BEGINNER'S GUIDE TO **SUSTAINABLE AVIATION FUEL**

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ATAG
AIR TRANSPORT ACTION GROUP

FLY NET ZERO

CONTENTS

THE IMPORTANCE OF AVIATION

- Aviation provides the only rapid worldwide transportation network, is indispensable for tourism and facilitates world trade.
- Air transport improves quality of life in countless ways. It is a major global employer and contributor to global economic prosperity.
- Air transport moves around **4.5 billion** passengers annually and **61 million** tonnes of freight[1].
- The air transport industry generates a total of **87.7 million** jobs globally[2].
- Air transport is necessary for transporting high value, time-sensitive goods: **35%** of world trade by value and less than **1%** by volume[3].
- **58%** of international tourists travel to their destination by air[4].
- Aviation's global economic impact is estimated at **$3.5 trillion** (including direct, indirect, induced and tourism catalytic)[5].
- If the aviation industry were a country, it would rank **17th** in the world in terms of GDP[6].
- Aviation is one of the few sectors in the world to have an industry and UN-backed goal of **net-zero carbon by 2050** (aviationbenefits.org/flynetzero/) and roadmaps in place to show how it can work.
- The global aviation industry produces around **2%** of all human-induced carbon dioxide (CO_2) emissions[7].
- A typical new generation single-aisle aircraft emits around **50 grams of CO_2** per seat kilometre. This is equivalent to **2 litres** of fuel burned per passenger for 100 km and comparable to the efficiency of compact cars[8].

INTRODUCTION

Efficiency has always been a tremendous driver of progress in aviation and has made air travel and mobility central to modern life. Indeed, today, our engines are at the cutting edge of efficiency and our aircraft are more aerodynamic and lighter than ever before. We are making improvements in air traffic control efficiency, how we fly our aircraft and in developing less environmentally-impacting operations at airports. But we are still, for the vast majority of flights, using the same fuel. That is now changing.

Aviation's drive for fuel and operational efficiency has helped the industry limit its emissions. To go even further, the aviation industry has embarked on a journey that will lead us to net-zero carbon emissions by 2050. Sustainable aviation fuel (SAF) has a crucial role to play in providing a cleaner source of energy to power the world's fleet of aircraft and help the billions of people who travel by air each year to lower the impact of their journeys. The industry's *Waypoint 2050* analysis suggests that SAF will contribute between 53 and 71% of the emissions reductions needed to get to net-zero by 2050.

This guide looks at the opportunities and challenges in developing sustainable aviation fuel for the commercial aviation sector and the measures that will be required for the aviation industry to scale up production with assistance from governments. To learn more about the other aircraft technologies and operational and infrastructure improvements underway across the aviation industry, see www.aviationbenefits.org.

Achieving net-zero carbon emissions by 2050

In October 2021, the commercial aviation industry adopted a long-term climate goal, net-zero carbon for air transport by 2050, confirming the commitment of the world's airlines, airports, aircraft operators, air traffic management companies and the makers of aircraft and engines to reduce CO_2 emissions in support of the Paris Agreement. It will be a significant challenge to meet net-zero carbon emissions by 2050, but the evidence shows that with the right support from governments and efforts across the value chain, especially within the energy industry, it is achievable.

A year later, in October 2022, governments meeting at the ICAO Assembly in Montreal adopted a long-term aspirational goal of net-zero carbon emissions for international flights by 2050, one of the only global sector-specific climate goals.

A mix of new technology – including innovative new propulsion technologies that could be powered by electricity and hydrogen, improvements in operations and infrastructure – will play their roles in reducing carbon emissions, but a transition to sustainable aviation fuel will be crucial to successfully achieving net-zero carbon for the aviation sector.

WHAT IS SUSTAINABLE AVIATION FUEL?

Sustainable aviation fuel, or SAF, is a safe replacement for conventional (fossil-based) fuel that could reduce carbon emissions. It is almost chemically identical to traditional jet fuel. It is generated from feedstocks that absorb carbon dioxide (CO_2) and provide a net reduction in CO_2 emissions when compared to fossil fuels.

Today, SAF is blended with conventional kerosene in ratios of up to 50% SAF to ensure compatibility with aircraft, engines or fuelling systems. Commercial flights are currently permitted to fly with a blend of SAF and conventional fossil-based kerosene. The industry is working towards commercial aircraft being permitted to fly with 100% SAF in the near future.

SAF can be produced from a variety of feedstocks and through several processes, which will be explored in this guide. Importantly, the aviation industry has committed to ensuring that sustainability is the highest priority for the development of this new energy source.

Other terms such as biofuel, renewable aviation fuel, renewable jet fuel, alternative fuel, and biojet fuel have similar intended meanings to SAF.

- There are a number of terms used to describe non-fossil based hydrocarbon fuel. Often, the term 'biofuel' is used. The aviation industry avoids this terminology as it does not specify the sustainability aspect of these fuels.
- Some biofuels, if produced from non-sustainable feedstocks, such as unsustainably-sourced oils or crops that lead to deforestation, can cause additional environmental damage, making them unsuitable for aviation's purposes.

The description of SAF comprises three key principles:

1. **Sustainability** in this context is defined as low-carbon raw material that can be continually and repeatedly resourced in a manner consistent with economic, social and environmental aims, specifically something that conserves an ecological balance by avoiding depletion of natural resources, does not compete with other requirements such as food, land and water use; and mitigates the aviation sector's contribution to climate change.
2. It is an alternative to traditional energy sources for **aviation,** in this case non-conventional or advanced fuels, and includes any materials or substances that can be used as fuels, other than conventional, fossil sources (such as oil, coal, and natural gas). It is also processed to create jet fuel in an alternative manner. Feedstocks for SAF are varied; ranging from cooking oil, plant oils, municipal waste, waste gases, agricultural residues, green hydrogen and even electricity - to name a few. Further information about this can be found on pages 15 and 16. It is important to note that not all "alternative" fuels are "sustainable".
3. **Aviation fuel** refers to drop-in fuel that meets the technical requirements for use in commercial aircraft and can be used in existing technology and fuel systems, ensuring the most important aspect of aviation operations - safety - is maintained.

The International Civil Aviation Organization (ICAO), a United Nations specialised agency, defines SAF as 'a renewable or waste-derived aviation fuel that meets the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) sustainability criteria'.

Sustainable aviation fuel - providing environmental benefits

Relative to fossil fuels, SAF results in a reduction in carbon dioxide (CO_2) emissions across the entire lifecycle of the fuel. This includes the

> Relative to fossil fuels, SAF results in a reduction in carbon dioxide emissions across its lifecycle.

CO_2 required to grow or produce the material being used to generate the fuel, the CO_2 required to capture, transport, and refine the material, and the CO_2 emitted when the fuel is burned. As a point of reference, CO_2 absorbed by plants during their growth, or captured from industrial sources is roughly equivalent to the amount of CO_2 produced when fuel is burned in an engine, which is returned to the atmosphere.

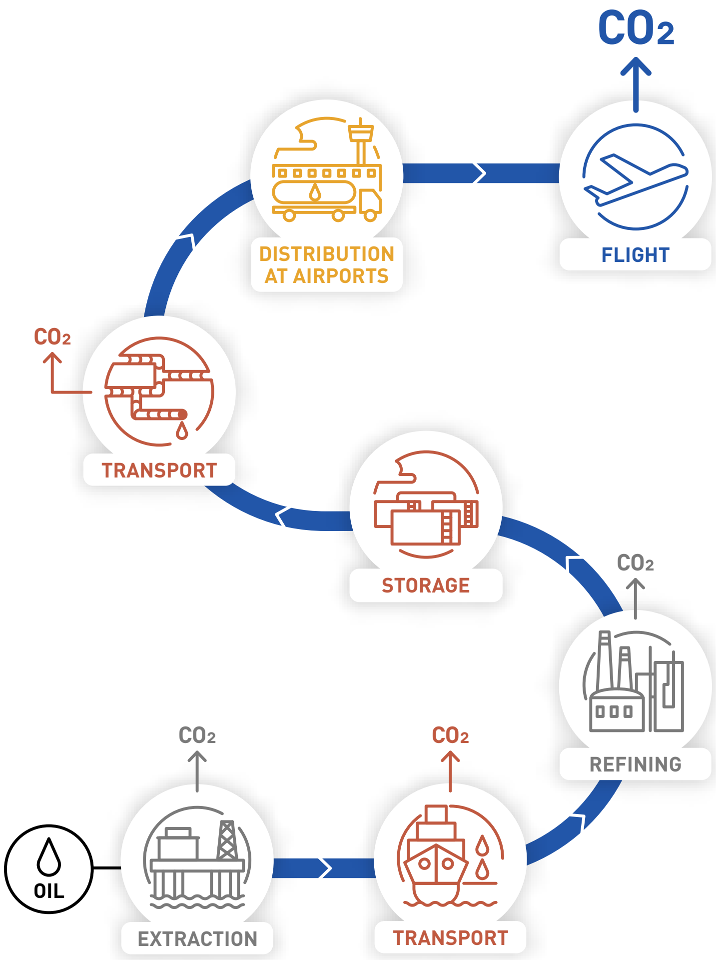
When all CO_2 elements are accounted for in the lifecycle of SAF, analysis shows the fuel provides significant reductions in overall CO_2 emissions when compared to fossil fuels. In the coming years, lifecycle CO_2 reductions across the different sources of SAF will average around 70-80%, but enhancements in the production process and the use of other instruments such as carbon capture could see this average increase - to 100% CO_2 reduction or possibly even higher.

