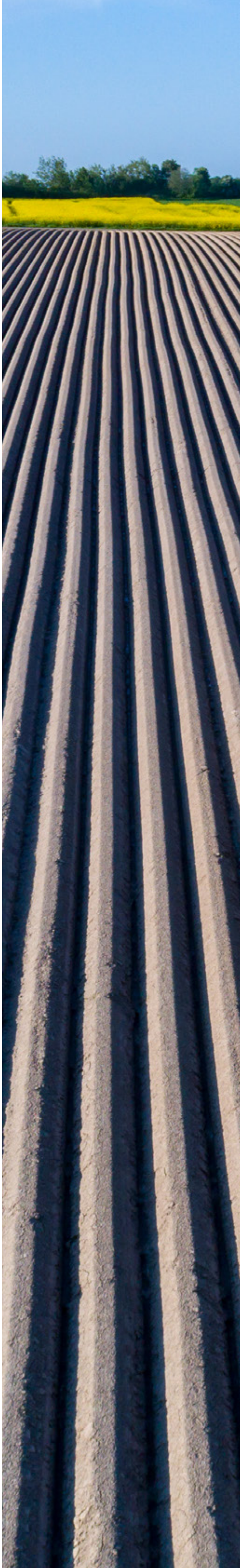
Capgemini invent

IDENTIFYING SUSTAINABLE PATHWAYS FOR SAF PRODUCTION

SOMMAIRE

1 FOREWORD



The aeronautics industry is facing increasing pressure to reduce its carbon footprint and mitigate its impact on the environment. Sustainable aviation fuels (SAFs) represent one major potential solution to this challenge, as they are seen as the main lever for decarbonization in the medium term due to the technological maturity of the production processes, allowing for a reduction in greenhouse gas (GHG) emissions around 53% (latest studies are expected a 65% contribution) by 2050 for the sector. However, their widespread adoption and commercialization require the careful consideration of various factors, including feedstock availability, sustainability, social impacts, the economic and regulatory landscape, production process yield, and potential competition with other sectors.

This study on SAF pathways aims to provide a comprehensive overview of the different feedstocks that could be used for SAF production, as well as the potential risks and opportunities associated with each. It analyzes the availability and sustainability of various feedstocks and assesses their suitability for use in SAF production.

One of the key focuses of this study is to assess the potential competition between SAF feedstocks and other sectors, such as agriculture (for food production) and industry. This is an essential consideration, as the use of certain feedstocks for SAF production could result in unintended consequences, such as the displacement of food crops.

This study also considers the key challenges and opportunities associated with feedstock development and assesses their potential to support the growth and scaling of the SAF industry, thanks to the different production process agreed by ASTM standards.

It is worth noting that the US and Europe have been leading the way in terms of local regulations and policies that promote the use of SAFs. These local regulations and policies have created a favorable environment for the development and deployment of SAFs and have provided incentives for stakeholders across the value chain to invest in them. However, the development of SAFs must not be at the detriment of other sectors, and the EU regulations for example take a clear position on feedstocks competition, especially for feed crops and food crops. In the meantime, the US has set up clear sustainability objectives for SAF production to ensure the achievement of CO2 reduction, with unprecedented financial and ecosystemic efforts on specific pathways.

We believe that continued collaboration between policymakers, industry leaders, and investors will be critical to further accelerating the growth and scaling of the SAF industry and to achieving the sustainability goals of the aviation industry. We hope that this study will contribute to a more informed and balanced discussion on SAF feedstocks and their role in the aviation industry's sustainability strategy. By providing a comprehensive overview of the feedstocks available for SAF production and their potential impacts, we aim to support policymakers, industry leaders, and investors in making informed decisions that balance the economic, social, and environmental factors associated with SAF production.

We remain committed to working with stakeholders across the industry to accelerate the development and deployment of SAFs and to support a more sustainable future for aviation and the planet as a whole.

2 EXECUTIVE SUMMARY

The International Air Transport Association estimates that the world produced 300 million liters of SAF in 2022. However, this is just 0.1% of the total jet fuel produced worldwide…

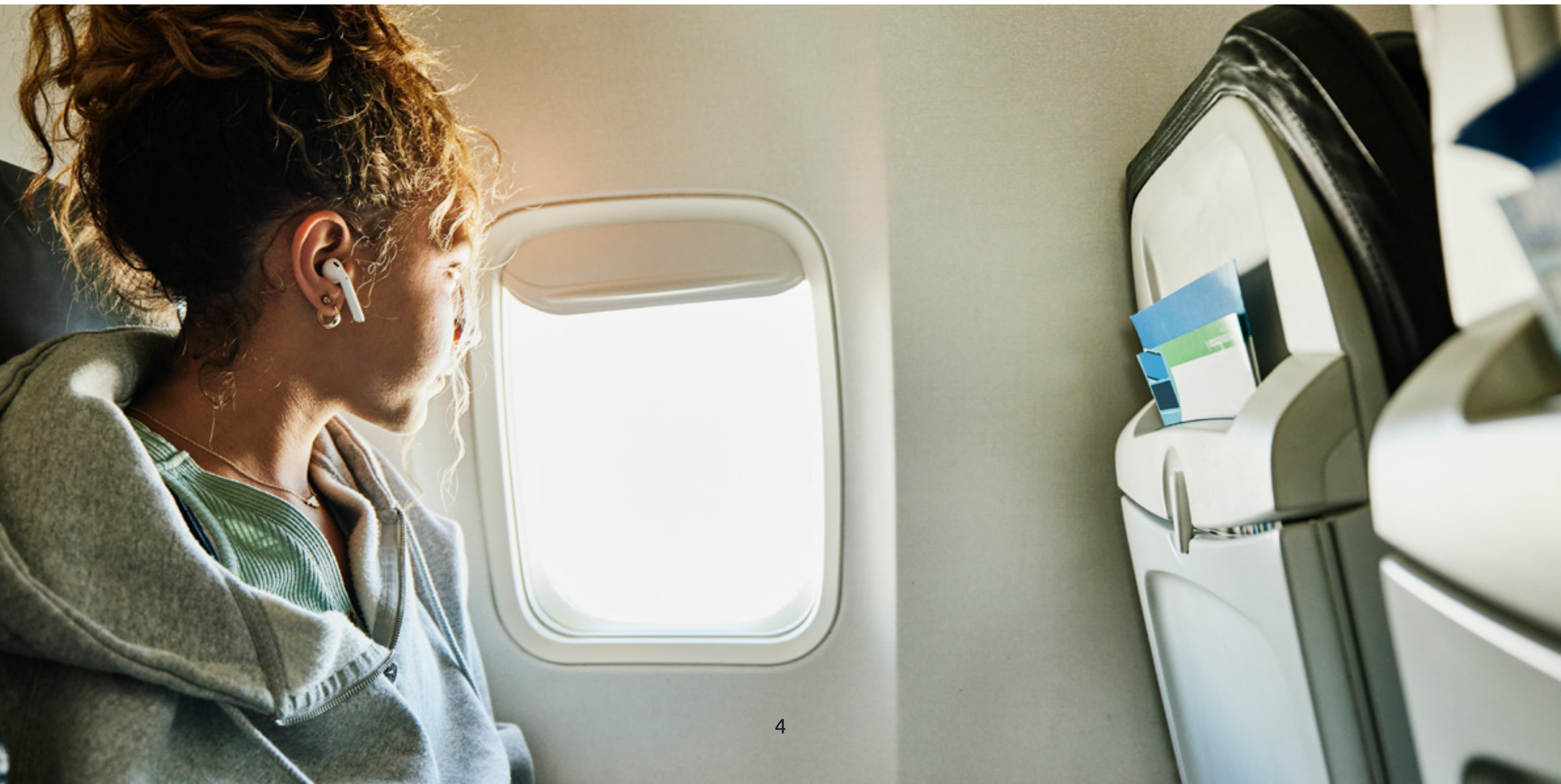
In 2016, the United Nations Framework Convention on Climate Change led an agreement known as the Paris Agreement. This was a landmark agreement between members **to limit the impact of global warming** – like limiting the global temperature rise far below to 2°C and targeting a maximum rise of 1.5°C. Member nations outlined their plans to achieve this target both individually and as a group with some taking actions more proactively than others.

Aviation as a sector is important for both economic and social reasons. Air travel is back to normal, and the number of commercial flights is back to pre-COVID-19 era numbers (in many cases even exceeding it). Hence, steps to decarbonize aviation is now needed more than ever to sustain the environmental goals for 2030.

SAF is widely accepted as the most promising solution to decarbonize aviation in the near term. SAF is synthesized from sustainable and renewable feedstock such as municipal waste, agricultural, forest residues, and waste lipids. It has the potential to reduce the carbon footprint by 50–80%.

SAF is a drop in fuel – which means that it can be used in aircraft without any changes in the engine design and architecture. There are other technologies like hydrogen and electricity, both promising but requiring R&D investments in aircraft design and production technology. Not to mention that the large-scale production of electricity and hydrogen in a sustainable manner is a challenge and uses a lot of land. This makes SAF an ideal candidate for quick wins in decarbonizing the aviation sector.

