Report

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Sustainable Aviation Fuels

THE BEST SOLUTION TO LARGE SUSTAINABLE AIRCRAFT?

Roland Berger

EXECUTIVE SUMMARY

Aviation needs a sustainability revolution. In 2019, civil aviation accounted for c. 3% of global CO_2 emissions — but while other polluting industries are able to reduce their emissions, aviation's share of anthropogenic greenhouse gas emissions is expected to grow.

At the same time, the industry has introduced ambitious long-term targets, such as a promise of net-zero growth after 2020, and a reduction of emissions to half of 2005 levels by 2050. Even if fuel efficiency continues improving at ~1% p.a., in-line with historical rates, it will not be enough to achieve these targets once air travel returns to growth again post-COVID-19.

In order to meet its emissions reduction targets, aviation will need to adopt more revolutionary measures, particularly with regards to propulsion. Sustainable Aviation Fuels (SAFs) are among the most promising new technologies.

SAFs are expected to play a crucial role alongside hydrogen and electrical propulsion in decarbonising aviation. Given density limitations for batteries and hydrogen fuel storage, SAFs are vital to enable net-zero long-haul aviation. They will also help to enable more sustainable aviation for all large commercial aircraft in the medium-term, before hydrogen and electric planes become technically and commercially available.

To enable the usage of SAFs at scale, several barriers will have to be overcome, chief of which is affordability. Whilst HEFA SAFs are currently the least expensive SAFs, it will likely be Power-to-Liquid SAFs which become the most economically viable in the long-term as renewable energy prices fall. They also have the lowest environmental footprint among key SAF pathways.

SAFs have a clear role to play in addressing the challenge of climate change. Aerospace, aviation, governments, and the energy sector alike should carefully consider investing in SAFs, in parallel with investments into other key sustainable technologies, to help realise their potential.

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1/ Sustainable Aviation Fuels versus electric and hydrogen

Sustainable Aviation Fuels, or SAFs, are a wide range of kerosene alternatives produced from chemical reactions from various feedstocks, both biological (e.g. Algae) and synthetic (e.g. Hydrogen and CO_2).

SAFs are one of three technological solutions for the de-carbonisation of aviation, the other two being electrical propulsion and hydrogen propulsion. Both electric and hydrogen systems have the potential to be 'true-zero' carbon solutions. Electric planes release zero atmospheric emissions in flight, while hydrogen power sources (both fuel cell and combustion) should also eliminate CO_2 emissions, as well as lowering NO_X emissions (while water vapour emissions rise significantly, appropriate operation of hydrogen aircraft has the potential to minimise or prevent contrail formation and aviation induced cloudiness). → A

By comparison, SAFs can be a net-zero solution to aviation's emissions, as atmospheric CO_2 is absorbed during their production process, meaning that CO_2 emissions on a net basis are reduced, and could even hit zero with the correct production and operational processes.

