SUSTAINABLE AVIATION FUELS

THE WAY FORWARD – FROM BIOLOGICAL TO SYNTHETIC FUELS

ecbi

Discussion Note

August 2023

by David Robinson (OCP)[1] with contributions from Blas L Pérez Henriquez (Stanford), Rod Janssen (EID), Thomas Jaramillo (Stanford), Benito Müller (OCP, ECI), Anthony Patt (ETH), John Rhys (Oxford), and Aldo Steinfeld (ETH)

Table of Contents

[1] Corresponding lead author, david.robinson@oxfordclimatepolicy.org

1. Introduction

As part of the global transition to address climate change, the aviation industry has committed to becoming fully sustainable, with net-zero emissions[2] by 2050. While aviation currently accounts for less than 3 percent of global GHG emissions, that share is projected to grow significantly. Achieving the necessary emission reductions by curtailing air travel is not feasible, nor even politically, economically, or culturally desirable. On the other hand, promising technologies can reduce or entirely remove reliance on fossil fuels to power aircraft.

Sustainable Aviation Fuels (SAF) are 'drop-in' fuels that replace fossil-based jet fuels (kerosene) without the need to change aircraft engines or the fuelling infrastructure. While SAF are already being used, today they are blended with fossil fuels and account for only a tiny proportion of jet fuel. According to the International Air Transport Association (IATA), however, it is possible that almost all fossil-based jet fuel could be replaced with SAF in the coming decades.

Several SAF technologies are being developed. Biofuels have been a particular focus, using waste cooking oil, animal fats, or biomass waste from forestry and agriculture. Both types of biofuels are hampered by insufficient availability on their own to enable the airline industry to meet its 2050 target.

Technologies based on electricity and solar power offer stronger prospects for reaching net-zero emissions. E-fuels and solar aviation (or "sun-to-liquid") fuels are both scalable and sustainable. Their costs are currently higher than conventional jet fuels and biofuels, but they have the potential to be very competitive.

E-fuels use electricity, ideally from a renewable source, to create a mixture of hydrogen and carbon monoxide, which is called syngas (or synthesis gas). With catalysts and the right temperatures and pressures, syngas can be converted into hydrocarbon liquids such as synthetic kerosene.

For solar aviation fuels, concentrated sunlight is converted to heat, and that heat – rather than electricity – is used to perform thermochemical splitting of water and CO2 molecules to produce syngas, which in turn is converted into synthetic kerosene.

Whichever SAF technologies are adopted and scaled, meeting the net-zero commitment of the aviation industry will not only depend on technological development. Equally, serious research must be undertaken with respect to public policies and private financial investment to support the industry's transition. Unlike other green technologies – such as renewable electricity – which supply local, national, or regional markets, SAF production technologies supply global aviation markets, which are highly competitive. This means that the policy and financing frameworks that were relevant to other types of green technology development must be adapted and re-conceived to support the transition to SAF.

In aviation, public policy will need to account for an environment where national aviation industry targets and standards have been adopted by some countries and not others; thus, some countries will need to take the lead. Policies must be designed in consultation with private sector investors, foundations, and development banks to create a policy and financial framework that will encourage investment and commercial agreements.

[2] "Net-zero" here refers to obtaining a balance between the carbon emitted into and the carbon removed from the atmosphere.

2. The case for Developing SAF

The airline industry is now responsible for less than 3 percent of global GHG emissions, but emissions are expected to grow significantly. During the five years preceding the pandemic, the top four US airlines – American, Delta, Southwest, and United – reported a 15 percent increase in the use of jet fuel. Although airline travel has not yet returned to the pre-pandemic level, it is fast approaching, with the International Civil Aviation Organisation (ICAO) projecting annual growth to 2050 of between 2.9 percent and 4.2 percent. The rise in demand for air travel is especially steep in large developing countries with growing economies and populations that are becoming more mobile internationally. This implies significant increases in CO2 emissions that must be avoided to meet the Paris climate targets. Indeed, some academic research estimates that aviation could account for 6-17 percent of the remaining carbon budget for the world to meet the 1.5ºC-2.0ºC temperature goal[3].

Government climate commitments for aviation are coordinated through ICAO, a UN agency with 193 member states. In 2016, governments established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to stabilize net CO2 emissions from international aviation beginning in 2021. Since 1 January 2019, CORSIA has required all international airlines with over 10,000 tonnes of CO2 to report their CO2 emissions on an annual basis.

In October 2022, ICAO set the CORSIA baseline at 85 percent of 2019 emissions for the period 2024 to 2035, and set a net-zero target for the global air industry by 2050. In a roundtable of Heads of State, Prime Ministers and Heads of International Organizations during COP27, ICAO Council President Salvatore Sciacchitano advocated for the realization of the ICAO Assembly's decision to reach net-zero emissions by 2050. The net-zero target marks a shift away from previous ICAO climate governance, which relied heavily on mitigating emissions through the purchase of emissions credits or offsets from other sectors. This goal favours CO2 reductions directly from planes and fuels rather than offsets. ICAO estimates that reaching net-zero will cost up to USD 4 trillion. ICAO has encouraged member states to regulate aviation emissions at the national level, rather than relying on ICAO to develop minimum global standards for all countries.

