6 and S$16 respectively. The levy will be passed onto passengers and will support the purchase of SAF by the CAAS, which will be centralised using the passenger levies.

Singapore has entered into bilateral sustainable aviation agreements with Australia, Japan, New Zealand, United Kingdom, and the US with the aim to scale up SAF adoption. One method of achieving this is to develop an 'Aviation Green Lane' as an end-to-end model, which the CAAS is developing with Japan and the US.

Exhibit 10: Aviation green lane concept

Initiatives could include:

- **Sustainable aviation fuel use**
- **Fuel-efficient aircraft**
- **Optimised air traffic management**
- **Sustainability measures in airports**
- **Use of high-integrity carbon offsets**

Aviation green lane serves as a potential approach to implement ICAO's basket of measures (technology and operational improvements, aviation cleaner energy use, and CORSIA). Through an end-to-end concept, it seeks to foster value chain collaboration, ensure credibility, and provide transparency to consumers.

Source: *Singapore Sustainable Air Hub Blueprint*

In terms of domestic supply, the company Neste has refinery capacity in Singapore that aims to produce 100 million litres of SAF annually using wastes and residue raw materials as feedstocks.

China

China have issued the Green Aviation Manufacturing Industry Development Program (2023-2035) to develop a green aviation industry (GAMIDP). Within the Civil Aviation Administration of China's (CAAC) 14th Five-Year Plan for Green Civil Aviation Development, the goal for SAF use 20m litres in 2025, cumulatively using 50m litres to 2027.

In the GAMIDP, there is a focus on battery technology. The document highlights the need to put into mass production 400Wh/kg lithium batteries for aviation, and carry out small-scale verification of 500Wh/kg class products. For comparison, typical Tesla cars have batteries that produce ~269Wh/kg.

Batteries do not change weight as they discharge (as fuel burns, the aircraft becomes lighter, extending the range), which is one of the reasons that makes batteries limiting for long-haul flights.

Japan

The Ministry of Economy, Trade, and Industry (METI) in Japan in May 2023 introduced a 10% SAF mandate. The runway towards this has not been specified.

Key takeaways

GHG removal requirements

Different SAF technologies have different GHG lifecycle removal properties. Note that the emissions from the aircraft are the same whether SAF is used or not - it is the lifecycle properties of the SAF feedstock that reduce the emissions.

Exhibit 11: GHG removal eligibility for SAF technologies for different SAF governance bodies

Governing body	GHG reduction for SAF eligibility
CORSIA	10%
UK (via Jet Zero)	40%
EU (via ReFuelEU)	65% biofuels/70% Power-to-Liquids
US (via IRA)	50%

Source: *CORSIA, UK Government, EU, US Department of Energy*

Near-term demand

Legislated near-term demand is driven by the EU (Exhibit 9). S&P Global estimate that in 2024, SAF production will reach 1875 million litres, which is ~3x the amount produced in 2023. Growth in SAF supply will have to continue in order to meet.

Exhibit 12: Near term legislated demand for SAF

Governing body	Year	Legislated SAF percentage	Amount (million litres)
EU	2025	2%	1158
UK	2025	2%	310
Singapore	2026	1%	106

Source: *UK Government, EU, Singapore, Macquarie Commodities*

There is a risk that near-term SAF supply constraints will lead regulatory bodies to soften legislated SAF percentages, or potentially enable the use of carbon credits to meet emission reduction targets with less SAF. However, if supply can be brought online, demand is there at SAF prices that are higher than traditional jet fuel.

Demand in 2030

There are two parts to medium term demand: policy and airline. Note that these generally overlap.

Exhibit 13: Policy demand to 2030

Region	Type	Annual amount in 2030 (million litres)
US	Incentivising policies	11,356
Canada	Incentivising policies	1,005
Brazil	Mandate	251
Norway and Sweden	Mandate	628
UK	Mandate	1,507
EU	Mandate	4,396
UAE	Incentivising policies	628
Japan	Mandate	1,130
India	Mandate	502
Singapore	Mandate	424
Total		**21,827**

Source: *IATA*

Supply in 2030

At present, the production output is unclear. Capacity has yet to come online, and the effect of policy on the production incentives between renewable diesel and SAF could lead to supply constraints. Changes of administration can also have an impact, especially in political environments that are bifurcated with respect to decarbonisation policies.

The IATA estimate SAF supply can meet demand if 30% of renewable fuel production is channelled towards SAF.

Exhibit 14: SAF production in 2030, assuming 30% of renewable fuels are channelled towards SAF

Region	Renewable fuel production in 2030 (million litres)	30% SAF output required to meet demand
Americas	40,594	12,178
Europe	18,024	5,407
Africa	3,040	912
Asia	4,635	1,390
APAC	13,075	3,922
Total	**79,368**	**23,809**

Source: *IATA*

IATA do not break out synthetic and non-synthetic components of production, which is a key differentiator in the EU.

Upside risk from production may come from China. Deloitte estimate that China can meet domestic SAF requirements. If China's aviation sector aligns with IATA's 5.2% SAF target, SAF demand is estimated at 8.4 billion litres by 2030. If all available feedstock is converted to SAF, China could produce 53.8 billion litres of SAF by 2030 although to achieve this, production costs would have to decline. For context, Chinese 2030 jet fuel demand is estimated at 170 billion litres per annum.

Types of Sustainable Aviation Fuel

At the time of writing, there are 11 approved feedstock conversion processes for SAF by the ASTM, and 11 more under review. We focus on those approved at the time of writing, which are most relevant to near term demand.

Approved SAFs

There are 5 underlying processes that support 8 approved SAF types and 3 co-processing SAF methods.

Approval process

Approvals for new SAF are detailed in **ASTM D4054**, a set of guidelines for SAF producers. There are two pathways: traditional and fast track.

- Traditional: 6-month initial examination, 6-month testing period with aviation partners, 2-3 years of further testing using 100,000 litres of neat fuel. The fuel then goes to a ballot of ASTM experts and Federal Aviation Administration approval.
- Fast track: same stringent standards, but fast tracked to ballot. SAFs through this channel can only be blended to 10% and the process has to be covered by an ASTM Annex.