Industry is currently investing in the large-scale production and transportation of SAF. Both these aspects have been challenging for the industry globally. Even though the volume of SAF produced in 2022 was approximately double than that produced in 2021, the world just produced 0.1% of SAF – of the total of jet fuel production – in the year 2022. Also the cost of SAF is generally admitted to be at least twice the cost of traditional jet fuel.



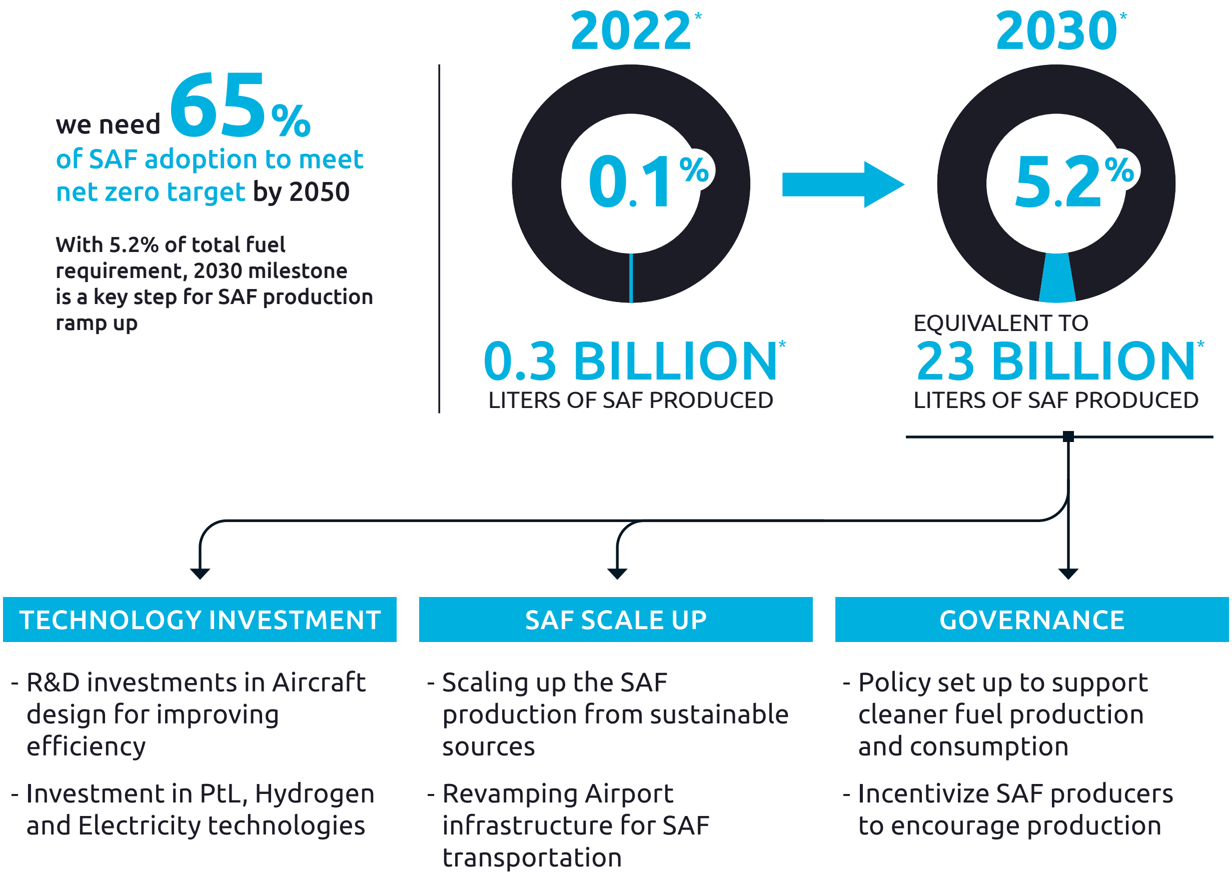


Figure 1: SAF production ramp-up requirement

**Source : IATA 2022 & 2023*

There are several pathways that have been established and certified for producing SAF – HEFA, the Fischer Tropsch (FT) process, Ethanol-to-Jet (EtJ), and Alcohol-to-Jet (AtJ). Enough feedstock is available in the world that can be used as raw material for these pathways. However, the use of these feedstocks is presently not organized. Hence, to ramp up production, industry will have to come up with a 360-degree innovation that is on the one hand socially acceptable and on the other technologically feasible.

Many of the feedstocks that can be used as a raw material for producing SAF are grown on agricultural farms. Hence, they directly or indirectly compete with agriculture and have a direct social impact.

It is imperative that the stakeholders understand that not all pathways can be followed in all regions. Different regions have different levels of technology maturity and feedstock availability. Hence, a careful selection of SAF production pathways per region is needed to produce SAF in a cost-efficient manner.

Effective governance will play a pivotal role in producing SAF. Governments worldwide can contribute in many major ways – providing subsidy to feedstock producers so that they are encouraged to produce more feedstock, bringing in legislation to mandate use of SAF along with jet fuel, and establishing policies for the sustainable logistics of feedstock.

This study specifically focuses on the assessment of the feedstock that is used to produce the SAF; the feedstocks that are grown or procured organically, mostly on farms or generated from farm waste, are discussed in detail (e.g., the Fischer Tropsch process with hydrogen from syngas of organic material). All processes that are not synthetized from organic materials are not considered in this report (e.g., the FT process with hydrogen from electrolysis).

3 INTRODUCTION

Rapid decarbonization in all industries is needed to meet the targets specified in the Paris Agreement. Aviation as a sector alone released 711 Mt of CO2 in the year 2021 according to the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Also, forecasts from the International Civil Aeronautic Organization (ICAO) expect an increase of up to 100–160% by 2050, meaning there will be a maximum of 500 Mt global jet fuel demand, depending on scenarios. Even advanced economies that have strict emission controls across segments are off track with respect to the Paris Agreement.

A CONTINUOUS RISE IN CARBON EMISSIONS DESPITE THE HALT LINKED TO COVID

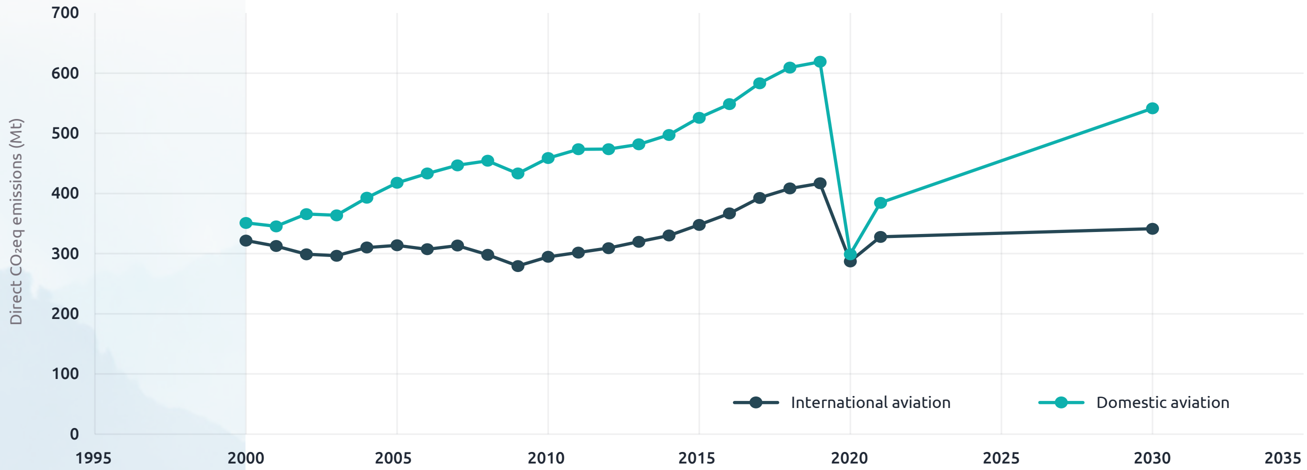


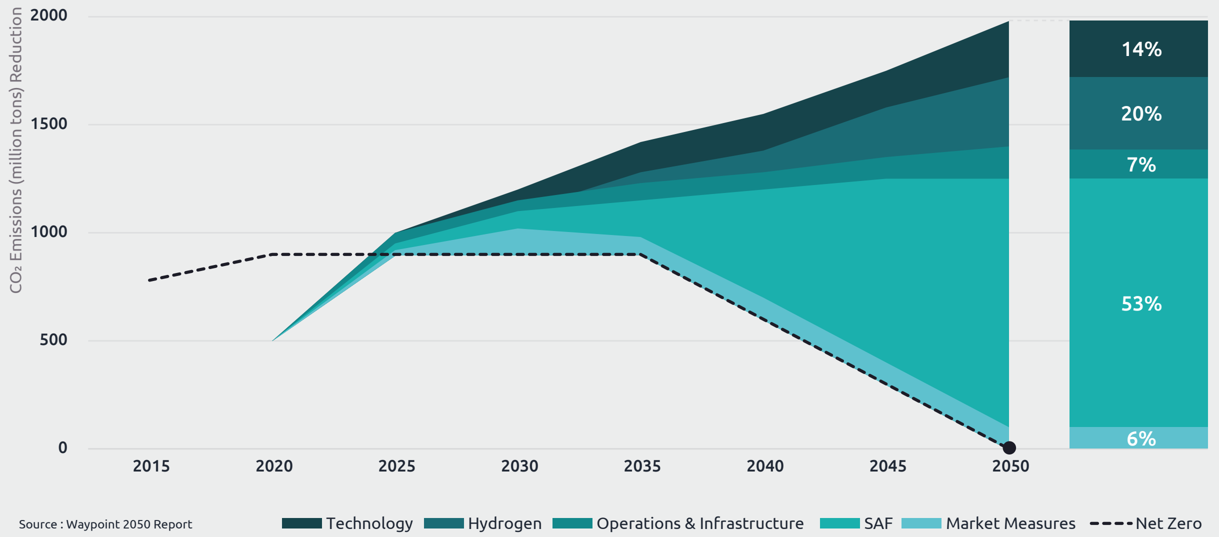
Figure 2: Direct CO2 emissions from the aviation industry by sector