IATA estimates that SAF could contribute around 65 percent of emission reductions needed by aviation to reach net-zero emissions in 2050, with the remainder coming from new technologies (13%), offsets and carbon capture (19%), and infrastructure and operational efficiencies (3%). Although SAF are currently blended with fossil fuels, they account for a tiny share (<1%) of jet fuel. Nonetheless, IATA argues that replacing almost all fossil jet fuel with SAF over the coming decades is feasible. Currently, there are limits on blending SAF with fossil fuels, with SAF representing a maximum of between 5 and 50 percent depending on the SAF. SAF production would need to rise from about 8 billion liters in 2025 to 450 billion liters in 2050 to meet the net-zero target.

Renewable electricity and green hydrogen are the main net-zero-alternative fuels to SAF. However, they are not drop-in fuels and consequently entail major costs and challenges related to changing airplane and engine design and the "fueling" infrastructure. While recognizing their potential contribution, the International Energy Agency (IEA) recently cautioned about these alternative fuels, stating the following:

[3] According to one 2021 academic study, "Aviation contributed approximately 4% to observed human-induced global warming to date, despite being responsible for only 2.4% of global annual emissions of CO2. Aviation is projected to cause a total of about 0.1°C of warming by 2050, half of it to date and the other half over the next three decades, should aviation's pre-COVID growth resume. The industry would then contribute a 6%–17% share to the remaining 0.3°C–0.8°C to not exceed 1.5°C–2°C of global warming".[https://iopscience.iop.org/article/10.1088/1748-9326/ac286e]

- "Using hydrogen in aircraft poses a significant set of challenges, including the need for innovative fuel storage and delivery methods, low-cost and lightweight cryogenic tanks, and redesigned airframes to accommodate them."
- "Current battery density and weight severely restrict the range of battery electric flights and size of aircraft."

One approach to achieving net-zero emissions would be to cap or abolish a significant amount of air travel and transport. Some countries, including France, have already begun to restrict domestic air travel. However, limiting the use of aircraft internationally would be socio-economically unsustainable in a globalized economy – especially because the greatest growth in aviation is forecast to be in countries that are outside the Organisation for Economic Co-operation and Development (OECD) and will be very reluctant to curb air travel. Making flying environmentally sustainable by reducing carbon emissions in line with the ICAO net-zero goal is clearly more feasible. To meet that target, SAF are essential.

Policymakers have already introduced measures that either promote the development of SAF or at least aim to. For example:

- The EU introduced a SAF blending mandate that starts at 2 percent in 2025 and reaches 70 percent by 2050. In June 2023, the EU tightened criteria for what counts as "green" under the EU's sustainable investment criteria, known as the taxonomy, with SAF required to make up 15 percent of a plane's fuel mix by 2030, up 5 percent from the previous proposal.
- The US Inflation Reduction Act (IRA) includes a blending tax credit of USD 1.25 per gallon for SAF that reduces emissions by 50 percent over the base fossil-derived jet fuel, plus an additional cent for every percentage point above 50 percent.
- Japan will introduce a regulation making 10 percent SAF mandatory for international flights using Japanese airports by 2030.
- China included carbon emissions reduction per ton-kilometer in its 14th Five-Year-Plan (2020-2025), with a goal of surpassing 20,000 tons of domestically produced SAF consumption by 2025 with state support.

Airlines, airline manufacturers, and oil and chemical companies are responding with their own initiatives. For example:

- Airlines have already undertaken 450,000 flights using biofuel SAF as part of the fuel mix.
- In 2021, Boeing announced a goal that committed its commercial airplanes to ensure they are capable and certified to fly on 100 percent SAF by 2030. Boeing recently published a sustainability report aimed at demonstrating its commitment to sustainability, which includes the purchase of 2 million gallons (7.6 million litres) of SAF for Boeing's commercial airplane operations.
- United Airlines has several ventures to produce SAF, has flown an aircraft full of passengers using 100 percent SAF, and has agreed to purchase 5 billion gallons of SAF.
- Airbus, Rolls-Royce, Safran, Singapore Airlines, and Turkish Airlines, among others, signed a Global SAF Declaration that commits them to promote the acceleration of the development, production, and consumption of SAF.
- TotalEnergies has begun producing SAF, partially in response to French legislation that calls for aircrafts to use at least 1 percent SAF.

- Swiss and the Lufthansa Group have concluded a strategic collaboration with Synhelion to bring its solar aviation fuel to market.

Despite the increasing policy and business momentum, the high price of SAF compared with conventional fuels means that significant investment and policy support is needed to encourage innovation, development, and cost reduction. Policies must be realistic but sufficiently challenging for the airlines. Whether SAF will be truly sustainable, and who will eventually pay the cost of decarbonising air transport, must be determined. The future demand for air travel and the distributional consequences in terms of who can afford to fly will depend on the cost of air travel, which in turn depends on the future cost of SAF.

3. The Main SAF Technology Paths

This section summarizes the main SAF technology paths, as well as their advantages, disadvantages, and prospects.

Three main SAF technology paths meet the CORSIA Sustainability Criteria: biofuels, e-fuels, and solar aviation fuels. All involve a drop-in replacement for the kerosene currently used in air transport and would be produced from CO2 and hydrogen. Ideally, the CO2 required to produce SAF would come from the atmosphere (direct air capture or DAC) or from a biogenic source so that the CO2 emissions released to the air by the fuel combustion are equal to those extracted from the air for its production. If, on the other hand, the CO2 is captured from the exhaust of an industrial process, it should at least substitute for fossil-fuel emissions elsewhere before it is released.

3.1. Biofuel-based jet fuels[4]

Technology pathways

SAF in the market today achieve direct carbon capture using photosynthesis. SAF currently in use include hydrotreated esters and fatty acids (HEFA), which are dependent on limited availability of feedstocks such as waste fat, oil, and grease. This is a biofuel obtained from non-crop feedstock, which IATA refers to as a second-generation feedstock (with first generation referring to food grade fats and oils). At present, 85 percent of SAF volume over the next five years are expected to be derived from this certified pathway.