Exhibit 15: Approved SAF processes under ASTM D7566

ASTM reference	Type	Conversion process	Year approved	Abbreviation	Possible Feedstocks	Maximum Blend Ratio
ASTM D7566 Annex A1	Fischer-Tropsch (FT)	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	2009	FT	Coal, natural gas, biomass, municipal solid waste	50%
ASTM D7566 Annex A2	Hydroprocessing Esters and Fatty acids (HEFA)	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	2011	HEFA	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A3	Synthesized Iso-Paraffins	Synthesized iso-paraffins from hydroprocessed fermented sugars	2014	SIP	Biomass used for sugar production	10%
ASTM D7566 Annex A4	Fischer-Tropsch	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	2015	FT-SKA	Coal, natural gas, biomass, municipal solid waste	50%
ASTM D7566 Annex A5	Alcohol-to-Jet	Alcohol to jet synthetic paraffinic kerosene	2016	ATJ-SPK	Ethanol, isobutanol and isobutene from sugars, cellulosic biomass, waste gases fermentation	50%
ASTM D7566 Annex A6	Catalytic hydrothermolysis	Catalytic hydrothermolysis, followed by hydrotreatment, hydrocracking, or hydroisomerization and fractionation	2020	CHJ	Vegetable oils, animal fats, used cooking oils	50%
ASTM D7566 Annex A7	Hydroprocessing Esters and Fatty acids	Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids	2020	HC-HEFA-SPK	Bio-derived hydrocarbons (at present only produced by algae), fatty acid esters, and free fatty acids	10%
ASTM D7566 Annex A8	Alcohol-to-Jet	Synthetic Paraffinic Kerosene with Aromatics	2023	ATJ-SKA	C2-C5 alcohols from biomass	50%

Source: *ICAO, U.S. Department of Energy*

The co-processing SAF methods are certified under the same Annex within ASTM D1655. Co-processing does not require new standalone facilities, and the blend percentage with traditional jet fuel can fluctuate depending on demand.

The advantage of co-processing is that no new plants or infrastructure are required to produce SAF through this channel. However, the blend ratios are generally lower, so the environmental benefits are less.

Exhibit 16: Approved co-processing SAF processes

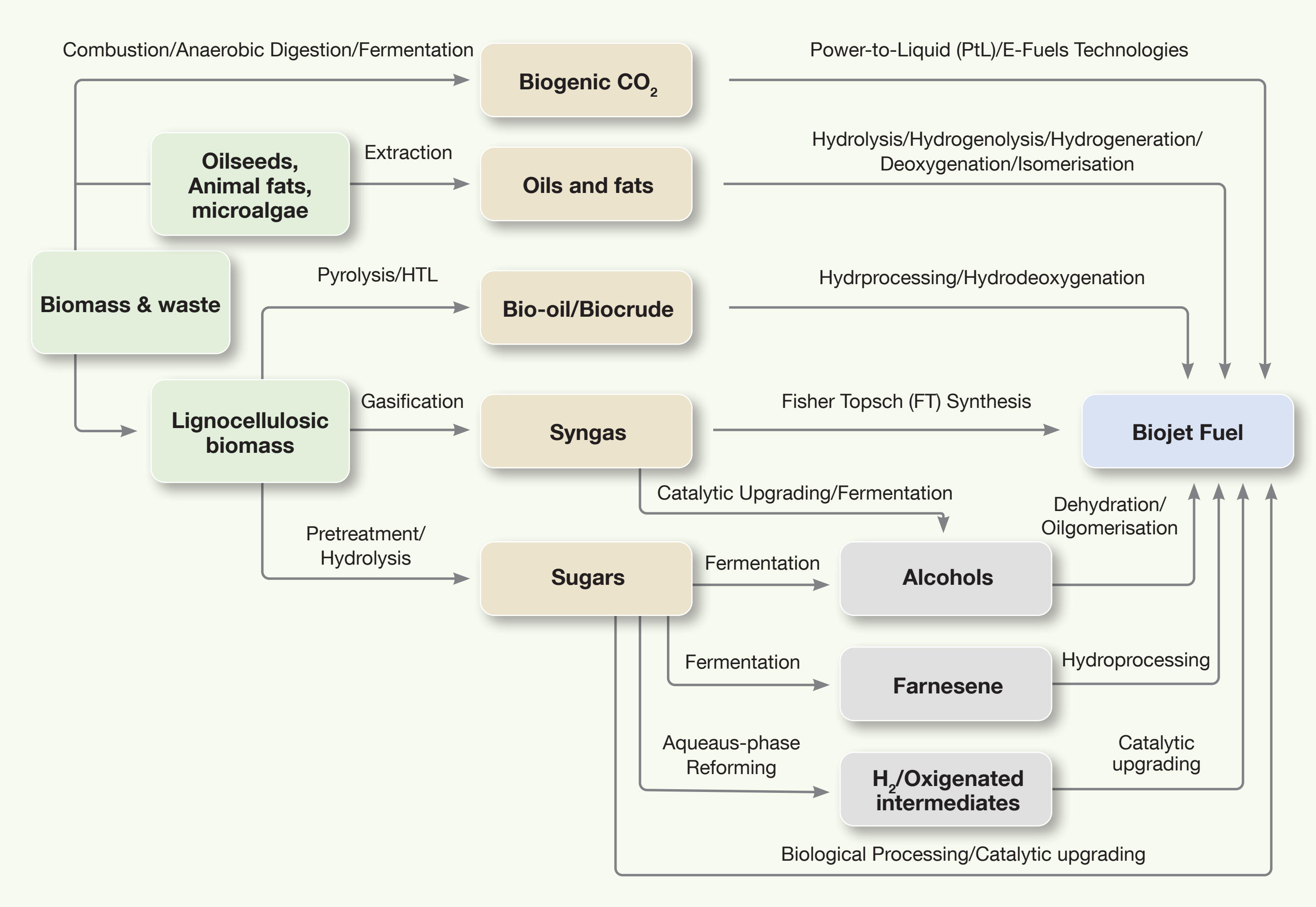
ASTM reference	Conversion process	Possible Feedstocks	Maximum Blend Ratio
ASTM D1655 Annex A1	Co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	Vegetable oils, animal fats, used cooking oils from biomass processed with petroleum	5%
ASTM D1655 Annex A1	Co-hydroprocessing of Fischer-Tropsch hydro-carbons in a conventional petroleum refinery	Fischer-Tropsch biocrude (unrefined hydrocarbons from Fischer-Tropsch reactor) co-processed with petroleum	5%
ASTM D1655 Annex A1	Co-processing of HEFA	Hydroprocessed esters/fatty acids from biomass’	10%

Source: *ICAO, U.S. Department of Energy*

Conversion processes

The process and feedstocks can be visualised as shown in Exhibit 17.

Exhibit 17: Schematic of SAF feedstocks and processes



Source: *Peters at al., 2023*

Fischer-Tropsch (FT)

Originally, the FT process was used to convert coal into a synthetic fuel through liquefaction. The process involved introducing metal catalysts to set off a variety of chemical reactions that resulted in liquid hydrocarbons.

