

SUSTAINABLE AVIATION FUELS AND ETHANOL



MAY 2023

MECAS(23)06



International Sugar Organization



Copyright © 2023 by International Sugar Organization

All rights reserved. No part of ISO publications may be reproduced, distributed, or transmitted in any form or by any means, including photocopying, recording, or other digital (e.g. e-mail) or analog methods, without the prior written permission of the International Sugar Organization except for the use of brief quotations making reference to the International Sugar Organization.



The views expressed in this document are those of the ISO Secretariat. They do not necessarily represent the views of the ISO Members.



**Sustainable Aviation Fuels and Ethanol
MECAS(23)06
May 2023**

International Sugar Organization

**One Canada Square
Canary Wharf
London E14 5AA**

**General Enquiries:
+44 (0)20 7513 1144**

**Publications :
+44 (0)20 7715 9436**

**E-mail :
Economics@isosugar.org
Publications@isosugar.org
Info@isosugar.org**

Web: www.isosugar.org

18 May 2023

Abstract

The aviation sector remains in need of decarbonisation. Unlike in road transportation, the low energy density of batteries means that electrification cannot be applied to commercial jets. Meanwhile, improvements in efficiency have not been able to keep up with an increase in demand.

Sustainable Aviation Fuels represent the option with the most potential to decarbonise aviation, and a solution which will remain relevant well into the 21st century. Other aircraft propulsion technologies are decades away from becoming viable and present efficiency challenges of their own. While SAF offtake is currently limited, usage is expected to grow sharply to achieve long-term voluntary sector targets as well as to comply with emerging inclusion policies. However, an enormous challenge for the SAF industry remains, as the jet fuel market is large, and demand is growing.

Importantly for the sugar sector, the standards of the Alcohol-to-Jet (ATJ) conversion process were revised in 2018 to include ethanol as an approved feedstock. This means that SAF can now be produced anywhere using ethanol from a suitable feedstock such as cane or beet. This represents a new diversification avenue and allows the sugar sector to continue to support the global decarbonisation effort.

The challenge for sugar industries will be in providing affordable and sustainable feedstocks that can be used for SAF conversion. Key in scaling up this energy transition will be an enabling policy environment that promotes the commercialisation of SAF and helps close the cost gap compared to petroleum-based jet fuel.

Table of Contents

Introduction	3
Chapter 1	4
1.1 Overview of the Jet fuel market	4
1.2 Emissions	5
1.3 The Challenge ahead	6
Chapter 2	9
2.1 What are Sustainable Aviation Fuels?	9
2.2 Where is it currently being distributed?	12
2.3 SAF already under offtake agreements	13
2.4 SAF Production	16
2.5 Recognised feedstocks under ICAO CORSIA	17
2.6 Approved conversion processes / processes under evaluation	19
2.7 Conversion yields, capital costs, and prices	22
2.8 Which pathway is the most relevant to the Sugar industry?	26
2.9 The ATJ process in more detail	26
Chapter 3	28
3.1 Policies in place or under development	28
3.2 SAF policy in Europe	29
3.3 SAF Policies in the US	29
3.4 SAF and Sugar Sector Feasibility Studies	30
Conclusion	33
Appendix	34

INTRODUCTION

The aviation sector is dominated by fossil-fuels and, alone, accounts for over 2% of global energy-related CO₂ emissions. It is also projected to grow substantially over the coming decades. With a pressing need to decarbonise transportation to achieve climate commitments, attention is shifting to so-called hard to decarbonise sectors such as Aviation. The aviation industry recognises this decarbonisation need, and airlines have committed to becoming carbon neutral by 2050. However, this commitment is not without its challenges. Despite efficiency improvements in aircraft design and engines, the rise in demand for aviation has led to increasing emissions.

Sustainable Aviation Fuels (SAF) have been touted as the best means of achieving emission reductions in the aviation sector in the short term, with importance that is set to remain in the long-term. Unlike road and rail vehicles, the commercial aviation fleet cannot be electrified with battery technologies. Other aircraft propulsion technologies are decades away from becoming viable and present efficiency challenges of their own. The production and use of SAF has historically been constrained by high costs, compared to fossil-based jet fuel, but the sector is set to grow rapidly if supported by government regulation, and as production pathways reach economies of scale.

Importantly for the sugar sector, the standards of the Alcohol-to-Jet (ATJ) conversion process were revised in 2018 to include ethanol as an approved feedstock. This means that SAF can now be produced anywhere using ethanol from a suitable feedstock such as cane or beet. This represents a new diversification avenue and allows the sugar sector to continue to support the global decarbonisation effort.

An overview of the jet fuel market is presented, discussing national and global emissions goals and the challenges ahead. Chapter 2 examines the nature of SAF, defining its meaning, examining the current state of the market and offtake structures. Attention is then shifted to the production of SAF, including the recognised feedstocks and approved conversion pathways, as well as their associated costs and prices, to better understand where the sugar sector can contribute. SAF policies are reviewed, highlighting differences in approach between the US and Europe. Findings from feasibility studies conducted by the Round Table on Sustainable Biomaterials (RSB) are discussed subsequently, highlighting the potential of SAF in Brazil and South Africa.

CHAPTER 1

1.1 OVERVIEW OF THE JET FUEL MARKET

When discussing biofuels or alternative fuels, the focus is usually on ground transportation, where ethanol and biodiesel are mixed with petrol or diesel at varying blend rates, or, in the case of ethanol, even used as a standalone fuel. These markets are highly segregated, with a vast pool of producers, sellers, and consumers, each with diverse needs. With such varied requirements from motorists, with some driving more and others less, the transactions for gasoline and diesel sales tend to be short-term, at spot values and in much smaller volumes, which can lead to greater price variability. The ground transportation market is also undergoing a transition towards electrification and, because of this shift to more efficient drivetrains and policies prioritising the electrification of the light-duty vehicle fleet in various parts of the world, the demand for gasoline is likely to fall in the coming decades.

The global jet fuel market is vastly different from the petrol and diesel ground transportation markets in terms of market size, consumers, fuel property variation, and demand locations. In contrast to ground transportation, the jet fuel market has a much smaller pool of customers (airlines and a few fuel distributors) who purchase most of their fuel using long-term purchase agreements, and some smaller volume customers who purchase fuel at spot prices. According to the International Air Transport Association (IATA), only about 290 airlines account for over four-fifths of air traffic, with several thousand smaller airlines, corporate fleets, and private owners representing the balance. Jet fuel accounts for up to 30% of airlines operating costs, which leads them to be very price sensitive.

Also, differently to road fuel markets, jet fuel specifications are not altered based on climate, time of the year, and location. The aviation industry has adopted rigorous safety standards and procedures, for operating and maintaining equipment, and this includes strict specifications for the fuel used. The two most widely utilized standards to ensure jet fuel is fit for purpose are the American Society for Testing Materials (ASTM) standard D1655 - *Standard Specification for Aviation Turbine Fuels*¹ and DEF STAN 91-91. The ASTM standard details the specifications for Jet A-1 fuel, setting requirements for composition, volatility, fluidity, combustion, corrosion, thermal stability, materials compatibility, water contamination, and additives such as antioxidants, metal deactivators, fuel system icing inhibitor, electrical conductivity improver, leak detection additive, lubricity improvers, and biocides. Because of this stringent quality control for aviation fuels, it is crucial

¹ [D1655 Standard Specification for Aviation Turbine Fuels \(astm.org\)](https://www.astm.org/standards/D1655)

that any fuel mixed with jet fuel be fully fungible and completely interchangeable – or in simple jargon a ‘drop-in’ fuel.

The jet fuel supply chain is also different from that of road fuels because of the large volumes of jet fuel delivered to airports. Generally, shipment is by pipeline or barge from refineries to transit terminals, and from there to storage near airports. Airlines must also purchase fuel from many suppliers, since not every fuel supplier operates at every airport. Many airlines also purchase fuel directly from refineries, which means the airline takes ownership of the fuel at the refinery gate and ships it to where it is needed, to minimise disruption².

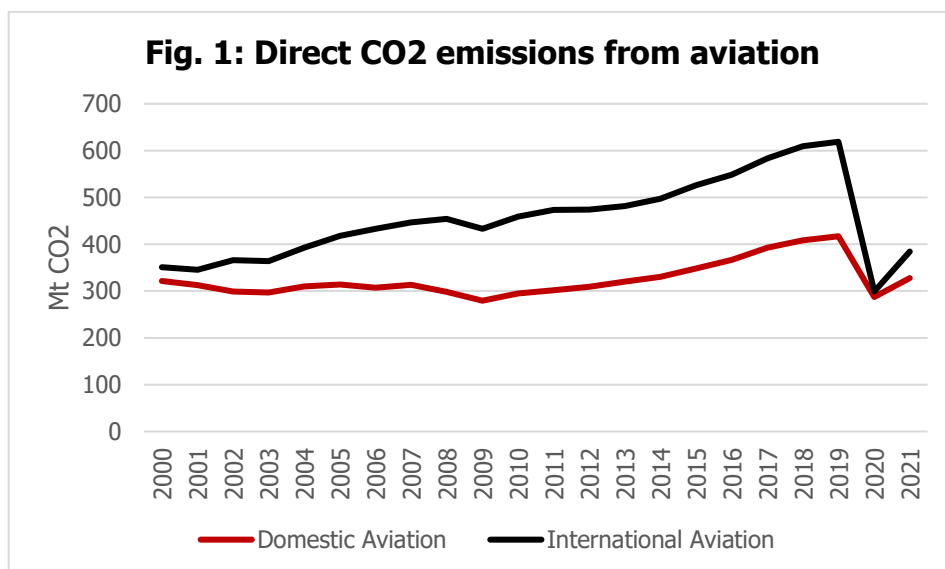
Finally, of particular importance is the fact that the commercial aviation fleet cannot be fully electrified with battery technologies. The low energy density of current batteries makes the required batteries very heavy and severely limits opportunities for electrification to only very smallest aircraft. Other propulsion technologies are under development, but according to the aviation industry their initial deployment is unlikely to occur before 2050. This presents a serious challenge to the aviation sector, as demand growth has spurred additional CO₂ emissions, despite efficiency improvements. This explains the sector’s current reliance on oil-based products and suggests that interest in alternatives, such as Sustainable Aviation Fuels (SAF), will have an important role to play well into the 21st century.