The lower the emissions are from SAF transportation, and from the conversion of feedstocks into jet fuel, the closer the SAF will be to carbon-neutrality. Furthermore, some forms of SAF contain fewer impurities (such as sulphur and aromatic hydrocarbons), which results in reductions of soot, sulphur dioxide and particulate matter emissions. Some studies have shown that SAF could also reduce the incidence of contrail formation and therefore may deliver other climate benefits.

In the case of SAF produced from municipal waste, for example, the environmental gains are derived both from avoiding fossil fuel use and from the fact that the waste would otherwise be either burned in the open air or incinerators, or left to decompose in landfill sites - producing gases such as methane. Instead, the SAF generated from this waste is used to power a commercial flight.

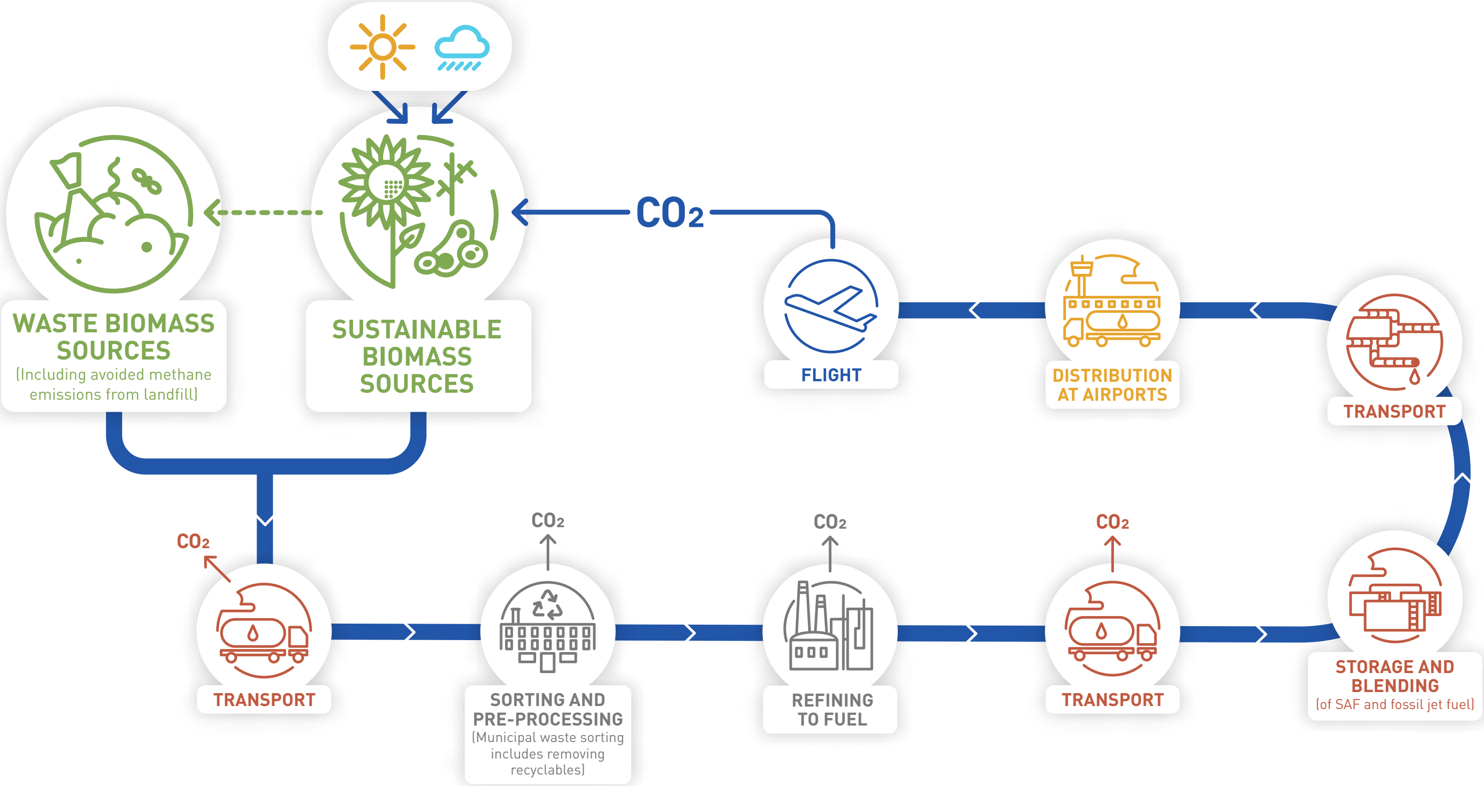
Fuel is typically the single largest operating cost for the airline industry. The fluctuating price of crude oil makes it very difficult for airlines and operators to plan and budget for long-term operating expenses. SAF when it becomes widely available, can be produced across the world using a wide variety of feedstocks, potentially reducing aircraft operators' exposure to the fuel cost volatility that comes with having a single fossil-based energy source, when it will be available at scale.

CARBON LIFECYCLE: FOSSIL FUELS



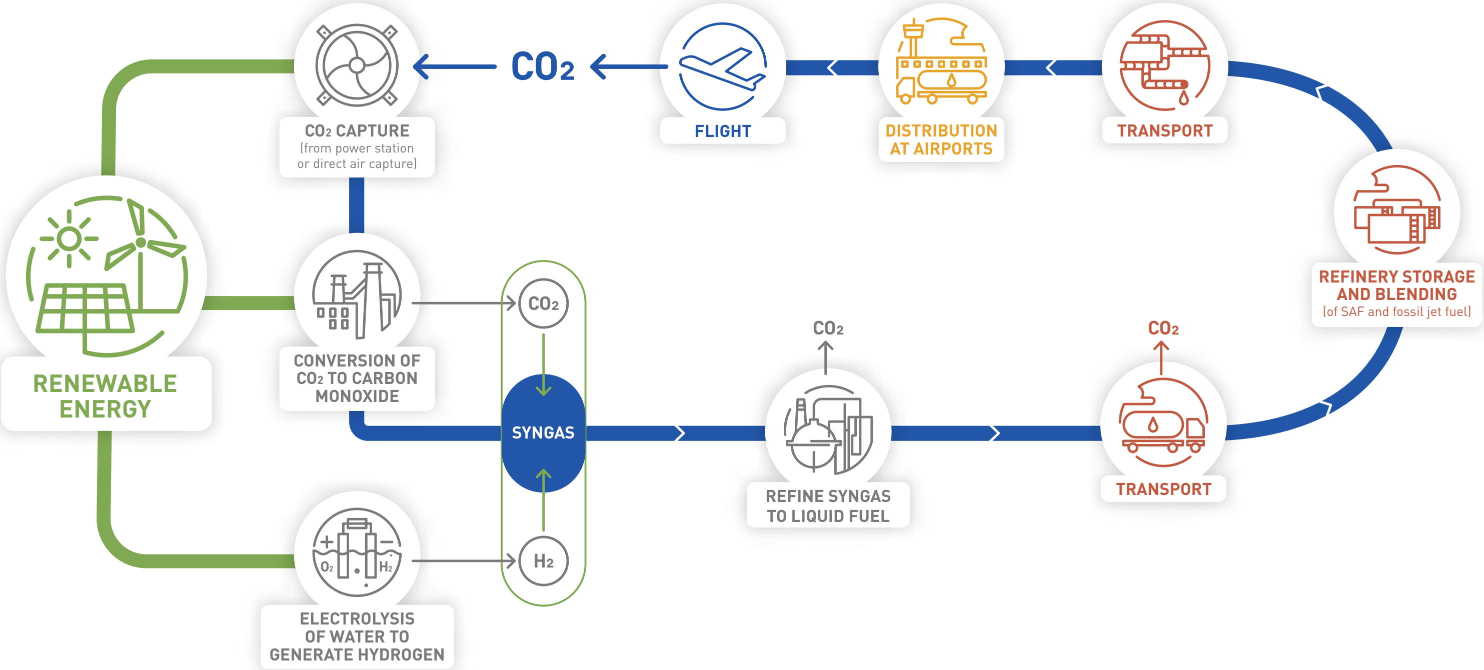
At each stage in the distribution chain, carbon dioxide is emitted through energy use by extraction, transport, etc.

