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Will Sustainable Aviation Fuels take off?

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Executive Summary

- The fuel used in **aviation produces 2% of global CO_2 emissions.** Replacing this fuel with **'Sustainable Aviation Fuel' (SAF) is a crucial element of net zero plans for airlines, but the reality may not match the hype.**

- **Current SAF production is dominated by the biomass-based HEFA process,** although **volumes are small and costs are on average 50% higher** than conventional fuel**.** Other biomass-based processes are possible, but most are immature and/or expensive.

- **SAF can also be produced synthetically,** using hydrogen and CO_2, or hydrogen and nitrogen to produce ammonia – but these processes are **currently more expensive than most biomass-based routes**.

- **Synthetic SAFs can have very low to zero lifecycle emissions if based on 'green' hydrogen** (produced using renewable energy). **Biomass-based SAFs only have low lifecycle CO_2 emissions if they use waste biomass** (e.g. used cooking oil).

- However, there are **concerns that virgin palm oil is being fraudulently misreported as used cooking oil – currently the main SAF feedstock**. Virgin palm oil can produce lifecycle CO_2 emissions for the resulting fuel similar to conventional fuel.

- **SAF production and use is likely to grow, but it is projected to achieve just half the 11% of all aviation fuel required under the IEA's Net Zero Roadmap by 2030,** hindered by high costs and limited policy support outside the USA and Europe.

- **Growth to 2030 will likely focus on the already-dominant HEFA process,** but waste biomass feedstock constraints mean **other biomass and synthetic processes are likely to become material by the end of the decade.**

- If **biomass-based SAFs were to satisfy global aviation energy demand in 2050, at least two-thirds of all sustainably sourced biomass would be required**. If **synthetic SAFs were to satisfy all EU aviation demand in 2030, they would require four times the bloc's entire current renewable electricity output**. These constraints mean that no single process is likely to dominate in the long run, and both will play a role.

***Note**: A technical annex is attached to the end of this brief, providing additional detail. References to sections in this annex are denoted by e.g., TA.1; TA.2, in the text.*

Decarbonising aviation

Aviation produces around 2% of global CO_2 emissions, with its share growing with demand.[1] International flights account for around two-thirds of this.[2] Aviation emits more than the fifth most-emitting country (Canada), and can dominate the carbon footprints of those individuals and households that fly.

Kerosene jet fuel is the main source of CO_2 emissions, although **the emission of water vapour and nitrogen oxide (NO_x) high in the atmosphere produces double the warming impact of the CO_2 emitted**.[3]

Aviation demand and emissions slumped during the pandemic, but are now rapidly recovering.[1] While demand growth may be constrained by high inflation, energy costs, emission mitigation measures,[4] and potential shifts towards high-speed rail for short-haul journeys,[5] **it is likely that growth in demand for air travel will remain relatively strong**.[6]

Aviation is considered a 'hard-to-abate' sector due to weight and size constraints of aircraft, long investment and innovation cycles, prioritisation of safety, and because key low-carbon technologies remain nascent, high cost and not yet available at scale.[7]

There are several decarbonisation pathways available for aviation, including that implied by the IEA's NZE roadmap.[8], and the SBTi's 1.5 Degree Aviation Pathway.[9] These pathways require aviation demand to remain stable or decline, with an increase in the rate of energy efficiency progress through technical and operational improvements. However, **Sustainable Aviation Fuel is the most significant decarbonisation driver**, expecting to **largely replace jet kerosene by 2050, in all decarbonisation scenarios for the sector**.

What are Sustainable Aviation Fuels (SAFs)?

There is no agreed definition of Sustainable Aviation Fuels (SAFs), but generally they are not derived from fossil fuels, and have lower lifecycle CO_2 emissions. **The term is mostly used to refer to biomass-based fuels, but may also include synthetic fuels, and the direct use of hydrogen or electricity**.

Different forms of SAF are summarised in Table 1 below, however the specific boundaries can vary, and alternative names can sometimes refer to specific sub-types.

Biomass-based and most synthetic fuels are 'drop-in' fuels, meaning they can be used without modification to the aircraft, engines or fuelling infrastructure. However, **most drop-in SAFs must be blended with conventional fuel** to reduce the risk of fuel leaks and engine damage.[10] Drop-in fuels must be blended at 10-50% with conventional jet fuel, with the blend ratio varied by production process. *(TA.2)*

Some manufacturers are developing engines able to accept unblended drop-in SAFs, including Airbus, Boeing, Rolls-Royce and Deutsche Aircraft[21]. with the first trans-Atlantic test flight having taken place late 2023.[11] Some SAFs are technically able to be used neat in conventional engines. The use of **100% SAFs is likely to be approved in the mid-2020s, along with blending of different SAFs to achieve the appropriate characteristics**.[12]

Type	Alternative names	Description	IEA NZE Roadmap[8]
Biomass-based	Bio-kerosene; bio-aviation fuel; biojet fuel, renewable jet fuel	**Different biomass feedstocks may be used**, depending on the SAF production process. There are **six broad categories of certified[1] processes, as follows** (see TA.1 for details) Other processes are undergoing evaluation for certification.[2] (1) **HEFA;** (2) **Fischer-Tropsch (FT);** (3) **ATJ;** (4) **CHJ;** (5) **HFS-SIP** (6) **HC-HEFA-SPK**	33% aviation energy use by 2050
Synthetic fuels	Electrofuels; e-fuels; power fuels; power-to-liquid; e-kerosene	A source of **CO_2** and a source of **hydrogen** are used to produce a **hydrocarbon fuel**. Alternatively, **hydrogen** may be combined with **nitrogen** to produce liquified **ammonia**. **Fischer-Tropsch (FT) is the only certified process**, producing e-kerosene. **Hydrogen must be produced through electrolysis**. **CO_2** is provided through **carbon capture** (direct air capture or industrial processes), or **biomass gasification/anaerobic digestion**. **Nitrogen** for ammonia production is **extracted from the air**.	37% aviation energy use by 2050
Hydrogen	N/A	Low-carbon hydrogen is produced through **water electrolysis using low-carbon electricity**	<10% aviation energy use by 2050
Electricity	N/A	Low-carbon electricity is used to charge an **on-board battery**	

Table 1 – Key categories of Sustainable Aviation Fuels (SAFs). [1]Before a SAF can be used in commercial aviation, it must be certified by the American Society for Testing and Materials (ATSM);[2] These processes are largely not discussed. Created by Greenwheel.