The next generation of biofuel based SAF includes biomass from surplus forestry and agricultural residues, municipal solid waste, food waste, and wet wastes. This involves a different technology path, using pyrolysis, which breaks the material into smaller molecules by applying heat to produce a hydrocarbon-rich liquid that can be processed into SAF. IATA refers to this as a third-generation feedstock.

Yet another biological pathway consists of growing algae which can harvest CO2 and sunlight to produce oils that can be readily converted into SAF.

Strengths

SAF based on used cooking oil and animal fats are available now and are being used by airlines. In July 2022, American Airlines took delivery of the first SAF to be verified as an admissible fuel under CORSIA. The Finnish firm Neste, the biggest producer of hydrotreated SAF, aims to produce 1.9

[4] See the following for more details on biofuel-based jet fuels.
https://www.sciencedirect.com/science/article/abs/pii/S0960148123002641

billion litres of SAF per year by the end of 2023 – about 15 times more than world production in 2021, but less than 2 percent of global jet-fuel consumption. Several other companies are in this business, including: World Energy, which uses an oil refinery in California; and a consortium including World Energy, Air Products, and Honeywell, which expect to produce 1.3 billion litres of SAF by 2025.

Weaknesses

IATA recognizes the limits to second generation feedstocks (HEFA) and considers that third generation feedstocks are the most attractive sources to scale up SAF production.

The cost of biofuel SAF (HEFA) from used cooking oil and fat is two to three times more than the cost of fossil kerosene. Even more important than the cost differential is the inability to scale due to the limited supply of raw material in the form of waste oils and fats. Scaling up substantially would require the use of fresh oils and fats that could otherwise be used as food or deforestation, for instance to produce palm oil.

A problem for all third-generation feedstocks (biomass from forestry and agriculture) is that the raw material is bulky and, consequently, expensive to gather, transport, and store.

Third generation feedstocks also raise concerns about deforestation and land use. Indeed, there are good reasons for restricting biomass based SAF to only bio-waste products. A dramatic scaling up of biofuel production from crops grown specifically for energy production would lead to perverse incentives with respect to deforestation, potentially contribute to food insecurity, and pose major problems with respect to water use for irrigation. These legitimate concerns explain why IATA maintains that the airline industry "is intent on ensuring feedstocks associated with deforestation, food-chain competition, and biodiversity loss are not incorporated within its viable feedstock mi".

Prospects

Biofuel-based SAF are likely to dominate the SAF market in the short to medium term. However, rising costs and raw material shortages will limit the market that can be served by these fuels to meet the 2050 net-zero commitment.

3.2. E-fuels

Technology pathways

An alternative to biofuels is to fix CO2 directly in an industrial plant. The best-known approach to direct fixation involves power-to-liquid (or "power to X") processes called electro fuels, or e-fuels, which rely on electricity. There are various technology pathways in this respect. A common one involves creating a mixture of hydrogen and carbon monoxide, which is synthesis gas or syngas. Using suitable catalysts and the right temperatures and pressures, syngas can be converted into hydrocarbon liquids, including synthetic kerosene. This conversion is the Fischer-Tropsch (FT) process, a well-established, scaled-up technology that has been employed to convert solid or gaseous carbon-based feedstocks, e.g., coal, biomass, or natural gas to produce liquid fuels. E-fuels could leverage the FT process by feeding it with CO from CO2 and the H2 from water.

Renewable electricity can be used to produce green hydrogen through water electrolysis, with CO produced by the partial reduction of CO2. The CO2 can be drawn directly from the atmosphere (through DAC) or extracted from industrial or other processes, such as fermentation in breweries. This pathway requires the production of substantial excess H2 by water electrolysis using renewable electricity that is subsequently consumed via the reverse water-gas shift (RWGS) reaction to obtain syngas suitable for FT synthesis. The RWGS reaction ($H_2 + CO_2 = H_2O + CO$) is endothermic by 96 kJ/mol at 800°C, and this high-temperature heat must be supplied by a renewable energy source.

Another approach is the electrolysis of CO_2 to produce gaseous or liquid fuels directly, or to produce CO which can be fed together with green H_2 into the FT process described above. Stanford University is developing several power-to-liquid pathways. The e-synthetic/renewable e-fuel pathway they are developing has already led to several start-up companies in the sector, such as Twelve – which at the 2023 Paris Air Show in Le Bourget, France, announced plans for a partnership with the US State of Washington for a commercial-scale SAF production facility from CO_2 and renewable energy.

Yet another approach involves solar photoelectrochemical (PEC) pathways, which involve photovoltaic (PV)-grade semiconductors combined with electrocatalysts. The Sunergy initiative in Europe and the Solar Fuels Hubs in the US reflect substantial industry and government interest in these technologies.

Strengths

If renewable energy is used to produce the hydrogen and the CO_2 is obtained through DAC, the resulting e-fuel will be a net-zero emission jet fuel that does not rely on offsets. Development of these fuels is underway. For instance, in Norway, which has abundant hydro resources, Norsk e-Fuel is building a DAC plant to produce SAF. The plan is to produce 12.5 million litres a day and start operations in 2024. Airlines are beginning to test e-fuels as well. Where DAC is not available, e-fuels can be produced but should not be defined as net-zero unless all emissions are captured.