More specifically, from Evans et al. (2012):

> *'The FT process converts synthesis gas (syngas) with a given hydrogen to carbon monoxide ratio into hydrocarbon liquids, waxy solids, with water as a coproduct via a stepwise polymerization process.'*

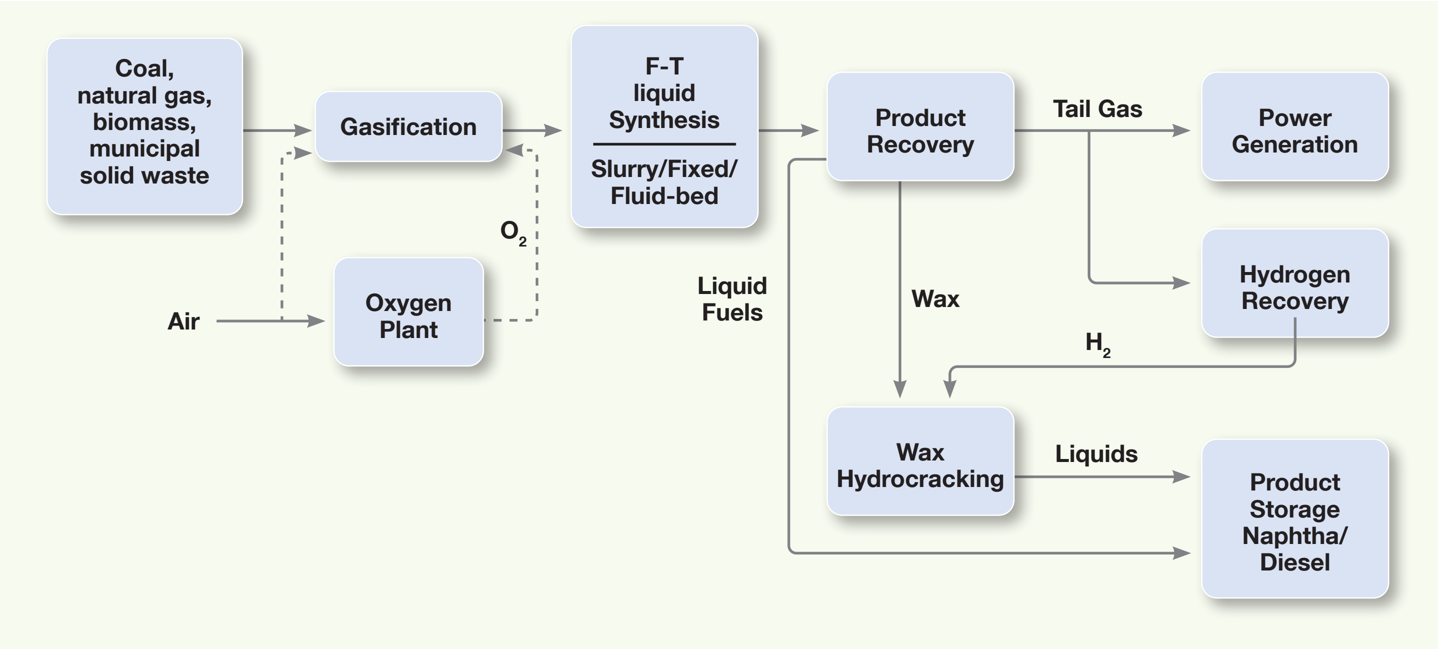
Syngas is generic term for raw gas produced from hydrogen feedstock and consists of hydrogen and carbon monoxide as primary components.

The FT process uses an iron or cobalt catalyst at 220-350°C at 2000-5000 kPa of pressure. It is a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H_2) in the syngas are converted into hydrocarbons of various molecular weights according to:

$$CO + 2H_2 + \text{heat} = CH_2 + H_2O.$$

Most of the alkanes (single bonded carbon and hydrogen atoms) produced tend to be straight chain (Exhibit 4).

Exhibit 18: Fischer-Tropsch process



Source: *: U.S. National Energy Technology Laboratory*

Hydroprocessing Esters and Fatty acids (HEFA)

HEFA uses vegetable oils (e.g., from plants such as the non-edible oilseed Carinata), waste oils, fatty acid esters (fatty acids with alcohol) as feedstock. Note that HEFA is not biodiesel, although the same feedstock is used.[2] The feedstock is hydrotreated in order to deoxygenate the oil and form useable alkanes. By products of this part of the process are water, carbon monoxide, and carbon dioxide. Then, the alkanes are refined using hydrocracking, which reduces the size of the hydrocarbons. After that, the hydrocarbons go through an isomerisation process, which changes the chemical structure, but not the chemical composition. Distillation then separates the components of the liquid hydrocarbons, yielding a kerosene range material called HEFA.

Exhibit 19: HEFA flow scheme

Source: *: Ajam and Viljoen, 2011, Platypus*

Alcohol-to-Jet (ATJ)

The core process bridges the gap between alcohols that can easily be produced form renewable resources and the hydrocarbon fuel necessary for jet engines. The process is based on three catalytic reactions: alcohol dehydration, alkene[3] oligomerization (which increases the carbon number of the molecule), and hydrogenation. These are then followed by fractionation of the hydrocarbon product. Established technologies constructed around alkene oligomerization have been used to generate gasoline and diesel, and are capable of generating jet fuel kerosene as well.

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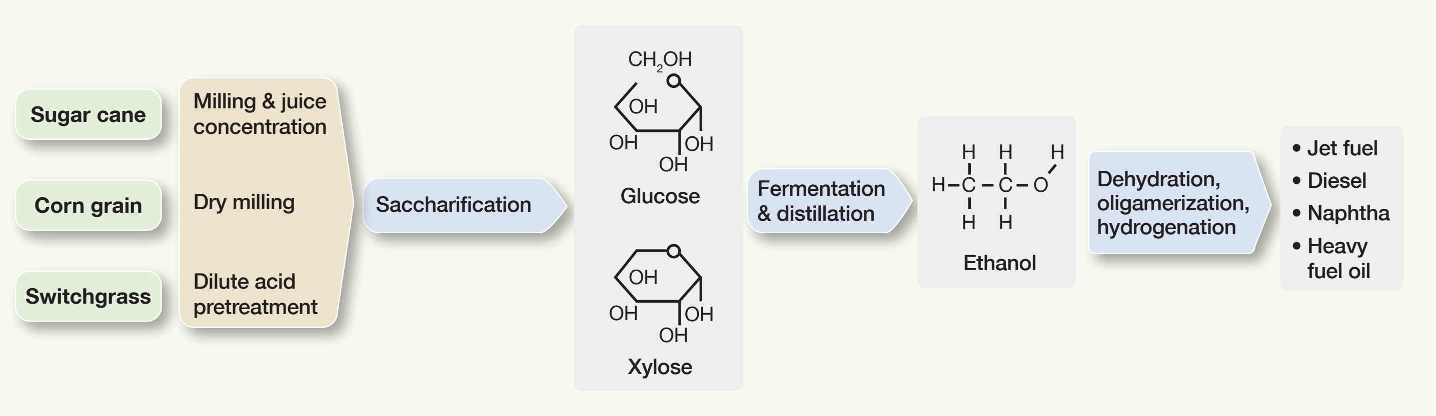
[2] For Biodiesel, the production process is different. The feedstock is treated with methanol in a trans-esterification process that produces fatty acid methyl ester (FAME) and glycerol.

