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Integration of Sustainable Aviation Fuels into the air transport system

EXECUTIVE SUMMARY

The most effective way to reduce the carbon footprint of the existing aircraft fleet is to replace fossil-based kerosene with carbon-neutral fuels. Sustainable aviation fuels (SAF) is the term used to define hydrocarbon fuels which are not from fossil origin and which compensate for the emitted carbon dioxide through the production/capture of their feedstock, making them fully or partially carbon-neutral.

While these fuels are already deployed in commercial aircraft today, their use is restricted to low blends with kerosene with a global uptake below 0.1%. It is anticipated that these fuels could provide the largest opportunity for aviation carbon emissions reductions to 2050, but for this to happen an unprecedented scale-up needs to occur. This paper presents the differences between conventional aviation fuels and sustainable aviation fuels, the beneficial advantages of SAF combustion on emissions and the challenges to increase its uptake to 100% on aircraft. The paper recognises the challenges to increase the supply of SAF and move the sector from today's early SAF facilitation to a mature scale-up period. Finally, it provides recommendations for stakeholders to consider when starting or scaling-up their SAF journey. The work is based on an extensive literature review and interviews with airports, fuel suppliers, academics, and manufacturers.

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PURPOSE AND OBJECTIVES

The purpose of this document is to provide an overview of the infrastructure and operational requirements of introducing sustainable hydrocarbon fuels at airports. It builds on the material presented in Airport Council International (ACI) Sustainable Energy Sources for Aviation: An Airport Perspective [1], and complements the Aerospace Technology Institute (ATI) and ACI joint report on the integration of hydrogen aircraft into the air transport system [2]. It addresses the practical challenges and solutions to deploy sustainable aviation fuels (SAF), from one-off flights to fully integrated supply chains. Detailed review of SAF pathways, sustainability criteria and life cycle emissions are outside of the scope of this document.

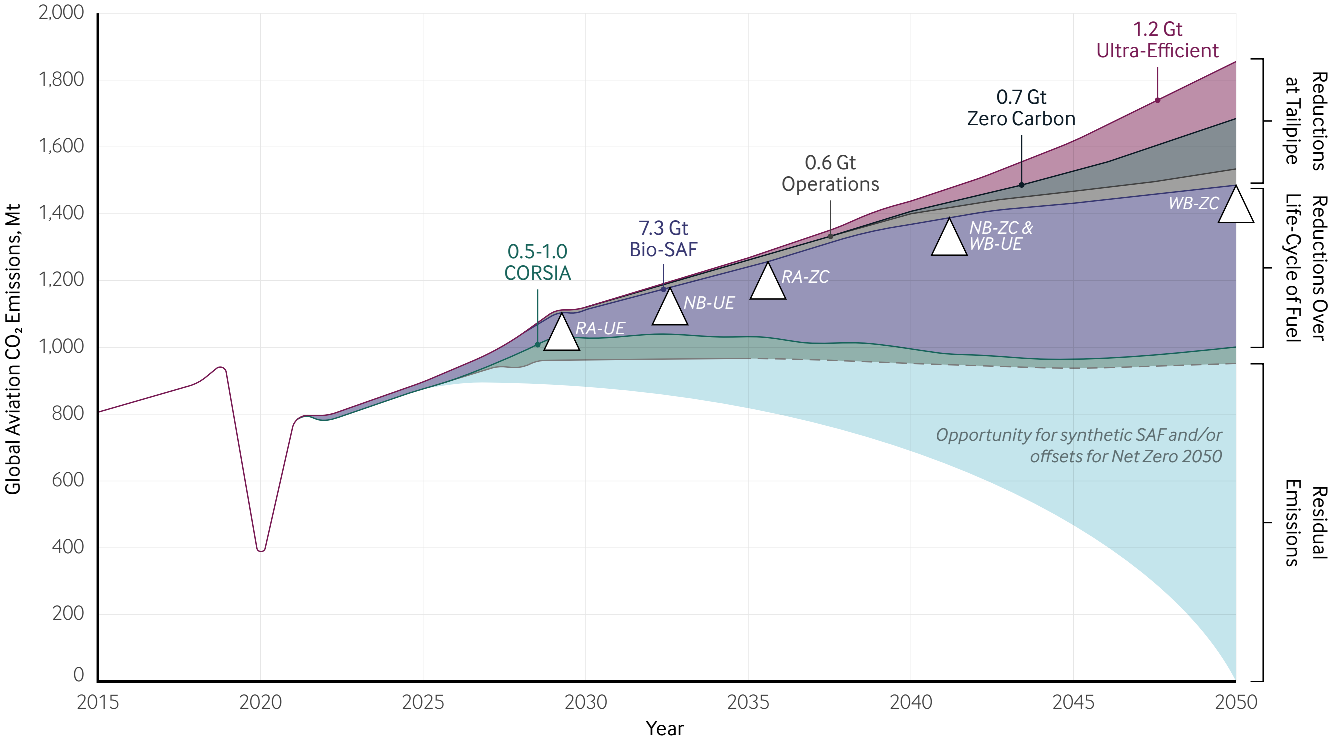
The objectives of this paper are:

- To reiterate the environmental benefits of SAF and their potential to reduce emissions from commercial aviation
- To provide basic technical information on the chemical properties of SAF along with the challenges of enabling flights with 100% SAF
- To inform aviation stakeholders about the SAF value chain and their potential roles within it
- To outline the infrastructure required to scale-up, produce, blend, transport, and store SAF
- To highlight logistical, technical, and infrastructure challenges and potential solutions to SAF becoming a major contributor in reducing aviation emissions

SAF emission testing - Image courtesy of Airbus.

INTRODUCTION

The aviation industry and many governments are setting ambitious goals to reduce the impact of aircraft emissions on climate change. Through the Air Transport Action Group (ATAG), the aviation industry is now targeting net zero CO_2 emissions by 2050 [3]. The ATI's own assessment towards net zero also shows that Sustainable Aviation Fuels (SAF) are critical to achieving this target (Fig.1) [4].



RA = Regional Aircraft
ZC = Zero-Carbon
NB = Narrowbody
UE = Ultra-Efficient
WB = Widebody
CORSIA = Carbon Offsetting and Reduction Scheme for International Aviation

Figure 1: ATI's scenario for Net Zero global aviation emissions

The global aviation fleet used some 300 million tonnes (Mt) of conventional aviation fuel (CAF) in 2019, generating over 900 Mt of CO_2 as tailpipe emissions, and close to 18 Mt of CO_2 through the manufacture and transportation of that fuel. Assuming the industry returns to its pre-COVID-19 growth trend, annual aviation fuel consumption will more than double between now and 2050 if no measures are taken. Therefore, in addition to efficiency improvements, zero-carbon fuels and market-based measures, aviation will require an increase in SAF production from today's 0.05 Mt per year to over 400 Mt per year by 2050 [5]. Today, global production is dominated by two producers with a few others producing SAF batches on demand. While blended and certified SAF is considered a drop-in solution, in its pure form work still needs to be done to make it fully compatible with existing distribution systems, storage infrastructure and aircraft. This means that the future SAF supply chain needs logistics and blending facilities for SAF that can scale to the hundreds of millions of tonnes required.

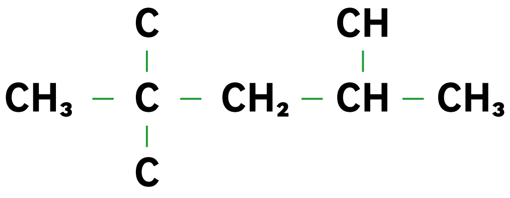
CONVENTIONAL AVIATION FUELS

Conventional aviation fuels (CAF) are mixtures of hundreds of different hydrocarbon compounds of typically between 8 to 16 carbon atoms per molecule with roughly twice the number of hydrogen atoms. The types of hydrocarbons found in kerosene are primarily n-paraffins, isoparaffins, naphthenes (cyclo-paraffins) and aromatics [6] [7]. The mix of hydrocarbon molecules in the fuel, and the presence of molecules containing other elements such as nitrogen or sulphur, will determine fuel properties such as density, energy content, freezing and boiling point, viscosity, and lubricity.

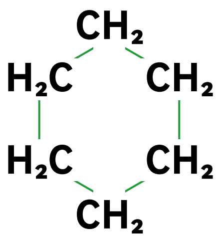
Paraffins, the major constituent of CAF [4], have lower densities than other hydrocarbon compounds with the same carbon number. They have a higher energy content per unit mass (MJ/kg) as they contain a higher proportion of hydrogen atoms. n-paraffins are straight hydrocarbon chains with a carbon backbone and hydrogen atoms surrounding them.

$$CH_3 - CH_2 - CH_2 - CH_2 - CH_2 - CH_2 - CH_2 - CH_3$$

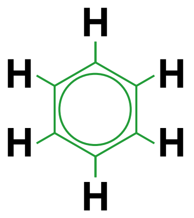
Isoparaffins (left) or cyclo-paraffins (right) have a similar structure to n-paraffins but contain hydrocarbon molecules branching from the backbone or forming a closed ring.



$$CH_3 - \overset{\displaystyle C}{\underset{\displaystyle C}{\overset{|}{\underset{|}{C}}}} - CH_2 - \overset{\displaystyle CH}{\overset{|}{CH}} - CH_3$$



Aromatics contain at least one benzene ring (see below). They have a higher density but lower energy content than other fuel hydrocarbons because they contain less hydrogen atoms. Current synthetic fuel standards limit the content of aromatics in aviation fuels to 8-25% due to their impacts on fuel sealing in aircraft engines and fuel systems*. The chemical structures of aromatics make them less reactive than other hydrocarbons; they combust less readily and tend to form more black carbon soot or carbon particles [8].