1.2 EMISSIONS

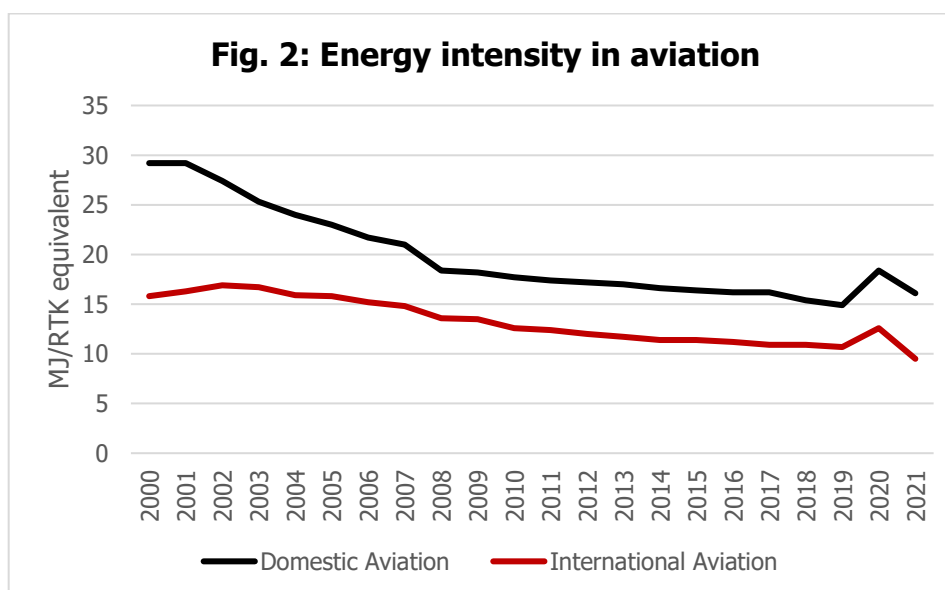
According to the International Energy Agency (IEA), aviation accounted for over 2% of global energy-related CO₂ emissions in 2021, however, it is growing faster in recent decades than road, rail, or shipping³. While emissions fell sharply in 2020 during the Covid-19 pandemic, in 2021, emissions have recovered by nearly a third of the fall and are expected to continue to grow rapidly, surpassing pre-pandemic levels in the coming years.

² ASTM, 2018 - <https://s3.wp.wsu.edu/uploads/sites/192/2018/03/clearinhouse.pdf>

³ <https://www.iea.org/reports/aviation>



While newer aircraft are up to 20% more fuel efficient than models they replace, see Fig. 2, the growth in the aviation sector has outpaced these efficiency improvements. With efficiency improvements slowing over time, the sector needs to consider alternatives in order to decarbonise and improve its green credentials.



1.3 THE CHALLENGE AHEAD

In its 41st Assembly, the International Civil Aviation Organisation (ICAO) adopted a long-term aspirational goal (LTAG) for international aviation of net-zero carbon emissions by 2050 to support the UNFCCC Paris Agreement's climate goals. Achieving this will be an enormous challenge, as the aviation industry must progressively reduce its emissions while accommodating growing demand.

The ICAO's Committee on Aviation Environmental Protection (CAEP) formed a Long-Term Aspirational Goal Task Group (LTAG-TG), in coordination with other CAEP working groups. This Group gathered data from internal and external sources and developed three integrated in-sector scenarios based on selected scenarios for technology, fuels, and operations, according to readiness and attainability levels. Scenarios were analysed to understand the impacts on CO₂ emissions, costs and investments, as well as potential implications on aviation growth, noise, and air quality. The LTAG-TG also documented underlying data for analysing the impact in all countries especially developing countries. It concluded that:

- Advanced tube and wing aircraft have a clear potential to improve the fuel (energy) efficiency of the international aviation system with some incremental contribution from aircraft with unconventional configurations.
- Hydrogen powered aircraft would exhibit worse energy efficiency, relative to aircraft operating on liquid fuels, noting that emissions reduction figures would come from life cycle analysis of the hydrogen.
- There are opportunities for operations to reduce CO₂ emissions through improvements in the performance of flights, including unconventional measures such as formation flying.
- The costs and investments associated with the scenarios are largely driven by fuels (e.g. SAF) acknowledging that incremental costs of fuels (i.e. minimum selling price of SAF compared to conventional jet fuels) further motivate fuel efficiency improvements from aircraft technology and operations. This will also require some investments from governments and industry.

Importantly, the LTAG-TG found that drop-in SAF fuels have the largest impact on CO₂ emissions driving the overall reductions by 2050. This is, to some extent, independent of the technology and operations scenarios. Hydrogen is not expected to have a significant contribution by 2050 (with a projected energy share of only 1.9% in 2050) but this may increase in the 2050s and 2060s if it becomes technically feasible and commercially viable.

The aviation industry agrees with this assessment. At its 77th Annual General Meeting, in October 2021, the International Air Transport Association (IATA), approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050⁴. To abate as much CO₂ as possible, many in-sector solutions were flagged, such as sustainable aviation fuels, new aircraft technology, more efficient operations and infrastructure, and the development of new zero-emissions energy sources such as hydrogen power. Meanwhile, any emissions that cannot be eliminated at source need to be eliminated through out-of-sector options such as carbon capture and storage and credible offsetting schemes.

⁴ <https://www.iata.org/contentassets/dcd25da635cd4c3697b5d0d8ae32e159/iata-agm-resolution-on-net-zero-carbon-emissions.pdf>

According to IATA's decarbonisation plan, the industry in 2050 will need to mitigate 1.8 gigatons of carbon. Their potential scenario is that 65% of this will be abated through the use of SAF. Adding efficiency improvements and new propulsion technologies (including hydrogen) to SAF would still not be enough to reach net-zero emissions. As such, the remainder of CO₂ abatement would need to come from carbon capture-and-storage (CCS) as well as carbon offsets.

Key to success for the IATA's plan would include fuel-producing companies bringing large scale, cost-competitive SAF to the market, as well as airport operators providing the needed infrastructure to supply SAF in a cost-effective manner. This energy transition would need to be supported by a holistic government policy framework. Technologies exist, but production incentives are still needed to increase supply and lower costs.

CHAPTER 2

In this chapter, Sustainable Aviation Fuels are discussed in more detail. First, a definition of SAF is provided and the current standards and characteristics are examined. Approved feedstocks and conversion processes are then discussed, in order to underpin where and how the sugar sector can contribute and benefit. Finally, cost profiles, investment requirements, and returns are examined to better understand trade-offs associated with various conversion processes.

2.1 WHAT ARE SUSTAINABLE AVIATION FUELS?

Sustainable Aviation Fuels (SAF) are non-petroleum-based 'drop-in' low carbon fuel alternatives to the jet fuel used in the aviation industry. It is an umbrella term, encompassing fuels that are produced from various feedstocks and through various conversion processes, and whose lifecycle emissions are significantly lower than traditional jet fuel. They have been defined by the International Civil Aviation Organization (ICAO) as fuels that:

- "(i) achieve net GHG (greenhouse gas) emission reductions on a life cycle basis;
- (ii) respect the areas of high importance for biodiversity, conservation and benefits for people from ecosystems, in accordance with international and national regulations; and,
- (iii) contribute to local social and economic development, and competition with food and water should be avoided"⁵.

The chemical and physical characteristics of SAF are nearly identical to those of conventional jet fuel and SAF can therefore be safely mixed with existing jet fuel to required blend levels, use the same supply infrastructure, and do not require the adaptation of aircraft or engines. Because of these properties, these fuels are fully fungible and considered 'drop-in' solutions, meaning they can be safely used in existing commercial aircraft and current aviation fuel infrastructure. As explained in the previous chapter, given that the same aircraft can be fuelled in different countries, international specifications have been adopted for jet fuels. The standard regulating the technical certification of SAF worldwide is ASTM D7566⁶. This standard evaluates which technologies, under specific circumstances, can be used for producing SAF, and its annex describes and sets out the maximum blend percentage with conventional jet fuel. As a result, in order to be considered an approved

⁵ ICAO 2017, https://www.icao.int/environmental-protection/knowledge-sharing/Docs/Sustainable%20Aviation%20Fuels%20Guide_vf.pdf

⁶ ASTM D7566, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. West Conshohocken, PA: ASTM International

conversion process, a new SAF production pathway requires significant and extensive evaluation.

Approved SAF are made in bio-refineries (facilities that convert biologically-based products into fuel) and delivered to airports via pipelines, stored in common fuel tanks, and then delivered to planes through conventional hydrant systems at major airports. Upon being blended, the fuel is certified to ASTM D1655 standards and is then regarded as conventional Jet A or Jet A1 kerosene.

However, simply meeting the ASTM technical certification criteria does not guarantee that the SAF is sustainable, as these merely describe the physical properties of the fuel. To be considered sustainable and fit for purpose, different SAF need to meet sustainability requirements whose criteria are being developed as part of the work on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). To demonstrate that the SAF can contribute to overall carbon emissions reductions, a lifecycle analysis and sustainability certification are required. Such certification usually considers various criteria to determine whether SAF is sustainable, including lifecycle carbon emissions, direct and indirect land use change, authorised land categories, water air and soil considerations, fertiliser and pesticide management, waste management, and invasive species controls.

Various organisations assess the production of SAF to determine whether it meets sustainability criteria. Nevertheless, there are still significant differences between the criteria and certification methods applied by each organisation⁷. According to IATA, a group of 28 airlines formed the Sustainable Aviation Fuel Users Group, which has pledged to only use SAF that meets internationally recognised criteria, such as those set out by the Round Table on Sustainable Biomaterials (RSB).