CARBON LIFECYCLE: SAF PRODUCTION FROM WASTE AND OTHER BIOMASS SOURCES

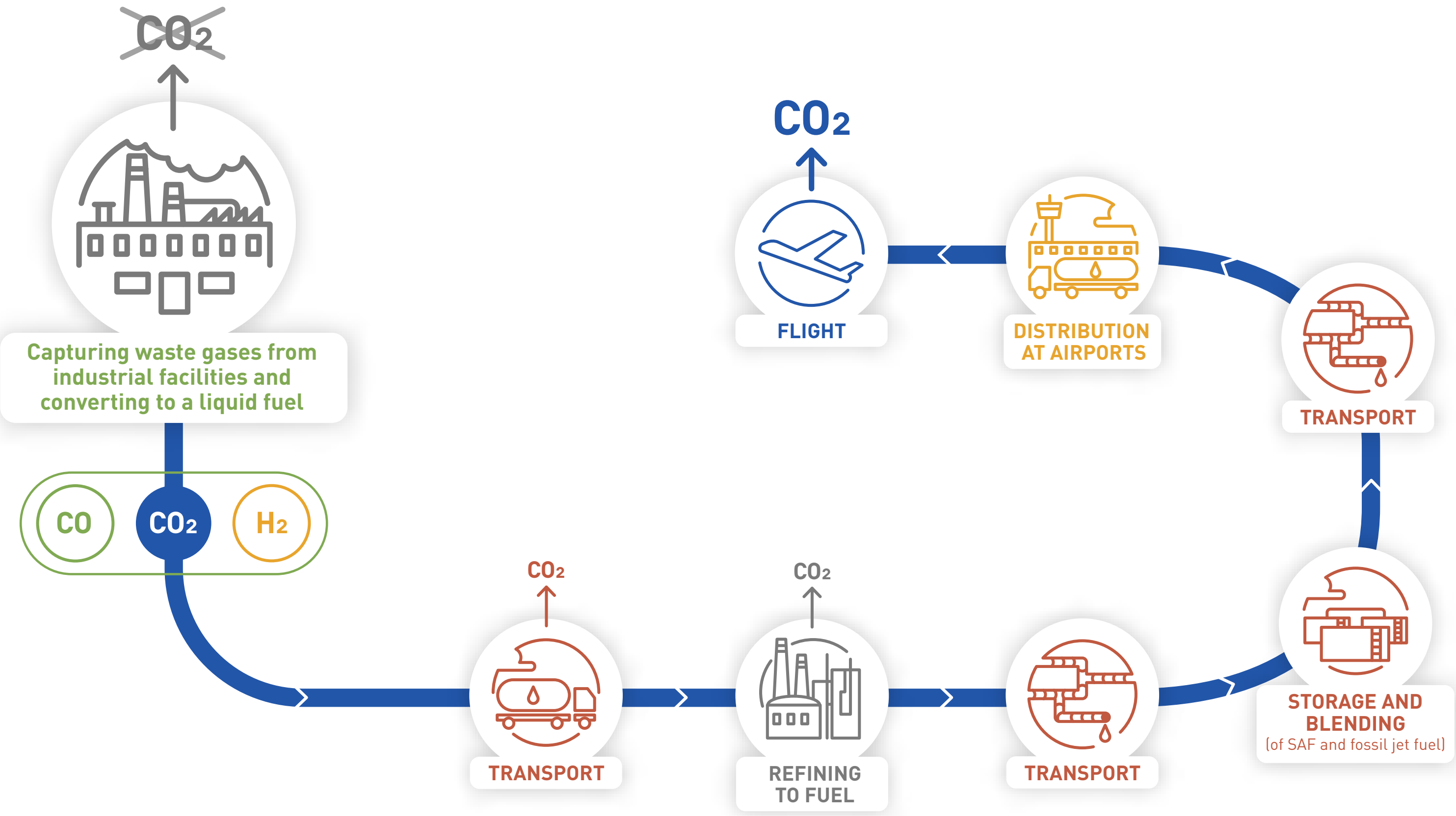


Carbon dioxide will be reabsorbed as the next generation of feedstock is grown.

CARBON LIFECYCLE: SAF PRODUCTION FROM THE POWER-TO-LIQUID (PtL) PROCESS



CARBON LIFECYCLE: SAF PRODUCTION FROM THE WASTE INDUSTRIAL GAS PROCESS



Emissions of CO_2 or equivalent gases are avoided and instead recycled.

Sustainable aviation fuel – providing economic and social benefits

For many developing countries, SAF represents a significant economic and employment opportunity – the shift to SAF could result in up to 14 million jobs being created or transferred from fossil fuel energy jobs.

SAF can also provide economic benefits to parts of the world that have large amounts of land that qualifies as marginal, abandoned or unviable for growing food, but is suitable for growing energy crops, or that have sources of feedstock (such as waste) that are not used for any other purpose. Many of these countries are developing nations that could benefit greatly from a new industry such as SAF production with the added benefit that it does not negatively impact their local food production and in some cases could actually strengthen the agricultural sector and improve food security for the region.

In many parts of the world, decomposing waste is a serious environmental problem. SAF can also be produced from waste materials such as municipal solid waste (including household food waste and waste cooking oils).

Why 'SAF' and not 'biofuel'?

When biofuels first came onto the market, they were initially produced and aimed at substituting fossil fuels in the road transport sector. These are sometimes termed 'first-generation' biofuels. The main types of biofuels used for automobiles are biodiesel and bioethanol. They are derived from crops such as sugarcane, corn grain, palm oil, rapeseed, and soybean oil – which typically can also be used as food for humans and animals.

Consequently, the unsustainable production of this type of biofuel can raise a number of concerns, including potential changes in the use of agricultural land, water use, the possible effect on food prices; and the impact of irrigation, pesticides and fertilisers on local environments. While these feedstocks could be used to create jet fuel through different processes, the aviation industry has been keen to avoid using them when they present sustainability risks. However, some forms of corn, for example, are not human food grade and can provide benefits that help with energy provision as well as feed for livestock.

To avoid these negative environmental impacts, the aviation industry has been careful to promote only those fuels that can be demonstrated to meet strong sustainability requirements and standards. This is why the industry uses the term 'sustainable aviation fuel', which has also sometimes been referred to as 'next generation' or 'advanced' biofuels. Additionally, some of the feedstocks used to create SAF are not strictly biological in nature (such as municipal waste, direct air capture CO_2 or point source industrial CO_2), rendering the word 'biofuel' inaccurate.

An ideal "drop-in" fuel

The chemical and physical characteristics of SAF are almost identical to those of conventional jet fuel (Jet A-1). SAF can be mixed with conventional jet fuel and, once blended is certified to exactly the same standard as conventional jet fuel. This allows use of the same supply infrastructure and does not require the adaptation of aircraft or engines. Fuels with these properties are called "drop-in fuels" (i.e. fuels that can be directly incorporated into existing airport fuelling systems and on board aircraft). As always in aviation, safety is the key driver.

"Lower carbon aviation fuels"

Lower carbon aviation fuel (LCAF) is a fossil aviation fuel that can contribute towards emission reduction obligations under the international CORSIA scheme. To comply, it must demonstrate a lifecycle improvement of at least 10% relative to the average global fossil fuel carbon intensity. While not common, it is theoretically possible to achieve this, thanks to lower carbon intensity crude oil, improving extraction methods and reducing flaring of gases. Without incorporating CO_2 capture and storage into the LCAF lifecycle, benefits are unlikely to be substantially more than 10% compared with conventionally-produced fuel, implying that LCAF is not a long-term decarbonisation solution (and should not be considered as SAF). However, while conventional fossil fuel is still used in the aviation system, all improvement opportunities should be utilised.

CO_2 reduction accounting

There are two main ways of accounting for the CO_2 reductions of the use of an alternative fuel. **Well-to-wake** emissions are representative of a fuel's carbon emission output across its entire value chain, including the emissions associated with feedstock sourcing (or oil extraction), processing, transportation, distribution and deployment. **Tank-to-wake** refers simply to the CO_2 produced when the fuel is burnt in flight.