The fuel can also contain other atoms like nitrogen or sulphur as shown below. Aviation fuel specifications allow up to 0.3% mass of sulphur and 0.003% mass of mercaptans (hydrocarbon chain with sulphur), although fuels nowadays typically contain less than half of that [6] [9].

$$CH_3 - CH_2 - CH_2 - CH_2 - SH$$

**Current limits for aromatics for CAF depend on the test method used and can be 25%vol (IP156) or 26.5%vol (IP436). Current limits for aromatics for SAF also include a minimum content of 8% (IP 156) or 8.4% (IP436).*

Emissions from the combustion of CAF

When a fuel is combusted in a jet engine, the hydrocarbons in the fuel react with oxygen in the air to produce carbon dioxide (CO_2) and water vapour (H_2O). The combustion process releases large quantities of thermal energy and jet engines utilise this thermal energy to produce thrust. A kilogram of jet fuel burned under ideal conditions produces 3.16 kg of CO_2 and 1.25 kg of water vapour. The only way to reduce the exhaust CO_2 from an aircraft using hydrocarbon fuel is to reduce the amount of fuel consumed by improving the aircraft energy efficiency. As jet engines ingest air, there is around four times as much nitrogen as oxygen in the combustor. In the highest temperature regions of the combustor, some of the nitrogen from the air and nitrogen in the fuel can end up being oxidised to nitrogen oxides (NO_x). NO_x emissions increase at the highest combustion temperatures and hence at higher engine powers, typically during aircraft take-off and climb. At lower engine power settings, the combustion temperatures are lower, leading to incomplete combustion and the formation of Carbon Monoxide (CO) and unburned hydrocarbons (UHC). Finally, the sulphur in the fuel will also react with oxygen in the high temperature of the combustor to create SO_x.

CAF supply chain and certifications

Currently, most of the fuel consumed by aircraft is fossil fuel – derived from crude oil [10]. Commercial airlines consumed 8% of global liquid fuels at a cost to airlines of USD 188 billion in 2019, which represented 23.7% of their averaged direct operating costs [11]. To support the predicted growth of the sector, in addition to the extra production capability, infrastructure will be required to increase the capacity of pipelines, tank storage, and airport distribution systems regardless of the fuel used.

Typically, crude oil is transported by tanker or pipeline to a refinery where CAF is produced along with other hydrocarbon products. Aviation fuel is then transported by multi-product carrying trains, boats or pipelines to intermediate storage locations called fuel terminals. Quality checks are in place to make sure the fuel is not contaminated with other fuels, external agents, water, or microbes. The final element of the transportation chain, known as secondary transport, typically occurs through dedicated jet fuel infrastructure which connects a fuel terminal or an off-site storage facility directly to the airport fuel farm. This is commonly pipeline or rail, but trucks are also used when there is no other infrastructure available, to cover for temporary peaks in demand or to address interruptions in the supply chain. In most cases, once the fuel from different suppliers enters the airport, it is mixed in common airport storage tanks. This results in a loss of traceability to its original refinery or producer [12].

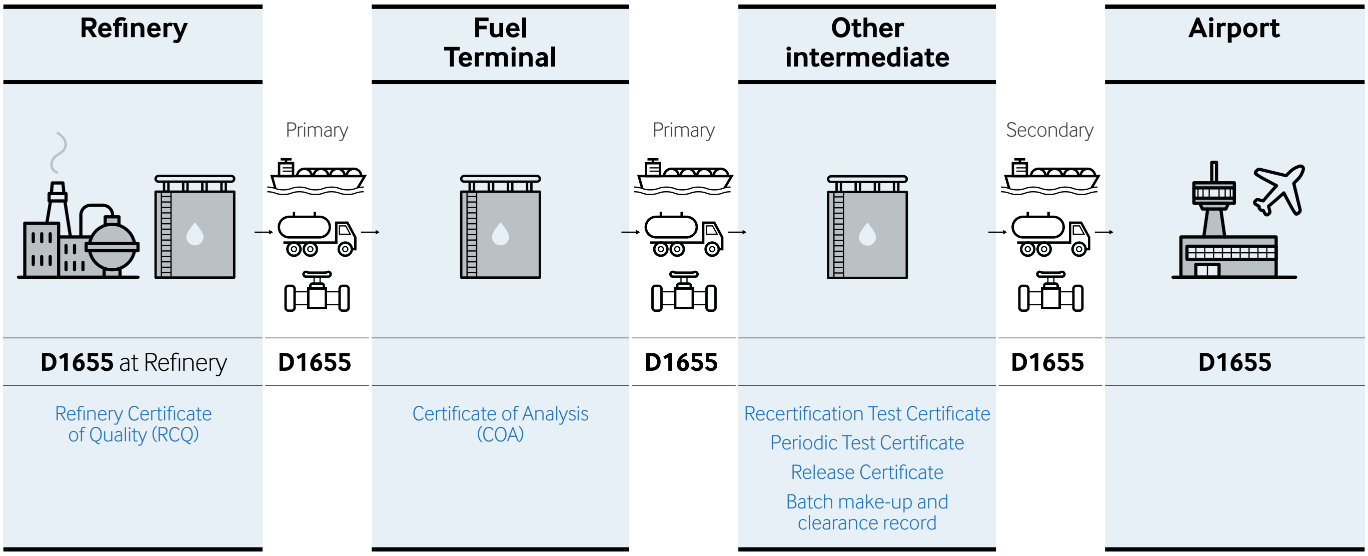


Figure 2: Generic conventional aviation fuel supply chain

Refinery quality certificates and other certificates of analysis are performed at various stages of the supply chain to ensure that once the fuel enters the airport it complies with the appropriate standards of quality and safety. More details on this can be found in references [12] [13] [14].

Many parties make up the supply chain of fuel to airports. The shipping or pipeline companies are often different to those which refine and produce the jet fuel. The fuel terminals are often owned and operated by different companies and the fuel farm at the airport can be owned and operated by other stakeholders. In some regions, it is common for airlines and fuel providers to form fuel consortiums, which operate, lease, and/or own the refuelling infrastructure at airports. These fuel consortiums coordinate with the airport authorities, airlines, fuel providers, pipeline operators, and refuelling companies. In other jurisdictions the fuel farm is owned by the fuel providers and in a few other cases the airport itself owns it.

Figure 3: Example of a conventional aviation fuel supply chain

When incorporating a new fuel into the supply chain, the appropriate quality requirements and checks need to be in place across the entire supply chain. Once SAF and CAF are blended they can be transported via the existing infrastructure and undergo the same quality checks as CAF alone. A parallel system with transport methods and quality checks would need to be in place for SAF up to the point where it is blended and subsequently incorporated into the existing CAF infrastructure, as explained in the following section.

SUSTAINABLE AVIATION FUELS

SAF is the term used to describe aviation fuels that are derived from non-fossil carbon resources, such as biofuels from biomass, organic derived waste feedstocks or synthetic fuels from carbon capture where the production energy ideally comes from renewable energy sources.

For SAF to be considered sustainable, it must comply to strict sustainability criteria. The International Civil Aviation Organization (ICAO) has defined default life cycle emissions for different feedstocks, along with a Life Cycle Assessment Methodology for aeroplane operators to have a consistent way of quantifying their offsetting requirements in the context of ICAO's CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [15] [16]. These criteria were adopted by the ICAO Council in November 2021 [17]. While ICAO's criteria are used for CORSIA's requirements, there are no globally accepted sustainability criteria for aviation fuels for all other purposes. For example, in Europe, the EU Directive on Renewable Energy describes specific European criteria for renewable fuels including aviation. For this reason, other organisations have developed sustainability criteria for SAF, and they often include some of the aspects below [18]:

- Greenhouse gas reduction value over its life cycle
- Quantity and quality of water required to make the fuel, as well as water rights
- Competition with food crops and food security
- Soil health implications of the biogenic feedstock
- Conservation of protected areas and avoidance of invasive feedstocks
- Use and disposal of waste chemicals and pesticides
- Human and labour and social development implications
- Land use and rights
- Renewable energy for its manufacture

SAF have similar constituent hydrocarbon compounds to CAF, however the mixture types of hydrocarbon compounds can be different. For example, SAF might be lower in aromatic content than CAF. When SAF of the same chemical composition as CAF are combusted, they produce nearly the same emissions as jet fuel in terms of CO_2 and water vapour. Therefore, the carbon emission savings do not come from the combustion of the hydrocarbon compounds but rather from their source and production; there is a net reduction in CO_2 emissions (see Fig.4). More details on the by-products of SAF combustion are given in the local air quality section.

[2] Some of the organisations which have developed SAF sustainability criteria are: the Food and Agriculture Organization (FAO), the Roundtable on Sustainable Biomaterials (RSB), the International Standard Organization (ISO), the European Union's Renewable Energy Directive (RED) and the International Sustainability and Carbon Certification (ISCC). Refer to each individual organisation for further details.