Some manufacturers are developing engines able to accept unblended drop-in SAFs, including Airbus, Boeing, Rolls-Royce and Deutsche Aircraft[21]. with the first trans-Atlantic test flight scheduled for late 2023.[13] Some SAFs are technically able to be used neat in conventional engines. The use of **100% SAFs is likely to be approved in the mid-2020s, along with blending of different SAFs to achieve the appropriate characteristics**.[14]

Recent Trends in SAFs

SAFs account for <0.1% of global aviation fuels. **Biomass-based HEFA is the most mature SAF process and dominates production, mostly using cooking oils**.[15] Virgin soy, sunflower and rapeseed oil are also used.[16] **However, there are multiple reports of fraud, with products claimed as used cooking oil from Asia containing virgin palm and other vegetable oils.[17]** Large volumes of reported used cooking oil are exported to Europe for biofuel production.

All drop-in fuel processes generate other products alongside SAF, including gasoline, diesel, naphtha, propane, liquified petroleum gas (LPG), waxes and animal feed. Most processes can be adjusted to focus on the production of different products.[21]

Fifteen SAF production facilities currently operate on a proof-of-concept or fully commercial basis, **with ten of these in Europe**, **three in the USA, and one each in Indonesia and Singapore**. **Most of these facilities use the HEFA process to produce biodiesel for road transport, with SAF as a secondary output**. Two facilities (one commercial and one proof-of-concept) use the biomass-based FT process.[18]

Major biomass-based SAF producers with commercial operations are Neste (Europe and Singapore), World Energy, Gevo, Fulcrum (USA), ENI (Italy) and Total (France).[18] The first synthetic fuel plant opened was opened by Aldi in Germany in October 2021.[21]

Around 100 airports are currently distributing SAFs on a commercial basis, with around two-thirds of these receiving ongoing deliveries. **These airports are heavily concentrated in**

Europe and the USA. Johannesburg airport was the first to deliver commercial SAFs, in 2017.[19]

Technical characteristics

Figure 1 illustrates the connections between key inputs and outputs of the SAF processes in Table 1. Table 2 summarises the technical characteristics of each SAF type.

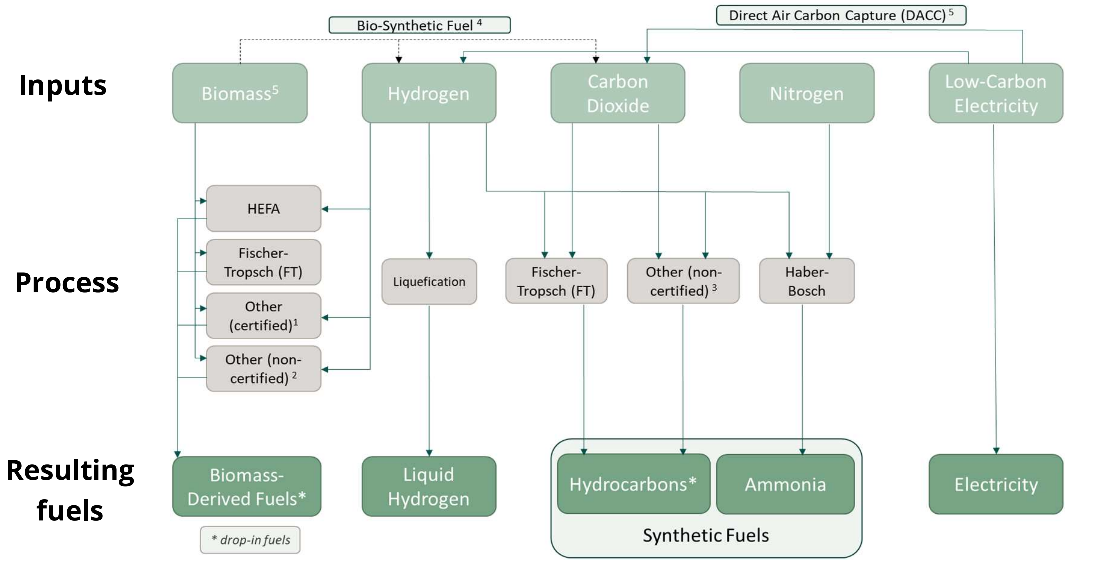

Figure 1: Simplified schematic of key SAF production processes. Notes: [1]See Table 1 for other approved processes; [2]Includes synthesized aromatic kerosene (SAK), Integrated hydropyrolysis and hydroconversion (IH2), Single recator HEFA (DILSAAF); [3]methanol-to-jet is undergoing certification (other potential process is methanol synthesis); [4]synthetic fuel produced using CO_2 and H_2 from biomass; [5]DACC uses electricity to extract CO_2 from the atmosphere. Graphic created by Greenwheel.