Emissions in the aviation industry pose special and different kinds of challenges. Firstly, the industry is globally dispersed. It is not possible for localized and non-harmonized policies to have significant impact on the airlines and the GHG emissions produced by their operations. Similarly, fleet changes in this industry are extremely slow and costly. Any changes in aircraft design and structure must be thoroughly validated, tested, and approved at various safety levels before the aircraft is released commercially. These design changes in aircraft to meet sustainability goals are slow and difficult. Economically, the cost of reducing the carbon footprint in aviation is extremely high when compared to other industries. These challenges demand innovative solutions to control emissions in the industry.

As per the International Air Transport Association (IATA), to meet the net zero target of 2050 we must produce SAF that is at least 5.2% of the total jet fuel requirement by 2030. This will only be possible when the industry and governments collectively invest in greener technology and infrastructure with a clear policy vision. Investments in R&D for aircraft design and other green technologies like hydrogen and gasification are needed to lay down the foundation of the net zero target. At the same time, scaling up SAF is needed to ensure that emissions are in check until more green technologies are fully developed.

Industry reports like the Waypoint 2050 estimate that around a 53% reduction in emissions can be achieved by focusing industry's efforts on SAF. Other factors like airport operations optimization or air traffic management are not likely to contribute to a significant reduction in emissions. In the long term, hydrogen is another major solution to reduce aeronautics emissions, especially on short flights.

~67% OF REDUCTION IN EMISSIONS CAN BE ACHIEVED BY FOCUSING ON BOOSTING SAF AND IMPROVING EFFICIENCY



SAF IS EXPECTED TO CONTRIBUTE AROUND 53% GHG REDUCTION
Conservative view, latest studies from IATA expect an average reduction up to 65%

SAF is easy to use drop in fuel that requires **minor to no changes in aircraft design**

TECHNOLOGY IMPROVEMENTS have potential to reduce emission by ~14% but **require significant R&D investments** and are not easy

HYDROGEN can contribute to **20% in emission reductions** for 2050 net zero target but will be **commercially available after ~2035**

	SAF	HYDROGEN		ELECTRICITY
		HYDROGEN CELL	HYDROGEN TURBINE	
CO2 EMISSION REDUCTION[1]	50-80% REDUCTION[2]	58 – 90% REDUCTION[3]		49-88% REDUCTION[4]
AIRCRAFT DESIGN	MINOR ADAPTATIONS	MAJOR ADAPTATIONS		MAJOR ADAPTATIONS
AIRCRAFT RANGE	ALL SEGMENTS	SHORT DURATION FLIGHTS	ALL FLIGHTS LESS THAN 10000 KM	SHORT DURATION FLIGHTS
AIRPORT OPERATIONS	SAME TURNAROUND TIMES	~2X LONGER TURNAROUND TIMES (SHORT DURATION FLIGHTS)	~3X LONGER TURNAROUND TIMES (LONG DURATION FLIGHTS)	SAME TURNAROUND TIMES
CHANGES TO AIRPORT INFRASTRUCTURE	SAME INFRASTRUCTURES	FACILITY TO TRANSPORT AND STORE LIQUID HYDROGEN		BATTERY CHARGING POINTS AND TRANSFER SYSTEM
COST COMPARISON[5]	~2X WHEN COMPARED TO TRADITIONAL JET FUEL	1.2X -1.4X WHEN COMPARED TO TRADITIONAL JET FUEL		0.7X WHEN COMPARED TO TRADITIONAL JET FUEL

POSITIVE ASPECT OF THE TECHNOLOGY | NEGATIVE ASPECT OF THE TECHNOLOGY

1. Life-cycle emission estimation consistent with CORSIA methodology - 2. SAF can reduce emission by potentially 90%, based on production pathways but currently technology limitations leave us with an achievable number of 60% reduction - 3. Depending on the hydrogen carbon intensity and the technology (higher for fuel-cell than turbine) - 4. Depending on the electricity carbon intensity, estimation for regional aircrafts only - 5. Only for the energy buying (no estimation of adaptation costs)

Source : ICTT 2022 ; IATA 2022 ; Capgemini experts

Figure 4: Comparison of SAF with other propulsion technologies

Therefore, SAF, when compared to electricity and hydrogen, is the best near-term solution to decarbonize the aviation industry, including long-distance flights. With only minor or no changes to the aircraft, it can be blended with normal jet fuel to be used for flying all segments. It has little to no impact on aircraft operations and can be used with the existing airport infrastructure.

Other technologies like electricity and hydrogen are currently being tested. However, presently these technologies have many limitations – R&D investments are needed by the industry to fully mature the technology. For example, electric powered aircraft can currently only fly ultra-short segments. Additionally, these aircraft will require investments in airport infrastructure to install battery charging points. Similarly, hydrogen also requires infrastructure investments in terms of transportation and the storage of liquid hydrogen

REPORT METHODOLOGY

This report is the result of several months of extensive research that involved analyzing existing literature and consulting with experts from the Capgemini ecosystem.

The report utilizes data from various sources, including public sources like academic literature, press articles, and Capgemini expert insights, used as complementary sources.

The different SAF production pathways and feedstocks in this report are ASTM-approved and the assessment focuses on seven streams:

- Plant-based feedstocks' impact on agriculture
- Different SAF production pathways and their yields
- Industrial-based feedstocks and their impact on industrial needs
- The social impact of feedstocks production on the population and the need of governance
- The regulatory landscape on SAF around the world, with specific focus on the US and EU
- The environmental impact of SAF production per type of feedstock and production process
- The economic assessment of feedstocks production

4 SUSTAINABLE AVIATION FUEL PRODUCTION AND LIFECYCLE

The world needs 450 billion liters of SAF by 2050 to just meet the aviation industry target for climate change...

SAF is defined as a synthetic fuel with a significantly smaller environmental footprint than a conventional fuel applied to aeronautics, meeting standards such as the ASTM D7566 or local criteria such as those defined by the European Commission. It is chemically very similar to traditional jet fuel but can reduce emissions by up to 80%. The world produced 300 million liters of SAF in 2022. SAF production needs a boost to meet the industry targets. As per the IATA, the world will need 450 billion liters of SAF by the year 2050. This is ~1,500 times the current production capacity. A gradual buildup of SAF production and feedstock procurement and supply are needed to grow the production at this scale.