[3] Alkenes are a class of hydrocarbons with at least one carbon-to-carbon double bond. They are more reactive than alkanes due to the double bond.

A subset of the ATJ process uses sugars derived from sugarcane, corn grain or switchgrass that are then fermented to ethanol. Sugarcane and corn grain are commonly used to produce ethanol in the US and Brazil, and switchgrass is used to produce cellulosic ethanol from plant fibre. As well as jet fuel, the final product slate includes diesel, naphtha, and heavy fuel oil (named due to its higher density). Non-fuel co-products are as follows:

- **Corn grain** – co-production of distiller dry gains and solubles (DDGS);
- **Sugarcane** – bagasse is produced after juice extraction (which can also be turned into ethanol through fermentation or processed via FT);
- **Switchgrass** – biomass residues generated after sugar extraction and fermentation can be co-fired to meet the electricity requirements of the refinery, with any excess electricity exported to the grid.

Exhibit 20: ATJ for sugarcane, corn grain and switchgrass feedstocks

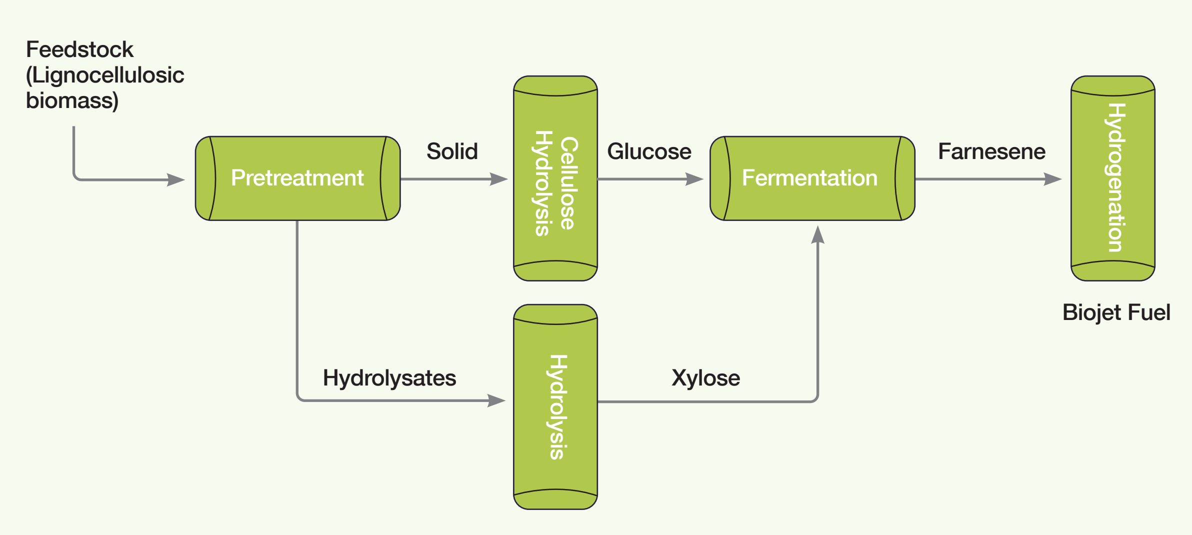


Source: *: Yao et al, 2017*

Synthesised iso-parraffins (SIP)

SIP uses micro-organisms to convert C6 sugars into farnesene (a branched alkene), which is hydrogenated (turns a liquid unsaturated fat into a solid fat by adding hydrogen) for use as SAF (Peters et al., 2023). There are multiple pathways from sugars to The first ASTM approved pathway, developed by the biotechnology company Amyris, uses yeast cells. The cells can convert both C5 and C6 sugars, and up to 95% of the farnesene is recovered.

Exhibit 21: SIP pathway to SAF



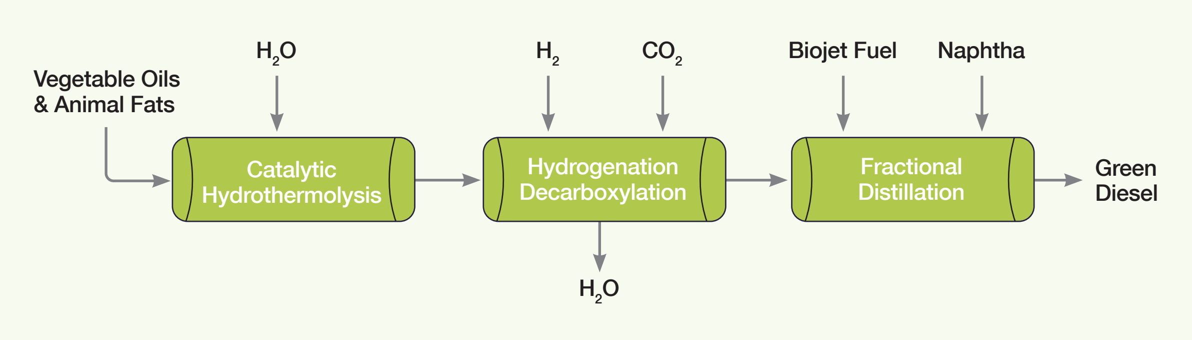
Source: *: Peters at al., 2023*

Catalytic hydrothermolysis

The plant oil based feedstocks (which include soybean oil, jatropha oil, camelina oil, carinata oil and tung oil) are subjected to high pressures and temperatures in the presence of a catalyst to produce SAF.

The triglycerides in the feedstocks (a type of fat, called a lipid) are converted to fatty acids, which are then hydrotreated to produce aliphatic and aromatic hydrocarbons. The hydrocarbons range from C6 to C28, which can then be fractured into different fuel products.

Exhibit 22: Catalytic hydrothermolysis process schematic



Source: *: Peters at al., 2023*

Power-to-liquids

Unlike the previous processes, this method does not require biological feedstocks. It is approved under the ASTM if produced through the Fischer-Tropsch conversion process (ICAO).

Power-to-liquids (PtL) is a synthetically produced liquid hydrocarbon. Renewable electricity is the key energy source, and water and carbon dioxide are the feedstocks used in PtL production.

The steps are as follows:

- Renewable energy powers electrolysers to produce green hydrogen;
- CO_2 from Direct Air Capture or another source is converted into carbon feedstock;
- The carbon is synthesised with green hydrogen via the FT process to generate liquid hydrocarbons;
- The liquid hydrocarbons are converted to jet fuel.

Comparison of pathways

There are significant differences between the ASTM approved pathways with respect to costs of production, limitations of feedstock, technology timelines, and CO_2 emission reductions.