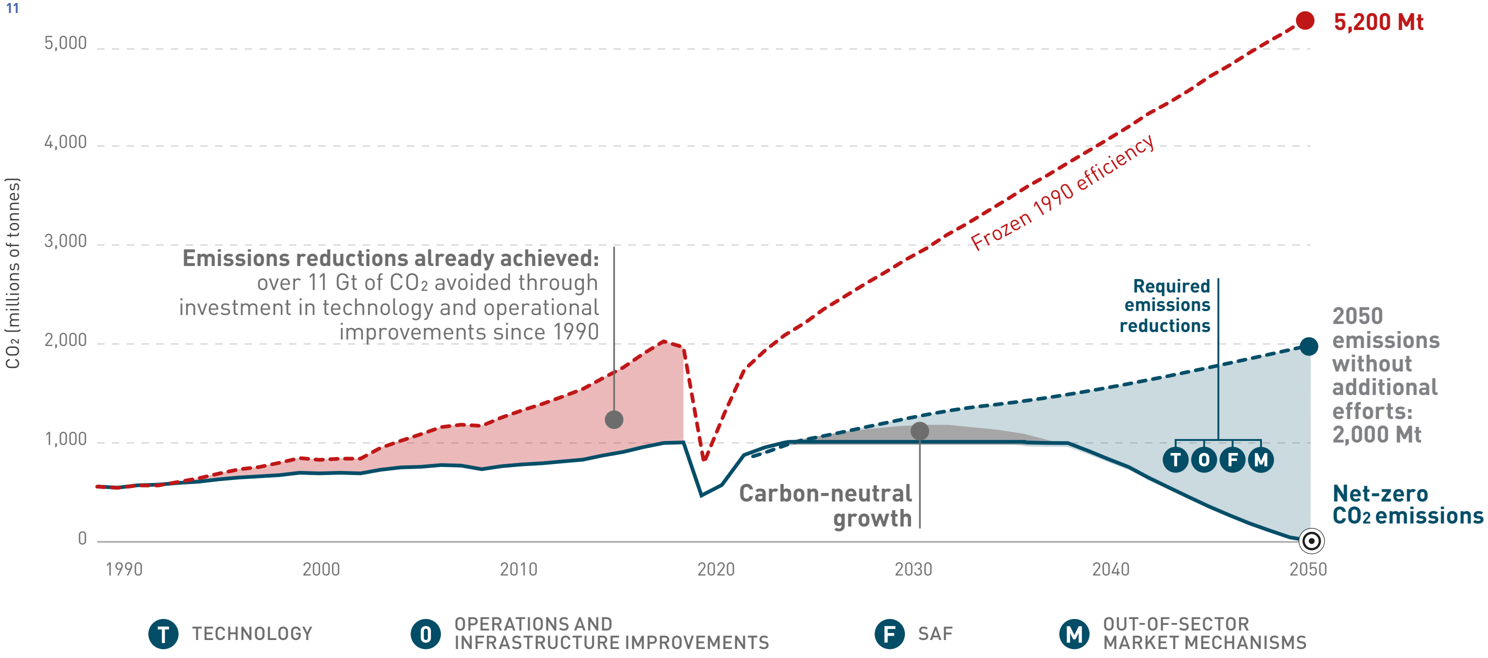
HOW SAF FITS INTO THE AVIATION DECARBONISATION PLAN

In 2021, the aviation industry established a challenging goal to achieve net-zero carbon emissions by 2050 (aviationbenefits.org/flynetzero/).

There were 46.8 million scheduled commercial flights[9] carrying 4.5 billion passengers in 2019, which generated roughly 2% of global human-induced carbon emissions equivalent to 914 million tonnes of CO_2[10]. Aviation's passenger numbers are expected to grow to up to 7.2 billion by 2035, meaning that effective action on reducing carbon emissions is essential to ensure the sustainable development of the industry.

> “SAF produces considerable reductions in CO_2 over its lifecycle, compared to fossil jet fuel – an average of 70% to 80% today, but this can vary.”

[11]



Companies across this sector are collaborating to reduce emissions through a four-pillar strategy of new technology, operations and infrastructure improvements, SAF and out-of-sector market mechanisms to fill the remaining emissions gap.

Using SAF provides the aviation industry with an alternative energy source, enables the industry to reduce its carbon footprint by reducing its dependence on fossil-based fuel sources and allows it to draw upon a variety of different energy providers. SAF will play a key role in achieving the industry's goal of net-zero carbon emissions by 2050.

Key advantages of SAF

- **Environmental benefits:** sustainably produced alternative jet fuel can considerably reduce (by 70%-80% today) emissions across their lifecycle, compared to conventional fossil jet fuel, but with 100% possible in the future. Additional **environmental benefits** include the diversion of waste from landfills or discharge into the environment.
- **Diversified supply:** SAF offers a viable alternative to conventional fossil kerosene and can allow for a more diverse geographical supply through sustainable sources and low-carbon energy.
- **Economic and social benefits:** SAF can generate economic benefits to all regions of the world, but especially developing nations, that have non-productive land for food crops which can be suitable for producing SAF feedstock. Refining infrastructure is likely to be installed close to feedstock sources, generating additional jobs and economic activity.
- **A drop-in alternative:** SAF can use existing fuel supply and distribution infrastructure, ensuring an energy transition can take place faster than other options which would require a wholesale change in the equipment we use.

Aviation efficiency - technology will only take us so far

The progress the aviation industry has made in reducing its impact on the environment is significant and has become one of the industry's central motivations. The aerodynamics of aircraft, the performance and efficiency of modern engines and the operational improvements by airlines, airports and air traffic systems have all combined to make aircraft over 80% more fuel-efficient since the introduction of modern jet engines in the 1950s.

The industry will continue to make technology improvements in the way aircraft are manufactured and how they are flown, with some significant improvements already in place. But while cutting-edge technology means the most modern aircraft are now more fuel-efficient than many cars per passenger-kilometre, the forecast growth in the number of people flying will see the industry's emissions continue to rise unless other means to reduce emissions are found.

Continual improvement in aircraft efficiency is still a key industry objective, and is especially important in order to minimise the demand for liquid fuels.

Hydrocarbon liquid fuel is the only option for aviation... for now

At this stage, the only option to power the existing fleet of large commercial aircraft sustainably in the coming decades is by gradually switching from fossil fuel to SAF. Encouraging progress has been made in recent years in the development of electric aircraft, with a number of small-scale prototypes having already been flown. It is expected that in a few decades, short-range, small, electric-powered commercial aircraft will be safe, certifiable and commercially feasible.

Hydrogen can also be burned in a turbine engine for aviation and there is significant progress being made on the technology that may allow this to happen. If the technology matures, short-range hydrogen-powered aircraft could enter service from around 2035 onwards. However, the majority of emissions come from flights on larger aircraft where both electric and hydrogen would not be viable until well into the middle of the century. There are 30,000 aircraft in today's fleet that can use SAF already. Many of these valuable assets will not be retired for a long time, another reason SAF remains the most important

> Modern aircraft are over 80% more fuel-efficient than those flown at the start of the jet age in the 1950s.

energy shift for aviation in the medium and potentially long-term. While SAF might not be the only long-term solution to decarbonising aviation, it is undeniably the best solution for action right now, alongside fleet renewal.

Hydrogen will be a significant energy source for aviation

Despite a lot of work being needed to develop hydrogen-fuelled aircraft and associated infrastructure to support them, green hydrogen still has an important role to play as feedstock for SAFs known as power-to-liquid (PtL) fuels (see page 15). It is therefore vital that as governments and the energy sector develop national hydrogen strategies, aviation is also considered a key user of the product.

Providing diversified supply

The aviation industry's reliance on conventional fossil fuels means that it is affected by a range of fluctuations, such as the changing price of crude oil and problems with supply and demand. SAF is an attractive alternative as its feedstocks are not limited to locations where fossil fuels can be extracted and refined. As SAF supply develops and scales, this should provide a more diverse geographic supply and potentially energy security for countries that today are net jet fuel importers. Opportunities will exist for existing oil and gas infrastructure to be repurposed such that they become compatible to process new feedstocks applicable to SAF production.

THE DIFFERENT TYPES OF SAF: FEEDSTOCKS

> The aviation industry has been careful to promote only sustainably-sourced alternative fuel, so as to avoid negative environmental impacts.

Current technology allows sustainable aviation fuel to be produced from a wide range of feedstocks, including:

- **Waste oils and fats:** this typically comes from plant or animal fats and greases that have been used for cooking and are no longer usable for further cooking (used cooking oil), or as waste from food production (such as tallow). This is currently the most widely used feedstock for SAF production, but supply is not endless and even though it will continue to play a role in SAF, other sources will grow to form a larger portion of the market.
- **Municipal solid waste:** carbon-based waste that comes from households and businesses. Some examples include: product packaging, grass clippings, furniture, clothing, bottles, food scraps and newspapers. There is great potential to use municipal solid waste as a sustainable feedstock, due to its vast supply. Rather than simply dumping municipal waste in a landfill site, where it will emit methane and other gases into the atmosphere, it can be used to create jet fuel instead.
- **Cellulosic waste:** this comes from excess wood, agricultural waste (such as corn stalks), and forestry residues (branches and leaves that are not tradeable). These residues can be processed into synthetic fuel through proven chemical reactions (i.e., the Fischer-Tropsch pathway) or converted into renewable isobutanol or ethanol and, further, into jet fuel through the "alcohol-to-jet" (AtJ) pathway. Other pathways are also under development.
- **Cover crops such as camelina, carinata, and pennycress:** cover or rotational oil seed crops that are grown in rotation with wheat and other cereal crops within the same year, when the land would otherwise be left fallow (unplanted) as part of the normal crop rotation programme. This provides growers with an opportunity to diversify their crop base and reduce mono-cropping (planting the same crop year after year), which has been shown to degrade soil and reduce yields and resistance to pests and diseases. With camelina, the leftover 'meal' from the oil extraction can also be used as animal feed in small proportions. Carinata is a non-edible oilseed crop with similar promise.
- **Non-biogenic alternative fuels:** these include 'power-to-liquid' (see page 8), which typically involves creating jet fuel from carbon sources such as industrial point source waste gases or, in the future, direct air captured carbon, combined with green hydrogen produced using renewable energy powered electrolysers. Alternatively, industrial waste gases can be converted into ethanol using biological conversion processes, and the ethanol subsequently converted into jet fuel. While direct power-to-liquid options are based on technically proven steps, the process is currently expensive and needs further technological and commercial development. Other more advanced technologies are in early stages of development, such as solar jet fuel (or sun-to-liquid), which use highly concentrated sunlight to break up water and CO_2 molecules. Because these processes are not relying on waste resources or non-food crops, there is theoretically an unlimited supply available and this will likely make up a large proportion of SAF production in the future.
- **Jatropha:** a plant that produces seeds containing inedible lipid oil that can be used to produce fuel. Each seed produces 30 to 40% of its mass in oil. Jatropha can be grown in a range of difficult

soil conditions, including arid and otherwise non-arable areas, leaving prime land available for food crops. The seeds are toxic to both humans and animals and are, therefore, not a food source. Crop yield in some conditions requires improvement for jatropha to be commercially viable.