SAF ARE EXPECTED TO REACH A PRODUCTION OF 449 BL, REPRESENTING 65% OF TOTAL FUEL REQUIREMENT IN 2050

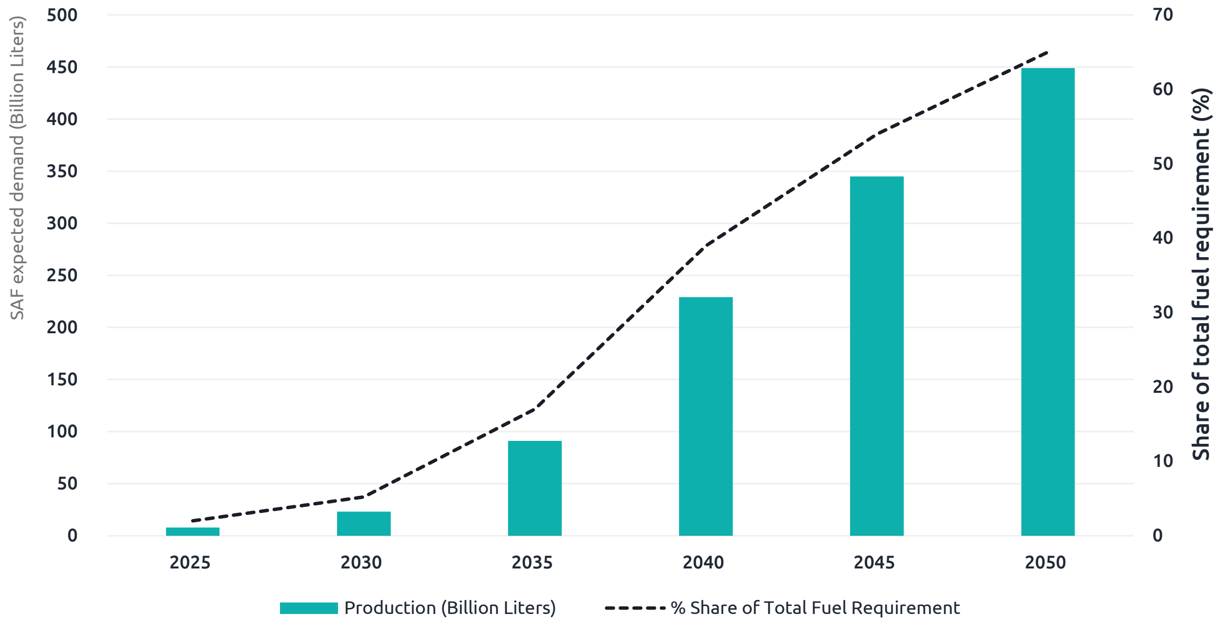
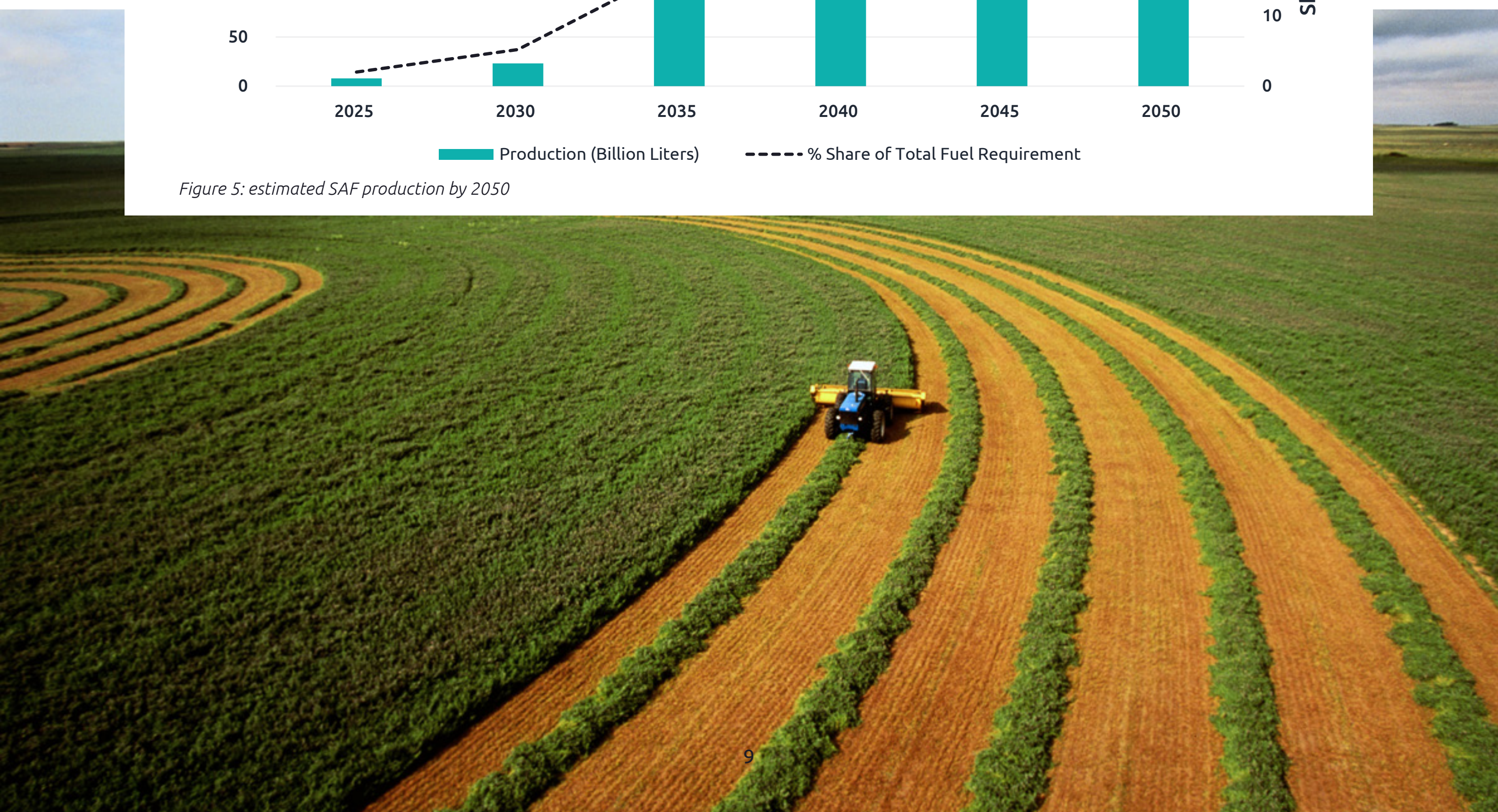


Figure 5: estimated SAF production by 2050



SAF production is dependent on feedstock availability and pathways. Each pathway has its own production lifecycle. Broadly, there are five major steps in the production of SAF:

FEEDSTOCK PRODUCTION	TRANSPORTATION TO PROCESSING CENTERS	FEEDSTOCK PROCESSING	SAF REFINERY	SAF TRANSPORT VIA DISTRIBUTION CENTERS
Some of the feedstock is cultivated in farms using sustainable methods. Other feedstock like agricultural residue are byproducts. There is a net absorption in the CO2 gases at this step.	Different feedstocks are centrally collected and segregated based on need. Here the feedstock is transported to processing centers. The idea is to transport it to the nearest processing center to reduce the carbon footprint.	The feedstock is converted to intermediaries using processing pathways. This intermediary is then used to produce SAF.	The intermediary is refined at SAF refineries. This step produces SAF as well as other byproducts like bio diesel and other oils.	The distribution centers distribute the SAF to airports where it is finally blended with jet fuel and used in aircraft.
1 FEEDSTOCK IS GROWN IN FARMS	2 TRANSPORT TO PROCESSING CENTERS	3 FEEDSTOCK PROCESSING CENTRES	4 SAF REFINERY	5 DISTRIBUTION CENTRE
CO_2 IS ABSORBED FROM AIR	CO_2 IS EMITTED IN AIR	CO_2 IS EMITTED IN AIR	CO_2 IS EMITTED IN AIR	CO_2 IS EMITTED IN AIR
Feedstock is produced using sustainable methods. Some of the feedstock that are by-product are agricultural residue and forest residue. Some are specially cultivated – like energy crops	Feedstock is centrally collected in a hub and transported. The emphasis is to add minimum carbon footprint while transporting the feedstock	The process produces intermediaries that is used in the production of actual SAF	Here the actual SAF is produced from intermediaries. The SAF yield depends in the feedstock and the pathway	SAF is transported to airports from the distribution centres

Figure 6: typical SAF value chain

SAF can be divided into synthetic fuel and biofuel. Synthetic fuel is produced directly by cracking or fermentation and indirectly by the X-to-Liquid (XtL) process. Among the biofuels – which are the scope of this paper – we can divide them along their generations.

The first generation includes plants and food crops. The depend on the esterification of vegetable or animal oils. In this case, SAF is limited to the sustainable production of used oils or animal fats to maintain the "sustainable" character of the solution.

The second generation of feedstocks use more dedicated plants like jatropha or miscanthus. They solve the issue of direct food consumption to an extent but have other issues like land availability. The process to produce SAF in this case is more specifically called BtL for Biomass-to-Liquid (or WtL for Waste-to-Liquid, if we consider household waste).

5 SAF PATHWAYS

The world needs 450 billion liters of SAF by 2050 to just meet the aviation industry target for climate change...

There are several pathways to produce SAF that are certified by international organizations like the ASTM. We will study major pathways that are either currently producing SAF or have the potential to develop in the future into a full-fledged commercial solution. The four processes that we will assess are the following:

1 SIP OR SYNTHESIZED ISO-PARAFFINS FROM HYDROPROCESSED FERMENTED SUGARS

This process was approved in 2014 and utilizes sugar-based feedstock fermentation into hydrocarbons. These hydrocarbons are later converted into SAF. Typical feedstocks for this process are sugarcane and sugar beet. Fuel produced from this method can be blended by a maximum of 10%v/v. The process conversion is approximately 28%.

2 HEFA OR SYNTHESIZED PARAFFINIC KEROSENE FROM HYDROPROCESSED ESTERS AND FATTY ACIDS

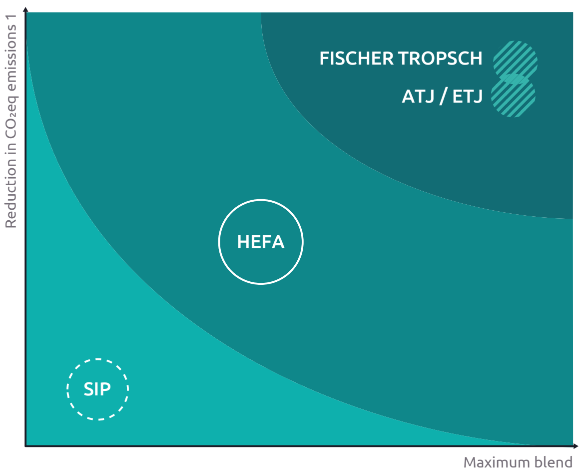
This process was approved in 2011 and utilizes lipids (oil and fat) to generate hydrocarbons used for producing SAF. Typical feedstocks include waste oil, used cooking oil, animal fat, soy oil, and corn oil. This process is well understood and is fully mature to commercially produce SAF. The typical yield of this process is 80–90%, out of which 50% directly results in SAF and the rest is converted into diesel to be used for other means of road transport.