A life cycle emissions approach

When considering the whole life-cycle emissions of the fuel (well-to-wake), the emissions related to the extraction, refining, and transportation processes are added to the combustion emissions. A baseline for the life-cycle emissions of CAF is required to compare the reductions achieved by SAF. Some CAF are made from cleaner crude oils and require fewer processing steps, some are transported for longer distances than others, etc. In the Chicago Convention Annex 16 Vol IV, ICAO defines the global average baseline for conventional aviation fuel life cycle emissions to be 89 gCO_2e/MJ [19]. This means that, on average, every time a unit of energy (1MJ) of aviation fuel is burned, 89 grams of CO_2 equivalent are produced (1 kg of aviation fuel contains about 43 MJ of energy). About 16% (~14 gCO_2e/MJ) of the life cycle emissions are from the refining and transportation processes, and about 84% (~75g CO_2e/MJ) from combustion [10]. SAF compensate for the combustion part of their emissions during their manufacturing and feedstock growth (or CO_2 capture). As renewable energy and low carbon transportation become more dominant, the non-combustion component of the life cycle emissions of fuels should reduce.

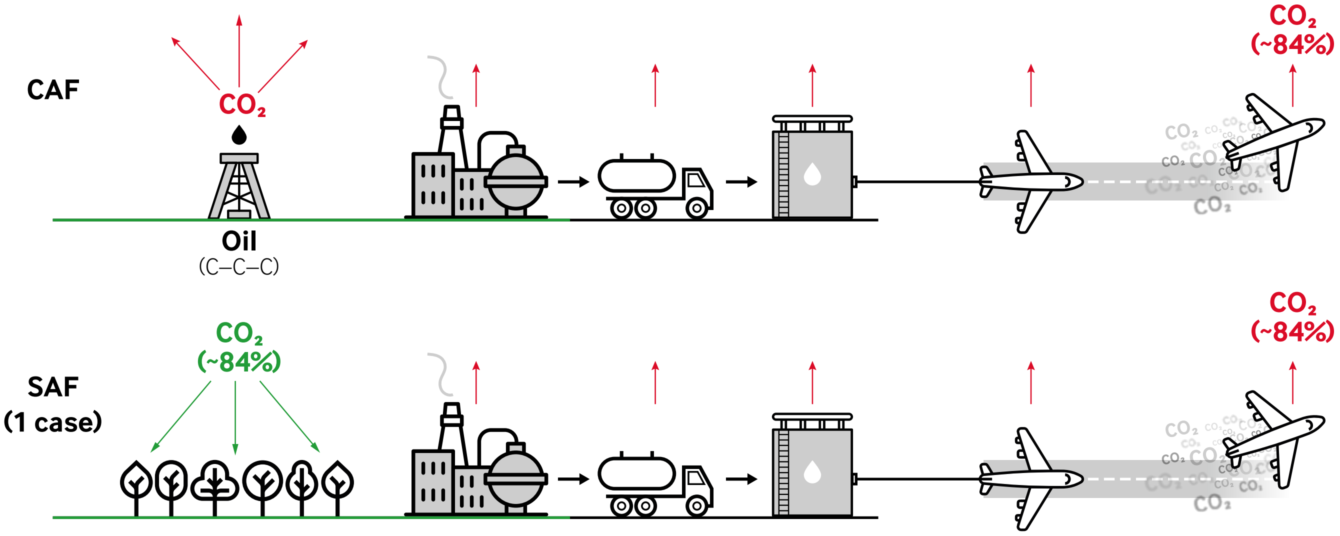


Figure 4: Life Cycle Emissions depiction of jet fuel and SAF. The 84% compensated through the carbon absorption is not linked to a specific pathway, and based on the current share of kerosene (~84% emissions during combustion, ~16% during manufacture and transport of the fuel)

While in some cases the carbon cycle can be fully circular (100% of the combustion, manufacturing, and transportation emissions are compensated), this circularity is accounted for on a mass basis only. The rate of absorption of CO_2 at the processing stage, however, is much lower than the rate of creation of CO_2 while the fuel is combusted. Therefore, while the mass while the mass of CO_2 will be eventually compensated for, this will not happen immediately. For example, a plant might take several months to grow and draw-down CO_2 from the atmosphere for its growth, but this CO_2 will be released in a matter of seconds when the bio-SAF is combusted in a jet engine.

Feedstocks for SAF

Sustainable aviation fuels are hydrocarbon fuels, derived from carbon-containing renewable feedstocks. The origins of the carbon of the different feedstocks are outlined below.

Biomass to Liquid (BtL)

Carbon sources which come from naturally grown biomass, such as sugary or oily crops, agricultural and forestry residues, or even algae. In these cases, the CO_2 is absorbed from the atmosphere by a plant which produces an oil which can be converted into fuel, as shown in figure 4. **Waste to Liquid (WtL):**, a subset of BtL which comes from carbon sources from used cooking oil, animal fat (tallow), or organic matter in municipal solid waste (MSW) [49]. While the origin of the feedstocks is also biomass, in these cases, the CO_2 benefit of SAF comes from avoiding the release of carbon dioxide (and other GHGs) from organic waste into the atmosphere.

Power to Liquid (PtL)

The energy input for PtL SAF comes from electric energy, which has to be produced from renewable sources. PtL SAF collects carbon from atmospheric or industrial flue gases. This carbon, in the form of CO_2, is converted to CO and is then combined with electrically produced hydrogen to produce a hydrocarbon fuel [50] [51].

Solar to Liquid (StL)

The energy input for StL comes from solar heat, by concentrating sun light into a chemical reactor, which converts CO_2 and water into CO and hydrogen to produce a hydrocarbon fuel as it is done with PtL. A first demonstration plant has been successfully tested in Spain. The StL technology is not yet ready for large scale implementation, however, it has a considerable potential: Working with heat instead of electricity makes it easier to achieve self-sustained operation from solar energy, as heat accumulated during the day is relatively easily stored for operation during night (salt/water tank heat storage) [53].

There are nine approved processes to convert carbon feedstocks into SAF, however almost all of the SAF available today comes from the HEFA (hydro-processed esters and fatty acids) process [20] (WtL origin). ICAO, through its Global Framework for Aviation Alternative Fuels (GFAAF), keeps a list on certified processes, the number of commercial flights which have operated with a blend of SAF and the number of airports distributing blended SAF [21]. A summarised list outlining some feedstocks and the corresponding production pathway taken from the World Economic Forum (WEF) is offered in Table 1 [22].

A recent study examined the availability of feedstocks to provide aviation with enough SAF to reach net zero by 2050 under the three scenarios identified by ATAG [23] [5]. Although HEFA is the most widely used SAF pathway today, it is the least scalable one in the long term, only being capable of providing 10% SAF by 2050 due to feedstock limitations. By 2050, advanced feedstocks processed through the Alcohol-to-Jet (AtJ) and Fisher Tropsch (FT) pathways, not available at large scale today, would account for about 40% of the total SAF. The remaining 50% would need to be produced from Power-to-Liquid, identified as being the most scalable in the future in terms of feedstock availability. A demonstration flight with a blend of PtL and conventional aviation fuel has already been trialled between Amsterdam and Madrid, using 500 litres of PtL fuel [24]. PtL would require enormous quantities of sustainable electric power for its production and the extensive deployment of the associated infrastructure, some of it which is highlighted in Reference [19] in the context of the SAF required to meet the ATAG goals.

Table 1: SAF feedstocks and production pathway, from WEF

Feedstock category – Carbon source	Production/Tech Pathways
Waste & Residue lipids	HEFA
Used cooking oil, fish oil, animal fat, palm oil residue	
Purposely grown oil trees	
Jatropha on degraded land	
Oily cover crops	
Camelina (Oilseed-bearing herbs)	
Cellulosic biomass	Gas/FT ATJ
Miscanthus (Cellulosic cover crops)	
Agricultural residues	
Forest residues	
Wood processing waste	
Municipal waste (Non-re-usable plastic)	Gas/FT
Direct CO_2 capture from air BECCS (Bio energy carbon capture) Industrial waste gas from burning fossil fuels (Carbon capture)	Power to Liquid (FT or Methane)

The feasibility of scaling up SAF will depend on the water, land, and energy requirements for their production. Hydrogen is required for most pathways, either to make the hydrocarbon chain from CO_2 capture, or for completing/saturating the hydrocarbon chains in fatty acid feedstocks. Today, most hydrogen used in the world is grey hydrogen, derived from natural gas with a high carbon footprint [25]. Likewise, most electricity used worldwide is not renewable, and is associated with a high carbon intensity [26]. Renewable energies are an absolute necessity to further decarbonise the processes associated to manufacturing, refining, and transporting sustainable aviation fuels.

Co-Production

Some refineries have the capacity to co-produce SAF. Co-production is different to blending, as the raw sustainable oils are refined along with the petroleum, so that the jet fuel end-product already contains hydrocarbons derived from sustainable sources. Not all refineries are equipped for this and currently only less than 5% biogenic feed can be mixed with the crude oil for the refining process. Co-processed SAF can utilise the supply chain for conventional fuel, as the product delivered by the refinery would be a certified CAF with renewable molecules in it. For example, in Italy, Eni has launched the production of co-processed SAF by using cooking oil as 0.5% of the feedstock into the refining process [27].

Quality and certifications: 100% SAF vs blended, and non-drop-in vs drop-in SAF

ASTM International sets the international technical aviation fuels standards for commercial aviation. The ASTM D1655 standard outlines all the properties required for conventional fuels including aromatic and sulphur content, density, freezing point, low heating value and others. Some regions use equivalent standards such as the Defence Standard (DefStan) 91-091 in the United Kingdom [28].

SAF needs to comply with the specifications in the ASTM D7566 standard which deals with non-petroleum hydrocarbon fuels [29]. ASTM D7566 includes the approved conversion processes and blending limits for different synthetic aviation fuels, depending on the pathway (1 annex per pathway). The standard specifies the limits on some compounds (like aromatics, cycloparaffins or trace compounds) that a fuel must have to be certified as aviation fuel. One of the critical criteria is the aromatic content which needs to be between 8-25% for the fuel to comply with its secondary functions of lubrication and sealing. The SAF commercially available today does not contain aromatics and is not compatible with aircraft and the current aviation fuel infrastructure in its pure form. For this reason, it must be blended with CAF to a level which will allow the blend to meet the minimum composition or performance outlined in the standards.