	Biomass-based	Synthetic	Hydrogen	Electric
Maturity	**Mixed**; HEFA & FT high, others low	**Medium** (FT); **low** (ammonia)	**Low**	**Low**
Resource needs & co-products	Different **biomass** depending on process; **Various co-products**	**Hydrogen** produced by low-carbon electricity (high); FT: **captured CO_2 with various co-products**; ammonia: **nitrogen with no co-products**	Low-carbon **electricity** input (medium); **no co-products**	Low-carbon **electricity** capacity (low); **no co-products**
Powertrain/aircraft compatibility	**Drop-in to existing engines**; blended 10-50% (possibly 100% in future, potentially with small modifications)	FT: **Drop-in to existing engines**; blended <50% (possibly 100% in future, potentially with small modifications); ammonia: **requires engine modification**	**Different powertrain and aircraft design** required	**Different powertrain and aircraft design** required
Airport Infrastructure compatibility	**High**; few additional requirements	**High** (FT): few additional requirements; **Low** (ammonia): additional storage requirements	**Low**; additional storage & refuelling infrastructure, plus fuel delivery infrastructure	**Low**; additional recharging infrastructure and/or battery swapping, plus electricity delivery/generation infrastructure
Tailpipe emissions*	**CO_2,** water vapour & NO_X as conventional fuel; less soot	**CO_2,** water vapour & NO_X as conventional fuel; less soot (hydrocarbon); **no CO_2** or soot (ammonia)	**No CO_2** or soot, but NO_x and more water vapour	**None**

Table 2 – Summary of technical characteristics. *See below for lifecycle emissions. Created by Greenwheel.

Biomass-based fuels

The HEFA process is the simplest and most mature of all certified processes.[20] Used cooking oils are the dominant feedstock (notwithstanding fraud claims). It is relatively energy efficient and[21] produces the highest energy yield from feedstock input of all biomass-based processes, however **only up to 15% of the output can be jet fuel, with the majority output (up to 100%), biodiesel for road transport**. The jet fuel output could increase to 50% but costs, energy consumption and lifecycle emissions would increase.[16]

Supply constraints to this process are likely to arise. **If drawing on waste oils and fats alone, HEFA could supply only around 1% of aviation energy demand by 2050**, even excluding competing demands for these feedstocks (such as bio-plastics and road biodiesel).[21]

Other processes, such as Fischer-Tropsch (FT) can use a wide range of biomass feedstocks (*TA.3)*. However, **if biomass-based SAFs were to satisfy all global aviation energy demand by 2050, at least two-thirds of all sustainably sourced biomass would be required**.[22] Competition for these resources from other sectors would likely creating demand for unsustainable biomass resources.

Except the FT process, all approved biomass-based processes require hydrogen, currently derived from fossil fuels. **Biomass-based SAFs produce CO_2 emissions comparable to conventional jet fuel when used**, **but lifecycle emissions are varied** (see below).

Synthetic fuels

Synthetic fuels are often known as 'electrofuels' (or 'e-fuels'), with the key hydrogen feedstock produced through water electrolysis. This includes 'green', 'pink' and 'yellow' hydrogen, produced through electrolysis powered by renewable, nuclear and grid electricity, respectively.

For most synthetic fuels a source of CO_2 is also required. **CO_2 may be captured from point sources** (e.g., steel or cement production), or **from the air using Direct Air Carbon Capture (DACC) technology**. Excess CO_2 produced during biofuel production (including SAF) may also be used[23], resulting in 'bio-synthetic fuels' (or 'bio-e-fuels'). Biomass used in these processes may also be a source of hydrogen.[21] *(TA.4)*

Electrofuels can be extremely electro-intensive, particularly if using green hydrogen and delivering CO_2 through DACC. **If synthetic fuel produced with green hydrogen and using DACC were to cover all EU aviation demand in 2030, it would require four times the bloc's entire current renewable electricity output.** Three times current renewable electricity output would be required just to produce the hydrogen.[24]

Although renewables are projected to grow several-fold in the coming decades, and the energy intensity of DACC may also fall substantially, **this presents a clear constraint to the growth of such fuels**.

The production of liquid ammonia requires a source of nitrogen instead of CO_2, but produces a lower range and requires more fuel storage infrastructure. **Although not a 'drop-in' fuel, existing engines may be modified to use it.** However, **meeting all EU aviation demand with ammonia in 2030 would require nearly one and a half times the EU's current renewable electricity output**.[25] *(TA.5)*

Hydrogen

The direct use of hydrogen would require significant aircraft redesign, particularly to allow much larger fuel storage**.** This means hydrogen aircraft are **likely to be limited to short haul, light-load flights**. It also **requires entirely different airport fuel handling infrastructure and safety procedures** due to its high flammability and leakage risk. **Producing green hydrogen to satisfy all EU aviation energy demand as a direct fuel would require the EU's entire current renewable electricity generation.** *(TA.6)*

Electricity

A lithium-ion (li-ion) battery would be nearly 30 times heavier, and around 20 times the volume of the conventional jet fuel it replaces.[26] It would also **require at least a quarter of the EU's current renewable electricity output to electrify the bloc's aviation energy demand**.

Other challenges concern safety, charging time and battery life. Li-ion batteries can overheat and catch fire when damaged or operating outside their safe operating conditions.[27] Recharging batteries would take significantly longer than conventional refuelling. Battery swapping could reduce this challenge but requires a greater number of batteries to be in circulation. Li-ion batteries also typically have a lifetime of fewer than 1,000 charge cycles, implying rapid turnover.

New technologies under development, such as solid-state batteries, would significantly increase energy density and reduce safety concerns. However, **full electric aircraft are also likely to be limited to short-haul flights with limited payload**, and although electric powertrains have been demonstrated, commercial deployment is not likely until at least the end of the decade.[21]

Are policy frameworks supportive?

Figure 2 illustrates key international regulation and private sector initiatives.