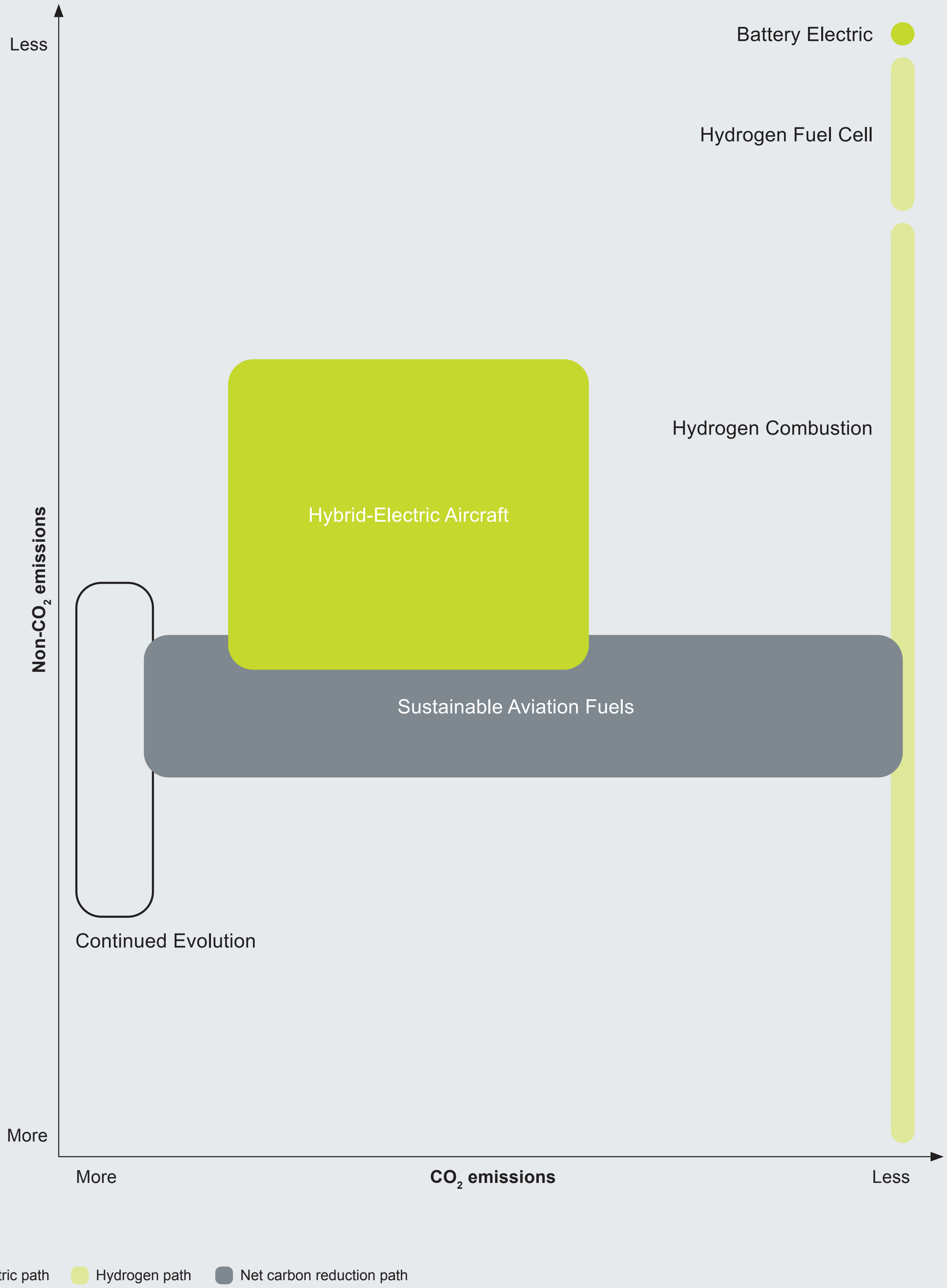
SAFs also have a somewhat reduced non-CO_2 footprint compared to conventional jet fuels. Their higher purity cuts soot emissions, in turn reducing contrail formation and aviation induced cloudiness (AIC). Additionally, SAFs often emit lower levels of NO_X than conventional kerosene due to lower combustion temperatures, further reducing their radiative forcing impact. SO_X emissions are also expected to be cut significantly by SAFs due to their non-oil origin.

SAFs can be used as drop-in fuels and should not require substantial reworking of current aircraft/engine designs, and thus represent minimal disruption to the aviation and aerospace industries, compared to the major design changes needed for hydrogen and electric aircraft.

SAFs may thus be key to meeting short-term aviation sustainability targets due to their ability to scale up ahead of other technological solutions. In the longer-term, they are expected to be the most viable option for sustainable long-haul flights. Additionally, SAFs may also be compatible with hybrid-electric aircraft and may help with the scaling of hydrogen infrastructure.