CAF with 16% aromatic (or more)

SAF with 0% aromatic

50-50 Blend with 8% aromatic Allowed!

CAF with 10% aromatic

SAF with 0% aromatic

50-50 Blend with 5% aromatic Can’t do!

If a jet fuel with 16% aromatics content was to be blended with a SAF which has no aromatics at all at a 50% blend, the final mixed fuel would have 8% of aromatics and would comply with the standard. However, if the base-fuel had, for example 10% aromatics, the final 50-50 (SAF-CAF) mix would have an aromatic content below the minimum specification and would not be certified as jet fuel. In this case the maximum allowable blend would be lower than 50%. For this reason, SAF providers usually prefer to blend with jet fuel which has a high aromatic content since this will ensure that they can achieve the maximum allowable blend.

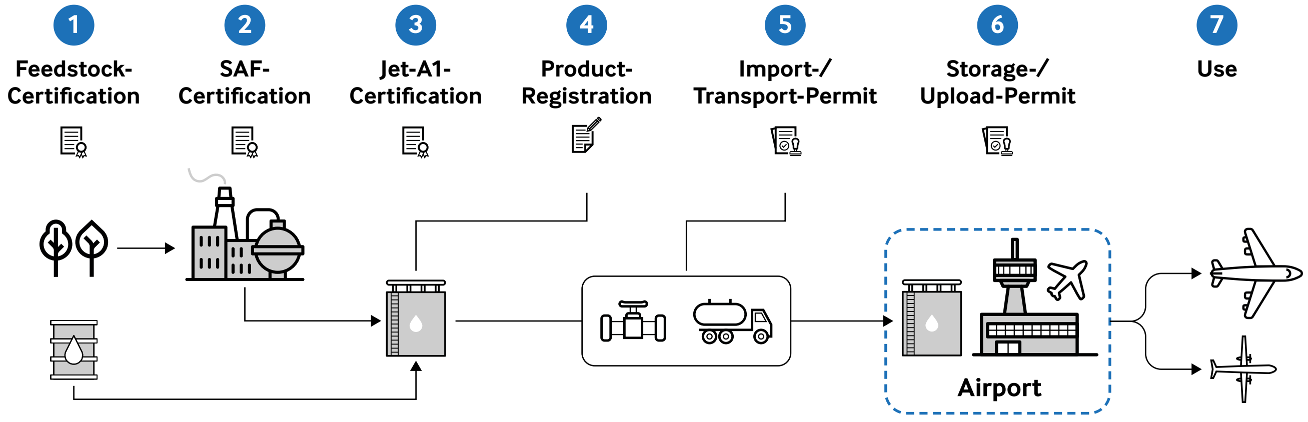


Figure 5: Production and certification steps of SAF, courtesy of Zurich Airport

Provided the SAF-CAF blend complies with the chemical properties in the ASTM specification, the blend can be re-certified to the general section of the ASTM D7566 standard (after step 3, fig.5) [12]. A fuel which has been re-certified to the general section of D7566 (as opposed to a specific annex) is automatically certified as conventional aviation fuel (D1655). This blended fuel (CAF + SAF) is considered a drop-in fuel which can be handled, stored, refuelled, and used in the same way as conventional aviation fuel and does not require extra infrastructure, procedures, or modifications to aircraft fuel systems [30]. The blending limits depend on the aromatic content and chemical composition of both the CAF which will be used as a base, and the SAF.

SAF: The 100% SAF challenge

The global uptake of SAF is low today and is focused in a few geographic areas. It is possible that regions with more incentives to use SAF will continue to dominate the market . For example, in the United States, the SAF uptake is being led by states with Low Carbon Fuel Standard (California, Oregon, Washington) which represent roughly one quarter of US jet fuel consumption. The possibility of increasing the blend limit will become important to enable large regional uptakes even if the global uptake of SAF is still on single-digit percentages.

As discussed above, 100% SAF has no aromatic hydrocarbons (vs the 8-25% of CAF), leading to impacts on both aircraft fuel systems and fuel infrastructure on the ground since SAF has different density, lubricity, and chemical composition.

In aircraft fuel systems, the lower density of SAF affects fuel gauging, but should not be a major issue once changes to the gauging system are made. The density change may also impact range for flights flying close to their range limit. Lubricity and sealing issues on fuel systems are long-term effects that can be addressed by modification to fuel system components. Limited demonstration of aircraft operation with 100% SAF has already been carried out. Boeing, in partnership with FedEx flew a 777 freighter with 100% SAF in 2018 and committed to delivering a 100% SAF-compatible aircraft by 2030 [31]. Airbus has recently completed a campaign doing exhaustive testing on an A350 aircraft flying with 100% HEFA-SAF, and plans to complete a transatlantic flight powered by SAF on an A380 in the near future [32]. Engine manufacturers are also investigating ways to enable turbofans to run on 100% SAF. Rolls-Royce has conducted extensive ground running to investigate steady state and transient behaviour [33]. Future experimental engine testing will include a flying test bed with a state-of-the-art aeroengine [34].

How can we make aircraft and infrastructure compatible with 100% SAF uptake?

Although new aircraft can be made compatible with 100% SAF through different materials for the seals or calibrated gauging, older aircraft which are not certified for 100% SAF would either need to be retrofitted and made SAF compatible or airports would need to ensure availability of both SAF and CAF. This would require separate storage and handling of both fuel types and careful management of aircraft refuelling to prevent uploading the wrong fuel. It could be more convenient for airports to only stock blended fuel compatible with all aircraft.

All aircraft could use 100% SAF without modification by developing a fully formulated SAF containing both paraffins and aromatics that closely match the CAF composition. Enablers to this would be bio feedstocks for sustainable aromatics or sustainable synthetic manufacture of aromatics. Although some SAF pathways (e.g., Fischer Tropsch synthesised kerosene with aromatics (FT-SKA)) produce some synthetic aromatics as the fuel is made, they are currently limited to a 50% blend by ASTM [35]. The disadvantages of fully formulated SAF are that with an increased aromatic content, an increased level of carbon particulates would be emitted relative to non-formulated SAF (also known as paraffinic SAF), impacting local air quality and propensity for contrail formation, thereby reducing the non-CO_2 benefits of SAF. The first demonstration flight with over 100 passengers was flown in 2021 by United Airlines operating one engine with 100% fully formulated SAF and another one with kerosene [36].

SAF EMISSIONS

In most respects, SAF offers improvements in emissions because of its higher hydrogen to carbon ratio and lower contents of nitrogen and sulphur-containing compounds. Care needs to be taken, however, when comparing SAF with CAF emissions as the composition of CAF has considerable variability within the fuel specification limits (according to specification aromatic content can range from 8% to 25%, for example). These emissions benefits from SAF reduce when SAF is blended with CAF, although not necessarily linearly. The early emissions data on SAF is gathered from testing on military aircraft and APUs using military specification fuels [28]. While the last decade saw an increase of testing using commercial aircraft engines, these studies are limited and there is still a need for more experimental testing on civil aircraft with commercially available SAF/ CAF blends preferentially conforming to ICAO Annex 16 Volume II engine testing, carefully controlling the variables outlined. For dilute blends of SAF (<5%) the emissions benefits are insignificant [6]. Engine emissions depend on other factors beyond the fuel composition such as engine design, engine operating conditions ambient conditions, and SAF-CAF blend ratio [19] [37] [35] [38]

CO_2 and H_2O

The higher hydrogen to carbon ratio of SAF relative to CAF improves the specific energy density by 0.5-1%, depending on the blending ratio. This would reduce the fuel mass flow required for a given thrust, reducing the associated emissions , because a reduction in fuel flow causes all emissions to decrease, if the combustion quality does not change [39] [37].

Non-CO_2 emissions

Non-CO_2 emissions like NO_x, CO, and SO_x have different effects at different flight segments. Near the ground and at airports, these emissions deteriorate local air quality and can affect local water quality, flora, and fauna. At altitude, they contribute to global warming and in the case of carbon particles, enhance the formation of contrails which are another contributor to warming when formed. The exact effect is still associated with uncertainties and variability and is currently being studied by industry and academia.

NO_x emissions

As NO_x emissions are primarily driven by combustion temperature, they are essentially unaffected by SAF. Most references in the open literature mention no change in NO_x emissions, while a few have found insignificant increases or decreases. It is unknown whether inclusion of a specifically designed synthetic kerosene into the design of gas turbines, would offer advantages for low NO_x optimisations.

CO emissions

As with NO_x, CO formation is thermally driven and hence essentially unaffected by SAF.

SO_x emissions

SO_x emissions depend on the sulphur content of the fuel. In and around airports the concentrations of sulphur emissions are not monitored to the extent that NO_x is, and their concentration usually tends to be lower (1-2 $\mu g/m^3$ compared to 21-28 $\mu g/m^3$ for NO_x at some airports) [40]. An important aspect of sulphur emissions is their coating effect on soot non-volatile particles. Whereas the health impact of sulphur-coated particles is not yet known, such particles are active in the creation of ice nuclei during cruise, enhancing contrails and affecting the climate impact. It is known that reduction of soot and sulphur in the exhaust reduces the number of ice crystals and hence contrail formation. Regulations allow up to 0.3% sulphur content in aviation fuel, however, today's fuels have much lower concentrations than that (0.05-0.1%) [6] [41]. SAF having no sulphur would essentially eliminate SO_X emissions if used at 100% [35] [42]. These reductions, will change once the fuel is blended depending on the blending ratio and the base CAF. Since some CAF already have very little sulphur content there could be cases in which the SO_X emissions of a SAF blend (<50%) are the same as those from CAF. There is no information on what the average global composition of sulphur content in CAF is because this varies greatly between world regions, so the SO_X reductions will vary on a case-by-case basis.