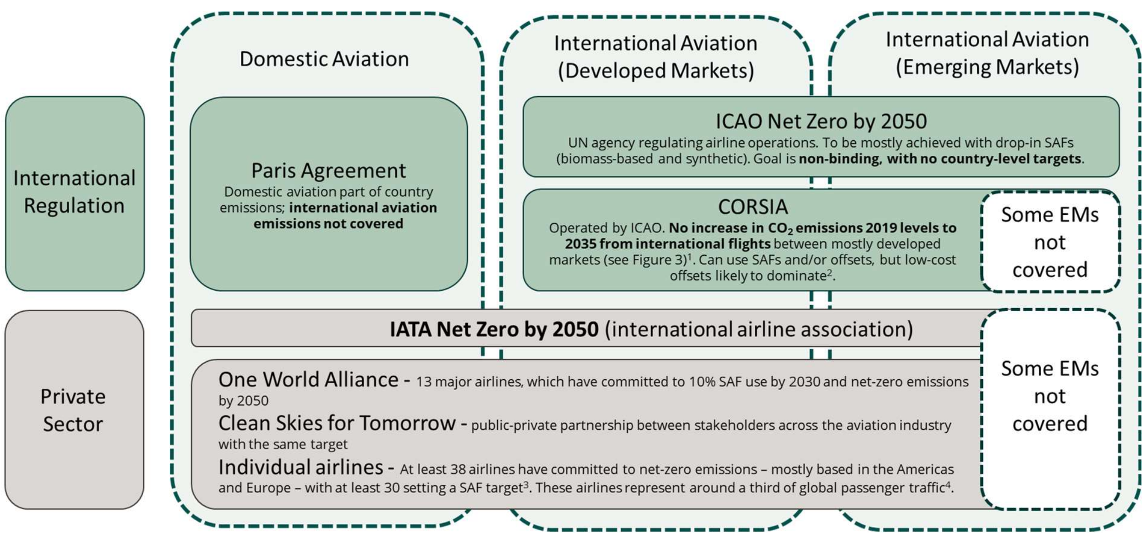

Figure 2 – international regulation and private sector commitments. [1]Changing to 85% below 2019 levels from 2024; [2] S&P, 2022; [3]BNEF (2022); [4]McKinsey (2023). Graphic created by Greenwheel.

Until 2027, countries participating in CORSIA states are largely limited to North America, Europe and Oceania. From 2027, **large countries such as China, Brazil, India and Russia are scheduled to join, but many other emerging, frontier and small economies will remain exempt**.

Key country and regional policy measures are illustrated in Table 3.:

Country/region	SAF objective*	Policy
United States	**15%** (2030); **100%** (2050)	**Inflation reduction Act:** tax credit **$1.25/gallon**. Additional 1 cent for each percentage point additional lifecycle emissions reduction max. **$1.75/gallon**.[28]
European Union	**2%** (2025); **6%** (2030); **20%** (2035); **70%** (2050)	**Requires airports to supply fuel at these proportions**.** Synthetic fuel sub-targets of 1.2% (2030) and 35% (2050). **EU ETS applies** to domestic aviation **in full from 2026**, potentially international from 2027 (some free allocation for SAF use).[29] Jet fuel tax exemptions progressively removed; exemptions/discounts for SAFs.[30]
United Kingdom	**10%** (2030); **net zero emissions** (2050)	**Blending mandate**, likely same proportional synthetic sub-targets as EU; **cap on HEFA fuels**; >5 SAF plants under construction by 2030.[31]

Table 3: Key country and regional SAF policies. *Across biomass-based and synthetic drop-in fuels. **Some member states have blending targets that exceed EU ambitions. Created by Greenwheel.

Japan has a 10% SAF blending mandate for 2030, focused on biomass-based fuels. **Norway**'s blending mandate is set to increase to 30% by 2030. **India** is exploring a 1% blending mandate for domestic flights for 2025. **Indonesia** aims to reach 5% SAF blending by 2025, although this is likely to be missed.[32]

Other countries, particularly across Asia and Oceania, are likely to advance SAF policy soon.[32] **China currently has no clear SAF policy framework**, although the Civil Aviation Administration of China (CAAC) has set a negligible target of *cumulative* SAF consumption of 50,000 tonnes by 2025.[33]

Are SAFs economically viable?

Figure 3 illustrates SAF and convention fuel cost ranges. For most SAF processes data are either modelled or based on early demonstration facilities, rather than commercially operating plants.

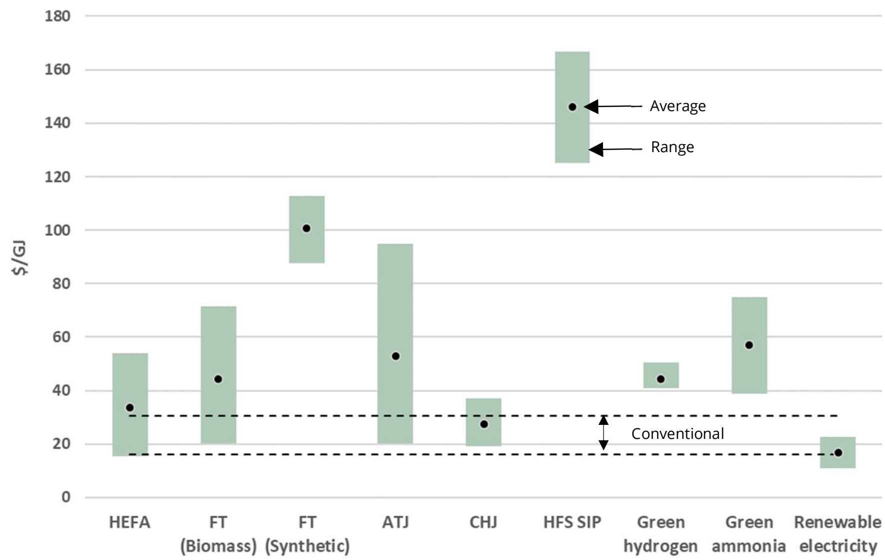

Figure 3: Estimated cost ranges for SAFs and conventional fuel. Source: Royal Society (2023), except HFS-SIP and renewable electricity. **Notes**: GBP to USD XR 1.2. HFS-SIP values calculated based on IRENA (2021) data, converted assuming 34.7 MJ/l. Renewable electricity range based on 2023 and 2021 levelised cost of electricity data for offshore wind and solar PV, respectively, from IRENA. Conventional fuel range from June 2021 to September 2023. Graphic created by Greenwheel.