Emissions reductions depend on the feedstock

Different processes lead to different total emissions factors. There are two main parts to the calculation: the core lifecycle analysis (LCA) and the induced land use change (ILUC) LCA. The sum of the LCA and the ILUC LCA equals the total emissions factor for the SAF process.

The ILUC accounts for emissions removed or added by the feedstock. For example, removing high carbon stock vegetation to plant feedstock will increase total emissions, and vice versa for land use changes that remove additional carbon.

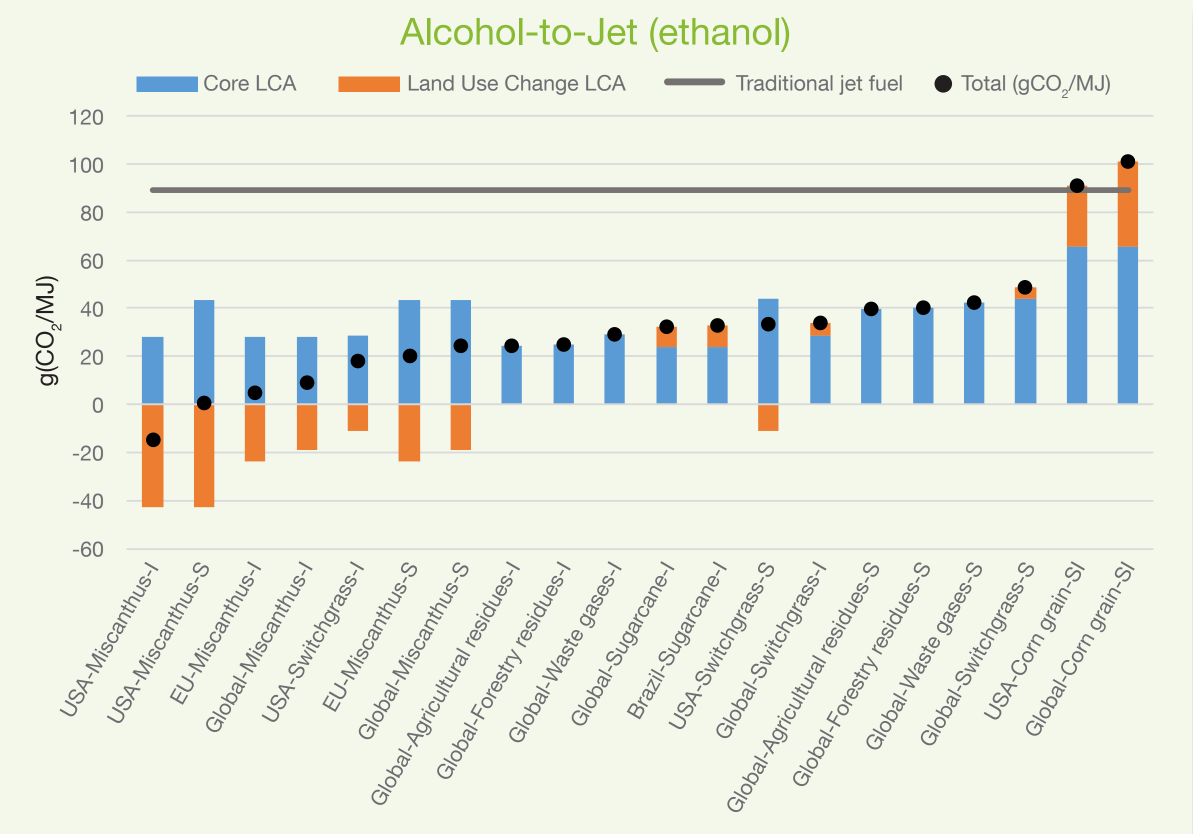
In March 2024, CORSIA confirmed that negative ILUC LCA values will count towards the total emission calculation, which means that some SAF fuels have negative total emission factors.

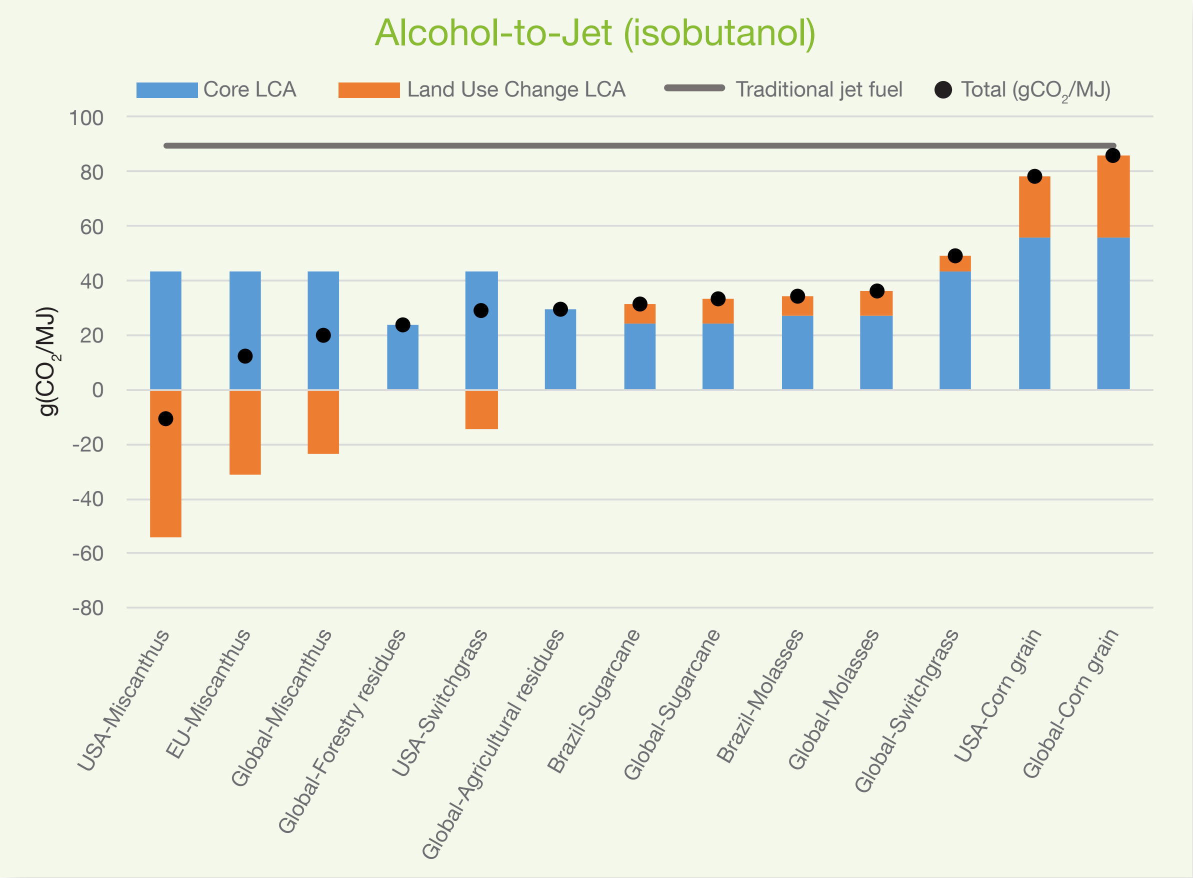
Within SAF processes, CORSIA make the distinction between standalone and integrated:

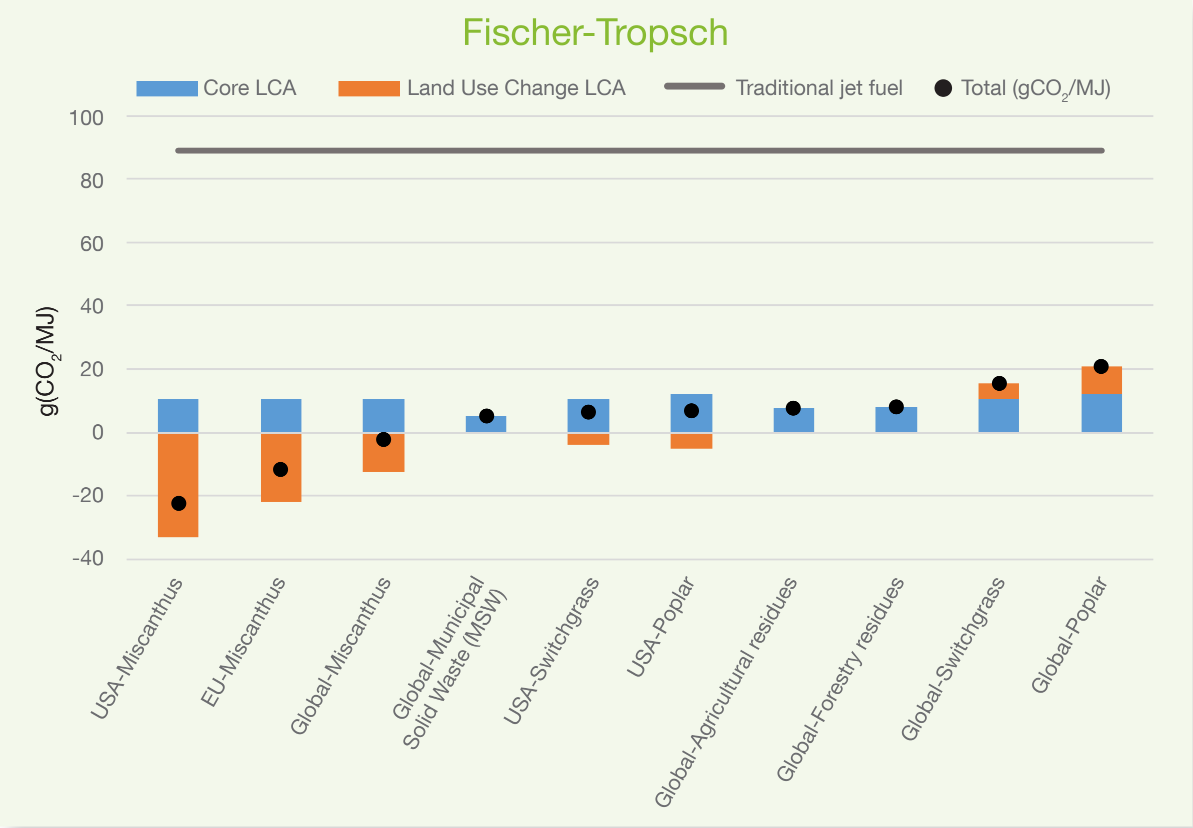
- ***Standalone*** – facility that produces fuel from an intermediate product that is **not** co-located with the facility that uses the fuel feedstock to produce the intermediate feedstock.
- ***Integrated*** – facilities are co-located, with heat integrated between systems that produce the fuel and the intermediate products.

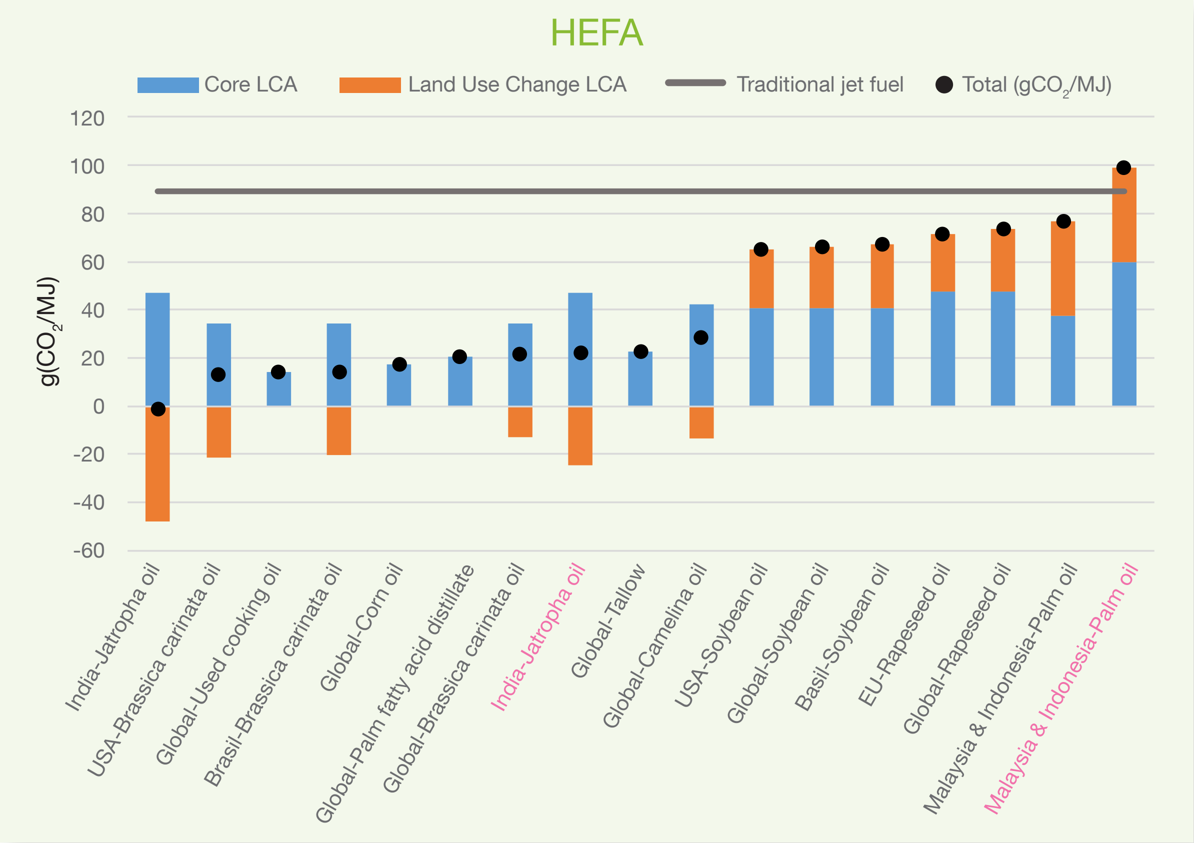
As seen in Exhibit 23, different geographies for the same underlying process can have different emission characteristics.