Non-volatile particulate matter

Non-volatile particulate matter (nvPM) emissions depend on the aromatic content of the fuel, along with engine design, engine operating conditions and atmospheric conditions [35] [39]. Experimental testing of nvPM emissions has consistently shown a significant reduction with the use of SAF, with the level of reductions depending on the specific SAF used, the aircraft it is applied to, and the CAF baseline it is compared against. An ACRP review saw reductions of between 38-51% for a 50% SAF blend and 30-100% for 100% SAF [42]. For a 50% FT SAF blend, Lobo et al. found a reduction of 28-42%, and 48-56% for 100% SAF [37] consistent with the experimental testing from reference [39].

Airports should be cautious in applying fixed nvPM reduction factors when estimating emissions inventories, since actual operational reductions might greatly differ from controlled experimental testing. The reductions in particulate matter need to be compared to a certain baseline. A SAF blend with 8% aromatic content could produce similar nvPM emissions as a CAF with the same level of aromatics but will produce considerably less nvPM than a CAF with the highest aromatic limit of 25%. The SAF-CAF blend might, thus, contain different CAF base for blending than the pure CAF that is present at the airport's fuel farm. These considerations need to be analysed when forecasting the local air quality effects of SAF at airports, along with the present or expected blending ratios.

Contrails

Particulate matter at the engine's exhaust provides nucleation sites for the formation of ice crystals which form from the exhaust water vapour, and which could create persistent contrails when aircraft fly across ice supersaturated regions. A recent study published in partnership between NASA and DLR investigated in-flight PM emissions and contrail production of a narrow body civil aircraft burning jet A-1 and different blends of SAF [39]. The results showed a drop in PM emissions and a subsequent drop in contrail formation and ice crystal characteristics. More experimental campaigns of this nature, with representative civil aircraft operations are needed on the ground and during flight to increase the confidence in the magnitude of such non-CO_2 emission improvements.

SAF SUPPLY CHAINS

Some countries have started legislating mandates for minimum SAF content in aviation fuel, obliging fuel providers to supply SAF blends that comply with ASTM D7566 (which can then be re-certified by as ASTM 1655, DEF STAN 91-091 or equivalent). At present, the global supply chain infrastructure for SAF is extremely limited as SAF has only been used in low volume blends on commercial aircraft and in higher blends in limited demonstration/ research flights. ATI's fleet modelling analysis shows that if SAF could scale up to fully meet aviation demand by 2050, 20-30% of the active fleet by then would still not be compatible with 100% SAF (assuming manufacturers start delivering all aircraft compatible with 100% SAF after 2030). For these reasons, it is likely that the supply chain development will mostly be around SAF blends that can use the same infrastructure as CAF, followed by transition to 100% SAF flying once the fuels are certified and the aircraft are all fully compatible with the fuel.

The best place for blending and the optimum SAF transportation method to the blending facility and onwards to storage and use will depend on individual circumstances and will be influenced by the volumes of fuel used. Some options for blending and a general description of the supply chain are illustrated in Figure 6,

1. The feedstocks are sourced locally or regionally and processed into SAF or a renewable intermediate oil from which the SAF will be made.
2. If the refinery does not have the capabilities to produce SAF, the intermediate-step oil will be sent to a different refinery for its conversion into aviation fuel. For example, the Neste plant at Porvoo (Finland) sends a product similar in properties to biodiesel to different refineries depending on where the SAF will be used.
3. If the SAF producing facility has access to conventional jet fuel, this can be procured for blending on-site. In California (USA), for example, SAF is normally blended at a ratio of 30% at the producing facility.
4. If the SAF producing facility does not have access to jet fuel or infrastructure for blending, SAF will be transported into an intermediate location like a fuel terminal where it will be blended with conventional aviation fuel and stored.
5. The blended SAF will then be transported to the airport. It is fundamental that the SAF arrives to the airport already blended, to save costs and time, and maximise the use of existing infrastructure and expertise.

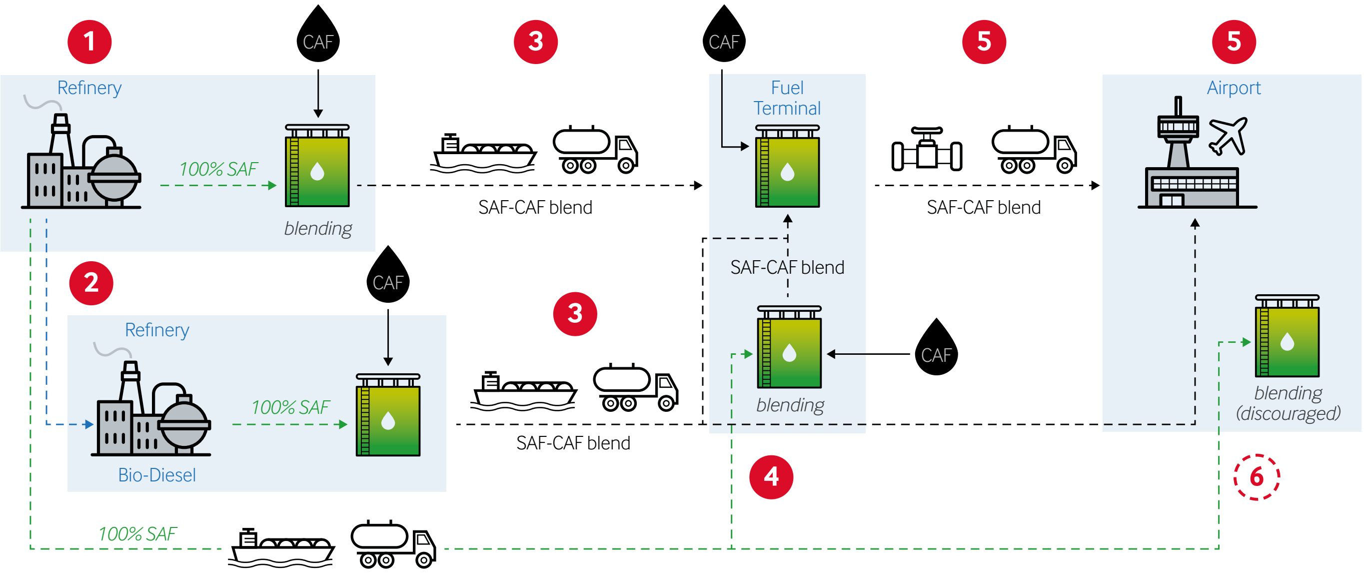


Figure 6: Generic options for SAF and CAF blending

Blending requirements and locations

SAF and CAF could be blended at any of the intermediate storage locations shown in Fig.6. Past studies have evaluated different options for blending and transporting SAF with their associated infrastructure costs. Some of the criteria for selecting the best location to receive and/or blend SAF are [43] [44]:

- The quantity of SAF required
- The location of the SAF and CAF refineries with respect to the airport
- Sufficient available space for blending and storing infrastructure
- Load-offload racks, storage tanks, blending system, pipeline connections, testing facility and administration offices will be required. Locations that already have these facilities will be at an advantage.
- Availability of volume-scalable transport options
- Acceptability from an environmental perspective: Installing blending facilities in industrial locations such as refineries or other transfer points upstream of airports may prove to be more environmentally acceptable. Some airports may be restricted from having fuel operations other than storage on site
- Availability of the land for purchase or lease
- The land use, air quality and broader environmental regulations should permit the desired fuel infrastructure

A US National Renewable Energy Laboratory study views that SAF would be delivered in a special tank and checked for quality and compliance with D7566 before blending occurs. While the quality of 100% SAF can be controlled by the producer, the quality (aromatic content, sulphur content etc.) of the CAF varies depending on its source (see section 2.2). For this reason, the base jet fuel also needs to be tested and pre-blends are necessary to assess the final properties of the SAF-CAF blend before the full-scale blend is done. After full blending is completed, the final mix needs to be re-certified as an ASTM D1655 jet fuel. Depending on the volumes, at least two extra tanks are required for this, one for the 100% SAF and one for blending, along with the infrastructure and systems to support the fuel transfer and the laboratory to test and certify the fuel. Introducing SAF directly into CAF without mechanical or hydrodynamic mixing could lead to a non-homogeneous blend due to the density difference between the two fuels [13], so specialised blending processes are needed. The advantages, disadvantages, and limitations of the different blending locations and the transportation methods are summarised below.

Blending at a fuel terminal

It is likely that fuel terminals will have more capacity and space than airports. 100% SAF would need transporting into the terminal via infrastructure dedicated for SAF (ship, rail, truck or pipeline). For smaller volumes, trucks would be suitable, but this must shift to more efficient modes for higher volumes. Offloading platforms for trucks, trains, or water vessels will be required to accept 100% SAF, as well as tanks to store and blend it [44] [13].