- **Halophytes:** salt marsh grasses and other saline habitat species that can grow either in salt water or in areas affected by sea spray where plants would not normally be able to grow. They provide biomass for fuels through the production of oil seeds or their lignocellulosic biomass. A demonstration project developed in the UAE showed the potential of growing halophytes integrated with seawater aquaculture, such that an integrated system could produce both food (i.e. fish from aquaculture) and feedstock for fuels.
- **Algae:** these are microscopic plants that can be grown in plastic sleeves (micro algae) or polluted or salt water, deserts and other inhospitable places (macro algae). They thrive off CO_2, which makes them ideal for carbon sequestration (absorbing CO_2) from sources like power plants. One of the biggest advantages of algae for SAF production is the speed at which the feedstock can grow. It has been estimated that algae produces up to 15 times more oil per square kilometre than other equivalent feedstock. Algae are well suited to be grown on marginal land unsuitable for growing food. Algae has yet to fulfil its early promise due to commercialisation challenges, however, continued research and development may result in wider application of this feedstock in the future.

THE DIFFERENT TYPES OF SAF: PRODUCTION PATHWAYS

There are currently seven SAF production pathways approved by ASTM International[12] with each pathway representing different processes for production depending on the type of feedstocks. A number of other pathways are also going through the rigorous assessment process for their viability for use in aviation.

Each pathway has potential benefits such as feedstock availability and cost, total carbon reduction, or processing complexity and cost. Some SAF pathways may be more suitable than others in certain areas of the world depending on feedstock availability and processing capabilities. All pathways, however, have the potential to enable the aviation sector to reduce its carbon footprint significantly, assuming all sustainability criteria are met.

> Thousands of commercial flights have now been operated using SAF.

While blend limits exist today for technical and safety reasons, this is not seen as an impediment to SAF development. SAF production is in the early stages and is not likely to be limited by technical blend limitations indefinitely. The major airframe and engine manufacturers are working to ensure that all aircraft can safely operate on 100% SAF by 2030. The continued testing and development of new processes and feedstocks will yield useful data to support revision of the specification to allow more flexibility in the supply chain, as well as potential benefits in terms of fuel price stability and availability.

An additional method to accelerate SAF production is 'co-processing' which involves the use of sustainable feedstock as a small percentage of input into the refining of conventional fossil-based jet fuel. This process enables major fuel producers to incorporate sustainable feedstocks into their existing production processes and facilities, which represents a significant opportunity to scale up SAF production through current infrastructure, while dedicated facilities scale-up. ASTM currently limits co-processed SAF to 5% by volume of conventional fossil-based jet fuel in two specific pathways (see table on page 18), though there are plans to re-evaluate these limits in 2023.

It should be noted that fuels produced using these feedstocks can be both sustainable and unsustainable, depending on the methods used to produce the feedstocks and the process used to create the fuel. This is why the commercial aviation industry is careful to follow strict, independently-verified sustainability standards, including those developed by governments, industry and environmental groups at the United Nations.

SAF PRODUCTION PATHWAYS

Pathway	Feedstock	Certification Name & Blend Limit
Fischer-Tropsch	Energy crops, lignocellulosic biomass, solid waste	FT-SPK (up to 50%)
Hydroprocessed Esters and Fatty Acids (HEFA)	Waste fats, oils, greases (FOGs) from vegetable and animal sources	HEFA-SPK (up to 50%)
Direct Sugars to Hydrocarbons (DSHC)	Conventional sugars, lignocellulosic sugars	HFS-SIP (up to 10%)
Fischer-Tropsch with Aromatics	Energy crops, lignocellulosic biomass, solid waste	FT-SPK+A (up to 50%)
Alcohol to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	ATJ-SPK (up to 50%)
Catalytic Hydrothermolysis Jet (CHJ)	Waste fats, oils, greases (FOGs) from vegetable and animal sources	CHJ or CH-SK (up to 50%)
HEFA from Algae	Micro-algae oils	HC-HEFA-SPK (up to 10%)
FOG Co-Processing*	Waste fats, oils, greases (FOGs) from vegetable and animal sources	FOG-CP (up to 5%)
FT Co-Processing*	Fischer-Tropsch biocrude	FT-CP (up to 5%)

*Co-processing pathways

GETTING IT RIGHT: A COMMITMENT TO SUSTAINABILITY

The commitment by the commercial aviation industry to achieve net-zero carbon emissions by 2050 is its main motivation to use SAF as a means to meet the aviation industry's ambitious net-zero climate goal. However, simply deploying any form of alternative fuel on aircraft does not necessarily reduce overall carbon emissions. The fuels used must demonstrate a net carbon reduction through the full life cycle of the fuel, as described on pages 5-11, as well as other sustainability criteria in order to be deemed 'sustainable aviation fuel'.

Sustainability certification standards have been developed for SAF by two independent, non-governmental organisations known as the Roundtable on Sustainable Biomaterials (RSB) and the International Sustainability and Carbon Certification (ISCC) organisations. RSB and ISCC pay particular attention to a number of sustainability principles, including:

- Lifecycle greenhouse gas emissions
- Direct and induced land use change
- Water supplies
- High conservation value area and biodiversity
- Socio-economic conditions of farmers and local population (particularly in developing countries)
- Improving food security in food insecure regions.

In addition to RSB and ISCC, individual governments establish sustainability requirements under various incentive programmes such as the US Renewable Fuel Standard and the EU Renewable Energy Directive.

As part of the government, environment group and industry process to develop the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a set of sustainability criteria have been adopted. This framework provides a common set of international standards to ensure all SAF meets the criteria needed to be considered truly sustainable. In some countries, particularly in the US and EU Member States, governments offer financial incentives for alternative fuel that meets sustainability criteria; and a document confirming sustainability is one of the pre-requisites to demonstrate eligibility. Moreover, in the US, France and the Netherlands (with more EU States potentially to follow) deployment of alternative fuel can contribute towards the overall targets for renewable transport fuels.

> “The development of SAF will support a number of the UN Sustainable Development Goals.”

In the US, a coalition of airlines, manufacturers, energy producers and US government agencies joined together to form the Commercial Aviation Alternative Fuels Initiative (CAAFI)[13], which aims to facilitate the commercial deployment of SAF, making it economically viable and environmentally sound. Joint initiatives in other countries - such as the UK's Jet Zero Council - are adopting similar collaborative approaches.

On the production side, governments' large-scale incentives are vital to expand the use of SAF and fulfil aviation's net-zero commitment by 2050. The US in particular has introduced significant assistance for the development of SAF production with a 'Grand Challenge' being promoted by the White House to incentivise the shift to between 10% and 15% of US jet fuel in 2030 (or around 9 million tonnes / 11 billion litres), along with tax incentives recently introduced under the Inflation Reduction Act of 2022. Other countries such as those in Europe are seeking to introduce mandates on the use of SAF, including the ReFuel EU process which has set a 2030 goal on SAF use.

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Making sure SAF is fit to fly
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Key challenges and the next steps
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SAF and the UN Sustainable Development Goals

In 2015, the United Nations announced the 2030 Agenda for Sustainable Development. Underpinning the Agenda is a set of 17 Sustainable Development Goals (SDGs), which are intended to address the root causes of poverty and drive development globally.

Aviation, in general, supports many of the aims of the goals[14]. The increasing production of SAF will help to work towards SDG 7 (Affordable and clean energy) and SDG 13 (Climate action). Through the diversification of feedstock supply, the commercialisation of SAF can also help support some of the more socially and economic- focused SDGs (such as 'No poverty' and 'Reduced inequalities'), by providing employment opportunities in developing countries. As the production of SAF is scaled up, the industry will also be focusing on avoiding negative impacts on SDG 6 (Clean water and sanitation) and SDG 15 (Life on land).

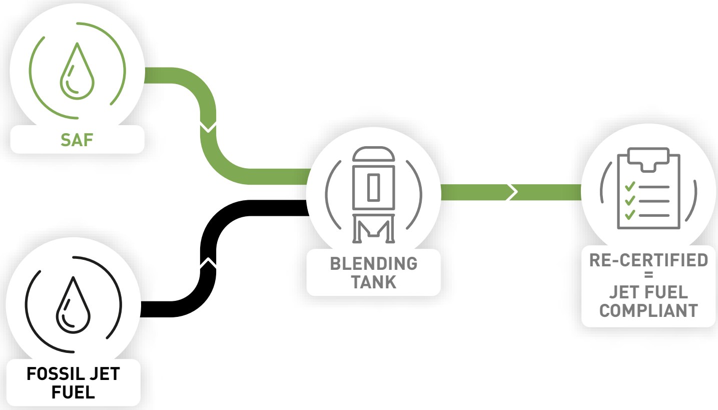
For more information see www.aviationbenefits.org/SDGs

MAKING SURE SAF IS FIT TO FLY

Aviation is well-known for its exacting safety standards and the fuel we use is no exception. For it to substitute conventional jet fuel, SAF must have the same qualities and characteristics as jet fuel. This ensures that manufacturers do not have to redesign engines or aircraft and also ensures that fuel suppliers and airports do not have to build new fuel delivery systems. At present, the commercial aviation industry's focus is to use SAF as a "drop-in" replacement to conventional jet fuel. SAF is currently combined with the petroleum-based fuels as a blend, but test flights using 100% SAF have taken place.