Weaknesses

The main challenges e-fuels face are operating costs and investment capital. Costs are a short-term challenge that could potentially be resolved in the longer term. The other major challenge is attracting significant investment. Investors need confidence adequate demand will exist at prices that will bring returns in line with investments of equivalent risk. This has been done before – for example, with the right policies and investment incentives, the PV industry has scaled up at over 10 percent per year for the past 20 years.

However, even if some costs are reduced through scaling, costs are associated with e-fuels due to: (a) the energy inefficiency related to the multiple steps and conversions needed in the production chain (i.e., generating and transporting electricity, electrolysis, and RWGS); and (b) the social and economic challenges of building enough renewable generation and of developing hydrogen networks and storage to meet projected hydrogen requirements. SAF are only one of the synthetic fuels that can be produced from green hydrogen. However, to put the challenge in perspective, to meet projected hydrogen demand for 2030, the EU would require an additional 500 TWh of renewable electricity[5]. As with some biofuels, this is a matter of the land required to generate, transport, and store the necessary electricity to deliver the required e-fuels. In addition to these technical challenges, public resistance to the siting of renewable power and the building of networks is growing.

There is also a new concern about the leakage of hydrogen. The Norway-based CICERO Center for International Climate Research argues that some of the benefits of hydrogen could be negated if too much hydrogen leaks into the atmosphere during its production, use, and transportation. This is because the global warming effect of leaked hydrogen is almost 12 times greater than that of CO_2.

---

[5] In 2022, the EU produced 2 641 TWh of electricity. Almost 40% came from renewable sources.

Prospects

Because of the very strong political commitment among the world's leading economies to develop green hydrogen, as reflected in the substantial public financial support, e-fuels have excellent growth prospects. However, due to the costs and risks, misplaced optimism with respect to the market for green hydrogen is possible.

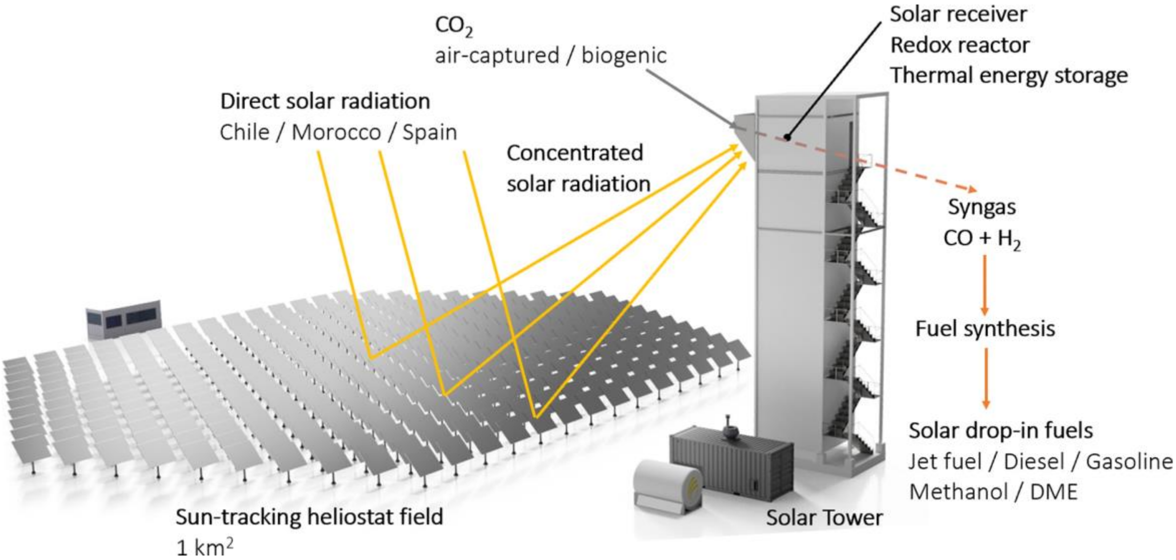
3.3. Solar aviation fuels

Technology Pathway

The technology pathway called the "sun-to-liquid" process[6] consists of converting concentrated sunlight to heat and using that heat – rather than electricity – to perform the thermal splitting of water and CO2 molecules. There are three thermochemical steps.

1. DAC extracts CO2 and H2O directly from ambient air, driven by waste heat (from step 2) at 95ºC.
2. The solar redox cycle, which converts CO2 and H2O into a tailored mixture of CO and H2 (syngas), is driven by high-temperature heat (1300-1500ºC) from concentrated solar energy received from a heliostat field of mirrors.
3. The exothermic FT process converts syngas to kerosene.

Solar thermochemical production of drop-in fuels



Source: *Science of the Total Environment* 901, 166005 (2023).
https://doi.org/10.1016/j.scitotenv.2023.166005

---

[6] Technical, economic, and environmental analysis of solar thermochemical production of drop-in fuels, *Science of the Total Environment*, Volume 901, forthcoming 25 November 2023, 166005.
https://www.sciencedirect.com/science/article/pii/S0048969723046302

Strengths

This pathway, which was developed mainly at ETH-Zurich and the DLR-German Aerospace Center, has worked in pilot plants using solar dish and solar tower configurations to concentrate solar radiation and supply the high-temperature heat required to perform the thermochemical conversions. This technology pathway can potentially achieve higher energy efficiency compared to the e-fuels route because, in contrast to the "power-to-X" pathway, the thermochemical pathway bypasses the renewable electricity generation, electrolysis, and RWGS steps. Instead, it directly produces solar syngas of the desired composition for FT synthesis, i.e., three steps are replaced by one. It is also highly selective, as it was designed to eliminate any undesired by-products that would have to be separated and/or recycled. Furthermore, by integrating the storage of high-temperature heat in a thermocline-based packed bed of rocks (which is significantly cheaper than storing electricity), the solar fuel plant should be able to operate around the clock.