3 ALCOHOL-TO-JET (ATJ) AND ETHANOL-TO-JET (ETJ) PROCESSES

These processes were approved in 2016 and 2018, respectively. The AtJ process utilizes dehydration, oligomerization, and hydroprocessing to convert alcohol feedstocks into a pure hydrocarbon fuel blending component. The blend limit that is established for SAF produced by this process is 50%v/v. Typical feedstocks for these processes are agricultural and forest residue, municipal solid waste (MSW), and energy crops like switchgrass.

4 THE FISCHER TROPSCH PROCESS

This process uses municipal waste and other feedstock that is used in the AtJ/EtJ process to generate a gas known as syngas. This syngas is then catalytically produced into liquid hydrocarbons. This process was approved in 2009. It has a few variations based on the type of gasification and catalyst used. As a process, this is still in the commercial pilot phase with the potential to turn into a full-fledged commercial SAF producing process.



FISCHER TROPSCH
Agricultural and forest residues, short rotation woody crops, herbaceous energy crops

- Commercial pilot technology
- Up to 99% reduction in CO2 emissions
- Maximum blend of 50 %v/V

ATJ / ETJ
Agricultural and forest residues, municipal solid waste, energy crops – switchgrass

- Commercial pilot technology
- Up to 95% reduction in CO2 emissions
- Maximum blend of 50 %v/V

HEFA
Oil plants like corn, palm, soy, rapeseed, used cooking oil

- Fully mature technology
- Up to 85% reduction in CO2 emissions
- Maximum blend of 50 %v/V

SIP
Sugarcane, sugar beet

- Mature technology
- Up to 50% reduction in CO2 emissions
- Maximum blend of 10 %v/V

1.vs traditional jet fuel, following LCA approach

For the purposes of this assessment, we have chosen 24 feedstocks. These feedstocks are the most widely used and approved by the ASTM as referenced in the ASTM D7566 standard. Also, for purpose of easy identification we have numbered these pathways (starting from PW-1 to PW-24). Note that these numbers are not standard numbering but are done to easily identify these pathways in our report.

ASTM SPECIFICATION D7566 FOR SAF QUALITY STANDARDS

S NO	PROCESS	FEEDSTOCK
PW-1	Fischer-Tropsch	Agricultural residues
PW-2		Forestry residues
PW-3		Municipal solid waste (MSW), 0% NBC
PW-4		Poplar (short-rotation woody crops)
PW-5		Miscanthus (herbaceous energy crops)
PW-6		Switchgrass (herbaceous energy crops)
PW-7	SIP	Sugarcane
PW-8		Sugar beet
PW-9	HEFA	Tallow
PW-10		Used cooking oil (UCO/WCO)
PW-11		Palm fatty acid distillate
PW-12		Corn oil
PW-13		Soybean oil
PW-14		Rapeseed oil
PW-15		Sunflower oil
PW-16		Brassica carinata oil
PW-17		Camelina oil
PW-18	ATJ	Agricultural residues
PW-19		Forestry residues
PW-20		Sugarcane
PW-21		Corn grain
PW-22		Miscanthus (herbaceous energy crops)
PW-23		Switchgrass (herbaceous energy crops)
PW-24		Molasses

Figure 8: Establishing SAF pathways

6 FEEDSTOCK ASSESSMENT

All the pathways that produce SAF require sustainable feedstocks. These feedstocks range from municipal waste to purposefully grown crops. While it is recommended that feedstock should be a waste or discarded product, it is rarely entirely a discarded product. For example, wheat residue is already used as fodder for cattle, making bedding and cultivating mushrooms, or mulching. If all wheat straw were instead diverted to biofuel production, the other uses would lack raw materials and require an increase in production of substitutable materials. Understanding a feedstock's displacement effects is critical for ensuring GHG savings as well as determining quantities that can be diverted to biofuel production without reducing its availability for use in other applications. Taking this into account, a proper assessment of feedstock in terms of agricultural, industrial, social, and environmental parameters needs to be performed for its selection to produce SAF.

The market is both complex and diverse with many feedstock types, geographic distributions, and export restrictions. Hence, not all feedstocks are available to produce SAF in all regions.

AREAS TO ASSESS FEEDSTOCK FEASIBILITY

Figure 9 : Areas to assess feedstock feasibility

KEY QUESTIONS TO ANSWER...

	Question	Food for Thought
1	Which SAF Pathway to consider?	• Based on technology maturity and cost feasibility • Based on vision of climate goals per region
2	Which feedstock to choose?	• Which sustainable feedstock is available? • Does feedstock drive social and economic competition?
3	What ecosystem changes are necessary?	• SAF Logistics and Infrastructure operations • What production capacity is needed to meet the target
4	How can governments support SAF production?	• Value chain Stakeholder Harmonization • Policies and grants to boost production

6.1

AGRICULTURAL ASSESSMENT OF FEEDSTOCK

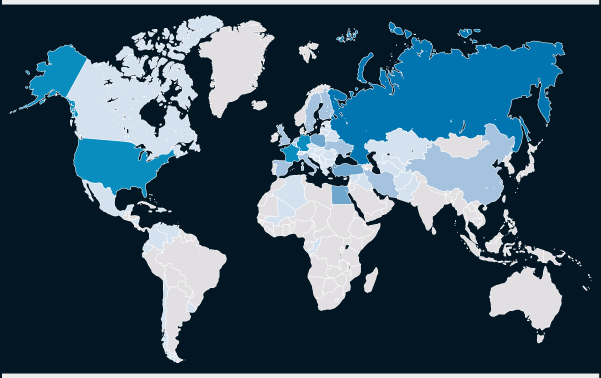
6.1.1 ASSESSING FEEDSTOCK AVAILABILITY ACROSS THE GLOBE

Chapter 2 of the ICAO document on sustainability states the following:

"CORSIA SAF will not be made from biomass obtained from land converted after 1 January 2008 that was primary forests, wetlands, or peat lands and/or contributes to the degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks."

If we consider the availability of feedstock worldwide as per the IATA, there is enough feedstock available to produce an SAF quantity that meets the 2050 target.

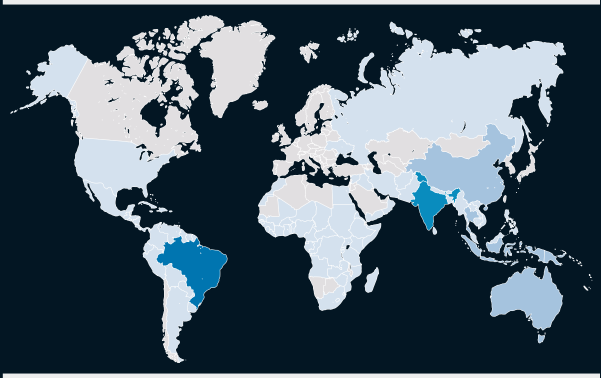
SUGAR BEET PRODUCTION (IN TONS)



Total production of sugar beet in 2021 - 270 M Tons.

The top producting regions are North America, Russia, Europe and China.

SUGARCANE PRODUCTION (IN TONS)



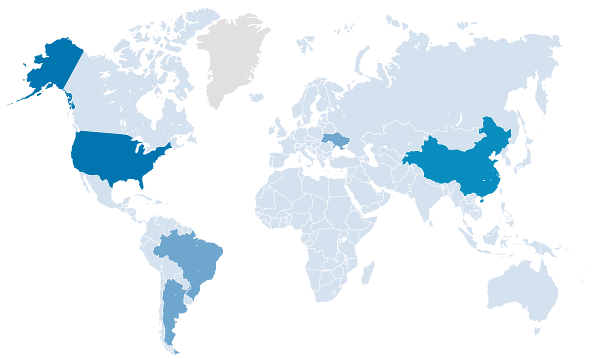
Total production of sugarcane in 2021 - 1859 M Tons.

The top producting regions are Brazil, India, China, Russia and USA.

Source : Food and Agriculture Organisation of the United Nations 2023

Regions like South America (Brazil) and Asia (India and China) are major producers of sugarcane in the world. The total production of sugarcane stood at 1,859 million tons. Brazil alone produced 61 million tons in 2021. North America, Russia, and parts of Europe produce sugar beet in large quantities. In 2021, the Russian Federation produced 41 million tons of sugar beet.

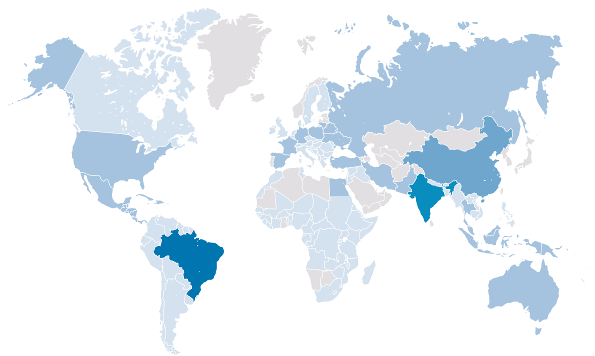
CORN PRODUCTION (IN TONS)



Total production of corn in 2021 - 1210 M Tons.