To ensure technical and safety compliance, SAF must undergo strict laboratory, ground, and flight tests under an internationally-recognised standard, which is led by ASTM international, a collective organisation bringing together hundreds of researchers, technical experts and scientists to determine the technical requirements to ensure fuel safety.

CONVENTIONAL JET FUEL IS BLENDED WITH SAF AND APPROVED FOR TECHNICAL COMPLIANCE



> “SAF undergoes strict laboratory, ground, and flight tests under an internationally-recognised standard.”

Safety is the aviation industry's top priority. Given this and the specific requirements for any fuels used in aircraft, the process for testing potential new fuels is particularly rigorous. Through testing in laboratories, in equipment on the ground and under the extreme conditions of in-flight operations, an exhaustive process is used to evaluate and qualify the suitability of each type of SAF before it is deployed.

In the laboratory

In the lab, researchers develop processes to produce SAF that has properties comparable to conventional jet fuel. This is especially important because fuel is used for many purposes inside the aircraft and engine, including as a lubricant, cooling fluid and hydraulic fluid, as well as for combustion that powers the aircraft.

On the ground

Rigorous tests assess specific fuel consumption at several power settings, ranging from ground idle to take-off speed, which is then compared to performance with conventional jet fuel. Assessments are made on the time it takes for the engine to start, how well the fuel stays ignited in the engine and how the fuel performs in acceleration and deceleration. Tests ensure that the fuels don't have a negative impact on the materials used in building aircraft and components. Finally, an emissions test determines the exhaust emissions and smoke levels for the SAF.

Technical requirements for SAF

- A fuel that can directly substitute conventional jet fuel with no requirement for different airframe, engine or logistical infrastructure (i.e., a 'drop-in fuel').
- A high-performance fuel that can withstand a wide range of operational conditions.
- A fuel that meets or exceeds current jet fuel specifications.

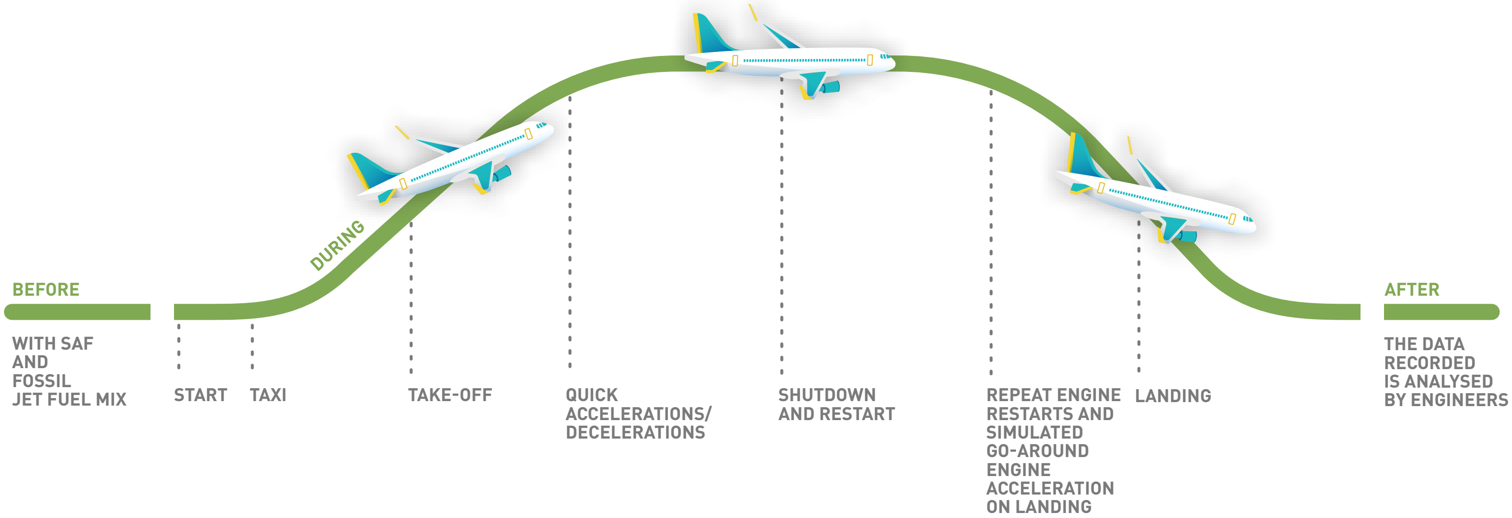
In the air

Once the lab and ground testing has been completed, the SAF is ready to be tested on aircraft under normal operating conditions. During the early years of SAF development, a number of airlines provided aircraft for flight trials designed to:

- provide data to support fuel qualification and approval for use by the aviation industry;
- demonstrate that SAF is safe and reliable; and
- stimulate SAF research and development.

During the test flight, pilots perform a number of standard tests, as well as simulating exceptional circumstances, to ensure the SAF can withstand use under any operating condition.

FLIGHT TRIALS – EVALUATION OF ENGINE PERFORMANCE DURING ALL PHASES OF FLIGHT: INCLUDING A NUMBER OF EXTRAORDINARY "MANOEUVRES" (E.G., SHUTTING DOWN THE ENGINE IN-FLIGHT AND ENSURING IT CAN RESTART).



This flight profile is an example of one of the SAF trials.

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How SAF fits into the aviation decarbonisation plan
The different types of SAF: feedstocks
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The testing continues

Even though we have undertaken extensive testing for the first phase of SAF deployment, the aerospace sector is working to ensure 100% compatible aircraft[15].

The A380 is the third Airbus aircraft (following the A350 and the A319neo) to test unblended sustainable aviation fuel. The A380 test in March 2022 lasted about three hours and operated one of its engines on 100% SAF. It was also the first Airbus flight test to use 100% SAF on all flight phases, from take-off and climb to cruise and landing. These flights were supported by engine manufacturers to ensure engine compatibility; with Pratt & Whitney providing support for the Auxiliary Power Unit (APU). While the first flight test phase focused on outboard engine behaviour of 100% SAF and APU testing, the forthcoming second flight test phase will test this fuel type on the inboard engine and its impact on fuel gauging. Due to the A380's engine and fuel system configuration, analysing engine and fuel system behaviours with 100% SAF will be managed over multiple flights. Airbus is committed to deliver its commercial aircraft capable and certified to fly on 100% SAF by 2030.

In 2021, Boeing committed to deliver its commercial aircraft capable and certified to fly on 100% SAF by 2030. This is an important step, given these aircraft will still be in the skies in 2050, a time when aviation needs to be using predominantly SAF. For several years Boeing has been working on enabling the safe introduction of 100% SAF. In 2018, the Boeing ecoDemonstrator made the industry's first commercial aircraft test flight with 100% SAF in both engines of a 777 Freighter in partnership with FedEx. In February 2023, Boeing announced a pivotal testing milestone — the development of jet reference fluids to enable SAF compatibility testing to help fulfill the company's commitment to producing 100% SAF-capable airplanes.

> “Once a fuel has been fully approved, it is recognised as jet fuel and can be used without any restrictions.”

Approval

Due to the very strict standards required in the aviation industry, SAF must be approved as safe and appropriate for commercial use. The aviation industry works closely with international fuel specification bodies, such as ASTM International to develop standards and certificates.

The process includes the test programme; the original equipment manufacturer internal review; and a determination by the specification body as to the correct characteristics for the fuel. The approval process looks at a minimum of 11 key properties, including energy density, freezing point, appearance, viscosity, and composition.

To become approved for use, SAF must meet certain specifications from the hundreds of aviation and fuels experts meeting at ASTM. Once it has demonstrated compliance with the requirements, it is blended with conventional jet fuel at no more than 50% by volume (according to current standards) and re-tested to show compliance. The reasons for the current blend limits are to ensure the appropriate level of safety and compatibility with the aircraft fuelling systems. This is mainly due to the level of aromatic compounds found in conventional fossil-based fuels that are necessary for some systems that use nitrile rubber seals. It is likely that higher blend limits will be approved in the future as synthetic aromatic compounds are approved for use and as major aircraft manufacturers work to ensure aircraft are compatible with 100% SAF by around 2030.

Once a SAF has been fully qualified it is recognised as jet fuel and can be used without any restrictions, allowing it to become compliant with other international standards.

JET FUEL SPECIFICATIONS

Criteria	Explanation	Jet A-1 specification
Flash point	The temperature at which the fuel ignites in the engine to cause combustion to occur (°C)	38° minimum
Freezing point	The temperature at which the fuel would freeze (°C)	-47°
Combustion heat	The amount of energy that is released during combustion, per kilo of fuel (MJ/kg)	42.8 MJ/kg minimum
Viscosity	The thickness of the fluid or ability to flow (mm^2/s)	8.000 max
Sulphur content	The amount of sulphur in the fuel (parts per million)	0.30
Density	How heavy the fuel is per litre (kg/m^3)	775-840

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THE SCALE-UP: FROM TRIALS TO UNIVERSAL USE

The fossil fuel industry has a 100-year head start compared to SAF, which is still emerging as an energy source. A concerted effort by governments and industry alike is required to foster these promising renewable options to help drive their long-term viability.