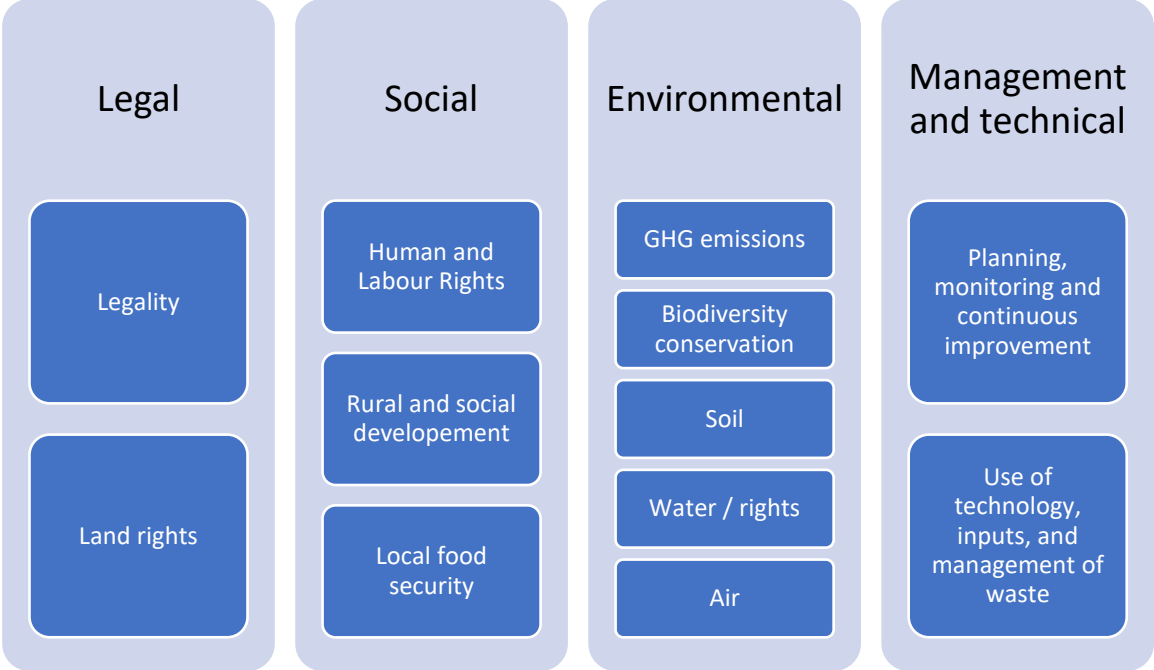
⁷ <https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-and-sustainability.pdf>

Box 1 RSB Principles & Criteria

The Roundtable on Sustainable Biomaterials (RSB) is a global, multi-stakeholder, independent organisation that drives the development and expansion of a bio-based and circular sector on a global scale through sustainability solutions, certification, and collaborative partnerships.

The sustainability standard developed by the Roundtable on Sustainable Biomaterials (RSB) is recognised by the aviation industry to be best-in-class, covering many sustainability aspect — including food security, rural development, and the protection of ecosystems. Certification to the RSB Standard covers the production from any bio-based feedstock, biomass derived material, or advanced fuel — as well as complete supply chains and new technologies.

Fig. 3: RSB Principles and Criteria



Source: RSB

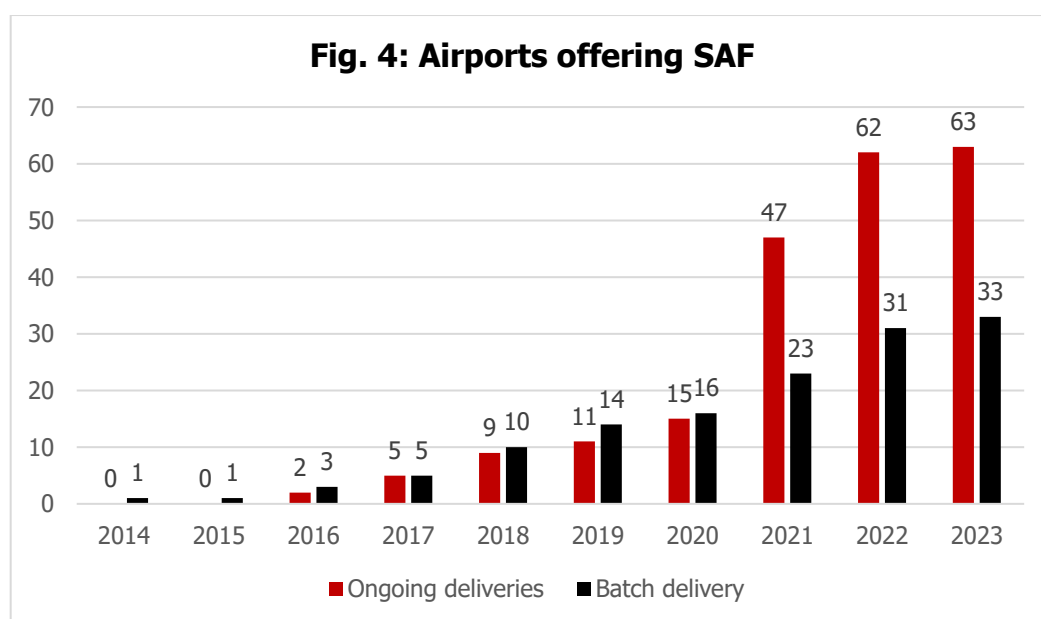
In 2016, CORSIA was adopted by Member countries of the ICAO to stabilise net CO₂ emissions from international aviation from 2021. It has applied to international aviation since January 2019, with all airlines required to report their CO₂ emissions on an annual basis. From January 2021, international flights became subject to offsetting obligations. The original CORSIA baseline (from which offsetting requirements would be calculated) was agreed to be an average of 2019 and 2020 emissions. With the Covid-19 pandemic, and due to the sharp fall in air transport demand in 2020, the ICAO Council decided to use only 2019 emissions as CORSIA’s baseline for the period of 2021-2023. In October 2022, ICAO set a target of 85% of 2019 emissions as CORSIA’s baseline from 2024 until the end of the scheme in 2035. To take into account the special circumstances and national capacities to comply, ICAO member states agreed to implement CORSIA’s offsetting requirements in phases - a pilot phase (2021-2023), a first phase (2024-2026), and a second phase (2027-2035)⁸. For the first two phases (2021-2026),

⁸ <https://www.icao.int/environmental-protection/CORSIA/pages/default.aspx>

participation is voluntary. From 2027 onwards, participation will be determined based on 2018 Revenue Tonne-Kilometres (RTK) data⁹. As of January 2023, 115 countries announced their intention to voluntarily participate in CORSIA, with 4 more countries (Seychelles, Sierra Leone, Solomon Islands, and Mauritius) announcing their intention to participate from January 2024.

2.2 WHERE IS IT CURRENTLY BEING DISTRIBUTED?

About 300 mln litres of SAF were produced in 2022 and used by more than 50 airlines in over 450,000 flights¹⁰. This compares to a global jet fuel market of around 400 bln litres. According to ICAO, several airports are now offering SAF either continuously or in batches. Fig. 4, below, shows how the number of initiatives to deploy SAF in airports has grown quickly over the last decade, from only a single airport in 2014 to 96 airports so far in 2023.



The majority of these airports are located in the US and Europe, although a few airports located in Australia, China, Japan, Malaysia, New Zealand, South Africa, and the UAE are also currently providing SAF.

⁹ One Revenue Tonne-Kilometer is generated when a metric tonne of revenue load is carried one kilometer.

¹⁰ <https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/#tab-2>

2.3 SAF ALREADY UNDER OFFTAKE AGREEMENTS

As noted earlier, conventional jet fuel accounts for up to 30% of airlines operating costs. Large airlines have significant bargaining power and tend to negotiate offtake agreements with fuel providers for long periods. SAF is currently much more expensive than conventional jet fuel. Nevertheless, airlines and companies have an interest in reducing their dependence on conventional fuel by using SAF and find that SAF can also be valuable as a marketing tool. As a result, SAF production has increased, logistics are improving, and SAF is being gradually introduced into regular airlines operations. Table 1 and 2, below, list offtake agreements which shows the major players in SAF production and consumption today.

Table 1: SAF Offtake Agreements

	Fuel producer	Total offtake volume (mln litres)	Number of offtake agreements
1	Gevo	9550.03	14
2	Fulcrum	6719.10	3
3	Alder Fuels	5678.12	1
4	Shell	2792.92	5
5	Neste	2295.22	14
6	Raven SR	1561.64	1
7	DG Fuels	1457.38	1
8	OMV	1433.45	5
9	Aemetis	1272.43	9
10	Dimensional Energy	1135.62	1
11	Velocys	1105.34	2
12	ECB Group	1050.08	2
13	Total Energies	999.45	1
14	Air Company	999.18	3
15	SkyNRG	936.98	1
16	DG Fuels	749.59	1
17	SG Preston	526.17	2
18	SAF+ consortium	405.82	1
19	Wastefuel	378.54	1
20	Fidelis New Energy	348.26	1
21	RedRock	158.99	2
22	World Energy	106.92	10
23	IdunnH2	56.22	1
24	Lanzajet	46.94	2
25	Prometheus Fuels	37.85	1
26	BP	30	1
27	Phillips 66	9	3
28	Others	2.50	10
	Grand Total	41846.64	99

Source: ICAO

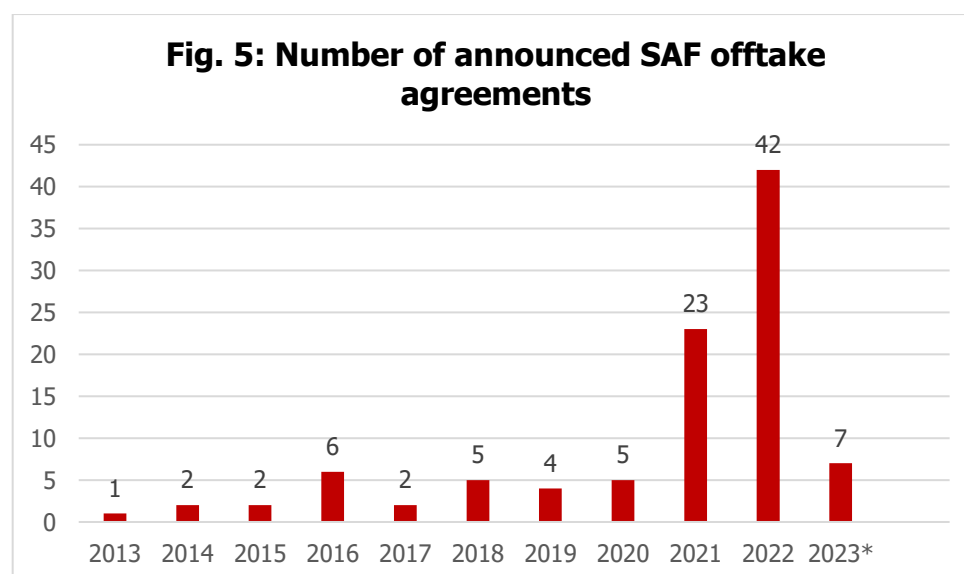
Table 2: SAF Offtake Agreements (Purchasers)