Low capital costs, low feedstock prices, and high efficiency make HEFA the cheapest commercially-available SAF process, with an average cost comparable to recent peaks in conventional fuel prices. Costs at the lowest end of the range use used cooking oil feedstock. The **CHJ process has the lowest potential costs, however these estimates are not based on operational facilities, and so are uncertain**.

The biomass-based FT process is the next cheapest drop-in fuel, with average costs around 50% higher than recent peaks in conventional fuel. Its capital costs are more than double those of HEFA, with similar feedstock costs if using energy crops or agricultural residues. Costs are lowest when using municipal solid waste (MSW) as a feedstock.

ATJ **produces the second-highest average drop-in fuel cost of approved processes, but with a significantly larger range.** Costs are comparable to biomass FT when using corn grain or sugarcane, but significantly higher when using agricultural residues or energy crops. However, **the highest drop-in fuel costs by far are from HFS-SIP process**, due high capital costs, and high energy and hydrogen requirements.

Excluding subsides**, synthetic drop-in fuels are around five times more expensive to produce than conventional fuel prices** when using green hydrogen, driven by the cost of renewable electricity, hydrogen electrolysers and carbon capture technology (particularly if delivered by DACC).

The average cost of green hydrogen and ammonia is 2-3 times average conventional fuel prices, **within the range of lower-cost SAFs. The average cost of electricity from new renewables is similar to the lower bound of recent conventional jet fuel**. Cost trends and growing policy support mean that **these fuels have the greatest potential for significant cost reductions**, although as they are not drop-in fuels, **the cost of reconfiguring aircraft and supporting infrastructure is much greater.**

SAF price support for under the USA's IRA brings average HEFA costs in line with conventional fuel. It also brings a greater range of biomass-based FT and ATJ fuels to within cost competitiveness. HFS SIP fuels remain highly uncompetitive. In the EU, the combined impact of full exposure to the EU ETS and fuel tax would have a similar impact by making conventional fuels more expensive. However, **in the US, when incorporating price support for green hydrogen and CO_2 capture through DACC, the costs of synthetic fuel production through the FT process is comparable to conventional fuel prices**.[34]

How 'sustainable' are they?

(a) CO_2 emissions

The 'sustainability' of SAFs are mainly measured by their lifecycle CO_2 emissions, relative to those of conventional fuel. The International Civil Aviation Authority (ICAO) considers a SAF to be a fuel that achieves lifecycle CO_2 emissions at least 10% below those of conventional fuel. In the USA this value is 50%, and in the EU it is 65% (for biomass-derived) or 70% (for synthetics).

Excluding FT (synthetic), **the ranges in Figure 4 represent only processes, feedstocks and regions for which the ICAO has undertaken lifecycle analysis and have set 'default' lifecycle values**. SAF suppliers can only apply these values when the fuel conversion process, type of feedstock and where it is sourced matches those assumed by ICAO. **Otherwise, suppliers must follow a set methodology to produce their own values.**[35] **This includes synthetic fuels, for which ICAO has not set any default values** *(TA.7)*.

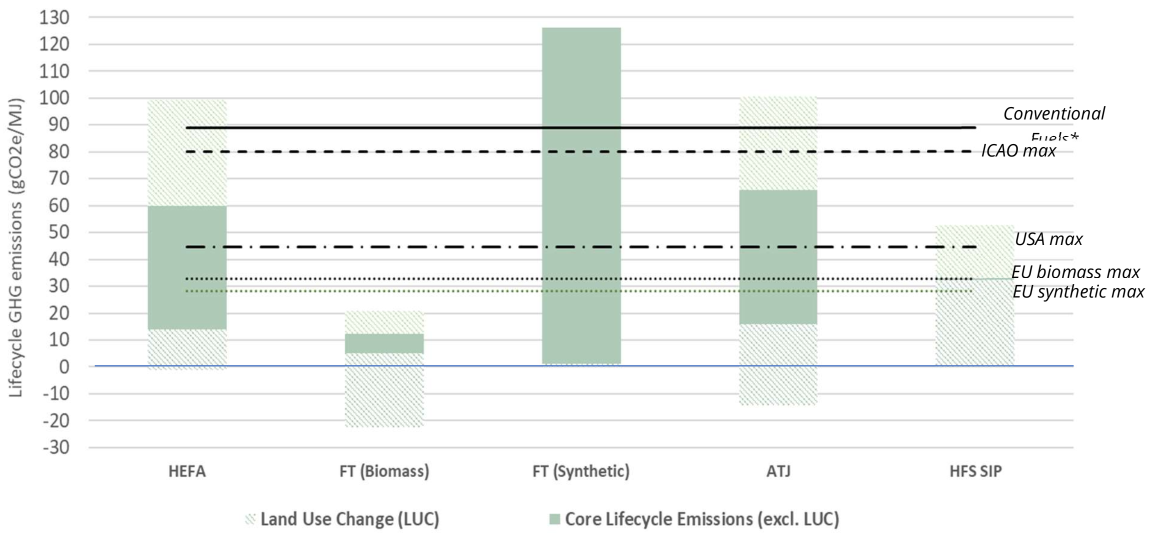

Figure 4 – lifecycle CO_2 emissions*.* Sources: ICAO (2022) (biomass-based) and Schmidt & Weindorf (2016) for FT (synthetic). *Emission intensity of conventional fuels according to ICAO (89gCO_2/MJ). In the EU, the conventional fuel baseline is higher (94gCO_2/MJ) Note: FT (Biomass) excludes values for MSW with non-biogenic content. FT upper value uses approx. grid average CO_2 intensity of electricity in Europe. CHJ excluded due to unreliable data. Graphic created by Greenwheel.