Exhibit 23: Emission pathways from SAF feedstocks. The suffix S refers to Standalone and I refers to Integrated. The ICAO estimates traditional jet fuel emits 89 gCO_2-e/MJ. LCA refers to lifecycle analysis




Alcohol-to-Jet (isobutanol)
Core LCA
Land Use Change LCA
Traditional jet fuel
Total (gCO₂/MJ)
g(CO₂/MJ)
100
80
60
40
20
0
-20
-40
-60
-80
USA-Miscanthus
EU-Miscanthus
Global-Miscanthus
Global-Forestry residues
USA-Switchgrass
Global-Agricultural residues
Brazil-Sugarcane
Global-Sugarcane
Brazil-Molasses
Global-Molasses
Global-Switchgrass
USA-Corn grain
Global-Corn grain


Fischer-Tropsch
Core LCA
Land Use Change LCA
Traditional jet fuel
Total (gCO₂/MJ)
g(CO₂/MJ)
100
80
60
40
20
0
-20
-40
USA-Miscanthus
EU-Miscanthus
Global-Miscanthus
Global-Municipal Solid Waste (MSW)
USA-Switchgrass
USA-Poplar
Global-Agricultural residues
Global-Forestry residues
Global-Switchgrass
Global-Poplar

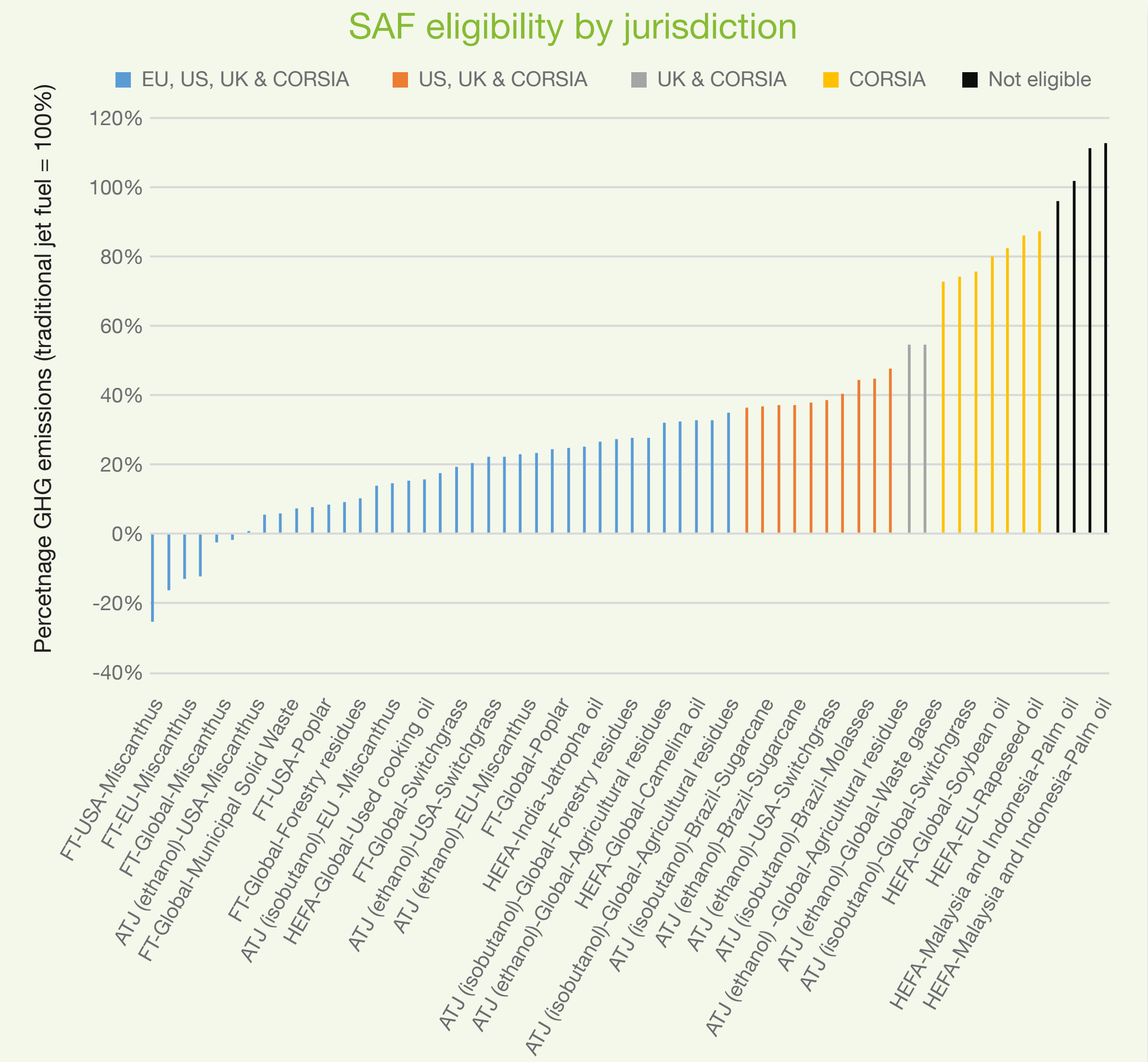


Source: *: CORSIA, Platypus*

The technologies detailed above all produce offtakes that have lower GHG emissions than traditional jet fuel. However, when accounting for change in land use for the feedstock, the lifecycle GHG emissions can increase above traditional jet fuel. These calculations are produced by CORSIA, and so is the measurement used to qualify for SAF eligibility under CORSIA.

Exhibit 23 shows the GHG removal requirements for different SAF technology pathways. Using this information, we highlight the technologies that can provide offtakes to different regulatory bodies. (Exhibit 24).

Exhibit 24: SAF eligibility by jurisdiction using CORSIA



Source: *: CORSIA, Platypus*

At the time of writing there is no standardised approach that accounts for SAF emissions. SAF certification (called SAFc) has been discussed at the World Economic Forum and builds on the CORSIA methodology, but is yet to be universally adopted.

Cost of production

Traditional jet fuel sells for various prices, but we estimate that Qantas paid about **1.18c** per litre in 1H FY2024. Note that one of the reasons that this is lower than the price paid at service stations is the tax differential: the tax on petrol is 49.6c per litre while the tax on jet fuel is 3.6c per litre.

Global averages

Watson et al. (2024) have published a review of SAF that, covers the market dynamics.