The top producting regions are North America, Mexico, China. It is grown and consumed globally in various forms.

MOLASSES PRODUCTION (IN TONS)



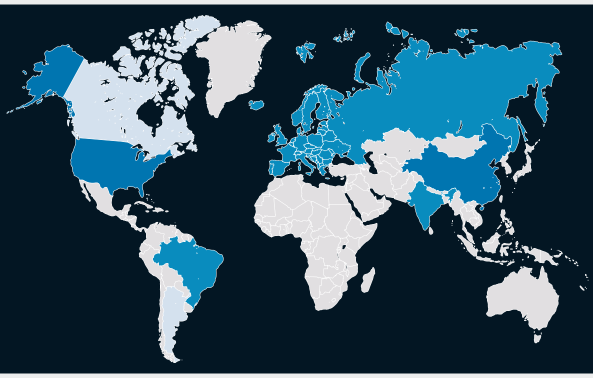
Total production of Molasses in 2020 - 61 M Tons.

The top producting regions are Brazil, China, USA and Russia.

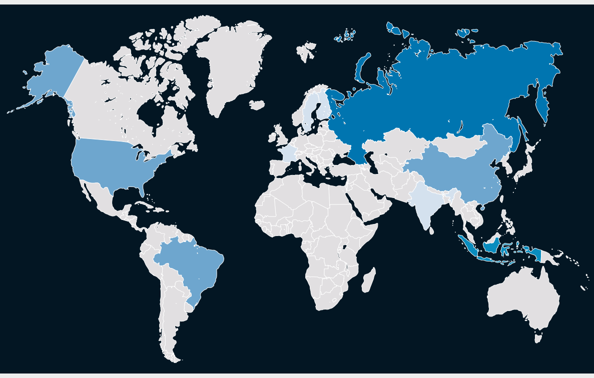
Source : Food and Agriculture Organisation of the United Nations 2023

Corn is grown and consumed globally in various forms. The USA, China, Africa, and parts of South America are large producers of corn globally. Molasses is a byproduct produced after refining sugarcane. This is produced in places where sugarcane is produced and processed in large quantities (Brazil and India).

AGRICULTURAL RESIDUE PRODUCTION ESTIMATE (IN TONS)	FOREST RESIDUE TOP PRODUCERS (IN TONS)



The top producing regions are North America, Brazil, Europe, Russia, India, China (based on top 10 producers)



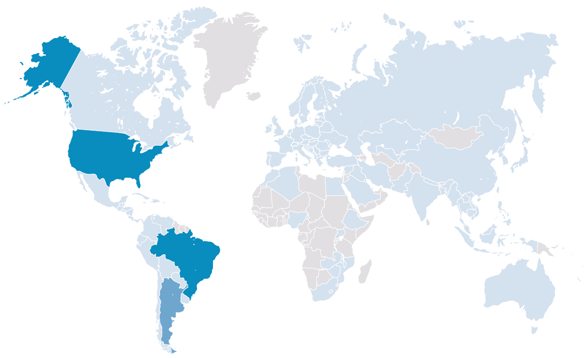
The top producing regions are Russia, Mexico North America, Brazil, China, India (based on top 10 producers)

Source : Research Gate, 2022

Agricultural residues are leftover crop residues that remain in the field. Typically, farming-intense regions have a large stock of agricultural residues. Countries like India, China, the USA, Brazil, Russia, and parts of Europe generate large quantities of agricultural residues.

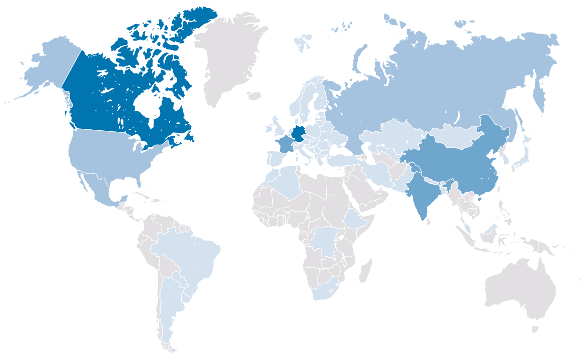
Similarly, forest residues are generated in large quantities in regions like Russia, Europe, India, China, the USA, and Brazil.

SOYABEAN OIL PRODUCTION ESTIMATE (IN TONS)	RAPESEED OIL PRODUCTION ESTIMATE (IN TONS)



Total production of Soyabean Oil in 2020 – 59 M Tons

The top producing regions are China, USA, Brazil. It is grown and consumed worldwide



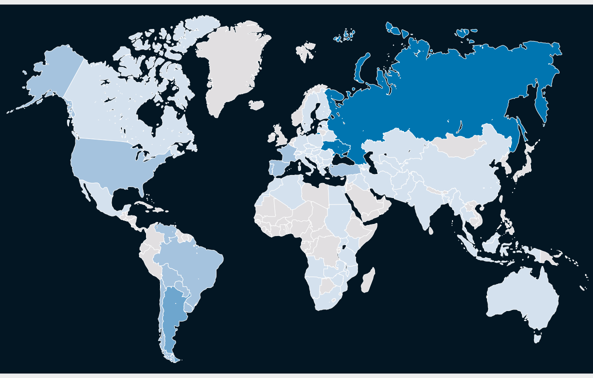
Total production of Rapeseed Oil in 2020 – 25 M Tons

The top producing regions are North America, Europe, Asia and parts of South America.

Source : Food and Agriculture Organization of the United Nations 2023

Soyabean oil is produced globally from soyabean. The total production of soyabean oil was 59 million tons in 2020. China, the USA, and Brazil are top producers. Similarly, rapeseed oil, which is used in the HEFA process, is produced in large quantities in India, China, Canada, and parts of Europe.

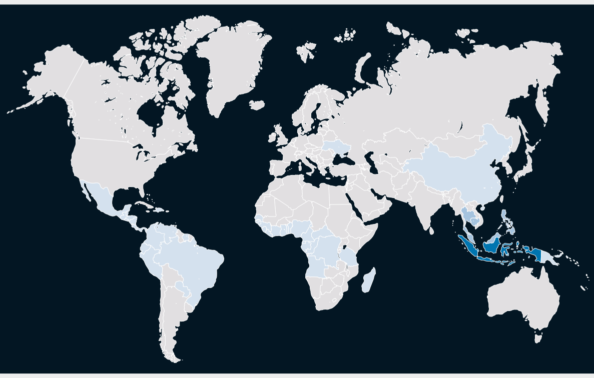
SUNFLOWER OIL PRODUCTION ESTIMATE (IN TONS)



Total production of sunflower oil in 2020 – 20.5 M Tons

Russia and Europe are the top producers of Sunflower Oil.
It is produced globally for consumption in various forms

PALM OIL PRODUCTION ESTIMATE (IN TONS)



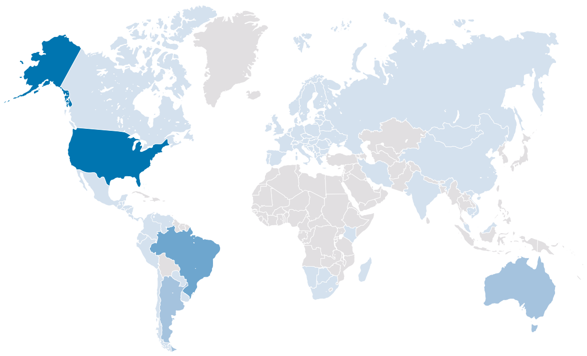
Total production of palm oil in 2020 – 75 M Tons

The top producing regions are Indonesia, China, parts of Africa and South America

Source : Food and Agriculture Organization of the United Nations 2023

Sunflower oil is produced throughout the globe from sunflower seeds. Russia is the biggest producer of sunflower oil globally. Palm oil is majorly produced in Indonedia and parts of Asia (China) and South America. This production results in significant palm fatty acid distillate deposit which are by-products of this industry. This is used in the HEFA process to produce SAF.

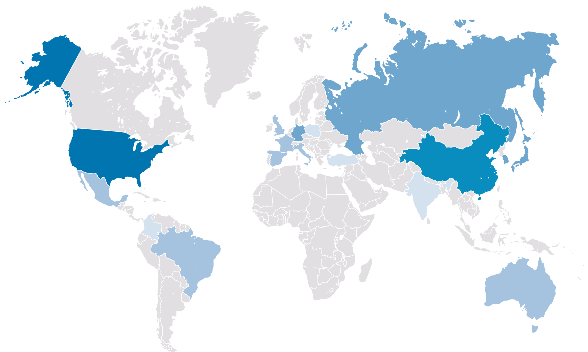
TALLOW PRODUCTION ESTIMATE (IN TONS)



Total production of Tallow in 2020 – 7.8 M Tons

The top producing country is the US, while some producers are located in South America, Europe, Asia and Australia.