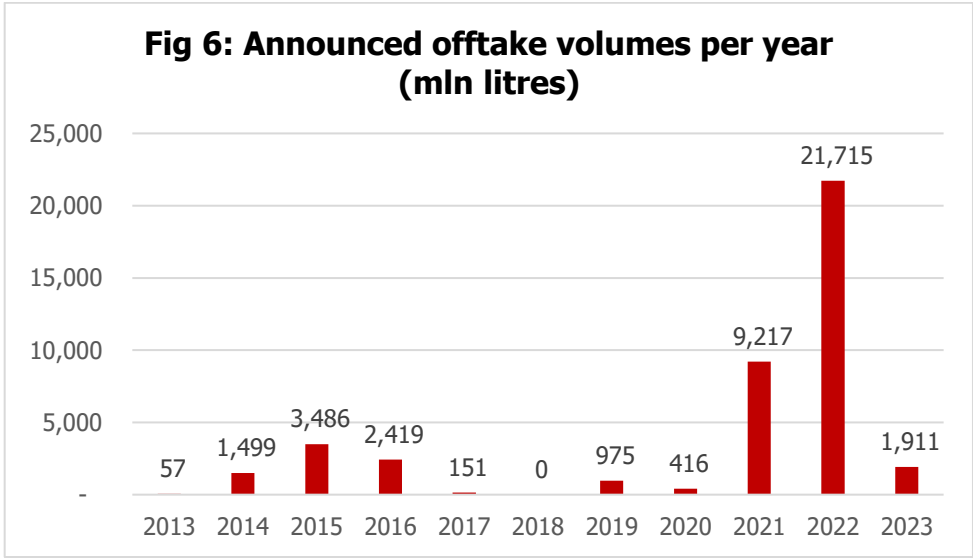
	Fuel purchaser	Total offtake volume (mln litres)	Number of offtake agreements
1	United Airlines	10,513.98	6
2	Delta	3862.25	8
3	OneWorld	3785.41	1
4	Lufthansa Group	3247.98	2
5	Air France - KLM	2988.34	3
6	AirBP	2192.71	2
7	American Airlines	2134.21	4
8	Japan Airlines	1561.64	1
9	Cathay Pacific	1419.53	1
10	KLM	937.04	4
11	Southwest Airlines	829.00	1
12	DHL Express	798.72	1
13	Shell	750.08	1
14	Alaska Airlines	719.98	3
15	Ryanair	650.38	3
16	Virgin Atlantic	646.02	3
17	Undisclosed	526	1
18	JetBlue	499.67	3
19	Air Transat	408.82	1
20	Jet Blue	379.87	2
21	Netjets	378.54	1
22	IAG	373.78	2
23	oneworld	280.88	1
24	Wizz Air	231.12	1
25	Hawaiian Airlines	189.27	1
26	Jet Blue	189.27	1
27	Finnair	158.99	2
28	Lufthansa	151.42	1
29	Qantas	151.42	1
30	Air Lingus	118.68	1
31	Iberia	113.56	1
32	JAL	100.31	1
33	Qatar Airways	94.64	1
34	Qantas	83	2
35	Southwest	79.49	1
36	FedEx	79.49	1
37	Cathay Pacific	57.54	1
38	Icelandair	56.22	1
39	British Airways	46.94	2
40	SAS	18.93	2
41	Air Canada	9.5	1
42	IAG Cargo	9	2
43	Amazon Air	6.81	1

44	Boeing	2.27	1
45	Austrian Airlines	1.87	1
46	Singapore Airlines / Scoot	1.25	1
47	VistaJet	0.38	1
48	SAS, BRA, Kalmar Municipality	0.3	1
49	Lufthansa Cargo / Kuehne + Nagel	0.13	1
50	Gulfstream	0	1
51	Cathay Pacific / Airbus	0	1
52	Airbus / China Airlines	0	1
53	Airbus / Jet Blue	0	1
54	Swedavia	0	1
55	AirTotal	0	1
56	All Nippon Airways (ANA)	0	1
57	Korean Air Lines	-	1
58	ADR Rome Airport	-	1
59	Deutsche Post DHL	-	1
60	SEA Milan Airports	-	1
61	Airbus	-	1
62	Lufthansa	-	1
Grand Total		41846.64	99

Source: ICAO

Currently, a major challenge for SAF suppliers, intending to supply the aviation market, is the risk of demand continuity. Given the high price of SAFs and airlines' low profit margins, many airlines have been hesitant to commit to large SAF purchases. Nevertheless, Figs. 5 and 6, demonstrate how the number of announced offtake agreements has increased quickly over the last decade, and how this has significantly boosted offtake volumes.

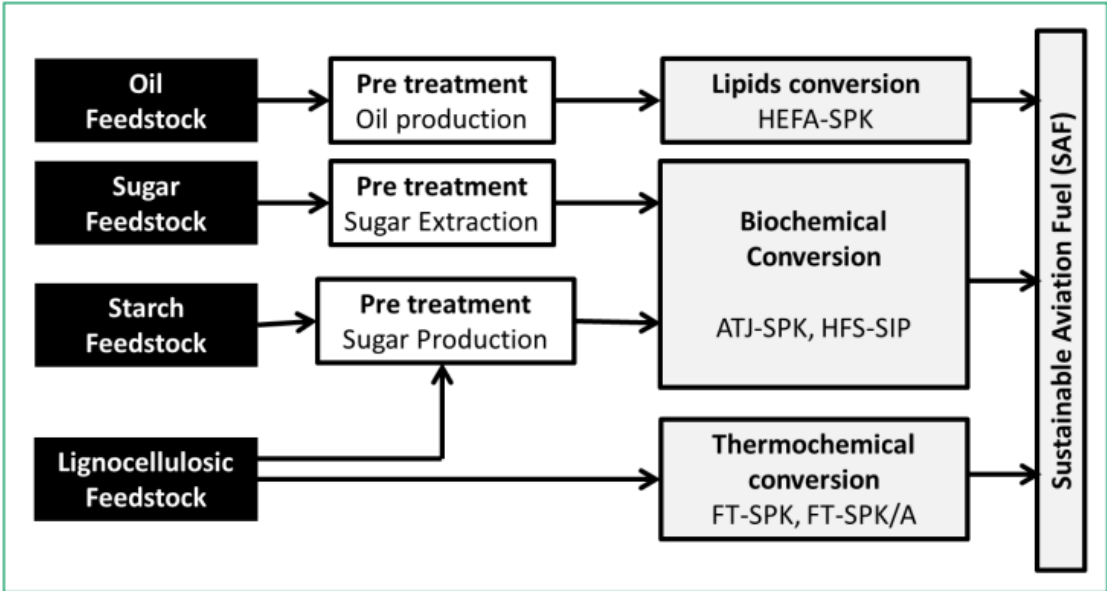




2.4 SAF PRODUCTION

The production of SAF must undergo a series of stages, which begins with feedstock production, followed by a pre-treatment in preparation for a conversion process which produces the SAF. Fig. 7, below, illustrates a general view of SAF pathways today.

Fig. 7: General view of SAF pathways



Source: ICAO

As discussed previously, only fuels that achieve the ASTM 7566 standard specifications and are certified as sustainable should be considered for commercial use under the heading of SAF.

2.5 RECOGNISED FEEDSTOCKS UNDER ICAO CORSIA

Various feedstocks can be used to produce SAF. Under the ICAO's CORSIA framework, these feedstocks are broadly grouped into five categories:

- **Primary and co-product feedstocks** are the main outputs of a production process. These products have significant economic value and elastic supply, (i.e., there is evidence that there is a causal link between feedstock prices and the quantity of feedstock being produced).
- **By-products** are secondary outputs with inelastic supply and low economic value.
- **Wastes** are materials with inelastic supply and no economic value. A waste is any substance or object which the holder discards or is required to discard. Raw materials or substances that have been intentionally modified or contaminated to meet this definition are not covered by this definition.
- **Residues** are secondary materials with inelastic supply and little economic value.

Under the CORSIA framework, by-products, wastes, and residues are entitled to an ILUC value of zero on the calculation of the life cycle emission value of the SAF. Primary and co-products can also be given a zero ILUC value with the use of low LUC risk methodologies defined in Chapter 5 of the ICAO document "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values"¹¹.

Table 3, below, details these feedstocks and their respective classification. For the sugar industry, the feedstocks are sugarcane and sugar beet (main products), Molasses (co-product), residues such as bagasse and straw (trash), and possibly waste gases (biogas). It is important to note that the list is constantly under assessment and the proposal of inclusion of new SAF feedstocks is possible.

Table 3: Feedstocks Currently Recognised for SAF Production

Feedstock	Classification	Reference ¹²
Palm fatty acid distillate	By-product	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values"
Technical Corn oil	By-product	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values"
Molasses	co-product	Table 1, ICAO document "Actual LCA methodology"

¹¹ <https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions.pdf>

¹² ICAO document containing "Default LCA values" and "actual LCA methodology":
<https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx>

		Table 3, ICAO document "Default LCA values"
Brassica carinata oil	Main product	Table 2, ICAO document "Default LCA values"
Camelina oil	Main product	Table 2, ICAO document "Default LCA values"
Corn grain	Main product	Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Jatropha oil	Main product	Table 2, ICAO document "Default LCA values"
Miscanthus (herbaceous energy crops)	Main product	Table 1, ICAO document "Default LCA values" Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Palm oil	Main product	Table 2, ICAO document "Default LCA values"
Poplar (short-rotation woody crops)	Main product	Table 1, ICAO document "Default LCA values"
Rapeseed oil	Main product	Table 2, ICAO document "Default LCA values"
Soybean oil	Main product	Table 2, ICAO document "Default LCA values" Table 6, ICAO document "Default LCA values"
Sugar beet	Main product	Table 5, ICAO document "Default LCA values"
Sugarcane	Main product	Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values" Table 5, ICAO document "Default LCA values"
Switchgrass (herbaceous energy crops)	Main product	Table 1, ICAO document "Default LCA values" Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Agricultural residues: Bagasse	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Cobs	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Husks	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Manure	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Nut shells	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Stalks	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Stover	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Straw	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Bark	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Branches	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Cutter shavings	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Leaves	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Needles	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Pre-commercial thinnings	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Slash	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Tree tops	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Crude glycerine	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Crude Tall Oil	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Empty palm fruit bunches	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Forestry processing residues	Residue	Table 1, ICAO document "Actual LCA methodology"

Processing residues: Palm oil mill effluent	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Sewage sludge	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Tall oil pitch	Residue	Table 1, ICAO document "Actual LCA methodology"
Municipal solid waste (MSW)	Waste	Table 1, ICAO document "Default LCA values" Table 1, ICAO document "Actual LCA methodology"
Tallow	Waste	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values" Table 6, ICAO document "Default LCA values"
Used cooking oil	Waste	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values" Table 6, ICAO document "Default LCA values"
Waste gases	Waste	Table 1, ICAO document "Actual LCA methodology" Table 4, ICAO document "Default LCA values"

Source: ICAO

2.6 APPROVED CONVERSION PROCESSES / PROCESSES UNDER EVALUATION

As of April 2023, 9 conversion processes for SAF production have been approved by ASTM and 8 other conversion processes are currently under evaluation. A conversion process is defined as a type of technology which is used to convert a feedstock into aviation fuel. The main criterion for the industry is for the SAF to be able to be dropped-in to conventional jet fuel, with a blend of up to 50%. These processes can then be largely classed into four groups: hydroprocessed esters and fatty acids - HEFA, alcohol to jet - ATJ, Fischer-Tropsch (FT), and pyrolysis. Each technology can utilise different feedstocks, discussed in more detail later, and therefore have varying associated costs and minimum selling prices, impacting their competitiveness.