The large range of values within and between processes is driven by the feedstock and the CO_2 intensity of energy and other inputs. For biomass feedstock, emission intensities are significantly driven by land use change, which can have positive or negative implications for CO_2.

Default values are often global averages that disguise wide variation across a range of factors, from the CO_2 intensity of electricity used in the process, to the use of waste materials and co-products.

Used cooking oil has the lowest core lifecycle emissions for the HEFA process, and have no LUC effects. However, **the HEFA process can achieve *negative* lifecycle emissions if using jatropha oil from India, due to carbon sequestered into the soil where plantations replace cropland**.[37]

Virgin palm oil has the highest lifecycle emissions from the HEFA process,[36] displacing tropical peat and swamp forest in Malaysia and Indonesia, which are significant carbon stores. **This excludes almost all palm oil for use in SAFs**, supported by the **ICAO's exclusion of biomass from land converted from primary forest, wetland or peatland** after 2007,[37] and a similar ban in the EU.[38]

All fuels from the biomass-based Fischer-Tropsch process qualify as SAFs, except when using feedstock that contains any non-biomass components, such as some municipal waste. **SAF produced in the USA with miscanthus has a strongly negative value** if using marginal land.[38]

Lifecycle emissions from synthetic fuels depends on the source of electricity, and can be almost zero if using all renewable electricity to both produce the hydrogen and required and run DACC plants.[39] *(TA.8)*.

(b) Wider environmental & social elements

From January 2024, CORSIA adds other ecosystems that constitute significant carbon stores to the list of areas prohibited for biomass production, if converted after 2007. **They also add other environmental and social requirements for the production of SAF**, including: the permeance of any emissions captured and stored, maintenance or enhancement of water quality and availability, maintenance of soil health, minimisation of negative air quality impacts, maintenance of biodiversity and ecosystem services, responsible management of waste and chemicals, the protection of land use, water and indigenous rights, and promotion of social and economic development and food security.

In the EU, SAFs cannot come from food or fuel crops, agricultural waste and residues cannot be sourced from highly biodiverse forests, and evidence for soil protection must be provided. For forest biomass (including waste and residues), laws must be in place to avoid the risk of unsustainable harvesting.[40]

The production of synthetic fuels, hydrogen and (renewable) electricity have significantly fewer environmental and social concerns related to land use, although concerns around siting projects, the environmental and social risks associated with the raw materials they contain, and demand for freshwater implied by widespread green hydrogen production remain.

SAFs must be certified to make sure all environmental and social requirements are met. The two approved certification schemes are provided by the International Sustainability and Carbon Certification (ISCC) initiative and the Roundtable on Sustainable Biomaterials association (RSB). **However, there are concerns that the ISCC scheme relies heavily on self-reporting rather than verified information, with poor transparency and governance dominated by the producers, processors and traders from within the biomass supply chain**.[41] Concerns have also been raised about the RSB certification scheme.[42] This is supported by concerns of fraud, discussed above.

Outlook for Sustainable Aviation Fuels

Projections suggest that **biomass-based SAF production will increase nearly forty-fold between 2021 and 2027**, driven by increasing demand and production capacity in the US and EU, and that **this would satisfy just 1-2% of fuel consumption in 2027**,[15] **rising to 5% by 2030**.[43] This is less than **half the value required by the IEA's Net Zero Roadmap**, **and reflects the key constraints of high costs, relatively limited policy support, long lead times and feedstock constraints**.[15]

Short-term outlook (2030)

- **Growth in SAF demand and production is likely to be strongly concentrated in Europe and the USA**, due to existing capacity and the supportive policy environments. CORSIA is unlikely to be a significant driver for SAF adoption, with **growth in most emerging markets – including China – likely to be low or negligible**.

- **Biomass-based SAFs are likely to dominate growth**, **focused on the HEFA process. Of the 30 new biomass-based production facilities planned or under construction around the world, 18 are HEFA**.[18] **The biomass-based FT process is also likely to grow**, given longer-term limitations with HEFA (e.g. feedstock availability and traceability), and policy incentives to diversify. **8 of 30 announced biomass SAF facilities use the FT process**.[18] Despite the economic and environmental attractions of CHJ, its immaturity and overlapping feedstock issues with HEFA are likely to prevent its meaningful take-up.

- **Synthetic drop-in fuels are likely to remain limited until the end of the decade**, given high costs, limited availability of renewable electricity, green hydrogen and carbon capture technology. New SAF plants also have a lead time of 5-6 years.[44] Any development is likely to be largely limited to the USA or Europe, given policy drivers. **All-electric, ammonia and hydrogen-based aviation may advance, but operate only in demonstration projects, or commercially in niches** toward the end of the decade.

Long-term outlook (beyond 2030)

- **Without further policy action, SAF demand and production is likely to remain concentrated in the USA and Europe**, but with growth emerging elsewhere as costs reduce. **Growth in SAFs as a proportion of global aviation energy demand may slow, as aviation demand grows disproportionately in emerging markets,** and if progress in other efforts to decarbonise aviation, such as increased technical and operational efficiency, stalls.

- **Growth is likely to focus on the FT process, producing both biomass-based and synthetic fuels**, as HEFA feedstock constraints are increasingly felt, the availability of synthetic fuel inputs increases and costs reduce, and policy incentives and requirements drives demand. **Other certified and currently non-certified processes may take some market share as their maturity and costs improve**.

- **All electric and hydrogen-based aviation would likely remain limited to some short-haul commercial routes**. The relatively young age of the global aircraft fleet, coupled with the dominance of Boeing and Airbus in aircraft manufacturing, and with a backlog of several years[45], means that demand and production capacity for entirely new aircraft powertrains is likely to be limited. As it faces fewer of these barriers, ammonia-based aviation may see greater adoption.