Notably, the optical components for concentrating solar radiation at a large scale, e.g., solar dishes and solar towers with heliostat fields, are already established for industrial-scale Concentrated Solar Power (CSP) plants. In addition, there are substantial technological spillovers from solar thermal electricity to solar thermochemical fuels.

Synhelion, a spinoff of ETH Zurich, announced in August 2022 that an experimental solar tower was producing syngas. It is currently finishing an industrial-scale facility in Germany that will supply solar jet fuels to Swiss International Air Lines (SWISS), which is owned by Lufthansa. Another plant is due to open in Spain in 2025. By 2030, Synhelion expect to produce 850 million litres per year, about half of the jet fuel needed by SWISS. The target for 2040 is 50 billion litres per year.

Furthermore, there are co-benefits to developing this thermochemical technology, notably the potential to decarbonise cement and develop net-zero-carbon electricity storage[7]. The global cement industry is responsible for about 8 percent of CO2 emissions caused by the calcination process and the combustion of fossil fuels for heat generation. Synhelion has linked up with Cemex, a Mexican company that is one of the world's biggest producers of cement[8]. Synhelion's technology is applied to generate high-temperature steam using concentrated solar energy. The steam is in turn used to heat the limestone and drive off CO2. The process avoids the CO2 emissions derived from fossil fuels and the emissions derived from the calcination are captured in pure form – which is an ideal raw material for processing solar SAF. Having tested the solar-driven process successfully in Spain, the two companies aim to build a trial plant at one of Cemex's sites.

Other benefits from developing this technology path include: the geopolitical attraction of being sited anywhere with good solar conditions; the avoidance of the challenges of siting additional renewable generation plants to produce e-fuels; and the potential to reduce costs through increased scale, learning economies, better use of waste heat, and use of different chemical redox agents. A techno-economic study[9] identified the following additional benefits. First, unlike biofuels, this technology path could meet global jet fuel demand by using less than 1 percent of the world's arid land, which does not compete with food or fodder production. Second, a life cycle assessment of the solar fuel production

[7] For more information on decarbonising industrial processes and storing excess renewable electricity, with high-temperature solar heat, see these articles: https://synhelion.com/solar-heat and https://pubs.acs.org/doi/10.1021/acs.energyfuels.0c02572?ref=pdf.

[8] See https://www.reuters.com/business/energy/mexicos-cemex-announces-first-step-toward-solar-powered-plants-2022-02-03/ and https://www.cemex.com/w/cemex-and-synhelion-achieve-breakthrough-in-cement-production-with-solar-energy.

[9] An integrated techno-economic, environmental and social assessment of the solar thermochemical fuel pathway. *Sustainable Energy & Fuels* 4. 3992 (2020).

chain indicates 80 percent avoidance of GHG emissions with respect to conventional fossil jet fuel, with emissions in the range of 0.1–0.6 kg CO2-equivalent per litre of jet fuel. Third, emissions approach zero when construction materials (for example, steel and glass) are manufactured using renewable energy, because the amount of CO2 emitted during jet fuel combustion equals that captured from the air during its production.

Weaknesses

As with e-fuels, the main weakness of this pathway is the challenge of lowering the cost of solar fuels and attracting investment capital. For example, the costs are currently about 10 times the price of regular kerosene (e.g., 1.11 Euros-litre, Chile). However, a recently published technical, economic, and environmental analysis suggests that jet fuels can be produced (by 2030) from sunlight and air in Chile for 2.5 Euros-litre and that solar jet fuel costs in Chile could reach 0.6-1.3 Euros-litre in the longer term (during the 2030s)[10].Thus, significant capital is needed, meaning that investors must be confident that demand and price will be sufficient to provide a risk-adjusted return on capital.

Another challenge is that solar synthetic fuels (or synfuels) are less well-known than all the other pathways and are more expensive than the biofuel SAF already in use by several airlines. On the other hand, e-fuels and solar fuels should both benefit from the political enthusiasm for hydrogen and from the significant subsidies available for green hydrogen.

There are two other potential weaknesses. First, solar fuels require good solar sources, somewhat limiting the availability of suitable locations – whereas e-fuels can work with multiple sources of renewable energy. Second, solar fuels are not a modular technology, and we have seen that in the case of PV vs CSP, PV has largely won out because of its modular nature. The minimum size of a solar fuels plant is driven by the economic benefits of having relatively large heliostat fields.

Prospects

Solar fuels share many of the benefits and co-benefits of e-fuels for providing a long-term sustainable supply of SAF, without some of the disadvantages of e-fuels and biofuels (especially related to land use). The biggest challenges for solar aviation fuels are to develop the scale and technological improvements that will drive down costs and to raise capital. This involves competing for the public policy and financial market support that currently favours e-fuels. A study published in *Nature*[11] identifies research and development (R&D) efforts and discusses the economic viability and policies required to bring solar aviation fuels to market.