Table 4, below, lays out the approved conversion processes, their possible feedstocks, and the maximum blend that is authorised. Of these, the lowest hanging fruit for the sugar industry is the ATJ process, with FT also being touted as a possibility, if cost constraints can be overcome.

Table 4: Approved SAF Conversion Processes

ASTM reference	Conversion process	Abbreviation	Possible Feedstocks	Blending ratio by volume
ASTM D7566 Annex 1	Fischer-Tropsch hydroprocessed, producing synthesized paraffinic kerosene	FT	Coal, natural gas, biomass	50%
ASTM D7566 Annex 2	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	HEFA	Bio-oils, animal fat, recycled oils	50%
ASTM D7566 Annex 3	Synthesized iso-paraffins from hydroprocessed fermented sugars	SIP	Biomass used for sugar production	10%
ASTM D7566 Annex 4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	FT-SKA	Coal, natural gas, biomass	50%
ASTM D7566 Annex 5	Alcohol to jet producing synthetic paraffinic kerosene	ATJ-SPK	Biomass from ethanol or isobutanol production	50%
ASTM D7566 Annex 6	Catalytic hydrothermolysis jet fuel	CHJ	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%
ASTM D7566 Annex 7	Synthesized paraffinic kerosene from hydrocarbon - hydroprocessed esters and fatty acids	HC-HEFA-SPK	Algae	10%
ASTM D1655 Annex A1	co-hydroprocessing of esters and fatty acids in a conventional petroleum refinery	co-processed HEFA	Fats, oils, and greases (FOG) co-processed with petroleum	5%
ASTM D1655 Annex A1	co-hydroprocessing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery	co-processed FT	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

Source: ICAO

The conversion processes listed in Table 4 have been listed in order of date of approval by ASTM. The **Fischer Tropsch synthesized isoparaffinic kerosene (FT-SPK)** was approved by ASTM D7566 in 2009. Within this process, coal, natural gas, or biomass feedstocks are gasified into a syngas comprised of hydrogen and carbon monoxide. The hydrogen is then catalytically converted to a liquid hydrocarbon fuel blending component in a FT reactor. Subsequently, in 2015, the **Fischer Tropsch synthesized kerosene with aromatics (FT-SPK/A)** was approved by ASTM. This is a variation of the FT process, where a synthetic alternative fuel containing aromatics is produced.

In 2011, **Hydroprocessed Fatty Acid Esters and Fatty Acids (HEFA)** were approved by ASTM. In this HEFA process, lipid feedstocks such as plant or algae oils, tallow (animal fats), or waste greases such as cooking oils need

to be deoxygenated and then hydroprocessed in order to produce a pure hydrocarbon fuel blending component. Today, the majority of SAF that is commercially produced comes from lipids that remain a low-cost feedstock. However, the market is still in its infancy, and lipid routes are not able to meet the SAF volume demand alone given current feedstock supply that meets the sustainability standards. New low-cost feedstocks are, therefore, needed. **Hydroprocessed Hydrocarbons-HEFA (or HC-HEFA)** were approved in 2020 by ASTM. This addition describes the hydroprocessing of bio-derived hydrocarbons, which come from oils found in specific algae. The main oil plants in terms of the amount of vegetable oil that is produced globally are oil palm and soybean. These crops are used for both food and fuel (biodiesel) production. Palm oil is considered to have the highest productivity, with plants requiring typically five years' growth before they are able to start commercial production, which goes on for 20 years. This is typically seen as an advantage over annual oil crops such as soybean, rapeseed, and sunflower. The cultivation of annuals imposes greater costs and climate impacts.

In 2014, **Synthesized Iso-Paraffins (SIP)** were approved by ASTM. The SIP pathway uses a fermentation process to convert a sugar-rich feedstock into a hydrocarbon molecule that can then be blended into conventional jet fuel. As early as June 2012, Amyris, an integrated renewable products company focused on this process to provide sustainable alternatives to a broad range of petroleum products, and partnered with Total, one of the largest integrated oil and gas companies in the world, to demonstrate a flight with their renewable jet fuel. An Embraer E195 jet flew on renewable fuel, produced from sugarcane in Brazil. This fuel was produced using engineered microorganisms that convert plant sugars into Biofene, Amyris's brand of renewable farnesene, a long-chain, branched hydrocarbon. According to Amyris, however, the cost of production of farnesene from sugar cane was around USD1.75/litre, far too expensive to be used for fuel production. Reducing costs, therefore, is critical if the use of this pathway is to be successful.

In 2016, ASTM approved the **Alcohol-to-Jet (ATJ)** pathway using isobutanol with a maximum 30% blend limit. Later in 2018, ethanol was included as an ATJ feedstock and the blend limit was increased to 50%. Via this pathway, alcohol feedstocks are converted to a pure hydrocarbon fuel blending component. The ATJ conversion process will be discussed in more detail in the next chapter, as it is considered particularly relevant to the global sugar industry.

More recently still, the **Catalytic Hydrothermolysis Jet Fuel (CHJ)** process, also known as hydrothermal liquefaction, was approved by ASTM. Under this process, clean free fatty acid (FFA) oil from the processing of waste oils is combined with preheated feed water and passed onto a CH reactor. Under high temperature and pressure conditions, FFAs are cracked,

isomerized, and cyclized into paraffin, isoparaffin, cycloparaffin, and aromatic compounds used for SAF production.

ICAO also publishes a list of conversion processes that are currently under evaluation and are listed in Table 5, below. Of particular importance to the sugar sector are the ATJ conversion pathways using biochemical production of isobutene (pioneered by Global Bioenergies, which has strong ties to French sugar producer Cristal Union) and the pathway developed by Swedish Biofuels.

Table 5: Conversion processes under evaluation

Conversion process under evaluation	Abbreviation	Lead developers
Synthesized aromatic kerosene	SAK	Virent
Integrated hydropyrolysis and hydroconversion	IH2	Shell
Alcohol-to-Jet (ATJ) derivative utilising biochemical production of isobutene	-	Global Bioenergies
ATJ derivative starting with the mixed alcohols		Swedish Biofuels
Single Reactor HEFA (Drop-in Liquid Sustainable Aviation and Automotive Fuel)	DILSAAF	Indian CSIR-IIP
Pyrolysis of non-recyclable plastics	ReOIL	OMV
Co-processing of pyrolysis oil from used tires		
Co-processing of hydroprocessed biomass		

Source: ICAO

2.7 CONVERSION YIELDS, CAPITAL COSTS, AND PRICES

In order to underpin their SAF projections and to better inform policymakers and project developers, CAEP experts from Washington State University, supported by experts from Hasselt University in Belgium, devised a few “rules of thumb”. These are order of magnitude estimates related to SAF costs, investment needs, and production potential. These were calculated using US costs and financial assumptions, which of course, can differ significantly if other countries are considered. However, their intended purpose is merely to illustrate the larger trends for costs, processing technology and feedstock comparisons.

Four SAF manufacturing technologies were assessed: Gasification Fischer-Tropsch (GFT), ATJ, HEFA, and pyrolysis. For each of the technologies, multiple feedstocks and two levels of technology maturity were assessed: n^{th} plant (when the technology is established and mature) and pioneer plant. The “rules of thumb” provide the impact of feedstock cost, fuel yield, facility scale (total volume of distillate and SAF), total capital investment (TCI) and minimum selling price (MSP).

Tables 6 and 7 below provide the result of the study, with most likely costs and facility scales based on the Techno Economic Assessment (TEA) models, existing literature and expert opinion.

Table 6: Conversion technology, feedstock price, yields, annual distillate scale, annual SAF production for nth and pioneer facilities

Processing Technology	Feedstock	Yield (wt/wt)	Feedstock Price	Scale (million L/yr)		SAF Production (million L/yr)	
				n th	pioneer	n th	pioneer
FT*	MSW	0.31	\$30/t	500	100	200	40
FT*	forest residues	0.18	\$125/t	400	100	160	40
FT*	agricultural residues	0.14	\$110/t	300	100	120	40
ATJ	ethanol	0.6	\$0.41/L	1000	100	700	70
ATJ	isobutanol-low	0.75	\$0.89/L	1000	100	700	70
ATJ	isobutanol-high	0.75	\$1.20/L	1000	100	700	70
HEFA	FOGs	0.83	\$580/t	1000	-	550	-
HEFA	soybean oil***	0.83	\$809/t	1000	-	550	-
FT	CO ₂ from Direct Air Capture (DAC), H ₂	0.24	\$300/t, \$6/kg	1000	-	200	-
FT	waste CO ₂ , H ₂	0.24	\$300/t, \$6/kg	1000	-	200	-
Pyrolysis**	forest residues	0.23	\$125/t	400	100	180	40
Pyrolysis**	agricultural residues	0.21	\$110/t	400	100	180	40

*feedstock price is for pre-processed feedstock

**pyrolysis ASTM approval is pending

***2013-2019 average price of soybean and canola oils

Source: CAEP, Washington State University

From the previous Table, and as illustrated in Fig. 8, it is apparent that the HEFA pathways offer the highest feedstock yield, followed by ATJ. HEFA conversion is already commercially used, its processes are well understood and, as such, yields of SAF distillate per tonne of feedstock are at their optimal level. Important to note is that in this study, the ethanol calculations are US corn-based, rather than sugarcane or beet-based.