MAJOR PRODUCERS OF MSW (IN TONS)



The top producing regions are Russia, Mexico North America, Brazil, China, India (based on top 18 producers)

MSW production data is not recorded for all countries. Only a few countries estimate the generation and collection of MSW. Countries like the USA, China, India, Australia, and parts of Europe and South America report the generation of MSW. Tallow is a byproduct generated after processing beef. North America is the largest producer of tallow. Other regions include parts of Asia, Europe, South America, and Australia.

6.1.2 DOES SAF FEEDSTOCK PRODUCTION COMPETE WITH AGRICULTURE?

S NO	PROCESS	FEEDSTOCK	COMPETITION WITH AGRICULTURE?	COMPETITION IMPACT SEVERITY
PW-1	Fischer-Tropsch	Agricultural residues	NO	NOT APPLICABLE
PW-2		Forestry residues	NO	NOT APPLICABLE
PW-3		Municipal solid waste (MSW), 0% NBC	NO	NOT APPLICABLE
PW-4		Poplar (short-rotation woody crops)	NO	NOT APPLICABLE
PW-5		Miscanthus (herbaceous energy crops)	NO	NOT APPLICABLE
PW-6		Switchgrass (herbaceous energy crops)	NO	NOT APPLICABLE
PW-7	SIP	Sugarcane	YES	HIGH
PW-8		Sugar beet	YES	HIGH
PW-9	HEFA	Tallow	NO	NOT APPLICABLE
PW-10		Used cooking oil (UCO/WCO)	NO	NOT APPLICABLE
PW-11		Palm fatty acid distillate	NO	NOT APPLICABLE
PW-12		Corn oil	YES	MEDIUM
PW-13		Soybean oil	YES	MEDIUM
PW-14		Rapeseed oil	YES	MEDIUM
PW-15		Sunflower oil	YES	HIGH
PW-16		Brassica carinata oil	YES	HIGH
PW-17		Camelina oil	YES	HIGH
PW-18	ATJ	Agricultural residues	NO	NOT APPLICABLE
PW-19		Forestry residues	NO	NOT APPLICABLE
PW-20		Sugarcane	YES	HIGH
PW-21		Corn grain	YES	HIGH
PW-22		Miscanthus (herbaceous energy crops)	NO	NOT APPLICABLE
PW-23		Switchgrass (herbaceous energy crops)	NO	NOT APPLICABLE
PW-24		Molasses	NO	NOT APPLICABLE

Figure 10: SAF competition assessment with agriculture

Competition Impact Severity (categorized by high, medium, and low) is determined by assessing the total crop production, the total area under cultivation, and human consumption. The more difficult it is to produce enough crop that is needed for human consumption, the higher the value of the severity of competition.

Crops that compete directly or indirectly with agriculture are deemed as non-sustainable for SAF production and should be best avoided in case other options are available. We define agricultural competition as any crop that is produced on farm for direct or indirect human food consumption. These crops directly conflict with human sustainability when diverted to the production of SAF. For example, using soy to produce SAF in the USA is not a sustainable option in the long run.

Feedstocks like agricultural residues, forest residues, MSW, used cooking oil, miscanthus, switchgrass, and poplar are some of the feedstocks that do not compete with agriculture.

6.2 PROCESS YIELD OF SAF

The yield of SAF depends on the production pathway and the nature of feedstock that is used. The conversion rate determines the process efficiency of the pathway. There are two steps in determining the conversion rate of the process:

1 INTERMEDIATE YIELD.

This is the percentage of the intermediate produced from a feedstock, depending only on the process efficiency to convert feedstock into the total outputs (SAF + other outputs). This intermediate is then used to produce the actual SAF. The rest is either waste or is used for producing other products such as road fuels (gasoline, diesel) or light ends (LPG, naphta).

2 FINAL YIELD.

This is the final percentage of SAF produced from the feedstock.

PATHWAY	S NO	FEEDSTOCK	INTERMEDIATE YIELD		SAF YIELD	
			USA	EUROPE	USA	EUROPE
FT	PW-1	Agricultural residues (Corn-US/ Wheat-EU)	+	+	−	+
	PW-2	Forestry residues	NO STUDY FOUND	+	+	+
	PW-3	Municipal solid waste (MSW), 0% NBC	NO STUDY FOUND	−	−	−
	PW-4	Poplar (short-rotation woody crops)	+	NA	−	NA
	PW-5&6	Miscanthus & switchgrass (herbaceous energy crops)	NO STUDY FOUND	+	−	+
SIP	PW-7	Sugarcane	+	NA	+	NA
	PW-8	Sugar beet	+	+	+	+
HEFA	PW-9	Tallow	−	NA	+	NA
	PW-12	Corn oil	−	NA	NO STUDY FOUND	NA
	PW-13	Soybean oil	−	−	+	+
	PW-14	Rapeseed oil	+	−	+	+
	PW-17	Camelina oil	+	NA	+	NA
ATJ	PW-18	Agricultural residues (Corn-US/ Wheat-EU)	NO STUDY FOUND	+	+	−
	PW-19	Forestry residues	NO STUDY FOUND	+	+	−
	PW-20	Sugarcane	+	NA	+	NA
	PW-21	Corn grain	NA	NA	+	NA
	PW-22&23	Miscanthus & switchgrass (herbaceous energy crops)	NO STUDY FOUND	+	+	+

Figure 11: Process yield of pathways taking the US and EU as examples

As a case study, we compared the data of the US and Europe for process yields. The lowest intermediary yield was seen in oil seeds, whereas sugar beet, agricultural residues, and woody and energy crops had the highest yields. However, contrary to the intermediary yields, the SAF yield was high for oil seeds, which can be attributed to the high process efficiency of HEFA. Pathways in SIP and HEFA were overall better performing due to better process efficiencies (>1000L of SAF fuel/ton of intermediary). Fisher-Tropsch pathways had the lowest process yields (averaging from 11 to 200 L of SAF fuel/ton of intermediary), although their intermediary yields were one of the highest.

Another important point to highlight is that the difference between the intermediate and final yield is the percentage of outputs used by other industries (mobility for road fuels and industry for light ends). Increasing the SAF final yield will deplete the production of other outputs and could increase the competition between the aeronautic and mobility industries.

6.3 INDUSTRIAL ASSESSMENT OF FEEDSTOCK

The industrial competition assessment of feedstock must answer two vital questions related to industrial uses and its impact of these feedstocks:

1 WILL SAF PRODUCTION FROM FEEDSTOCK COMPETE WITH OTHER INDUSTRIES?

The answer to this question will imply what ecosystem changes are needed to generate more feedstock for SAF production. Competition with other industries will mean that a choice will have to be made for feedstock availability for SAF production versus other industrial uses.
This is a difficult choice to make and is dependent on a large number of social, economic, and political factors.

2 WHAT IS THE IMPACT TO THE ECONOMY OF A REGION IN CASE ALL THE FEEDSTOCK IS DIVERTED TOWARD SAF PRODUCTION?

This question assesses the importance of feedstock in the economy of the region. To lay out a sustainable pathway for SAF production, we must choose a pathway with feedstock that has limited interference with the present economic fabric of the region.

SNO	FEEDSTOCK	Will SAF production from this feedstock compete with other Industry?	Which Industry SAF production will compete? [1]	What will be the impact on economy in case all of feedstock is diverted to SAF production? [2]
1-18	Agricultural residues	YES	Dairy Industry	HIGH
2-19	Forestry residues	YES	Paper industry	NOT APPLICABLE
3	Municipal solid waste (MSW)	YES	Energy - biogas	MEDIUM
4	Poplar	NO	Not Applicable	NOT APPLICABLE
5-22	Miscanthus	NO	Not Applicable	NOT APPLICABLE
6-23	Switchgrass	NO	Not Applicable	NOT APPLICABLE
7-20	Sugarcane	YES	Sugar Industry	HIGH
8	Sugarbeet	YES	Sugar Industry	HIGH
9	Tallow	YES	Animal Feed, Soap	LOW
10	Used cooking oil	YES	Soap	LOW
11	Palm fatty acid distillate	YES	Soap & candles	LOW
12	Corn oil	YES	soap, salve, paint, erasers	HIGH
13	Soybean oil	YES	Food	MEDIUM
14	Rapeseed oil	YES	Food	MEDIUM
15	Sunflower oil	YES	Food & Agriculture	MEDIUM
16	Brassica carinata oil	YES	Food	LOW
17	Camelina oil	YES	Cosmetic	LOW
21	Corn grain	YES	Sugar Industry	HIGH
24	Molasses	YES	Food & Liquor (Rum)	MEDIUM

1. Only major industries listed. Feedstock may be used at other industries as well
2. Impact may be higher. Only contribution of major products calculated
Source : Capgemini Research ; Capgemini experts

Figure 12: Industrial assessment of feedstocks

As this assessment just focuses on feedstocks and not on the pathways (feedstocks linked to a production process), these 24 ASTM-approved pathways are clustered into 19 feedstocks. Only three feedstocks are not competing with other industrial applications. They are miscanthus, switchgrass, and poplar. These feedstocks can be safely diverted toward SAF production if they are available in the region.