Key Information

No investment strategy or risk management technique can guarantee returns or eliminate risks in any market environment. Past performance is not a guide to future results. The prices of investments and income from them may fall as well as rise and an investor's investment is subject to potential loss, in whole or in part. Forecasts and estimates are based upon subjective assumptions about circumstances and events that may not yet have taken place and may never do so. The statements and opinions expressed in this article are those of the author as of the date of publication, and do not necessarily represent the view of Redwheel. This article does not constitute investment advice and the information shown is for illustrative purposes only. Whilst updated figures are not available for all sources, we have performed further analysis and believe that this data has not significantly changed and is reflective for 2024.

Endnotes

[1] IEA (2023)
[2] Bergero et al (2023)
[3] Lee et al (2021)
[4] Weston et al (2023)
[5] Sharmina et al (2021)
[6] ITF (2021)
[7] McKinsey (2023)
[8] IEA (2023)
[9] SBTi (2023)
[10] Anuar et al (2021)
[11] Gavine (2023)
[12] Van Dyk (2022)
[13] Gavine (2023)
[14] Van Dyk (2022)
[15] IEA (2023)
[16] IRENA (2021)
[17] Carroll (2023)
[18] ETIP (2023)
[19] ICAO (2023)
[20] Bauen et al (2020)
[21] Su-unnkavatin et al (2023)
[22] Based on values provided by Becken et al (2023)
[23] Or anerobic digestion, for the production of bio-e-methane.
[24] Approx. 450 mtCO_2 required by 2030 (Source: Michelli, 2022), with 2 MWh/tCO_2 captured (Source: ETC (2022).Approximately 33MWh/tonne hydrogen energy content, ~66% electrolyser efficiency. FT conversion efficiency of 70%, jet fuel fraction 40% EU electricity. 12.5MWh jet fuel energy content. Renewable generation data from Ember (2023).
[25] For both the hydrogen production and the electrified Haber-Bosch production process (Source: Royal Society, 2023)
[26] Based on energy densities: 10.3 kWh/l and 12.84 kWh/kg (jet fuel) and 0.5 kWh/l and 0.,45 kWh/kg (lithium-ion battery).
[27] Sripad *et al* (2021)
[28] US DOE (2022)
[29] European Commission (2022)
[30] European Council (2023)
[31] DfT (2023)
[32] ITF (2023)
[33] Yuhan (2023)
[34] Cheng et al (2023)
[35] RSB (2023)
[36] ICCT (2021)
[37] ICAO (2021)
[38] ICAO (2022)
[39] GEA (2016)
[40] EC (2023)
[41] Greenpeace (2021)
[42] Carroll (2023)
[43] BNEF (2022)
[44] MPP (2022)
[45] Luman & Zhang (2023)

Technical Annex

TA.1

(1) **HEFA (**Hydroprocessed Esters and Fatty Acids), also known as HRJ (Hydroprocessesed Renewable Jet)
(2) **FT-SPK** (Fischer-Tropsch Synthetic Paraffinic Kerosene)
(3) FT-SPK/A (as above, plus aromatic compounds)
(4) ATJ-SPK (Alcohol-To-Jet Synthetic Paraffinic Kerosene)
(5) CHJ (Catalytic Hydrothermolysis Jet), sometimes also known as hydrothermal liquefaction (HTL), but which can also refer to a separate (uncertified) process.
(6) **HFS-SIP** (Hydroprocessed fermented sugars – synthetic iso-paraffinic kerosene), also known at Direct Sugars to Hydrocarbons (DSHC)
(7) **HC-HEFA-SPK** (Synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids)

TA.2

Conventional kerosene jet fuel naturally contains 'aromatics' (e.g. benzene). Despite lowering the energy density of aviation fuel and driving key non-GHG related climate forcing through soot and contrail formation, **aromatics encourage rubber seals in the engine to swell, minimising the chance of leakage**.

Most biomass-based and synthetic SAFs have no natural aromatic content. While this means they produce lower climate forcing (and reduced air pollution when taxiing), they may shrink or degrade seals, increasing the risk of fuel leakage and engine damage. Adding aromatics or blending SAFs with conventional jet fuel can overcome this problem., striking a balance between energy content, performance, and aromatic content. **Different SAFs currently cannot be blended with each other**.

TA.3

HC-HEFA-SPK is a new variation of the HEFA process that uses oil produced by algae as a feedstock. However, the blend ratio limit is currently 10%.[45]

The **CHJ process** also uses oil-based inputs, and although it is **currently limited to a 50% blend**, **it contains sufficient aromatics to be feasibly used without blending, or in a blend with other SAF.** However, the process has yet to be demonstrated in an operational environment.

The Fischer-Tropsch (FT) process is commonly used to produce synthetic fuels and chemicals. It can be used to produce SAFs using any carbon-based input, allowing for a wide range of primary, residual, and waste biomass feedstocks. Although its energy yield and energy density is lower than HEFA, its energy efficiency is extremely high, and it may be blended at 50%.[Error! Bookmark not defined.] The ratio of jet fuel output is also 25-40%.[16]

Alcohol-to-jet (ATJ) can use sugary and starchy biomass including agricultural and forest residues, and various grasses and crops (e.g. sugarcane, corn grain and switchgrass), and thus **can also draw on a wide range of biomass inputs**. Its energy yield sits between the HEFA and FT processes, with an energy efficiency around half that for the FT process although the jet fuel output can be very high, at up to 70%.[16]

The **HFS-SIP** process also uses sugary biomass feedstocks, including sugarcane, sweet sorghum, sugar beets and tubers, with a yield similar to FT and process energy efficiency similar to ATJ, with a blend limit of 10%.**Error! Bookmark not defined.**

TA.4

Hydrogen and CO_2 are combined to produce 'syngas', in turn entering the FT process generating a SAF identical to the biomass-based FT process. The product is commonly called 'e-kerosene'.