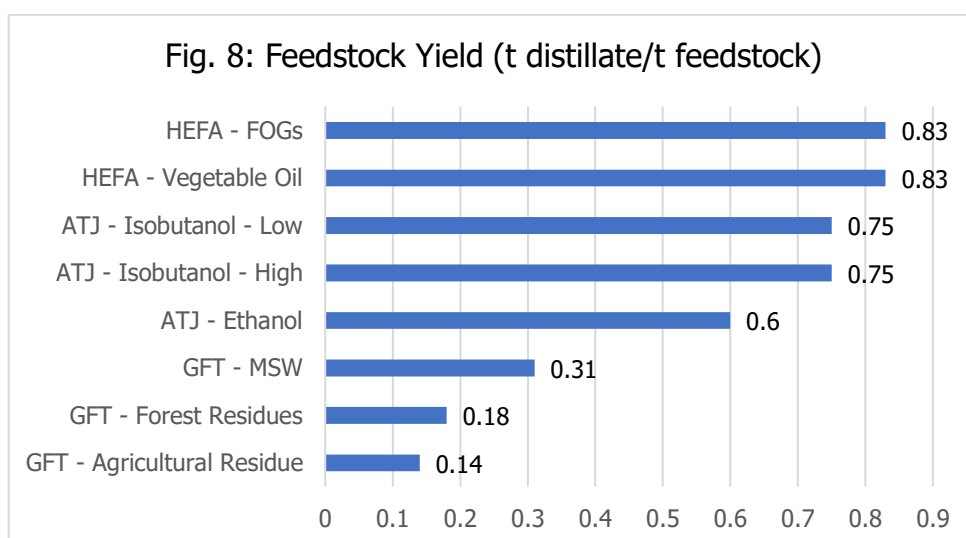


Table 7, below shows total capital investment (TCI), capital costs, and minimum selling prices for nth and pioneer facilities for each pathway.

Table 7: Total Capital Investment, Capital Cost, and Minimum Selling Price for nth and pioneer facilities

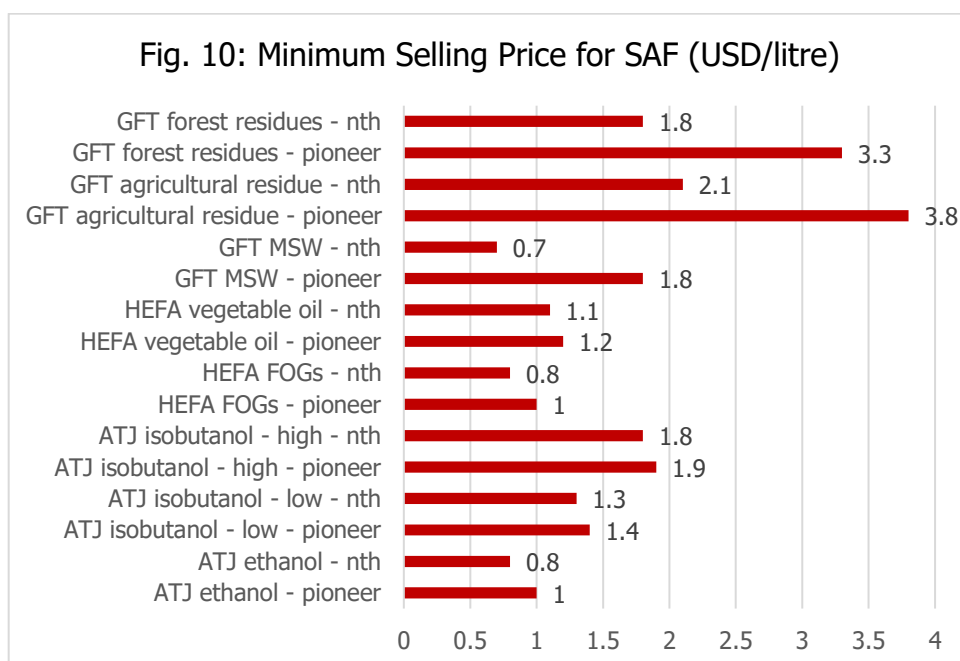
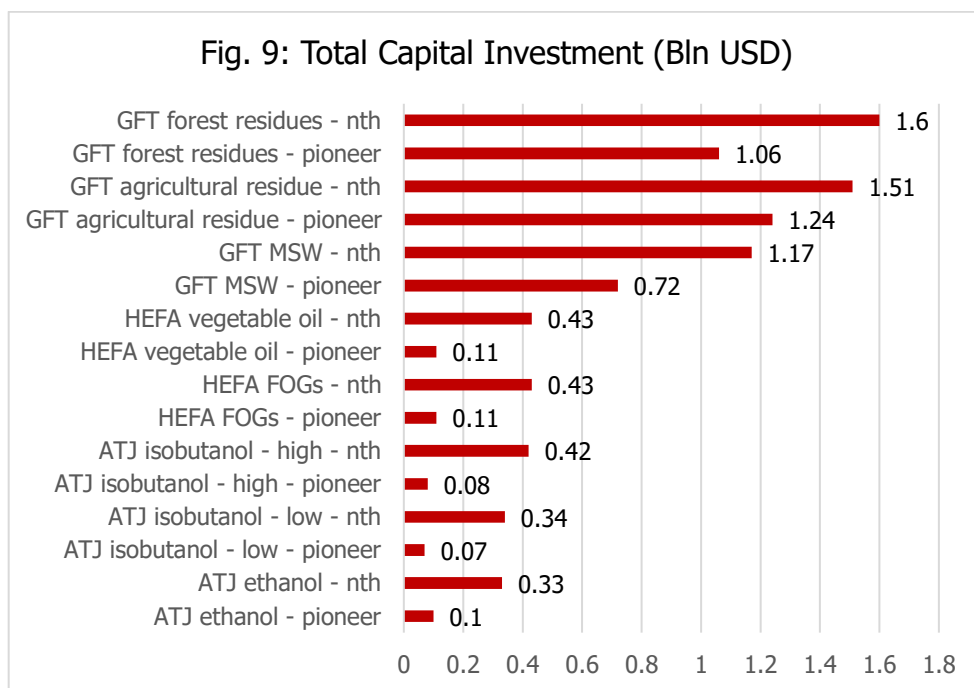
Processing Technology	Feedstock	TCI (million \$)		Capital Cost total distillate (\$/L)		MSP (\$/L)	
		n th	pioneer	n th	pioneer	n th	pioneer
FT*	MSW	1428	813	2.9	8.1	0.9	2.1
FT*	forest residues	1618	1088	4	10.9	1.7	3.3
FT*	agricultural residues	1509	1267	5	12.7	2	3.8
ATJ	ethanol**	328	117	0.3	1.2	0.9	1.1
ATJ	ethanol, agricultural residues	581	170	0.6	1.7	2.2	2.5
ATJ	isobutanol-low**	332	94	0.3	0.9	1.3	1.5
ATJ	isobutanol-high**	410	110	0.4	1.1	1.7	1.9
HEFA	FOGs	448	-	0.4	-	0.8	-
HEFA	vegetable oil	456	-	0.5	-	1	-
FT	DAC CO ₂ , H ₂	3366	-	3.4	-	4.4	-
FT	waste CO ₂ , H ₂	3209	-	3.2	-	3.5	-
Pyrolysis***	forest residues	1038	594	2.6	5.9	1.3	2.1
Pyrolysis***	agricultural residues	1084	619	2.7	6.2	1.3	2.2

*feedstock price is for pre-processed feedstock

**alcohol feedstock is corn-based

***pyrolysis ASTM approval is pending

Source: CAEP, Washington State University



Figs. 9 and 10 summarise these findings and shows advantages of the ATJ process using isobutanol and ethanol compared to other pathways. The total capital investment is deemed to be the lowest for ethanol ATJ, followed by HEFA, FT, and lastly pyrolysis. Capital and production costs are heavily impacted by economies of scale. If short-term demand remains low, the scaling up of production will remain limited, impacting production costs and the price of SAF. However, improved demand certainty via off-take agreements, as discussed previously, is an important means of overcoming this issue. It not only underpins supply commitments to airlines, but it also allows suppliers to invest in new production facilities and increase output capacity.

2.8 WHICH PATHWAY IS THE MOST RELEVANT TO THE SUGAR INDUSTRY?

The ATJ pathway is of particular relevance to the sugar industry. As noted in the previous section, the standards were amended in 2018 to include ethanol as an approved feedstock. This amendment also increased the blending limit to 50%, from 30% previously. Importantly, this change meant that SAF produced via ATJ can use ethanol produced from any feedstock including cane, beet, corn, cassava, or others.

While ethanol produced from any feedstock is chemically identical, as explained in MECAS(22)17 – Climate Smart Agriculture and the Sugar Sector, sugar crops should be the feedstocks of choice. This is due to better output per hectare than other crops, the lack of pre-treatment prior to fermentation, and, in the case of sugarcane, the significant GHG emission savings compared to other feedstocks as combined sugar-and-ethanol mills are powered by bagasse-based cogeneration.

Today, companies producing SAF using the ATJ process include:

- Amyris
- BASF
- Blue Blade Energy
- Byogy Renewables
- Gevo
- Global Bioenergies
- Honeywell
- Lanzatech
- SaFFiRE Renewables (an acronym for SAF from Renewable Ethanol)
- Swedish Biofuels
- Vertimass

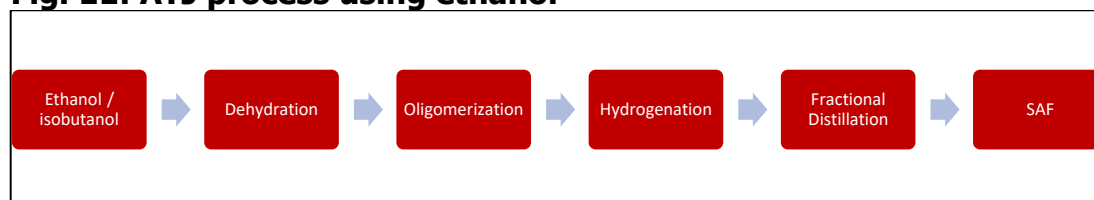
2.9 THE ATJ PROCESS IN MORE DETAIL

Thick juice directly from sugarcane or sugarbeet is easily distilled into alcohol (ethanol or butanol), a substrate from which SAF can then be produced. In the case of sugar crops, fermentable sugars are easily obtained by mechanical processes like milling or diffusion. Crucially, this eliminates costs incurred during pre-treatment and is an important differentiator from other starch crops such as maize, wheat, and cassava, where sugars are not readily available but must be obtained via a chemical reaction.

As was shown in the previous chapter, the conversion of sugars into SAF is typically done via a biochemical conversion. In the ATJ conversion process, SAF is made from ethanol and isobutanol. The typical ATJ process involves dehydration (removing water from the feedstock), oligomerization (which

converts small molecules to more complex molecules), and hydrogenation (addition of hydrogen). The hydrocarbon mixture that results from this is then heated and different hydrocarbons are separated based on their boiling points. This latter process is known as fractional distillation. The simplified ATJ process using ethanol is shown in Fig. 11, below.

Fig. 11: ATJ process using ethanol



Other technologies have also been developed that offer novel ways of sustainably producing feedstocks, such as isobutene, which are then used for the production of SAF. One example is Global Bioenergies, whose conversion process is currently under approval by ASTM.