Table 2: Considerations for fuel blending at a fuel terminal

Advantages	Disadvantages	Limitations
Larger volumes can be blended than at the airport	Requires SAF-specific fuel supply infrastructure to the fuel terminal	Limited in space and capacity for the expectation of SAF uptake by 2050
Experience in handling biofuels		Efficient and transparent accounting system needed to track the fuel to the different airports
Available infrastructure to load and offload fuel. All downstream infrastructure to the airport can remain as is		
Industrial operation makes site more suitable than airport		
Many airports can be supplied by the same fuel terminal		
Some terminals might have experience in fuel blending		

Blending at a refinery

SAF refineries often procure conventional jet fuel to be blended with their 100% SAF to produce a product that is already blended and certified jet fuel. Oil refineries are the sites that handle the largest volumes of fuel and so they are well suited for large quantities of SAF [43].

Table 3: Considerations for fuel blending at a fuel refinery

Advantages	Disadvantages	Limitations
Expertise in handling different hydrocarbon products, including biofuels	Only suitable for very large quantities [13] [43]	Optimised for very large volumes, unlikely to blend small quantities [13] [43]
Expertise in handling jet fuel		Might be further away from the SAF facilities. Large quantities of SAF will need to be transported and this might require extra transportation infrastructure
Flexible transport infrastructure (pipelines, ports, railways) [43]		

Blending at the airport

Blending at the airport is not recommended and it would only allow smaller quantities of fuel to be handled.

Table 4: Considerations for fuel blending at an airport

Advantages	Disadvantages	Limitations
Fewer trucks for SAF are needed. (1 truck with 100% SAF vs 3 trucks with 30% SAF)	Requires airport infrastructure to receive, store, and blend the fuel	Trucks required for SAF transport if 100% SAF is not permitted in the pipeline (this is the case now), restricting delivery volumes
Reduced transportation costs [12] [44]	Requires duplication of fuel supply chains all the way through to the airport	Airport tank storage capacity is small compared to other locations [43] [44]
Increases visibility and presence of SAF to airport workforce	Certification of fuel needs to happen on-site [13]	Regulations for blending on-site would be required [28] [12] – Lack of expertise in certification requirements
	Ground traffic congestion [13]	Limited fuel can be offloaded via existing offload racks
		Lack of Legal framework to transport 100% SAF in some countries

Methods for transporting SAF

Enabling SAF use requires mapping of supply chains for each region and airport. Transport of SAF should consider existing and future infrastructure, as well as carbon emissions and risks associated with different transportation modes.

Truck

Trucks are only suited for transporting small volumes of SAF to airports but can be an important interim measure to enable SAF use while other delivery mechanisms are under development or when only limited amounts are available within certain regions. From an emissions lifecycle perspective, trucks are not the long-term solution that will enable scaling up SAF to the necessary levels of hundreds of millions of tonnes by 2050.

Table 5: Considerations for transporting SAF via truck

Advantages	Disadvantages
Flexible and resilient	Only suitable for small quantities
Do not require major transportation, loading or offloading infrastructure	Offloaded fuel quantity limited by airport's offload rack capacity [43] and compatibility requirements
	As volumes of SAF increase, transportation infrastructure (i.e., staging areas, access roads, etc.) may be needed [44]

Rail

Provided rail connections exist, they are a more efficient way to transport large volumes of fuel. Most SAF facilities are close to the feedstocks but further away from ports or pipelines, so as SAF is scaled up, developing the rail infrastructure for its transport could be an efficient way to connect 100% SAF into existing supply chains [43].

Table 6: Considerations for transporting SAF via rail

Advantages	Disadvantages
Suitable for larger fuel volumes	Require rail infrastructure from SAF refineries to blending locations
	Lacks flexibility, SAF refineries will need rail connections to the blending site

Barge

Normally, airports have no direct access to ports for fuel transfer. Waterborne transport is likely to be an intermediate step in a multi-modal transportation chain.

Table 7: Considerations for transporting SAF via barge

Advantages	Disadvantages
Large quantities of fuel can be transported	Many airports do not have ports to offload fuel
	Major infrastructure development is required if this is not already present
	Only refineries/terminals with water ports are suitable for this

Pipeline

Jet fuel, diesel, gasoline and other hydrocarbon products are typically transported in batches using the same pipeline. These products must be carefully sequenced to minimise cross-contamination. It is still under discussion whether 100% SAF would be allowed to be sequenced on these multi-purpose pipelines (it is not the case today), but the volumes would have to be substantial for this to be justified. In Europe, many of the pipelines supplying airports with fuel are owned and operated by NATO. For a new fuel to be transported using these pipelines, all NATO members must give permission. At the present, there is no agreement and so SAF is not permitted on NATO-owned pipelines. Purpose-made pipelines for SAF are unlikely to be built due to high capital costs of around $1M per kilometre [12].

Table 8: Considerations for transporting SAF via pipeline

Advantages	Disadvantages
Low operating cost	100%SAF is currently not permitted on multi-product pipelines (Suitable only in certain countries for already blended and certified SAF) [43]
Existing infrastructure to many airports	High capital cost of new infrastructure [12]
	SAF needs to enter the pipeline sequencing of other hydrocarbons, only justifiable for very large volumes

IMPLEMENTING AND SCALING-UP SAF

Previous sections have touched upon the global supply chain to scale up production of SAF. To support the understanding of what is necessary to enable an increased use of SAF, three stages of supply chain development have been identified:

- Initial facilitation
- Early ramp-up
- Scale-up

Initial facilitation period

In many locations, the initial use of SAF has commenced though single proof of concept pilot flights or limited duration usage. Preparation for such trials have provided opportunities to advance understanding of SAF as a safe fuel and to promote its use, as well as to map entire supply chain options to bring SAF into use at specific locations. There are examples of airports which have already completed this initial facilitation period (including Oslo, San Francisco, Los Angeles, Toronto Pearson and Heathrow) [12] [45]. Airports starting their SAF journey can learn from these previous experiences. This activity typically starts with the supply of SAF direct to an aircraft for a single flight, or to the airport fuel farm. As the quantities of SAF procured are small, airports and airlines are required to liaise with SAF providers to obtain a batch of blended fuel that will be dispatched from the blending point to the airport.

Close collaboration and coordination between many stakeholders, some of them with limited experience in managing SAF blends will be required when SAF is facilitated to an airport for the first time. These stakeholders could include:

- Airport operator
- Airline
- Ground handling and airfield operators
- Aircraft refuelling operator
- Conventional fuel supplier or aviation fuel consortium
- Fuel farm operator
- SAF supplier
- Customs
- Environmental Agency
- Local department for transportation
- Fire and rescue teams at the airport
- Logistic companies
- Environmental NGOs, familiar with aviation and the sustainability certification schemes of alternative fuels

While most airports are not part of the fuel value chain, they do play a role in facilitating the exchange and interaction between the different parties involved and can act to facilitate the introduction of SAF. Some airports have gone further by organising SAF flights and/or by playing a leading role in regional and national policy setting as well as international advocacy.

Based on the experiences of facilitation at different airports, five steps are suggested for airports to start their SAF journey at this early stage:

1. **Familiarisation with SAF:** All parties involved should familiarise themselves with the basics of SAF and SAF-CAF blends: ([20] [46] [47] [21]). This first phase should also reveal policies or incentives that can contribute to the facilitation process. A risk assessment on the process and economics should be performed to anticipate challenges and ways to solve them.

2. **Identification of current suppliers:** At the time of publication, there are only two active manufacturers in the world that produce SAF on a continuous basis through the HEFA pathway at scale(Neste & World Energy). It is likely that airports wanting to facilitate SAF will need to import it. At this stage, SAF should be procured in its blended form to minimise customs or transportation barriers.

3. **Creation of working groups:** Working groups from all involved stakeholders (listed above) should be established and clear goals defined. The exchange of information from all stakeholders should be as comprehensive as possible to ease the whole process. One of the outcomes of the working groups could be an infrastructure feasibility study and an activation plan. Suggestion for scoping these studies are:
    1. Types of feedstocks and location of local SAF production facilities, along with feedstock availability
    2. Locations to receive, blend and integrate SAF into the conventional fuel supply chain
    3. Sustainability and scalability of the SAF procured
    4. SAF price reducing and financing mechanisms, fuel policies, funds and incentives

4. **Process test flight:** A single or a short series of flights could be organised to test local processes and procedures in terms of administration and logistics where an aircraft is directly fuelled from a truck, or the SAF is offloaded into the airport fuel facilities. The latter is a more scalable approach as it avoids additional vehicles driving onto the tarmac and refuelling aircraft. Operators and airports need to be made aware of the requirements to ensure SAF is stored in a segregated tank or uplifted to a given aircraft, so a clear accounting system is recommended. This step will increase confidence in the SAF process by the parties involved and can be an intermediate step to establishing a continuous flow of SAF into the airport.

Figure 7: SAF upload to an aircraft at SFO, courtesy of SFO

Although many SAF facilities are currently in development, there are few SAF processing and blending facilities today, so SAF can have very extended supply chains, stretching across the globe. It is common today to see feedstocks, SAF and SAF-CAF blends being transported across continents (see Fig. 8). Whilst useful as a leaning and promotional exercise, this approach is not scalable or sustainable from a transport perspective.

Figure 8: Example of SAF supply chains around the world

Beyond these initial steps, the next stage should be to accelerate the delivery of SAF though continuous truck delivery to the airport into the existing fuel facilitates or using the fuel terminals that supply the airport to jointly coordinate a pipeline delivery of blended SAF.

Early ramp-up period

The early ramp-up phase is a period where SAF starts to be continuously delivered to airports through individual initiatives in small but constant volumes and where the approach used for the initial facilitation period is no longer viable. According to ATAG, in 2019, 32,000 tonnes of SAF (~0.01% of total aviation fuel) were supplied to just over 65,000 flights mainly to airports which are already on an early ramp-up period in the United States, Norway, and Sweden [11]. As larger volumes of SAF are used, the logistics of moving SAF feedstock, 100% SAF, and SAF/CAF blends mean that locations of SAF production, SAF/CAF blending, storage, and airports become much more important to the economics of SAF. Thorough assessment of logistics options will be required to achieve an optimal solution.