A / Comparing environmental impact

Potential solutions by intensity of CO_2 and non-CO_2 emissions

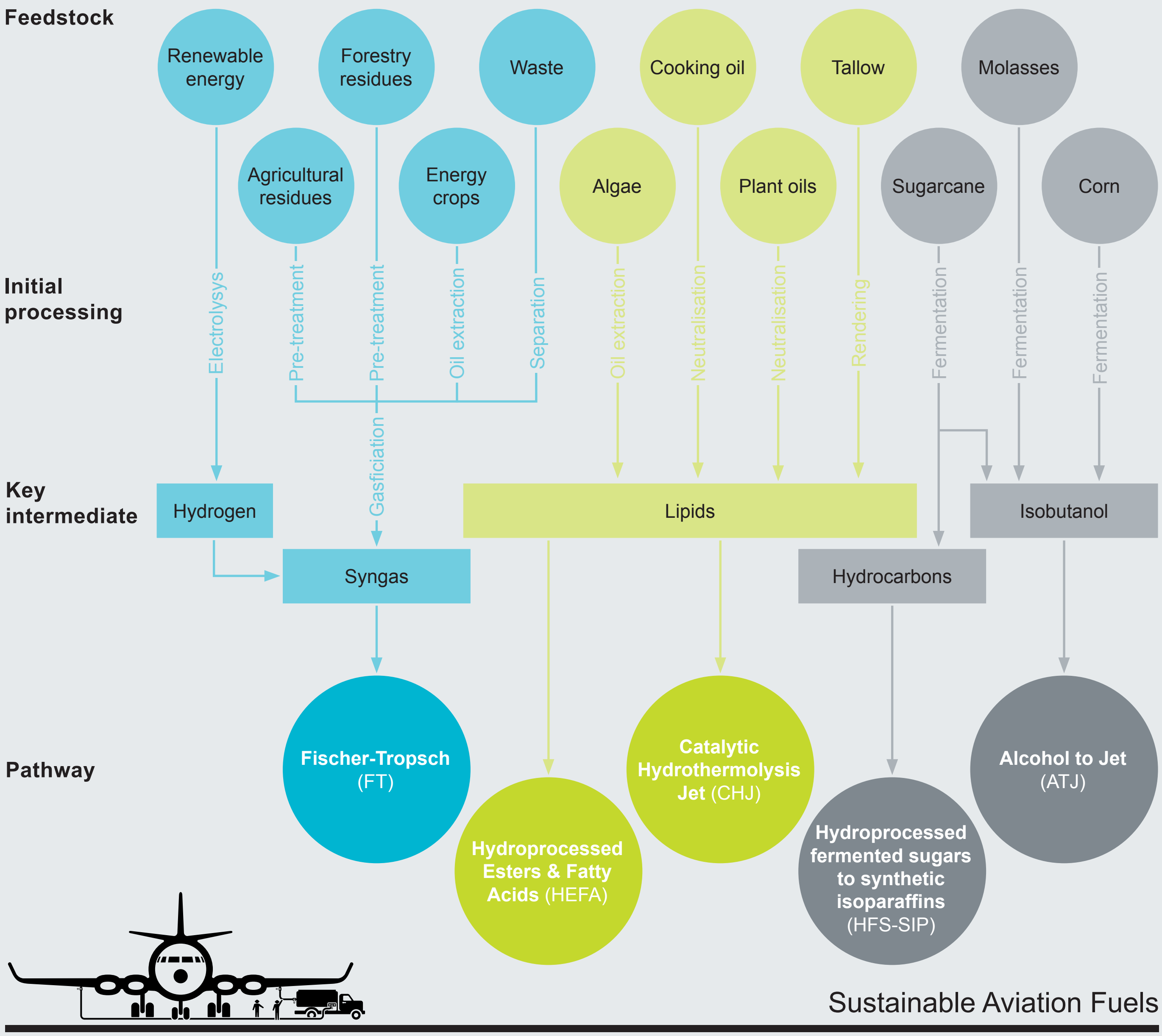


Source: Roland Berger

2/ SAF pathways and developments

Currently there are five pathways for SAFs production approved by ASTM International: Hydroprocessed Esters and Fatty Acids (HEFA), Gasification and Fischer-Tropsch (FT), Alcohol to Jet (ATJ), Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP), and Catalysed Hydrothermolysis Jet (CHJ).

B / Mapping of feedstocks to pathways



Source: Roland Berger

Most commercially available SAFs are produced through HEFA pathways, with some FT fuels also available, though at lower scale.