Box 2 Global Bioenergies

Global Bioenergies, a French company with ties to the sugar sector, has developed a unique process to convert plant-derived resources into isobutene to produce SAF, with ASTM approval pending. Isobutene has historically been derived from oil and has various applications, ranging from energy to building materials and cosmetics.

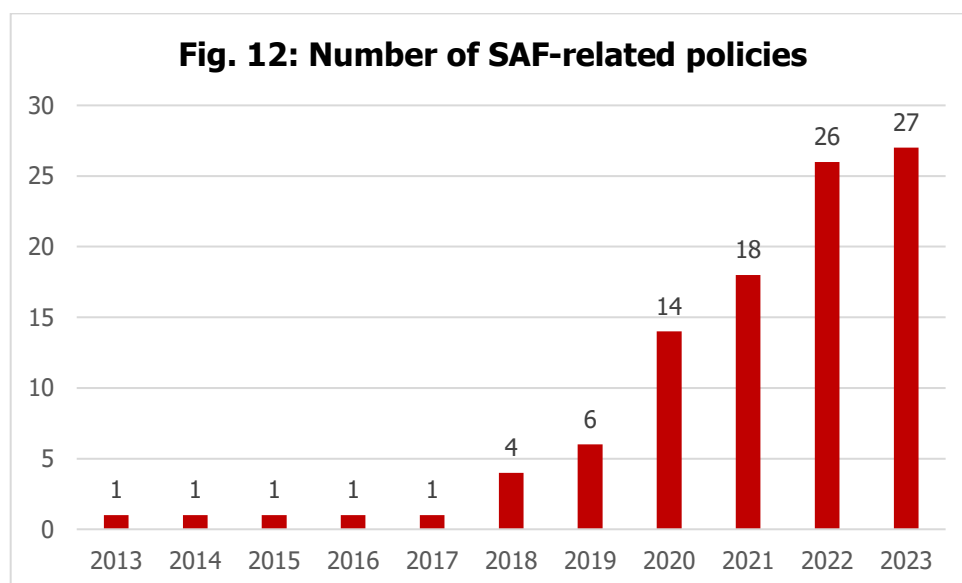
The company has taken 14 years of R&D to develop a strain of bacteria that can convert sugars into isobutene. First, transformed bacteria (with reprogrammed metabolism) is placed in a fermenter with sugars (cane sugar or beetroot). The bacteria then consume these sugars and produce isobutene, which can be subsequently used as a feedstock for SAF production.

Source: <https://www.global-bioenergies.com/the-isobutene-process/?lang=en>

CHAPTER 3

3.1 POLICIES IN PLACE OR UNDER DEVELOPMENT

The policy space surrounding SAF has changed rapidly over recent years and provides the basis for the expansion of the sector. Over the last decade, the number of SAF-related policies has grown from 1 in 2013, to 27 so far in 2023 (see Fig. 12). Annex I contains a list of these SAF-related policies per country with a short description.



With more countries pledging to reach net-zero emission targets by 2050, low-carbon aviation fuels are increasingly becoming a key area for climate policies.

According to ICAO, the first SAF policy was adopted in Indonesia in 2013, set up by the Indonesian Aviation Biofuels and Renewable Energy Task Force, with the goal to mandate 5% SAF inclusion by 2025.

There remains great potential for feedstock production, which might provide a solid foundation for many national policies. On a global scale, however, the EU and the US are leaders in the establishment of legally binding targets for the reduction of GHG emissions from aviation and for the incorporation of SAF in fuels blends. This commitment to reducing aviation emissions is reflected in the number of US and European companies already engaging in the SAF sector. A summary of European and US policy measures is provided below. While the approach of the EU has been geared towards regulation and obligations, the US has increasingly opted for incentive programmes and direct financial support to reduce project risk and create a more attractive business case for companies.

3.2 SAF POLICY IN EUROPE

The European Union has long contemplated the reduction of GHG emissions from aviation. In 2012, aviation was incorporated into the EU Emissions Trading System (EU ETS), a large carbon market. As part of the ETS, all European airlines are required to report emissions that result from their activity. The EU then grants “tradeable allowances”, which caps the airline’s allowed amount of pollution. These are certificates which are tradeable, so airlines that emit more than their share must purchase allowances from airlines that emit less than their allowance. This scheme was designed to incentivise measures to reduce CO₂ emissions.

Within the European Green Deal, which was adopted in 2020, the EU pledged to become the first net-zero continent by 2050. To achieve this goal, the EU set out its “Fit for 55” strategy, which describes a set of proposals to update EU laws to ensure that 2030 and 2050 targets remain within reach. Within the “Fit for 55” package, the European Commission released the ReFuelEU Aviation proposal, which sets out its commitment to decarbonise the aviation sector. Firstly, a mandate on fuel suppliers for the incorporation of SAF would be established. This blending obligation would start at 2% in 2025 and progress towards 63% by 2050, of which 28% would consist of synthetic aviation fuels. The legislation also included a sub-target for 0.7% of synthetic e-kerosene blending (produced from renewable hydrogen via pyrolysis) from 2030. ReFuelEU policy also aims to provide logistical support by requiring EU airports to provide the necessary infrastructure for storage and blending of SAF. According to IATA’s analysis of the policy, all airlines departing from EU airports will be obliged to take on jet fuel prior to departure. The amount of jet fuel purchased must correspond to the volume of jet fuel necessary to operate the planned flight, regardless of the destination. The yearly quantity of aviation fuel uplifted by a given operator at a specific EU airport shall be at least 90% of its annual aviation fuel requirement.

3.3 SAF POLICIES IN THE US

In the US, various policies exist at the state and federal level that aim to advance SAF production and inclusion. The California Low Carbon Fuel Standard (LCFS) was updated in 2019 to recognize SAF as an eligible fuel to generate credits. The GHG benefits of SAF are quantified through lifecycle assessment modelling that calculates the avoided emissions compared to conventional jet fuel. These credits can then be sold to other obligated parties under the LCFS, incentivising SAF production.

Under the US Renewable Fuel Standard (RFS), SAF is offered as a means of generating compliance units (Renewable Identification Numbers, or RINs), but without aviation fuel generating compliance obligations. This approach

intends to advance SAF's competitiveness, while refraining from imposing a mandated SAF use obligation.

In 2021 the US Congress introduced the Sustainable Skies Act to boost the use of SAF. The credit will start at USD1.50 per gallon for blenders that supply SAF with a demonstrated 50% or greater lifecycle GHG savings and rewards higher GHG achievement up to the maximum of USD2.0 per gallon. It requires eligible SAF to utilise ICAO's sustainability criteria to ensure environmental credentials. Another proposal includes a USD1 bln grant over five years to expand the number of SAF producers in the US.

In late 2021, the US also announced a new SAF goal to increase production to at least 3 bln gallons by 2030. Actions would include:

- A proposed SAF tax credit that aims to cut cost and rapidly scale up domestic production of SAF.
- Continuous funding to support SAF projects and fuel producers, with the launch of a new SAF Grand Challenge to ramp up domestic production of SAF.
- Closely working with international partners to support expanded global use and availability of SAF.

3.4 SAF AND SUGAR SECTOR FEASIBILITY STUDIES

This section presents findings from published RSB papers regarding the feasibility of the production of SAF utilising the ATJ production pathway with sugarcane as the feedstock.

RSB study on SAF in South Africa¹³

In October 2020, RSB published a joint document, with the South African Canegrowers Association (SA Canegrowers) and supported by Boeing, to explore the viability of South Africa's sugarcane output as a feedstock for SAF. In this study, the need for diversification of the sugar industry for its long-term survival is stressed, referring to the opportunity that ethanol provides as established in a 2016 assessment of bioethanol production from sugarcane in South Africa ¹⁴.

The study suggests that South African demand for fuel ethanol could be 2.4 bln litres per annum, with 75% (1.8 bln litres) from aviation, and 25% (600 mln litres) from road transportation under a national fuel blending mandate.

¹³ <https://rsb.org/2020/10/19/rsb-sa-canegrowers-research-points-to-huge-saf-potential-in-south-africa/>

¹⁴ An Economic Assessment of Bioethanol Production from Sugar Cane: The Case of South Africa. Available: https://econrsa.org/system/files/publications/working_papers/working_paper_630.pdf

If 50% of the cane produced can be diverted from producing sugar for the export market to domestic ethanol production, based on current yields, South Africa would be able to produce 700 mln litres of ethanol per annum, or about 30% of its potential fuel ethanol demand.

To be considered sustainable, the following criteria were established:

- SAF must have a substantially better (>50%) GHG balance than its fossil fuel alternative.
- The production/use of SAF must not cause environmental harm.
- The production/use of SAF must not cause socioeconomic harm.
- The production/use of SAF must not deplete natural resources.

A 'well-to-wing' lifecycle GHG emissions for SAF produced via the ATJ-SPK process, from sugarcane-based ethanol was examined and found to be approximately:

- 38.3 g CO₂ eq / MJ SAF for irrigated cane;
- 26.6 g CO₂ eq / MJ SAF for dryland cane;
- 24.6 g CO₂ eq / MJ SAF for dryland cane with green harvesting.

Cultivation, harvesting, and the conversion of ethanol to SAF are the biggest contributors to the total GHG emissions in all three scenarios, with the difference in emissions between irrigated and dryland scenarios largely attributed to higher electricity demand for pumping irrigation water. Given the predominantly coal-based power generation matrix, CO₂ emissions attributed to electricity in South Africa are high when compared to countries that use more renewable energy in their national energy mix.

For South Africa, the study concludes that dryland cane presents a particularly strong option for achieving GHG savings in the production of SAF, cutting 72% in overall emissions when the EU RED II fossil baseline is applied and an additional 2% with green harvesting included. Furthermore, savings are still significant if the CORSIA baseline is applied, giving 60% savings for dryland cane and an additional 3% when using green cane.

Meanwhile, costs projections point to SAF being between two to seven times costlier than conventional jet fuel (fossil based). According to RSB, the range of these costs is difficult to determine, as SAF is not a readily available commodity and as contracts for SAF purchase do not usually disclose price.

Ultimately, the price differential between SAF and conventional jet fuel is expected to improve due to several factors:

- Economies of scale in SAF production;
- Regulatory pressure to curb emissions;
- Increasing number of commercial airlines committing to sourcing SAF;
- Increase in the price of oil.

Nevertheless, challenges for SAF production in South Africa remain and include infrastructure investments into both ethanol production capacity and upstream processing capacity, thus increasing the level of investment required. For this to occur, clear policies and government support mechanisms are essential.