4. Potential to Reduce Costs of SAF

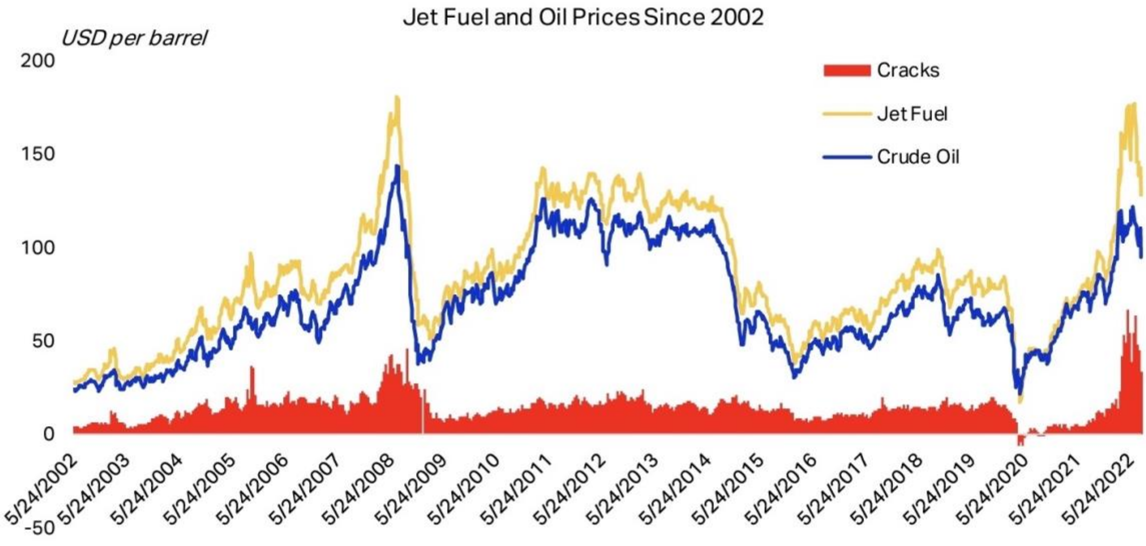
4.1. Cost comparison

Comparing the costs of aviation kerosene and SAF is not easy, in part because the market price of fossil fuels is very volatile and varies among regional markets and specific aviation products. Cost comparisons are also difficult because the environmental externalities of fossil fuels are often ignored. Where these externalities are included, the full cost of fossil-based aviation kerosene rises.

---

[10] The study also compares costs in Chile with those in Morocco and Spain.
[11] Drop-in fuels from sunlight and air. *Nature,* 601, 63-68 (2022).

The IATA chart below shows the significant volatility of the kerosene price (yellow line) since 2002. From its lowest point in 2020 during COVID, prices rose from less than USD 20/bbl to USD180/bbl.



Source: IATA Economics using data from Platts.

In a recent report, ING estimated the cost differential between conventional kerosene and certain SAF. Biofuel (HEFA) was about 2-3 times the cost of conventional kerosene; synthetic kerosene (e-fuel) based on green hydrogen was approximately 10 times the cost of conventional kerosene; and the differential was even greater when the process involves carbon capture and storage (CCS) or DAC technologies.

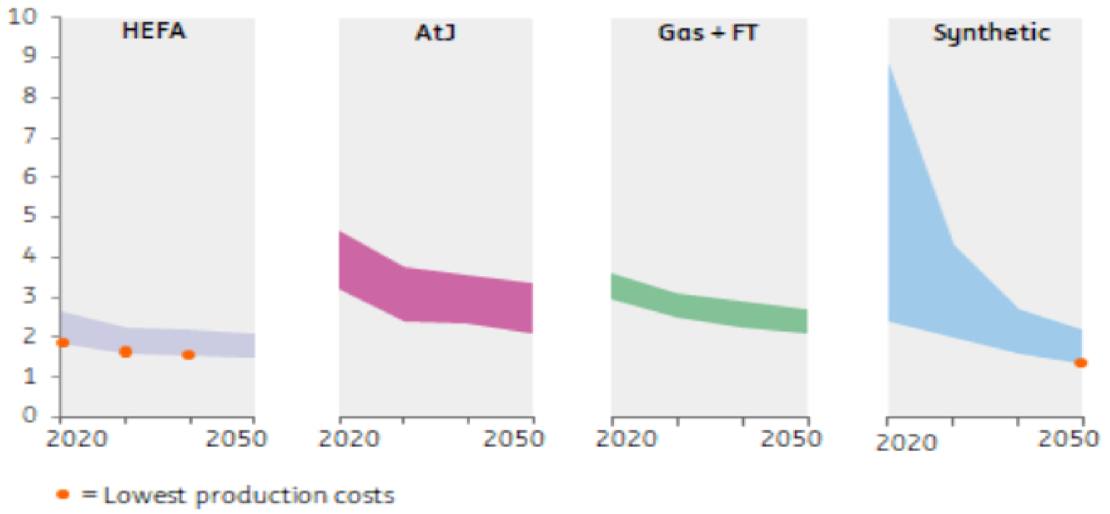
4.2. Cost-reduction potential

Boeing's chief executive David Calhoun recently told the Financial Times that, even though SAF costs will fall, they will never achieve the price of conventional kerosene. However, he was referring to biomass-based SAF and what he was assuming with respect to CO2 or other emission-related taxes is unclear. Although the cost differences with fossil kerosene are currently very significant, the future is obviously much harder to predict.

All SAF have the potential to lower their costs through improved technology, configuration, and learning. However, the potential to reduce the cost of biofuel SAF through increased scale is limited by the restricted access to raw materials and land. There is a greater potential to reduce the costs of e-fuels and solar aviation fuels due to the relatively immature nature of the technologies and the expectation of significant scale and learning economies, as well as improved efficiency. Both SAF technologies have an additional advantage, namely the shared costs associated with decarbonising multiple end-uses, in addition to jet fuels. However, the potential for e-fuels to reduce costs is limited by the amount of land needed to generate and transport the additional renewable electricity and to produce, transport, and store green hydrogen.