Since the first test flight in 2008, technological progress has been remarkable. However, the actual uptake of SAF is modest relative to total industry demand. This is in part due to SAF still being produced in relatively small quantities. Without economies of scale, the cost of SAF remains higher than traditional jet fuel and this price impediment, along with the limited supply is limiting broader uptake throughout the aviation industry. For SAF to be scaled up to commercially viable levels, substantial capital is required to develop the refining and process capacity.

Commercialisation of SAF - challenges

Moving a technology from the research to the commercial phase can be extremely challenging and requires substantial investment. Building a small-scale demonstration facility requires a fraction of the capital required to develop a commercial scale facility. However, even if a demonstration facility performs as expected, moving from small to commercial scale can still be risky. Addressing this funding gap must be a priority for policy makers who have the available tools and mechanisms to bridge the gap and enable progress in this new industry. This could be by direct investment or by providing support to the private sector, for example, though blended financing.

As SAF facilities are de-risked, the cost of production will fall and the cost of the new SAF will drop considerably, as has been seen in other renewable energy markets. Global policy developments are making SAF a more important strategic consideration for aircraft operators which has resulted in major forward purchase agreements from airlines, with most able to negotiate SAF supplies at an only slightly higher cost than

Economic viability of SAF

- Over time, it is expected that SAF will become economically viable and compete with fossil-based fuels as costs are lowered by improvements in production technology, the use of lower-cost feedstocks and through economies of scale in production, in addition to increases in costs of using fossil fuels.
- Governments have historically bridged the cost / price gap for consumers of new energy sources by providing economic incentives and support mechanisms. This is also true for new sustainable fuels, including SAF. Governments in the EU, UK, US, Canada, and Brazil have existing incentive programmes applicable to SAF, and more governments are considering support mechanisms.
- SAF also provides valuable economic opportunities to communities that can develop new sources of income – including in many developing nations. It is estimated that up to 14 million jobs could be created or sustained by the shift to SAF, creating new energy industries around the world: whereas 90% of fossil fuels come from just 22 countries today, sustainable alternatives could create opportunities in almost every country. Around 1.4 million people could be employed in the production facilities themselves and up to 12.6 million in the construction of facilities, collecting feedstocks (such as used cooking oil and agricultural waste) and the supply chain and logistics[16].

traditional jet fuel once subsidies have been taken into account. As of early 2023, around $40 billion in SAF purchase agreements have been made by airlines.

As more airlines and operators commit to purchasing SAF, including projects to deploy at airports, existing producers will attract more investment and the incentive to start new SAF companies will be created. As the economic potential of SAF is increasingly demonstrated, traditional energy companies are expected to use their investment resources to acquire or develop SAF businesses as part of their total product offering. We are already starting to see this happen with increasing numbers of SAF commitments and production facilities being announced.

Under the ICAO CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) agreement, the use of SAF by aircraft operators can count towards their net fuel use and reduce an operator's CO_2 emissions reduction obligation under the scheme.

Bringing SAF from feedstock to jet fuel supply

- This requires the production of sufficient sustainable raw materials and the industrial capability to process and refine it into SAF.
- The worldwide aviation industry consumed some 363 billion litres of jet fuel in 2019, which is 8% of global liquid fuel use[17].

Since 2011, SAF has been approved as suitable for use on commercial flights. However, ensuring economically competitive feedstock supply to sustain production has been an ongoing challenge. The worldwide aviation industry consumes some 363 billion litres of jet fuel annually. According to the ATAG *Waypoint 2050* report (September 2021), around 5.6 million tonnes or 7 billion litres of the total aviation fuel supply could be SAF by 2025 and without further policy measures, around 6-10% of supply by 2030[18].

> “The use of SAF will be taken into consideration under CORSIA.”

Substantial progress has been made in the number of off-take agreements between suppliers and aircraft operators: in 2019 around $7.5 billion worth of forward purchases of SAF had been committed by airlines. Today, that stands at over $40 billion. As of publication, there are 14 airports worldwide that have regular supplies of SAF, including: Los Angeles, San Francisco, Oslo, Bergen, Oakland and Stockholm. There are also a number of other airports currently exploring the possibility of regularly supplying SAF to airlines and operators flying out of them.

SAF is just one product generated

When fuels are being refined - either fossil fuel or renewable fuels - there is very seldom just one product generated. From a barrel of oil, a refinery can produce diesel, jet fuel, plastic, chemicals, automobile petrol/gas, lubricants and so forth. The same is often the case with refineries processing alternative fuels, although the product slate is often more specialised. Refineries can also be tweaked to produce more SAF or more renewable diesel, depending on market conditions.

Book and claim – helping scale up SAF deployment

Book and claim is a mechanism that will be used in the medium-term to help scale up aviation SAF deployment in the most efficient way, thereby accelerating the industry's decarbonisation efforts. It is a solution that will address the initial limited supply of SAF versus the growing demand and will enable airlines and operators to purchase SAF without being geographically connected to a SAF supply site. Before the full implementation of SAF development globally, it will be more economically efficient to produce SAF in certain parts of the world than in others. Airlines and operators wishing to take part in the early adoption of SAF, therefore, may wish to support SAF production sites in different parts of the world even if they do not fly to those locations. The book and claim system will save on shipping SAF around the world (which would increase complexity and emissions) as it focuses on decoupling the environmental 'credits' from the physical SAF. An airline, therefore, can buy the SAF it needs where it is most competitively produced and get the credit for the purchase of the fuel by reducing the CO_2 emissions it accounts for in its annual reporting. However, the physical SAF can be incorporated into the distribution systems of local airports located close to the SAF plant. Other airlines or operators using that airport will use the physical SAF, but only the purchasing airline will receive the credit for having purchased it and supported the scaling up of SAF.

KEY CHALLENGES AND THE NEXT STEPS

Key challenges to SAF's deployment

The extensive commercial flights and testing in numerous demonstration flights by 50+ different airlines[19] has illustrated that the barriers to increased SAF deployment are not technical, but rather economic and political in nature.

Some of the key challenges that remain include:

- ensuring that the cost is competitive, in order to compete with petroleum-based jet fuel;
- ensuring an adequate supply of sustainable feedstock and low-carbon energy;
- ensuring that aviation receives an appropriate allocation, relative to other forms of transport, of available sustainable feedstocks;
- ensuring that governments implement appropriate policy mechanisms to allow the SAF industry to scale up and deliver the economy of scale benefits, including incentivising the use of feedstocks to aviation as a priority over other sectors;
- reducing the risk for private investors to enable investment for more rapid SAF production capacity growth;
- ensuring all aircraft in the fleet are compatible with the use of 100% SAF – a task expected to be complete around 2030. Until then, the 50% blend limit of SAF and conventional jet fuel will remain.

> “Seven pathways for SAF production have now been approved, with others undergoing assessment.”

With seven pathways now approved for the production of SAF, and other potential pathways under consideration, options are increasing for the deployment of SAF, from both a technical perspective and feedstock diversity angle.

In January 2016, SAF entered the ‘commercial deployment phase’ with the first continuous production and supply entering the common airport distribution system at Oslo Airport, with Los Angeles International Airport and Stockholm Arlanda Airport following later in the same year.

The industry has called on governments to assist potential SAF suppliers to develop the necessary feedstock and refining systems - at least until the fledgling industry has achieved the necessary critical mass.

A major challenge - ensuring sufficient quantities and investment

One of the major challenges for this new energy industry is building up the demand and, therefore, production of sufficient quantities of SAF to make it commercially viable. In other words, ensuring an adequate supply of sustainable feedstock, low-carbon energy sources and production capacity to start realising economies of scale. This in turn will require significant policy support, investment, and cooperation within industry, governments, research institutions, financial institutions and traditional energy producers.

The use of SAF is expected to accelerate over the coming years as part of a wider shift toward lower carbon aviation energy sources, including low-carbon electricity and green hydrogen. It is modelled that aviation might need between 330-445 million tonnes (412-556 billion litres) of SAF per year by 2050[20] in order to achieve its net-zero 2050 goal. The capital investment required has been estimated at some $1.5 trillion over 30 years - or 6% of traditional oil and gas capital expenditure when averaged out each year[21].

Government commitment to net-zero by 2050

Achieving net-zero carbon emissions by 2050 cannot be done by the aviation industry in isolation. Government support is one of the crucial elements. On 7 October 2022, governments meeting at the ICAO Assembly in Montreal adopted a long-term aspirational goal of net-zero carbon emissions for international flights by 2050, one of the only global sector-specific climate goals.

This represents a milestone for the aviation sector. The air transport industry has always been able to work with governments to solve complex challenges and climate change is no different. Many States will need assistance in implementing a net-zero pathway in their own country. Financing the transition will be a priority for governments, industry and the investment sector. The build-up of SAF in this context will be key.