RSB study on SAF using residues in Brazil¹⁵

In 2021, RSB, in partnership with Agroicone, produced a study on the potential availability of residue and waste feedstocks for SAF production in Brazil. Five feedstocks were considered, using seven production pathways already approved by ASTM to be used with jet fuel at a maximum blend of 50%. These processes are grouped into FT plants, ATJ plants, and HEFA plants. The feedstocks considered were:

- Cane residues – bagasse as well as cane straw. Cane straw availability excludes straw that is left in the field for agronomical purposes.
- Forestry residues – resulting from the harvest of eucalyptus trees
- Combustion gases – from steel refining
- Cattle remains – waste obtained from the meat industry
- Used cooking oil

The study found that about 7.2 bln litres of SAF would be needed in order to help Brazil achieve decarbonisation pledges made by the industry. Importantly, using the ATJ pathway, surplus cane residues (bagasse and straw) would be able to supply 90% of demand (6.48 bln litres). If produced using the FT pathway, cane residues alone could produce 2.12 bln litres of SAF, or around 30% of total demand. In second place would be forestry residues, capable of producing 1.9 bln litres via ATJ. The three other feedstocks (meat industry residues, combustion gas, UCO) would be able to produce 0.36 bln litres, 0.23 bln litres, and 0.11 bln litres, respectively.

This illustrates that the ATJ pathway has by far the greatest production potential in Brazil, and importantly, this considers only residues. The potential for SAF production would be far greater if ethanol were also included as a feedstock, but suitable sustainability criteria would need to be set and met if this fuel were to qualify as sustainable.

¹⁵ <https://rsb.org/2021/05/19/rsb-agroicone-publish-study-to-support-sustainable-transformation-in-brazil-with-saf/>

CONCLUSION

The aviation sector remains in need of decarbonisation. Unlike in road transportation, the low energy density of batteries means that this technology cannot be applied to commercial jets. Meanwhile, improvements in efficiency have not been able to keep up with an increase in demand.

Sustainable Aviation Fuels represent the option with the most potential to decarbonise aviation, and a solution which will remain relevant well into the 21st century. While SAF offtake is currently limited, usage is expected to grow sharply to achieve long-term voluntary sector targets as well as to comply with emerging inclusion policies. However, an enormous challenge for the SAF industry remains, as the jet fuel market is large, and demand is growing. Crucial in scaling up this energy transition will be lowering the costs of SAF production when compared to petroleum-based jet fuel and ensuring that supply and demand drivers are in place to promote production and use.

While it possible to produce SAF via several pathways, HEFA is currently the least costly and is already commercially used. However, HEFA, using oil and fats, will not be able to meet the growing SAF volume demand alone. Alcohol-to-Jet, using sugar or starch-based feedstocks, is the second least expensive option, with abundant feedstock potential and of particular relevance to the sugar industry. ATJ standards were revised in 2018 to include ethanol as an approved feedstock for the ATJ process. This means that SAF can now be produced anywhere using ethanol from suitable feedstocks such as cane and beet. This represents an enormous potential as a new diversification avenue and allows the sugar sector to continue to support the global effort in decarbonising fuel markets.

There is great untapped potential for feedstock production, and novel conversion pathways are emerging, which are set to reduce costs through economies of scale. To achieve this, airlines will need to continue to increase voluntary commitments to decarbonise aviation fuel, creating greater demand certainty. Meanwhile, the challenge for sugar industries will be in providing affordable and sustainable feedstocks that can be used for SAF conversion. While there is great potential for the sugar sector, it is an opportunity that can only be realised with supportive government policies that promote the commercialisation of SAF and help close the cost gap compared to petroleum-based jet fuel.

Annex I: Summary of Policies that support SAF and Low Carbon Aviation Fuels

Date	Country	Policy Title	Policy description	Status
01-Jan-13	Indonesia	Indonesia	Mandate of 5% SAF use by 2025	Adopted
18-Apr-18	United Kingdom	Renewable Transport Fuel Obligation (RTFO)	The RTFO rewards SAF production with the same economic incentives given to road vehicles	Adopted
27-Jun-18	ICAO (International)	CORSIA	CORSIA allows airlines to reduce their offsetting requirements with the use of CORSIA eligible fuels, which include SAF and Lower Carbon Aviation Fuels	Adopted
27-Sep-18	United States (California)	Low Carbon Fuel Standard (LCFS)	Credits for fuel pathways and projects, based on a carbon intensity score	Adopted
04-Jun-19	Finland	Finland	A carbon neutral country by 2035: Increasing SAF obligation to reach 30% in 2030	Under Development
19-Nov-19	Norway	Norway	SAF blend 0.5% mandate started in 2020. Considering a 30% target for 2030	Adopted
13-Jul-20	Canada (British Columbia)	Renewable & Low Carbon Fuel Requirements Regulation	BC-LCFS sets CI targets that decline each year. Does not currently recognise GHG reductions within aviation and maritime fuel sectors. Ministry considering expanding the BC-LCFS to include such reductions and provide support for low carbon fuel by adding jet fuel class	Under Development
08-Sep-20	Spain	Spain	Climate Change Law: 2% SAF supply objective in 2025. Various new bio-refineries under planning with special focus on wastes and residues	Under Development
08-Sep-20	Portugal	Portugal	Roadmap for Carbon Neutrality: integrated approach to transport decarbonisation including aviation	Under Development
08-Sep-20	Netherlands	SAF Roadmap	SAF Roadmap under development with a blending mandate at the national or EU level. Focus on advanced feedstocks	Under Development
11-Sep-20	Sweden	Sweden	A carbon neutral country by 2045. Legislative proposal for 0.8% GHG reduction mandate in 2021, and gradually increase to 27% by 2030	Under Development

25-Sep-20	Germany	Germany	National legislation for GHG reduction of fuels (to transpose the REDII) and the German National Hydrogen Strategy foresee a SAF energetic sub-quota of 2% in 2030 and only for PtL-kerosene.	Under Development
12-Dec-20	France	France	SAF roadmap to reach a SAF supply of 1% by 2022, 2% in 2025 and 5% in 2030. Focus on advanced feedstocks	Under Development
18-Dec-20	Canada	Clean Fuel Standard	The Clean Fuel Standard will require liquid fossil fuel primary suppliers (producers and importers) to reduce the CI of their liquid fossil fuels used in Canada from 2016 carbon intensity levels. In 2022, the CI reduction requirement will start at 2.4 gCO ₂ e/MJ and gradually increase to reach 12g CO ₂ e/MJ in 2030.	Under Development
20-May-21	US	Sustainable Skies Act	Tax incentive up to USD2.0/gallon produced of SAF. The Bill introduced by White House aims to create a grant program authorised at USD1 bln over 5years to expand the number of facilities producing SAF and build necessary supporting infrastructure	Under Development
13-Jun-21	New Zealand	Sustainable Biofuels Mandate	Proposed policy requires fuel suppliers to reduce the GHG emissions from transport fuels by a defined percentage each year. It applies to all transport fuels, including domestic aviation fuel, and requires biofuels to meet sustainability criteria to certify that they do not impact on food production or indigenous biodiversity. It requires fuel suppliers to prepare annual reports to demonstrate compliance. There will be penalties for non-compliance, although there is some flexibility for fuel suppliers, including the ability to trade emissions reductions with each other, and to defer for two years	Under Development
16-Jul-21	EU	ReFuelEU	Proposed mandate of SAF use, starting from 2% in 2025 up to 63% in 2050	Under Development

25-Nov-21	Brazil	National Biokerosene Programme	The policy directs federal agencies and institutions to provide resources to SAF projects, as well as fiscal incentives.	Adopted
02-Jan-22	Denmark		Denmark Targets 2030 For Fossil Fuel-Free Domestic Flights	Under Development
07-Apr-22	US	Renewable Diesel and Sustainable Aviation Fuel Parity Act	The Renewable Diesel and Sustainable Aviation Fuel Parity Act of 2022 will: Require the Energy Information Administration to report on U.S. production and foreign imports of renewable diesel and sustainable aviation fuel, including the type, origin, and volume of feedstocks used for these fuels; Allow renewable diesel and sustainable aviation fuel production facilities to qualify for the Department of Energy's Title XVII loan guarantees under the Energy Policy Act of 2005; and Exempt renewable diesel that meets the same technical specifications as petroleum-based diesel from the labeling section of the Energy Independence and Security Act of 2007.	overridden by Inflation Reduction Act
18-May-22	Brazil	Brazil	Brazilian sustainable aviation fuel mandate that will take effect in January 2027 will target cutting Brazil's airline emissions by 1% of the sector's 2026's total emissions, with the possibility of raising that figure to 10%	Under Development
19-Jul-22	United Kingdom	Jet Zero Strategy	Increasing support for sustainable aviation fuels (SAF), by creating secure and growing UK SAF demand through a SAF mandate that will require at least 10% of jet fuel to be made from sustainable sources by 2030 and kickstarting a domestic SAF industry, supported by the new £165 million Advanced Fuels Fund.	Adopted

16-Aug-22	US	Inflation Reduction Act (SAF blenders tax credit)	The bill provides a \$1.25 per-gallon credit for each gallon of SAF sold as part of a qualified fuel mixture, including that it has a demonstrated lifecycle greenhouse gas (GHG) reduction of at least 50 percent compared to conventional jet fuel. The credit, available for two years beginning January 1, increases up to \$1.75 per gallon on a sliding scale based on the percentage of lifecycle GHG emissions reduced beyond 50 percent. Beginning in 2025, SAF would be eligible for credits up to \$1.75 per gallon under a new Clean Fuel Production Credit (CFPC). That credit is set to expire at the end of 2027.	Adopted
03-Oct-22	China	China Civil Aviation Green Development Policy and Action	Target of 50k tons of SAF use by 2025 SAF performance, testing, airworthiness certification, exploration of new paths for its development	Adopted
18-Oct-22	Japan		The Japanese government is seeking public comments on a draft policy to promote decarbonization in the aviation industry. The policy, in part, would require flights to be carbon neutral by 2050 and require airlines to use sustainable aviation fuel (SAF)	Under Development
16-Nov-22	India		SAF mandate blending under consideration	Under Development
13-Feb-23	US (Illinois)	Invest in Illinois Act	This legislation in Illinois provides a tax credit of \$1.50 per gallon for SAF used by aircraft in the state. For the SAF to qualify for the credit, it must reduce carbon emissions by at least 50% throughout its life. The credit applies to all SAF used in Illinois, regardless of where it is produced. However, credits for SAF used before June 1, 2028, must come from renewable sources such as biomass, waste streams, renewable energy, or gaseous carbon oxides. The tax credit will be available until January 1, 2033.	Adopted

Source: ICAO