Every pathway, except HFS-SIP, produces a synthetic paraffinic kerosene (SPK), allowing for ready blending with conventional jet fuels. Most of these pathways allow for up to 50% drop-in blends (given current regulatory limits), with HFS-SIP and HC-HEFA only approved for up to 10% blends. → B

For Fischer-Tropsch pathways (FT-SPK, FT-SKA), the feedstock is thermally converted into syngas (a mixture of Hydrogen and Carbon Monoxide). The syngas then undergoes a series of iron/cobalt catalysed reactions to synthesise kerosene.

In HEFA pathways (HEFA, HC-HEFA), oils are treated with hydrogen to reduce and isomerise them to appropriate hydrocarbons, which are then cracked and fractionated to create an appropriate mixture of paraffins for blending with Jet Fuel. CHJ proceeds via similar lipid intermediates to HEFA, before reacting the lipids with water under extreme temperatures and pressures to produce a mixture of hydrocarbons.

ATJ and HFS-SIP both proceed by fermenting carbohydrate feedstocks with separate secondary reactions and purification steps leading to differing intermediates and products, albeit with HFS-SIP not directly producing synthetic paraffinic kerosenes.

CURRENT USAGE OF SAFS

European countries are leading the push towards SAF adoption. Norway is a key proponent, with all aviation fuel sales mandated to have a blend of SAFs, and Oslo and Bergen among the first airports worldwide to offer SAFs commercially. Other European countries are also contributing, with the Netherlands mandating SAF blends for military aviation applications, and the UK government championing SAFs as vital for long-term sustainability and funding SAF infrastructure.

Independent of regulatory requirements, airlines are also voluntarily investing in SAFs. Lufthansa, for example, is working closely with Neste, both in testing of SAFs and in using SAFs on flights out of Frankfurt. Air France-KLM has partnered with SkyNRG to develop waste to fuel capacity in the US, using it on all LA-Amsterdam flights since 2016. IAG has partnered with Velocys to produce Fuel from Waste, with production due to start in 2022, and the aspiration of scaling up to 25% of its fuel usage in the long term. United Airlines has invested in a SAF developer and purchased c. 5 m litres of SAFs annually over 2017-2019. Business Jets are also adopting SAFs, with 23 aircraft flying to EBACE 2019 on SAF blends. Given that fuel represents a somewhat lower portion of the business jet cost base, adoption here may even be more rapid than across the rest of commercial aviation.

CONTINUED DEVELOPMENT OF SAFS

Development of new types of SAFs is continuing apace, with continued innovation essential to reducing cost and improving the environmental benefits of SAFs. Two new pathways (CHJ and HC-HEFA) were already approved in 2020, with many other new pathways going through certification.

Many new pathways undergoing certification build on existing pathways, often to either increase production yields, increase the maximum blending share, or ease production scale-ups.

Various companies are working on alternative ATJ pathways to allow for different feedstocks and increase yields. A group is also working on an ATJ equivalent to FT-SKA, that includes aromatic compounds, and can potentially increase blending share to 100%. Applications are also underway for approval of "co-processing" of various feedstocks which would ease scaling up of projects for HEFA and FT processes.

Some novel pathways, for example the Integrated Hydropyrolysis Hydroprocessed Fuel (IH2) and Pyrolysis (Hydrotreated Depolymerised Cellulosic Jet — HDCJ) pathways, are also moving through the approval process, enabling new feedstocks and potentially higher yields.