ING forecasts support the view that synthetic fuels have greater potential to reduce cost than other SAF. Whereas biofuel (HEFA) costs are expected to decline very little, synthetic e-fuels are forecast to fall dramatically, from about 10 times to less than two times the cost of conventional aviation fuel.

Development of production costs per SAF route (upper and lower boundary) as multiple of jet fuel



WEF, ING Research

ING does not specifically analyze the costs of solar aviation fuels. However, as mentioned above, a recent study finds that the cost of solar aviation fuels in Chile could fall to 2.5 Euros-litre by 2030 and that the cost could reach 0.6-1.3 Euros-litre during the 2030s. The implication is that solar aviation fuels could be increasingly competitive with conventional fuels.

5. Barriers to SAF Development

Many barriers to SAF development are described as weaknesses in Section 3 above. On the SAF demand side, the airline industry has an obvious short-term interest in limiting its consumption of SAF because they are more expensive than fossil-based kerosene. On the supply-side, airlines and airports face the costs of financing investment in SAF and the infrastructure to supply them. The funding needs were daunting even before capital markets tightened. Moreover, if these high costs are passed on to passengers, this could significantly reduce the number of air travelers, which is politically and socially a serious problem that could undermine the aviation industry's social license to operate.

The only way to drive down the cost of e-fuels and solar aviation fuels is through R&D and then widespread deployment, with the mass production of key components and learning-by-doing, in addition to investment in more efficient aircraft that can run fully on SAF.

IATA estimates a cost of USD 5.3 trillion between 2023 and 2050 to meet net-zero targets. Their report[12] makes three arguments to support the need for this investment.

- First, these sums must be seen in the context of airlines investment in R&D related to the production of more efficient aircraft (USD 1 trillion over the last 10 years) and the Boeing Commercial forecast market value of aircraft deliveries between 2022 and 2042 (USD 7.2 trillion).
- Second, the economic benefits of achieving the net-zero emissions goal justify the investment. In IATA's words, "This investment is necessary to ensure that aviation can continue to play a crucial role in driving economic development across the globe. Indeed,

[12] Finance, Net Zero Roadmap, IATA.

throughout economic history, advances in all forms of connectivity have helped propel economic welfare, and the poorest countries in the world are predominantly those sorely lacking in this respect, notably the landlocked countries in the center of Africa. Clearly, aviation is not sufficient to drive economic growth and development, but it is a necessary ingredient, as the COVID-19 crisis laid bare." The Air Transport Action Group (ATAG) summarised these benefits, highlighting the contribution the air transport industry makes towards the fulfilment of the 17 United Nations Sustainable Development Goals (SDGs), of which reducing poverty is number 1.

- Third, when the net-zero-related investments are spread over the number of passenger journeys expected during the 2023-2050 period, total investments would represent up to USD 45 per journey.

One could argue that "they would say this wouldn't they", especially when the air industry is seeking public funding and policy support to continue its expansion. However, the IATA emphasis on developing countries is appropriate not only because of the potential benefits of better connectivity to economic growth and the alleviation of poverty, but also because growth of air travel is likely to be greatest in countries experiencing rapid economic growth. IATA is also right to focus on the price impact for travelers and the effort to improve the efficiency of fleets to reduce the cost of meeting net-zero targets. Furthermore, they have helpfully identified several potential sources of finance that could be tapped at different stages of SAF development.

In the context of the enormous financial challenge, perhaps the greatest barriers are regulatory uncertainty for investors and the related perception that the aviation industry does not deserve or need public subsidies. Regulation is especially uncertain because a regulatory framework must be designed to suit the development of SAF in all parts of the world. Clear policy is also needed to support SAF development as well as collaboration among countries, including capacity building for SAF development and use.

6. Policies, finance, and business models

6.1. Existing policies

At a global level, three important policy and business commitments driving the development of SAF are:

- The CORSIA commitment to not exceed "2020" emissions (85 percent of 2019 emissions; because of COVID, the 2020 number is very low) until 2036.
- ICAO's 2020 target of net-zero emissions, with SAF accounting for 65 percent of the emission reductions.
- The accepted shift of focus from carbon crediting with implicit carbon prices, to lowering emissions by reducing direct emissions from airplanes and other improvements to planes and airports.

There are now "top down" political agreements including for the US, the UK, Japan, and EU Member States. Some sub-national governments, including California, are also introducing policies to support decarbonisation of airlines. There is also "bottom up" support from the aviation industry, as illustrated by the ICAO statement at COP27 and by the examples cited in Section 2 above.

Focusing on policy support, the US IRA offers tax credits for SAF production in the US. In parallel, the US Department of Energy Bioenergy Technologies Office (BETO) supports research, development and demonstration (RD&D) to overcome barriers for SAF deployment, while the Department of Energy has indicated it is working with the Departments of Transportation and Agriculture and other federal agencies to develop a comprehensive strategy for scaling up new technologies to produce SAF on a commercial scale.

The EU has introduced a number of rules to promote SAF, notably under the REFuelEU legislation adopted in April 2023. The most significant are mandates to increase volumes of SAF to fuel jets in Europe, starting at 2 percent of overall fuel supplied by 2025 and reaching 70 percent by 2050. Interestingly, the blending mandate covers biofuels, recycled carbon fuels, and synthetic aviation fuels (e-fuels), but excludes food and feed crops, on the grounds of supporting sustainability objectives. A second rule is that aircraft operators departing from EU airports must refuel only with the fuel needed for the flight, to avoid emissions related to extra weight or carbon leakage caused by 'tankering' practices (deliberately carrying excess fuel to avoid refueling with SAF). A third is that EU airports must ensure that their facilities are prepared for SAF distribution.