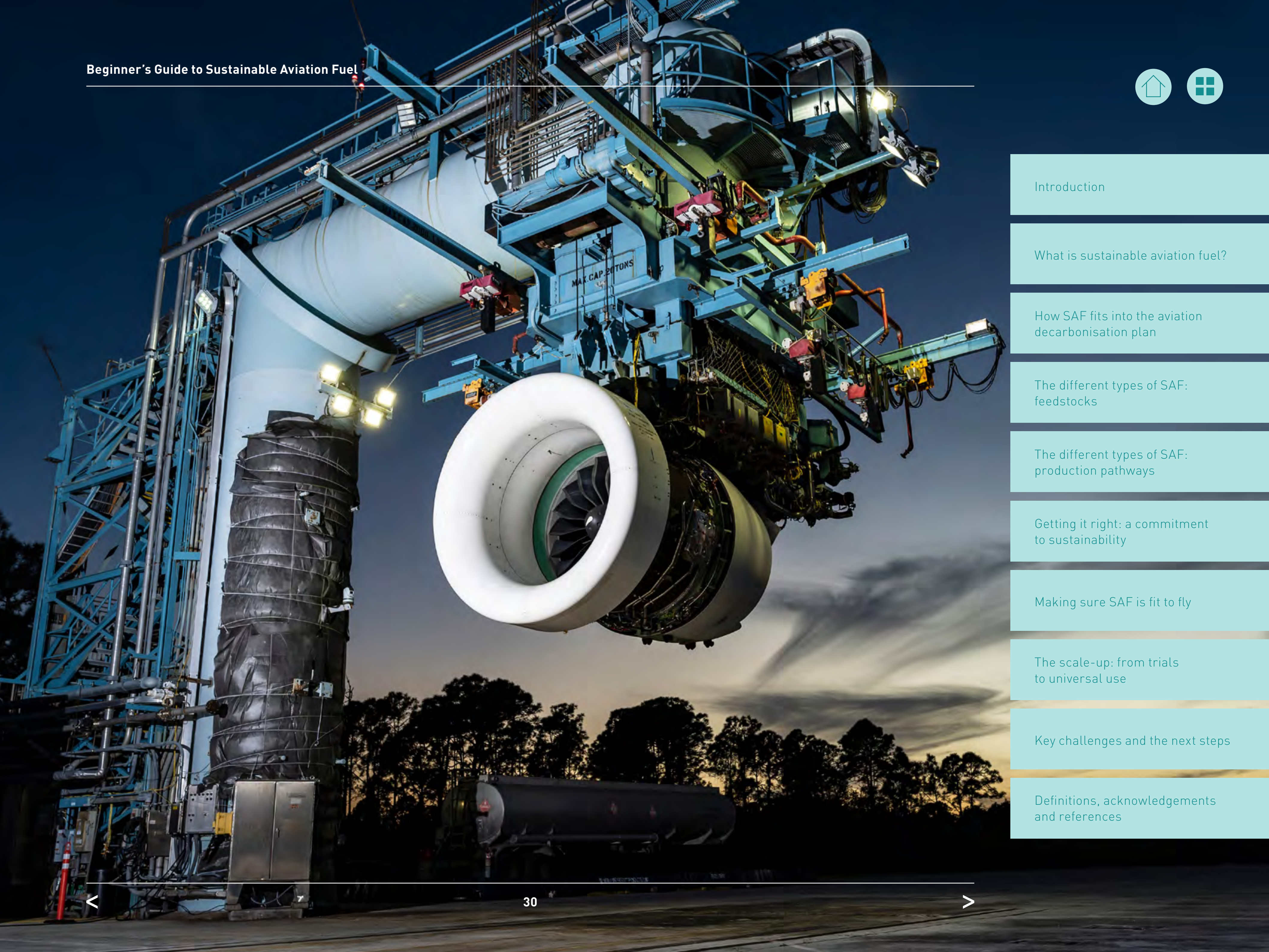
A five-step plan for governments going forward

There are five key steps that every government could take to help progress the energy transition for aviation and the upscaling of SAF production, thereby supporting green energy jobs in their countries:

1. Setting up adequate and stable policy measures, including:
    a. De-risking public and private investments in SAF through appropriate financing and policy measures
    b. Providing incentives for aircraft operators to use SAF from an early stage
2. Fostering research into new SAF feedstock sources and refining processes
3. Encouraging stakeholders to commit to robust international sustainability criteria
4. Understanding local green growth opportunities whilst at the same time working with global institutions such as the UN aviation body: ICAO
5. Establishing SAF development coalitions encompassing all parts of the supply chain

While these are not minor hurdles, they are not insurmountable. The history of aviation is marked by people achieving extraordinary things, despite many at the time telling them it could not be done.

The aviation industry is now on the verge of making another historical step forward, but the challenge of commercialising SAF is one that the entire industry needs to meet together. The industry made a bold commitment to start using SAF on commercial flights, a vision which was realised in 2011. It is very possible that a significant supply of alternative fuel in the jet fuel mix could be achieved by 2030 - perhaps between 6-10%. It is now up to dedicated stakeholders across the aviation sector, with help from governments, feedstock and fuel suppliers and investors to ensure that the low-carbon, alternative future for flight becomes a reality.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DEFINITIONS, ACKNOWLEDGEMENTS AND REFERENCES

Alternative fuel: has a specific meaning defined by ICAO, which is 'any fuel that has the potential to generate lower carbon emissions than conventional kerosene on a lifecycle basis'. It is also used as a general term to describe any alternative to petroleum-based fuels, including liquid fuel produced from natural gas, liquid fuel from coal and biofuels.

ASTM International: originally known as the American Society for Testing and Materials, this international organisation develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services. ASTM International works with aircraft and engine manufacturers, government authorities and fuel suppliers to set the standards for aviation fuels such as the required characteristics for jet fuel.

Biodiesel: a fatty acid ester diesel fuel produced from biomass; chemically different from conventional and renewable diesel and other fuels from crude oil. Not suitable for use in aviation.

Biomass: any renewable material, including wastes and residues, of biological origin (plants, algae, animal fats and so on).

Carbon footprint: net amount of carbon dioxide emissions attributable to a product or service (emissions from production and combustion, minus absorption during plant growth). For fossil fuels, the absorption of carbon dioxide occurred millions of years ago and so their carbon footprint is simply 100% of their carbon output.

Carbon-neutral: refers to balancing a measured amount of carbon released by an activity with an equivalent amount captured or offset. SAF represents a step towards carbon-neutrality: virtually all of the CO_2 it releases during combustion has been previously absorbed by growing plants, however emissions from feedstock and fuel production and transport have to be subtracted. Net-zero is another term for a similar concept and often these terms are used interchangeably, but net-zero usually refers to a status of having reduced CO_2 emissions as much as possible and then using out-of-sector carbon removals to deal with any remaining CO_2.

Carbon-neutral growth: the situation where an industry emits the same amount of carbon dioxide year on year while growing in volume. For the aviation industry this means being able to continue to increase passenger traffic and aircraft movements, while keeping net aviation industry emissions at the same level.

Drop-in fuel: an alternative and completely interchangeable substitute for conventional fossil fuel that doesn't require changes in aircraft or engine fuel systems, distribution infrastructure or storage facility. It can be mixed interchangeably with existing jet fuel and as supply grows, the proportion of fuel used can also grow.

Ethanol: a fuel produced from sugar-rich crops such as corn and sugarcane and used by ground vehicles, or potentially as a feedstock for the alcohol-to-jet process.

Feedstock: raw material from which fuel is produced.

Greenhouse gases: gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which trap the warmth generated from sunlight in the atmosphere rather than allowing it to escape back into space, replicating the effect glass has in a greenhouse. Human activities such as fossil fuel combustion and land-use change increase the emission of greenhouse gases into the atmosphere.

Hydrocarbon fuel: an organic compound consisting of hydrogen and carbon found in crude oil, natural gas and coal. Crude oil is sent to the refinery where it can be separated to make jet fuel[22].

Jet A: commercial jet fuel specification for North America.

Jet A-1: common jet fuel specification outside North America. (These two fuels are very similar and throughout this guide we used the term jet fuel to mean the fuel used by aviation).

Kerosene: the common name for petroleum-derived jet fuel such as Jet A-1, kerosene is one of the fuels that can be made by refining crude oil. It is also used for a variety of other purposes.

Net-zero carbon emissions: as identified by the Intergovernmental Panel on Climate Change (IPCC) is a situation "Where anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period[23]."

Non-conventional advanced fuels: alternate fuels, also known as non-conventional fuels and advanced fuels, are any materials or substances that can be used as fuels, other than conventional fuels. Some well-known alternate fuels include biodiesel, bioalcohol (methanol, ethanol, propanol, and butanol), refuse-derived fuel, waste derived oil, hydrogen, vegetable oil, and other biomass sources[24].

Renewable hydrocarbon: produced from biomass sources through a variety of biological, thermal and chemical processes[25].

Sustainability: the ability for resources to be used in such a way so as not to be depleted or to create irreversible damage. For humans to live sustainably, the earth's resources must be used at a rate at which they can be replenished, providing economic growth and social development to meet the needs of today without compromising the needs of tomorrow.

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