3/ Roland Berger SAF Sustainability Index

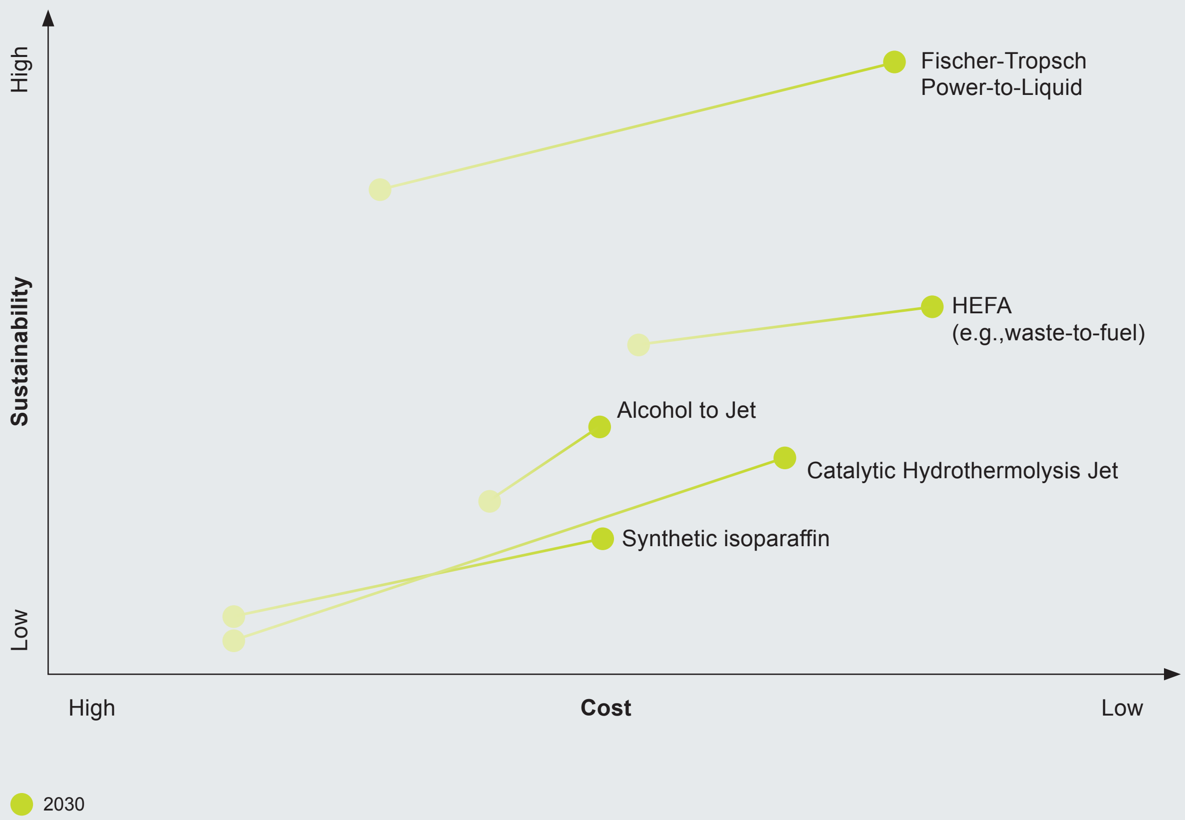
TRUE SUSTAINABILITY OF SUSTAINABLE AVIATION FUELS

Due to the different chemical reactions and feedstocks used in their production, different SAFs can have very different environmental impacts. In addition to differences in lifecycle atmospheric emissions, arable land and water usage are particularly important, especially given the constraints that these resources are expected to face over the coming years. Given the need for significant scaling of SAF production, feedstock availability is also important to assessing the true sustainability of a fuel.

In light of this, we have developed the Roland Berger SAF Sustainability Index, separately assessing the sustainability and cost of various SAF options, both at present and considering their development over the next 10 years. → C

Our SAF sustainability index takes into account lifecycle atmospheric emissions, natural resource consumption and constraints, and feedstock availability to create a composite sustainability score for each class of fuel. The specific sustainability characteristics of each fuel type are then discussed in the subsequent paragraphs.

C / Sustainability Index



Note: To assess "Sustainability", we assessed CO_2 reduction potential, non-CO_2 emissions, maximum blend percentage, feedstock availability, land usage, and water usage. To assess "Cost", we separately looked at capital expenditure, feedstock costs, and operational costs.

Source: Roland Berger

FISCHER-TROPSCH – POWER-TO-LIQUID (FT-PTL)

Power to liquid (PtL) projects have very low water and land usage, as well as very low lifecycle emissions, making them the most sustainable option in the long term. Currently much of the cost of PtL fuels is in the cost of renewable energy, presenting a significant opportunity for cost to reduce, as the cost of renewable energy continues to decrease. PtL fuels will also be able to leverage hydrogen infrastructure (both within aviation and across other industries) as their production is scaled up, increasing the likelihood of significant economies of scale in the future.