The EU is also introducing an Emissions Trading Scheme for transport that will raise the cost of fossil fuels by the value of the emission allowances, thereby narrowing the gap between the cost of SAF and fossil fuels. The EU continues to fund SAF-related RD&D, notably through the Horizon Europe Work Programme for 2023-2034.

Recently, the UK unveiled measures to accelerate the decarbonisation of transport, including a second round of funding of the £165 million Advanced Fuels Fund, to support the UK's commitment to construct at least five commercial-scale SAF plants in the UK by 2025. This is a central piece of the UK's Jet Zero Strategy. Additionally, the UK launched a second consultation on the SAF mandate.

6.2. Future policy, business, and financial initiatives

Further research is required to align public policies (individually and as packages) with investment in SAF technologies by financial institutions and charitable foundations. Investors need to be confident that there is adequate policy support to ensure sufficient demand and prices to warrant investing.

Government financial support and regulatory measures will be needed to attract the kind of private capital that has benefitted the development of renewable energies, such as wind and solar power. Financial support is particularly important during the early stages of bringing SAF to market, but credible policy commitments to meeting net-zero targets – for instance increasingly stringent blending mandates, carbon intensity targets, or carbon prices – are also critical. In addition, commercial opportunities in the sector must be advertised to venture capitalists and governments must monitor the industry for signs of lack of funding.

Charitable foundations also play a key role in the early stages through grants for R&D, pilot projects, and policy research. As the technology matures, the role of private sector financing grows, while that of governments evolves to focus on improved regulation and addressing any market failures. Most of the funds will be required during the 2030-2040 period when the scaling up of production and the development of market opportunities occur.

Forward-looking research should draw on the experience of policies designed to support SAF to date, as well as policies that have supported innovation, investment, and the development of other green technologies. The most important public policies to date include:

- A regulatory environment that gives confidence to investors, including economy-wide commitments to net-zero emissions, support for the pricing of carbon emissions, financial disclosure of climate-related financial risk, and expectation of continued political support for net zero emissions.
- Demand-side measures that support the use of SAF, such as rising SAF quotas/mandates, carbon taxation and emission trading, CO2 intensity targets, and Carbon Contracts for Difference.
- Supply-side measures, such as subsidies or tax credits for SAF, and competitive bidding for subsidies among SAF technology options, ensuring support for new sustainable technologies with potential for large-scale development.
- Measures to stop greenwashing because airlines claiming to be greener than they are will lead to litigation and undermine the credibility of the airline industry's commitment to achieving net-zero emissions.

There are, however, some critical differences that must be acknowledged in designing credible aviation policies. First, most other green energy technologies feed into local, national, or regional markets (i.e., for electricity or heat), whereas SAF production technologies feed into global fuel markets. Second, most of these policies have been introduced in the most advanced economies, whereas the aviation industry is global and highly competitive, requiring the design of policies that work for countries with, as well as those without, well-developed policies and the means to implement them. This is particularly relevant because aviation is growing fastest in emerging markets, and these countries may be particularly hostile to restricting economic growth.

Thus, future policies should reflect the international nature of sustainable aviation fuels. This implies the need for common or compatible international standards that will allow for fueling around the world and uniform monitoring of compliance, for example with blending mandates. Such policies will require: 1) leadership of certain countries in defining standards and in meeting ICAO commitments; 2) fuel blending mandates and other incentives to overcome barriers to SAF penetration; 3) fiscal and other financial incentives that are technology neutral with respect to SAF alternatives; and 4) technology-specific support, especially for the promising technologies that have the potential to meet net-zero emission targets sustainably. One policy example that covers a number of these requirements is ICAO´s Capacity-building and Training for Sustainable Aviation Fuels programme, for which the European Commission has recently announced its support.

Finally, in addition to policy support, meeting the ICAO 2050 net-zero target requires aviation industry business models, financial institutions, and charitable foundations to be aligned with that target. Early examples of alignment include the emergence of airline commercial models (e.g., offered by United) that replace customer payments for offsets (to compensate emissions during a flight) with a financial contribution to SAF technology development, and the commitment of airlines, like SWISS, to use solar fuel SAF. However, huge investments are required to develop SAF at scale, which is very unlikely to occur without investors having clarity about national and international policy frameworks. This includes policies related to the aviation sector, as well as policies and financial market rules requiring disclosure of climate and nature-based financial risks.

7. Conclusions

International aviation policy is now committed to net-zero carbon emissions by 2050, especially through direct reductions of airplane emissions. This is very different from previous aviation decarbonisation strategies that relied on carbon offsets. National and international aviation policies, industry business models, and financial incentives must be aligned to meet this 2050 net-zero target at the lowest cost possible.

The future of aviation depends on it becoming sustainable without raising prices to levels that choke international movement of goods and limit flying to only the very wealthy. This requires not only a long-term vision but a staged transition plan that involves public and private charitable and investment funding for: (a) research to develop public policies at the national and international levels that are designed to increase demand for SAF and reduce cost relative to fossil-based jet fuel; (b) R&D, technological innovation, and scaling up production to lower the cost of SAF; and (c) new airline, airport, and energy business models, as well as financial market incentives, aligned with the global aviation sector target of net-zero emissions by 2050.