Figure 9: SAF being unloaded into the Avinor Oslo International Airport fuel facilitites, January 2016. Courtesy of Avinor

At this stage, airports and airlines should work together to identify mechanisms to close the price gap between SAF and CAF. Low carbon fuel policies, for example, are an effective tool to reduce the gap. Additional considerations for both airlines and airports could include:

- Sustainable aircraft energy credits or vouchers sold to corporate customers and/or passengers to reduce the price premium. This could be done at point of ticket purchase or at airports selling SAF bonuses or in green lounges linked to passenger communication and information campaigns
- Coordinated requests for government support and investments, including government fleet commitments, research and development grants or corporate partnerships.
- Investments in alternative fuel providers, or pilot plants

In addition to this, other activities that airports can do to motivate the uptake of SAF are:

- Participation in establishing globally consistent, robust, and transparent sustainability criteria
- Involve airport leadership in the discussion and communication of these approaches to get the right government and passenger support
- Actively contribute to establishing the legal framework for 100% SAF to be transported and stored
- Socialising the SAF benefits to customers

Blending locations and fuel delivery methods will need to be assessed on a case-by-case basis for this period based on the considerations given earlier. As the quantities of SAF uptake increase, and the supply chain shifts to one that is more sustainable, the blending location will likely move further upstream and the transportation method move from trucks to trains or pipelines, depending on the existing delivery method.

Scale-up period

A SAF scale-up period is anticipated over the next few decades if the right economic incentives are in place to reduce SAF prices to more competitive levels, driving up demand and leading to increases in production. The IEA estimates that about 50 million tonnes of SAF could be needed by 2035 under a sustainable development scenario [48], while other reports like Waypoint 2050 estimate a demand of up to 445 million tonnes by 2050 [23].

As volumes of SAF are scaled up, it will be necessary to capitalise on existing well-established and optimised supply chains and infrastructure. Running two systems in parallel should be avoided as far as possible. The earlier the SAF can be incorporated into the existing supply chain the more efficient the transportation method will be and the lower the costs and environmental impact. For this stage, it is likely that SAF will either be transported to the crude oil refineries for blending or that the conventional fuel suppliers will produce the SAF on-site. The blended product could then leave the refinery using existing infrastructure.

SAF scale-up can be incentivised through appropriate policies, financial mechanisms or government support, an efficient accounting mechanism, national or regional mandates, or carbon markets. Local mandates (regional, national, or state level) would pass the responsibility to the fuel suppliers, probably shifting the blending point further upstream.

Government mandates on minimum SAF content in aviation fuel need to be designed with some flexibility and allow for practical solutions, starting at low levels and then increasing over time. Some airports will be better placed to receive SAF than others, so mandates should allow for an uneven distribution of SAF to occur through a regional book-and-claim system. Trying to ensure there is a proportion of SAF on every single flight departing from a jurisdiction with a mandate may be challenging. For high blending ratios, it is likely that the blended fuel price would increase noticeably as SAF is still expected to continue to be more expensive than CAF [22]. This could distort the fuel market regionally so there should be ways to monitor and limit unintended consequences of mandates, like fuel tankering. A list of current and future mandates can be found on Appendix 2.

Remaining barriers for SAF scale-up

Despite the success that individual initiatives have had on implementing SAF and the recent SAF mandates seen in a few countries, SAF still faces scaling-up challenges, as summarised below.

- Higher price- SAF continues to be 2-7 times more expensive than conventional jet fuel and while the price gap is expected to reduce, it is unlikely that price parity with CAF will be reached without government intervention. Successful government policies can be studied and reviewed for adoption building on existing best practice in other sectors.
- Lack of long-term regulatory and economic certainty for investors.
- Many policy incentives worldwide are focused on decarbonising road transport, and so they prioritise the manufacture of Renewable Diesel (RD) over SAF competing for production and often in the same facility.
- SAF has a reduced market value compared to Renewable Diesel, so biorefineries need incentives and appropriate policy to prioritise SAF manufacture over RD. Switching RD refineries to produce SAF could leave a gap in the decarbonisation of road transport which is expected to continue to rely on liquid fuels, especially in the heavy-duty vehicle segment, despite increasing vehicle electrification.
- A blending step is still required and can be complicated and infrastructure intensive.
- Production needs to increase from today's 0.05 million tonnes to hundreds of millions of tonnes in 10-20 years for SAF to play a significant role in the decarbonisation of the aviation sector by 2050. This will require substantial investments and policy incentives.

CONCLUSIONS AND CALL FOR ACTION

This paper has reviewed some of the challenges and potential solutions associated to implementing SAF at different volumes and timescales. The benefits related to SAF's life cycle as well as the co-benefits of the non-CO_2 emissions were explored. The main conclusions are summarised below:

- The SAF should arrive at the airport already blended to minimise airport infrastructure requirements.
- It is neither feasible nor sustainable for all airports to have SAF available onsite. Reliance on book and claim system could reduce logistics challenges and improve the life-cycle CO_2 emission reductions of SAF.
- Blending and associated supply chains and infrastructure are important elements in scaling up SAF, requiring early evaluation of infrastructure needs for supply chains to be optimised.
- The best place for blending SAF will depend on the volumes of SAF required. It is possible that this will move upstream as the volumes increase to capitalise on higher capacity infrastructure and existing supply chains.
- Many stakeholders need to be involved in the process of implementing SAF at airports and they must work in a coordinated way to make this possible.
- Enabling 100% SAF aircraft and the supporting infrastructure will be a requirement for achieving and maintaining a net-zero aviation goal.
- 100% SAF currently does not meet the specifications of conventional jet fuel and is incompatible with today's aircraft and infrastructure, requiring an extra blending step.
- Limited research to date indicates that SAF has a positive impact on non-CO_2 emissions and local air quality impacts from SAF combustion. More research is required to confirm this for civil aviation.
- Emissions tests with low SAF blends (below 5%), representative of the near-term introduction of SAF, and higher blends like 30%, 40%, 50%, representative of future aspirations, are required on modern civil aircraft using commercially available SAF and CAF measured with ICAO Annex 16 Vol. II conforming equipment.
- Individual SAF combustion emissions tests cannot be used as a rule to create airport emissions inventories, as these are case-by-case dependent.
- The current SAF production and planned facilities will need to quickly scale up for aviation CO_2 emissions to be reduced in line with most aviation decarbonisation roadmaps.
- Consistency and flexibility of policy measures across the globe should be promoted and re-evaluated periodically to adapt to the technology advancement and reduce risks of compromising the solution/objectives by unintended effects.

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APPENDIX 1: CURRENT AND FUTURE SAF SUPPLIERS

🟥 **– ACTIVE FACILITIES** 🟦 **– PLANNED FACILITIES**

LanzaJet FLITE	United Kingdom
Type	AtJ-SAF
Capacity	85,000 t/yr

Fulcrum & Essar Oil	Stanlow, UK
Type	FT SAF
Capacity	75,000 t/yr

Velocys	Immingham, UK
Type	FT SAF
Capacity	50,000 t/yr

Greenergy*	Thames Enterprise Park, UK
Type	Co-processing
Capacity	22,000 t/yr

LanzaJet FLITE	Port Talbot, South Wales, UK
Type	AtJ-SAF
Capacity	76,000 t/yr

LanzaJet FLITE	United Kingdom
Type	Norway
Capacity	76,000 t/yr

SAF+ Consortium	Quebec, Canada
Type	PtL
Capacity	23,000 t/yr

RedRock Biofuels	Lakeview, Oregon
Type	SAF
Capacity	46,000 t/yr

Phillips 66	Rodeo, California
Type	HEFA-SAF
Capacity	220,000 t/yr

Indaba Renewable Fuels	California
Type	HEFA-SAF
Capacity	267,000 t/yr

Gevo	Silsbee, Texas
Type	SAF & Renewable gasoline
Capacity	287 t/yr

ReadiFuels*	Hull, Iowa
Type	HEFA
Capacity	36mn USG/yr

LanzaJet	Soperton, Georgia

LanzaJet to produce 8,000 t/yr in 2022. Additional capacity could be coming from Japan as well.