Two other processes - methanation and methanol synthesis – are also possible, but are at early stages of development and are currently not certified. Methanation combines CO_2 and hydrogen to produce methane, which is liquified to produce synthetic liquified natural gas (LNG) – or 'e-methane'. Methanol synthesis instead combines these molecules to produce methanol, which may in turn produces 'e-methanol'.[45] Some small-scale demonstration plants are in operation, with several planned for the coming years, although the focus is largely on non-aviation applications. However, both processes require larger quantities of CO_2 feedstock, and are relatively inefficient.[45]

TA.5

Nitrogen is derived through air separation using the energy-intensive Haber-Bosch (HB) process, widely used to produce ammonia for use in agricultural fertilisers. The HB process is currently carbon intensive, using natural gas as both a feedstock and a heat source. A modified process using a green hydrogen and renewable electricity can eliminate most lifecycle emissions[45], but is immature. Although the hydrogen required is significantly less than for the synthetic FT process,

Ammonia may be stored onboard aircraft in the same way as conventional fuels, although it has a lower energy density, producing a lower range and requiring larger storage facilities. It also requires either pressurised storage or refrigeration to -33 °C under atmospheric pressure, although this temperature is maintained by ambient conditions at cruise altitude through heat exchanger systems. Ammonia is also highly corrosive and toxic, meaning appropriate tank materials and safety protocols are required.[21]

To improve the combustion properties of ammonia, it can be partly dissociated into its hydrogen and nitrogen components using an onboard 'cracking' unit, although this would require certification. Combusting ammonia produces no CO_2 emissions, but emissions of water vapour, nitrogen, and nitrogen oxides (NO_x) remain.[21]

TA.6

Liquid hydrogen has three times *more* energy content than conventional fuel per unit *weight*, but at least four times *less* energy per unit *volume*.[21] All else equal, this means that although it reduces weight for a given distance travelled, it **increases the required onboard fuel storage significantly. Using hydrogen as a standalone fuel also requires a significantly different powertrain and aircraft design and brings wider infrastructure challenges.**

Liquid hydrogen must be stored at -253°C, requiring an onboard cryogenic tank and insulation system, alongside high-pressure pumps, heat exchangers and modified engine components. **Although CO_2 emissions are absent, NO_x emissions are produced, and water vapour is significantly greater than conventional fuel**.[45] The equipment required for hydrogen aviation is heavy, and erodes the weight benefits of the fuel. The fuselage would also need to be redesigned to accommodate these components, with associated penalty for payload volume or drag.[21]

The first commercial hydrogen-based commercial flight is expected between London and Rotterdam in 2024[45], while Airbus intends to bring hydrogen-based flight into commercial operation by 2035.[45]

Liquid hydrogen requires a similar refuelling time as conventional fuel. However, **cryogenic storage tanks of greater volume would be required at airports, alongside suitable 'last mile' infrastructure to supply hydrogen to the aircraft**. Liquid hydrogen is highly flammable, and can easily leak due its small molecule size, meaning stringent safety procedures and requirements must be in place to address this risk.[21]

Hydrogen may be produced offsite and delivered or produced onsite. Both face significant challenges. If produced and liquified offsite, hydrogen must be transported either by pipeline or tanker truck, train, or ship.[45]. Conventional fuel is typically delivered by pipeline to major airports, and by tanker to smaller sites. Existing pipelines must be repurposed or replaced to handle hydrogen, and tanker deliveries would multiply to deliver the same energy content.

Although the simplest approach, **producing and liquefying hydrogen onsite implies even greater infrastructure challenges.** Challenges associated with transporting hydrogen are removed, but those with obtaining a sufficient electricity supply to drive electrolysis and liquefication are much greater. Reliably **generating sufficient low-carbon electricity onsite or nearby would likely prove infeasible in most cases, as would obtaining a sufficiently large capacity connection to the electricity grid.**

TA.7

CORSIA values and methodologies may be used to claim compliance with requirements in the USA. In the EU, the revised Renewable Energy Directive (RED II) sets its own default values and methodologies which must be used to claim compliance with domestic requirements. RED II default lifecycle emission values are similar, but typically slightly higher than CORSIA values.[45] While negative emissions are accepted for CORSIA's pilot phase, they may not be accepted from 2027.[38]

LUC values are derived from two well regarded models, but the values they produce are sometimes significantly different for vegetable oils and cellulosic crops (e.g., palm oil and miscanthus). **When this is the case, the lower of the two values is taken and slightly raised, introducing an optimism bias**.[45]

TA.8

Miscanthus in the ATJ process also produces low or negative lifecycle values. The highest values are associated with a corn grain feedstock, potentially exceeding conventional fuel. **Corn grain-based fuels would not qualify as a SAF under any definition. Sugar beet or sugar cane in the HFS SIP process would qualify the resulting fuel as a SAF in the USA based on default values, but not in the EU.**

The **CHJ and HC-HEFA-SPK processes have not been assessed by ICAO** and **have few assessments in the literature**. However, given overlapping feedstock, the results for CHJ are likely to be similar to HEFA. Lifecycle emissions from the HC-HEFA-SPK process, which draws on microalgae feedstock, are likely around the midpoint of the core values for HEFA – with no LUC emissions.[45]

If 'yellow' hydrogen is used for synthetic fuels, the grid CO_2 intensity would have to be <110 gCO_2/kwh to equal the lifecycle emissions of conventional fuel. Grid CO_2 intensity in Europe is around double this (setting the upper bound in Figure 4), **with the global average more than 50% higher again**.[45] The CO_2 intensity of electricity also dictates the lifecycle emissions of electricity and hydrogen used directly, and ammonia derived from them.

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