FISCHER-TROPSCH – BIOMASS AND MSW (FT-BIOMASS, FT-MSW)

Broadly any form of biomass is suitable for FT SAF production, with agricultural and forestry residues having the lowest net CO_2 emissions. Waste is also viable as a feedstock to produce syngas, although the lifecycle emissions from this process are currently relatively high due to the number of additional processing steps needed in this pathway. All FT fuels show a drop in NO_X emissions.

FT is the only pathway with a currently approved process to directly incorporate aromatics (primarily benzene) into the fuel. In the future, this should allow for higher blend percentages as it provides the full range of molecules found in current jet fuels, as opposed to just paraffins, thereby allowing better compatibility with current jet engines.

HYDROPROCESSED ESTERS AND FATTY ACIDS (HEFA-WASTE OIL, HEFA-ALGAE, HEFA-PLANT OILS)

HEFA fuels are currently the most commercially viable option. Within HEFA, waste cooking oils are currently the cheapest and most widely used and have very high emissions reduction potential. Plant based oils, e.g., from rapeseed or soy, are expected to be more available over the medium-term, but are less sustainable as they compete directly with food crops for arable land and water. Non-competing plant options exist but are in early stages of development (e.g. oils growable in deserts, algae feedstocks for HC-HEFA). HEFA fuels have also been shown experimentally to reduce NO_X emissions more effectively than other classes of SAF due to lower combustion temperatures.

CATALYTIC HYDROTHERMOLYSIS JET (CHJ)

CHJ is understood to currently have a high production cost due to high capital and operational costs. Current CHJ feedstocks are typically energy crops or waste oils, with either high land and water use or limited availability. As new feedstocks become more available, particularly algae, the land and water use concerns will reduce. CHJ may also allow for non-blended fuels in the long term, as their production process may be used to create a fuel with a more similar composition to current jet fuel.

ALCOHOL TO JET (ATJ)

The crops used as feedstocks for ATJ (sugarcane and corn grain) have high land and water use requirements, and these crops also lead to relatively high lifecycle carbon emissions due to indirect land usage considerations. ATJ is currently approved to be made from commodity feedstocks, which nevertheless represent a significant portion (~40%) of its cost base. ATJ is thus expected to only see limited cost improvement over the coming years.

HYDROPROCESSED FERMENTED SUGARS TO SYNTHETIC ISOPARAFFINS (HFS-SIP)

HFS-SIP, alongside CHJ, is currently the most expensive pathway, with very high operational costs due to necessary processing steps. The key feedstock of HFS-SIP, like ATJ, is sugarcane, which is highly available but has significant land and water use concerns. As HFS-SIP does not produce a synthetic paraffinic kerosene, HFS-SIP fuels currently only allow for a 10% drop-in volume, significantly below other approved processes. Costs are expected to improve more than for ATJ, with capital and operational costs (which are currently ~75% of costs) expected to reduce as the supply chain scales up.

4/ Challenges to adoption

The key challenges to SAF adoption largely relate to reducing costs, scaling up of the supply chain over time, and the necessary technical advances to maximise the SAF utilisation.

REDUCING COSTS

SAFs are currently significantly more expensive than traditional jet fuel — ~2.5x as expensive for the current most cost effective option (HEFA fuels). This means that currently SAFs are not the most economic method of carbon abatement. For SAF adoption to become prevalent, the costs of production must come down significantly, to below that of jet fuel plus conventional carbon offsets.

The fact that SAFs are admissible under CORSIA will aid their economic viability over the coming years. However, given that fuel already accounts for c. 25-40% of operating costs across the industry, there is very limited willingness for airlines to increase spend, especially in light of COVID-19.

As various projects scale up and economies of scale kick in, costs should naturally come down, especially for some pathways, most notably Power-to-Liquid. However, it remains unknown whether this will enable true cost parity with conventional fuels without regulatory costs of carbon increasing.