Fulcrum BioEnergy	Gary, Indiana
Type	SAF
Capacity	95,000 t/yr

Fulcrum BioEnergy	Reno, Nevada
Type	SAF
Capacity	33,000 t/yr

World Energy	Paramount, California
Type	SAF
Capacity	100,000 t/yr

Set to increase SAF production to 430,000 t/yr in 2022

Aemetis	Riverbank, California
Type	FT
Capacity	129,000 t/yr

Gevo/ New-Zero 1	Lake Preston, South Dakota
Type	SAF
Capacity	129,000 t/yr

Indaba Renewable Fuels	Missouri
Type	HEFA-SAF
Capacity	267,000 t/yr

Velocys Bayou Fuels	Natchez, Mississippi

Velocys to produce 72,000 t/yr by 2025 (not specifically jet)

ECB Group*	Villeta, Paraquay
Type	Co-processing
Capacity	800,000 t/yr

PKN	Plock, Poland
Type	HEFA
Capacity	7,500 t/yr

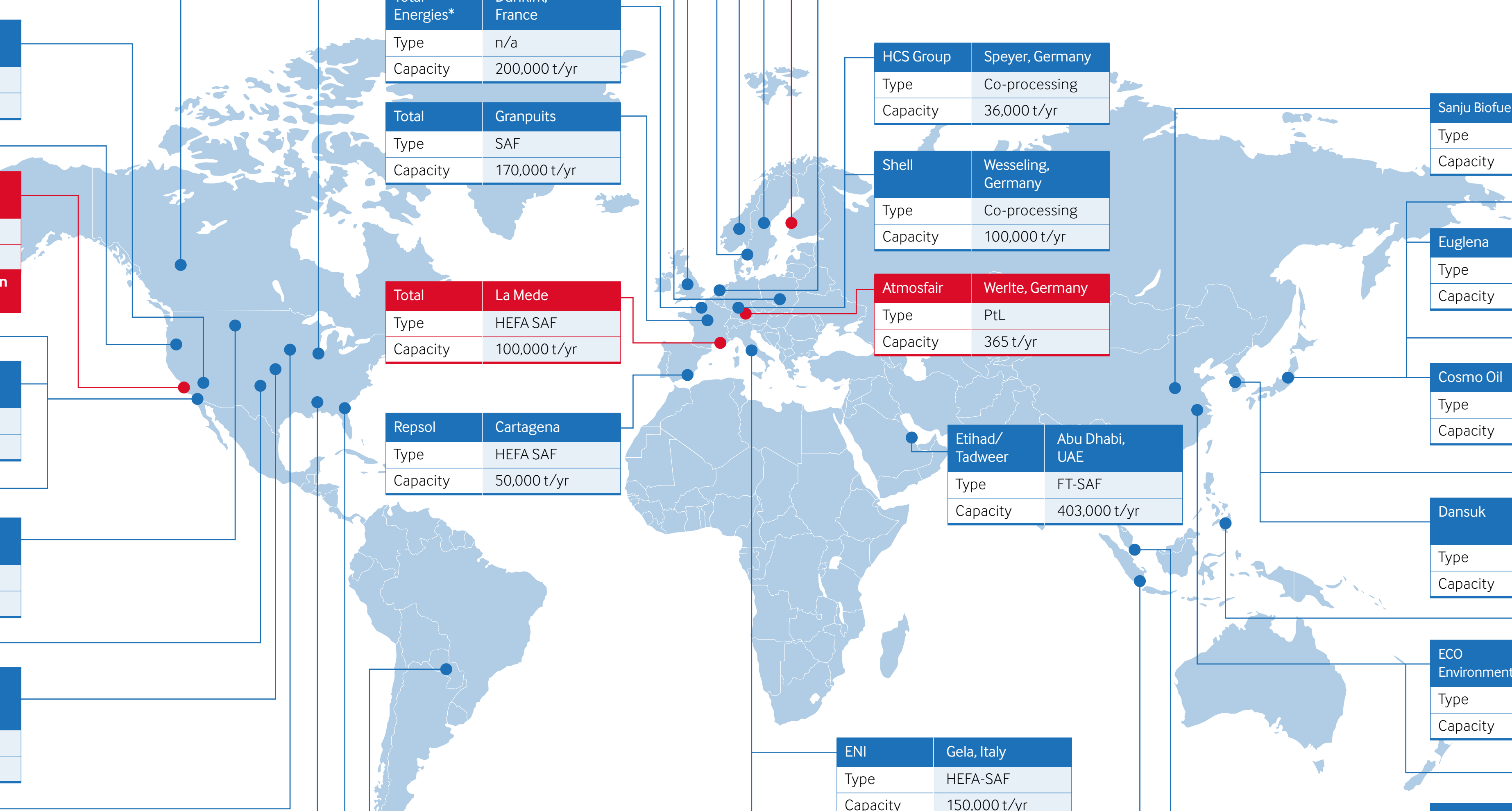
Total Energies*	Dunkirk, France
Type	n/a
Capacity	200,000 t/yr

Total	Granpuits
Type	SAF
Capacity	170,000 t/yr

Total	La Mede
Type	HEFA SAF
Capacity	100,000 t/yr

Repsol	Cartagena
Type	HEFA SAF
Capacity	50,000 t/yr

ENI	Livorno, Italy
Type	HEFA-SAF
Capacity	10,000 t/yr



ST1 + SCA	Gothenburg
Type	HEFA-SAF
Capacity	70,000 t/yr

Preem	Gothenburg
Type	Co-processing
Capacity	200,000 t/yr

Quantafuel	Eastern Norway
Type	FT SAF
Capacity	6,840 t/yr

Porsgrunn	Nordic Electrofuel
Type	PtL
Capacity	8,000

KLM	Vaxjo, Sweden
Type	SAF
Capacity	16,000 t/yr

St1 + SCA*	Ostrand
Type	HEFA
Capacity	300,000 t/yr

Shell/SAS/ LanzaJet	Forsmark, Sweden
Type	AtJ-SAF
Capacity	50,000 t/yr

Synkero	Amsterdam
Type	PtL SAF
Capacity	50,000 t/yr

Enerkem	Rotterdam
Type	PtL SAF
Capacity	60,000 t/yr

SkyNRG	Delfzijl
Type	HEFA-SAF
Capacity	100,000 t/yr

Neste	Porvoo
Type	HEFA-SAF
Capacity	100,000 t/yr

Shell	Rotterdam
Type	HEFA-SAF
Capacity	436,000 t/yr

Neste	Rotterdam
Type	HEFA-SAF
Capacity	500,000 t/yr

HCS Group	Speyer, Germany
Type	Co-processing
Capacity	36,000 t/yr

Shell	Wesseling, Germany
Type	Co-processing
Capacity	100,000 t/yr

Atmosfair	Werlte, Germany
Type	PtL
Capacity	365 t/yr

Etihad/ Tadweer	Abu Dhabi, UAE
Type	FT-SAF
Capacity	403,000 t/yr

ENI	Gela, Italy
Type	HEFA-SAF
Capacity	150,000 t/yr

ENI	Venice, Italy
Type	HEFA-SAF
Capacity	12,000 t/yr

ENI	Taranto, Italy
Type	HEFA-SAF
Capacity	267,000 t/yr

LanzaJet	TBD
Type	AtJ-SAF
Capacity	30,000 t/yr

Sanju Biofuels	Anyang, China
Type	HEFA-SAF
Capacity	100,000 t/yr

Euglena	Japan
Type	CHJ/HEFA-SAF
Capacity	221,819 t/yr

Cosmo Oil	Sakai, Japan
Type	Co-processing
Capacity	22,713 t/yr

Dansuk	Gusan, South Korea
Type	HEFA
Capacity	300,000 t/yr

ECO Environmental	Zhangjiaqsing, China
Type	HEFA-SAF
Capacity	50,000 t/yr

Neste	Singapore
Type	HEFA-SAF
Capacity	1,000,000 t/yr

Cilacap	Pertamina, Indonesia
Type	SAF
Capacity	334,000 t/yr

LanzaJet	Japan
Type	AtJ-SAF
Capacity	30,000 t/yr

Byogy	Kawasaki, Japan
Type	AtJ-SAF
Capacity	22,713 t/yr

LG Chem/ Dansuk	Daesan, South Korea
Type	HEFA
Capacity	150,000 t/yr

WasteFuel	Manila
Type	FT SAF
Capacity	86,309 t/yr

Sinopec	Zhejiang, China
Type	HEFA-SAF
Capacity	100,000 t/yr

Plaju*	Pertamina, Indonesia
Type	SAF
Capacity	905,000 t/yr

SAF production capacity map - courtesy of Argus media - adapted from: www.argusmedia.com/SAF

APPENDIX 2: EXAMPLES OF CURRENT AND PLANNED SAF MANDATES

Country	Blending level	Target type	Status
Norway	0.05% (2020), 30% (2030)	Mandate(2021)-target (2030)	Implemented mandate only
Sweden	0.8% (2021), 27% (2030)	Mandate (2021)-target (2030)	Implemented mandate only
USA	FAA-1 billion US gallon SAF/year (2018) US RFS: 36 billion gallons of renewable fuels (2022)	Policies	–
UK	10% (2030), Up-to 75% (2050)	Mandate	In consultation
Europe	2% (2025), 5% (2030), 0.7% e-fuel (2030), 20% (2035), 5% e-fuel (2035), 32% (2040), 8%-e-fuel (2040), 38% (2045), 11% e-fuel (2045), 63% (2050), 28% e-fuel (205p0)	Mandate	Proposed to implement in 2025
France	1% (2022)- Mandate, 2% (2025), 5% (2030), 50% (2050)	Mandate and Aspirational goal	On-going discussion for 2022
Spain	2% (2025)	Mandate	On-going discussion

ACKNOWLEDGEMENTS

Dr Alejandro Block
ATI

Dr Cristina Garcia Duffy
ATI

Prof. Simon Weeks
ATI

Juliana Scavuzzi
ACI

Jennifer Desharnais
ACI

Anu Joseph Padanilam
ACI/ENAC

Marina Bylinsky
ACI Europe

S. Le Moing
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R. Dean
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Dr. D. Parmenter
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Michael O Connor
Athens International

Anamaterou Evdokia
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Olav Mosvold Larsen
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Prof. Pericles Pilidis
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Elisabeth Woeldgen
Hasselt University

Robert Malina
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Tom Harrison
Heathrow Airport

Matt Prescott
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Dr Monica Soria Baledon
IATA

Alastair Blanshard
ICF

Prem Lobo
NRCC

Denise pronk
Royal Schiphol Group

Erin Cooke
San Francisco International Airport

Thomas Roetger
TRIAC

Myriame Gabay
Vancouver International Airport

Marion Town
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Emanuel Fleuti
Zurich Airport

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