Exhibit 25: Selling price at breakeven NPV

SAF Pathway (see Exhibit 15)	Average breakeven selling price ($/L)
SIP	6.05
FT	3.15
ATJ-SPK	2.56
CHJ	1.97
HEFA	1.70

Source: *Watson et al. (2024), Platypus*

This does not account for tax credits or any other jurisdiction dependent incentives. The average includes various feedstocks which would impact the economics of individual technology pathways.

Australia

We use data from a CSIRO report that focuses on SAF in Australia. The costs point to a possible competitive advantage for Australia.

Exhibit 26: CSIRO levelised cost of production in Australia, without regulatory support

SAF Pathway	Estimated production costs ($/L)
Power-to-Liquids (via FT using H_2 and CO_2)	4.1
ATJ (using ethanol)	2.75
FT (using Municipal Solid Waste)	2.25
FT (crop residue)	1.75
HEFA (vegetable oil)	1.42

Source: *CSIRO, Platypus*

Power-to-Liquids – Price of green hydrogen is a key cost driver for PtL. CSIRO estimates that SAF could use 25% of domestic green hydrogen supply from a $50b hydrogen industry.

ATJ (using ethanol) – Price of ethanol is a key cost driver. Domestically, there is a lack of commercial plants. For sugarcane, economic transport to processing is presently a roadblock.

FT (using Municipal Solid Waste) – CSIRO estimate feedstock is the highest ongoing cost, and initial capex for FT-MSW plants high.

FT (crop residue) – beyond logistical challenges to scale in Australia, supply certainty is impacted by climate variability that affects crop residue year to year.

HEFA (vegetable oil) – CSIRO see the largest challenge is the competition with the feedstock competing for use as food. Non-edible oilseeds such as carinata or pongamia are possible feedstock options as well.

Limitations of feedstock

Presently, HEFA is the most mature SAF production pathway. Over 95% of SAF product is from the HEFA technology pathway, and IATA estimate that over 85% of SAF coming online to 2028 will use HEFA technology.

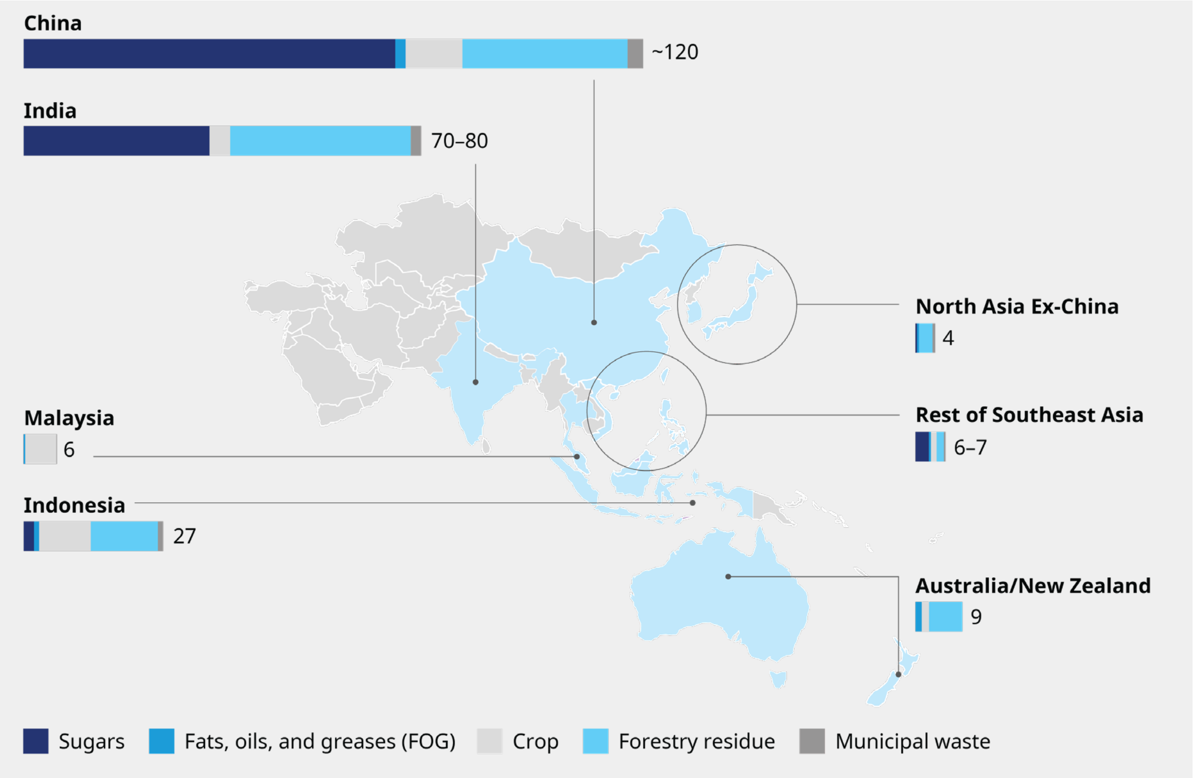
PWC estimate that that 100-200 SAF production sites will be needed by 2030 to meet global demand. PWC claim there are 11 SAF production sites in full operation as at 2023.

While there are near term supply constraints, it is not obvious that SAF supply will be constrained in the long term.

Asia

Oliver Wyman estimate that the global supply for biofuel feedstock is around 800 million metric tons. Note that the amount of SAF produced from a specific feedstock depends on the technology pathway. Asia produces about 40% of this global volume.

Exhibit 27: Estimate of Asia Pacific feedstock supply in million metric ton per annum



Source: *Oliver Wyman*

Australia

CSIRO estimate that domestic SAF supply can meet domestic demand requirements. There is enough feedstock to supply ~5 billion litres of SAF production by 2025 and up to 14 billion litres by 2050.

Technology timelines

If HEFA feedstock becomes more expensive, power-to-liquids will become more attractive. There are a number being constructed globally at the moment:

- ***Montreal, Canada*** - The SAF+ consortium aims to bring PtL to market by 2025-2026. The production site is in Montreal, Canada.
- ***Frankfurt am Main, Germany*** - A pioneer plant aiming to produce 3.3m litres, construction started in 2023.
- ***Hong Kong*** – State Power Investment Corporation to build 4 SAF plants, all of which will use a PtL process.

The technology for the PtL pathway has been developed, however, it is yet to achieve scale and cost competitiveness compared to HEFA. We expect that PtL will take a number of years to replace HEFA as the dominant technology pathway.

Why do all this?

This work is integral to our investment decisions. At Platypus, we have the opportunity to own listed companies that either purchase or are part of the sustainable aviation fuel (SAF) supply chain. As investors, we need to understand the ecosystem, the data, and the regulatory environment in order to form a complete view of the SAF market.

As such, this research has an impact on our investment and portfolio construction decisions.

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