SCALING THE SUPPLY CHAIN

Significant volume increases will be necessary over the coming years to match total aviation fuel usage. About 360 bn litres of Jet Fuel were used in 2019, with the current production of SAFs standing at around 50 m litres, or ~0.01%. The vast majority of feedstocks currently used for various SAF pathways are likely to be unrealistic for long-term availability and scaling. Waste sources are not expected to be sufficient, and other biological feedstocks require significant arable land or water (likely worsening food or water shortage concerns). The only viable long-term scalable technology is thus Power-to-Liquid, which has significantly lower land and water requirements than any biological feedstock, but requires scaled-up renewable energy production.

The **high traceability and quality control requirements** for aviation fuels will also add to the challenges of scaling production, particularly for biological feedstocks, as each new provider requires certification. Indeed, the safety critical nature of jet fuel has already led to a rigorous approval process for approval of new fuels.

Given that SAFs are currently a niche fuel type, **widespread support infrastructure** is far from being a reality. While SAFs will be able to leverage conventional fuel infrastructure to some extent, new systems will also be required. For example, pipelines and storage may be required in different locations than for conventional fuels due to different production feedstocks and processes leading to development of new plants outside the existing supply chain.

OVERCOMING ENGINE TECHNOLOGY CHALLENGES

To ensure the emissions reduction potential of SAFs is maximised, they need to be usable without any conventional kerosene. Current SAF pathways are limited to 50% blend shares, due to a lack of chemical equivalence of conventional fuels and SAFs. This arises as most current SAF pathways only replicate the paraffin content of jet fuel, with limited options for including other components, most notably aromatics, which are necessary for ensuring engine longevity.

While new SAF pathways may allow for 100% SAF utilisation in the future, it is very likely that engine design changes will also be necessary to maintain optimal engine performance, given the different chemical compositions (particularly impacting on combustion temperature) of SAFs versus conventional kerosene.

5/ The path ahead

Sustainable Aviation Fuels are set to play a critical, but changing, role as the industry transitions to become sustainable.

Over the relatively near term, SAFs are likely to be introduced into the market in increasing scale significantly before electric and hydrogen planes become technically and commercially viable, playing a notable role in meeting aviation's sustainability targets. Production of SAFs is expected to scale up rapidly over the next five years, from around 50 m litres today to ~7 bn liters in 2025, representing ~2% of global jet fuel demand. By contrast, the first large commercial electric or hydrogen aircraft are not expected to reach the market before 2035. Furthermore, SAFs may be compatible with future hybrid-electric aircraft, making SAFs vital to minimising their environmental impact.

In the long-term, electrical propulsion is expected to be most relevant for smaller aircraft, while hydrogen and hybrid-electric will likely compete in the narrowbody/ Middle-of-the-Market sector. However, we expect SAFs to be the only carbon neutral means of long-haul aviation, particularly for widebody aircraft.

A number of key challenges need to be overcome for SAFs to displace conventional jet fuel, including reducing costs, scaling up the supply chain, and enabling 100% rather than drop-in usage.

Despite HEFA waste-to-fuel options currently being the cheapest options, Fischer-Tropsch Power-to-Liquid fuels are expected to become the most cost-effective technology, enabled by quickly reducing renewable energy costs. They are furthermore expected to be the most sustainable option, while also not having any obvious scale limitations, without overt water or arable land constraints.

CONCLUSION

Despite decades of technological homogeneity in aerospace and aviation, the future looks more complex as the industry grapples with the challenge of sustainability. SAFs — particularly Power-to-Liquid fuels — will play a key role in tackling this challenge, alongside other revolutionary technologies such as electric and hydrogen propulsion.

In the near-term, the industry should capitalise on SAFs being available before electric and hydrogen technologies to contribute towards sustainability targets. In the medium-term, as hybrid-electric technologies start coming to market, they should be designed to be SAF-compatible, allowing a double environmental benefit to serve the narrowbody/ Middle-of-the-Market sector. In the long-term, SAFs will likely remain the only viable solution for sustainable long-haul aviation, particularly for widebody aircraft.

Given their clear role in helping to address climate change, executives should allocate resources to ensure the potential of SAFs is fully exploited, in parallel with investments into electric and hydrogen-powered flight.

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