There are five feedstocks whose industrial application dependence are lower than other feedstocks. These feedstocks (like tallow, used cooking oil; palm fatty acid distillate; brassica oil; and camelina oil) are used in other industries but have a low impact on the economy and have alternatives that are established. Hence, these feedstocks may also be considered for SAF production in case they are available in sufficient quantities.

Feedstocks like corn, sugarcane, sugar beet, molasses, agricultural residue, soyabean oil, rapeseed oil, and MSW have medium to high economic impact. Hence, a careful assessment must be done before diverting a portion or all of the feedstock toward SAF production.

6.4 SOCIAL ASSESSMENT OF FEEDSTOCK AND SAF GOVERNANCE

As air travel increases and the demand for travel grows, the demand for jet fuel and SAF will continuously keep rising. This generates opportunities beyond just CO2 emission reduction. The focus on SAF production has significant social benefits as well, such as sustainable waste disposal, extra income for farmers, and boosting energy sovereignty. When implemented in a sustainable way, this will help address five sustainable development goals laid down by the United Nations – namely, good health and wellbeing; affordable clean energy; industry, innovation, and infrastructure; decent work and economic growth; and climate action. It will help reduce the total social cost of carbon.

KEY SOCIAL BENEFITS OF SAF PRODUCTION...

ADDRESSES FIVE UN SUSTAINABLE DEVELOPMENT GOALS...

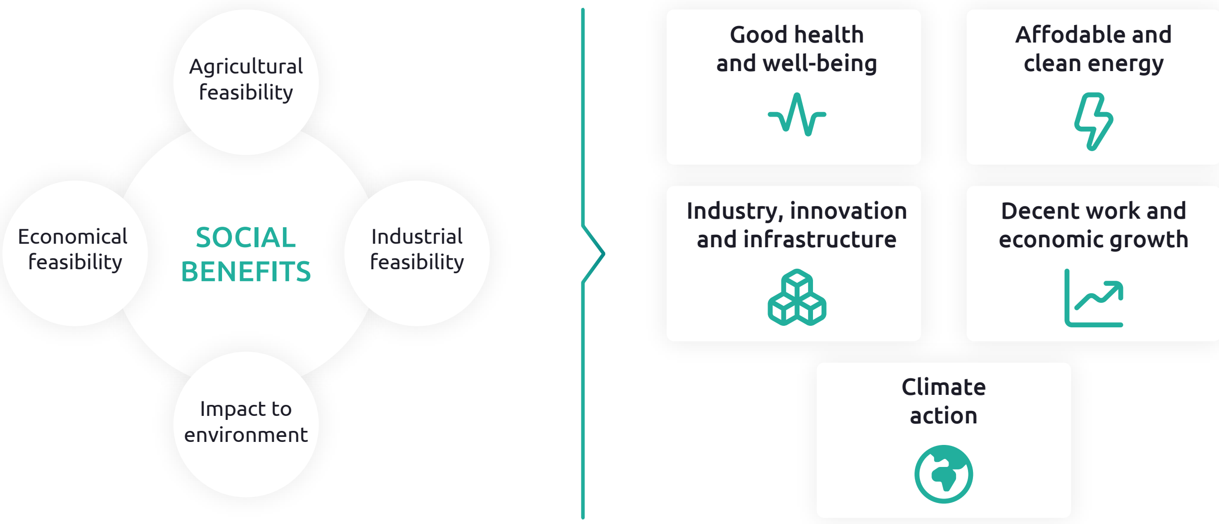
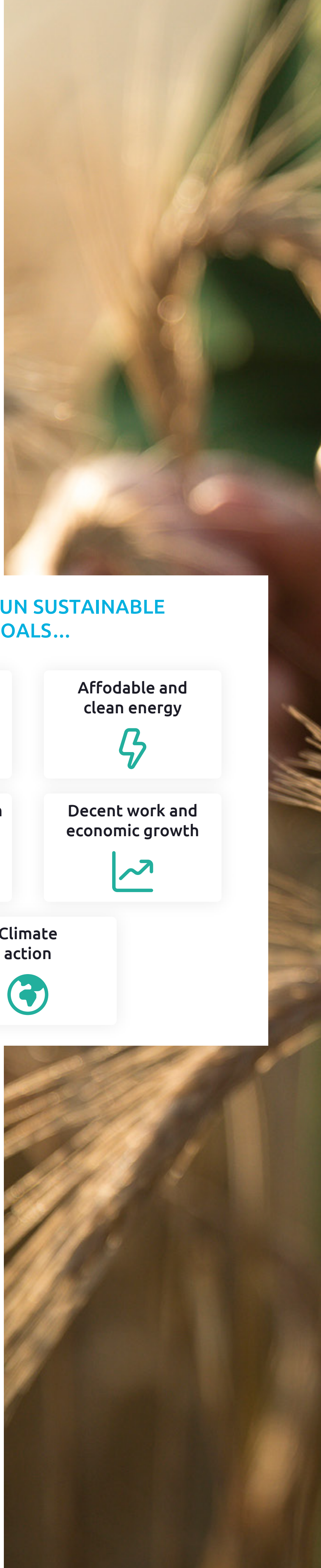


Figure 13: Social impacts assessment

Feedstocks like agricultural residues can provide extra income to farmers throughout the world. This is especially significant for countries where the income of farmers is low – this additional income can help promote better economic growth for the farmers in those regions. Farmers (typically in Asia) burn the agricultural residues to get rid of them in an cost-effective way. This releases a large amount of carbon in the air, causing severe pollution.

SAF production brings opportunity to plan efficient waste disposal mechanisms, leading to cleaner cities and less need for landfills. MSW can be collected and sent to SAF producing plants for processing and production.



6.5 SAF LEGISLATIONS AROUND THE WORLD

The world is coming together to formulate legislation to mandate SAF. Europe and the USA currently lead the race toward SAF mandates. The EU has laid down the clear foundations for mandating the use of SAF along with traditional jet fuel. The blend target is incrementally increasing in the EU from 2% in 2025 to 70% by 2050. Similarly, the USA has targeted to reduce aviation emissions by 20% by 2030. Brazil, which is a major consumer and producer of SAF, has launched a national biokerosene program. A clear SAF mandate is expected by 2027.

However, Asia is a clear whitespace in the SAF sphere. While major economies are discussing the use of SAF, there is no clear legislation that is approved. Countries like India, China, and Japan are discussing SAF mandates, but the decision is yet pending in their national parliaments. There needs to be an immediate consensus in Asia, especially in the big economies like China, Japan, and India, to implement an SAF mandate. This is required to boost the industrial production as well as consumption of SAF by airlines.

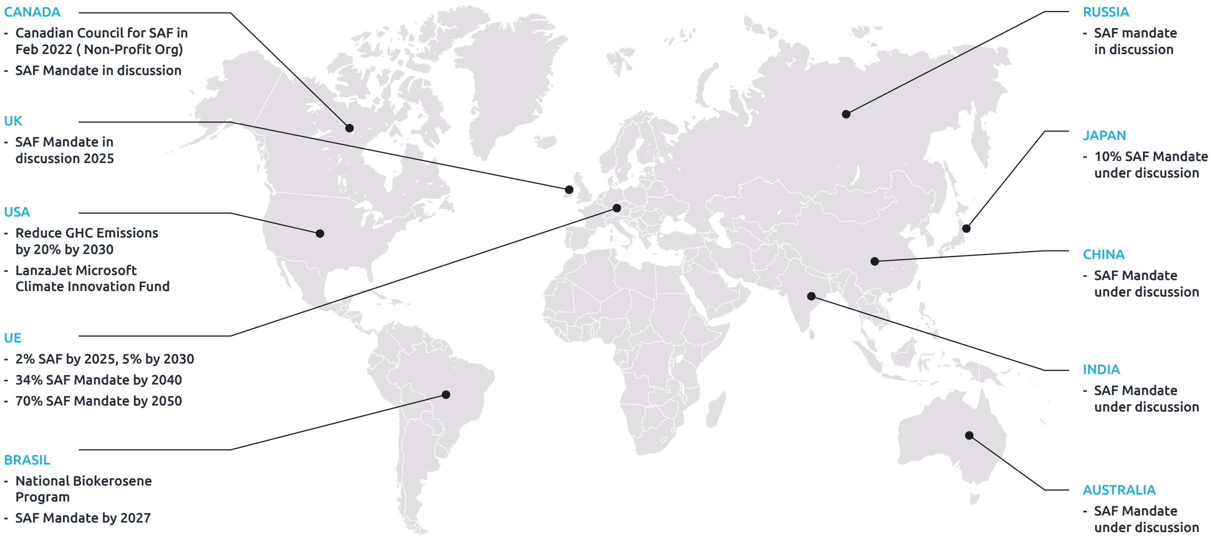


Figure 14: SAF mandates by major economies

Based on our comprehensive assessment of the regulatory landscape in different countries, we can distinguish two levels of involvement: countries with leading SAF regulations and countries with a gap in implementing SAF regulations.

In this geographical overview, not all of the EU appears as a leader in SAF regulations. In fact, although the legislative framework is European, each country is free to choose whether to implement the guidelines through its own laws. Thus, only France, Spain, and Sweden are leading European countries in this regard.

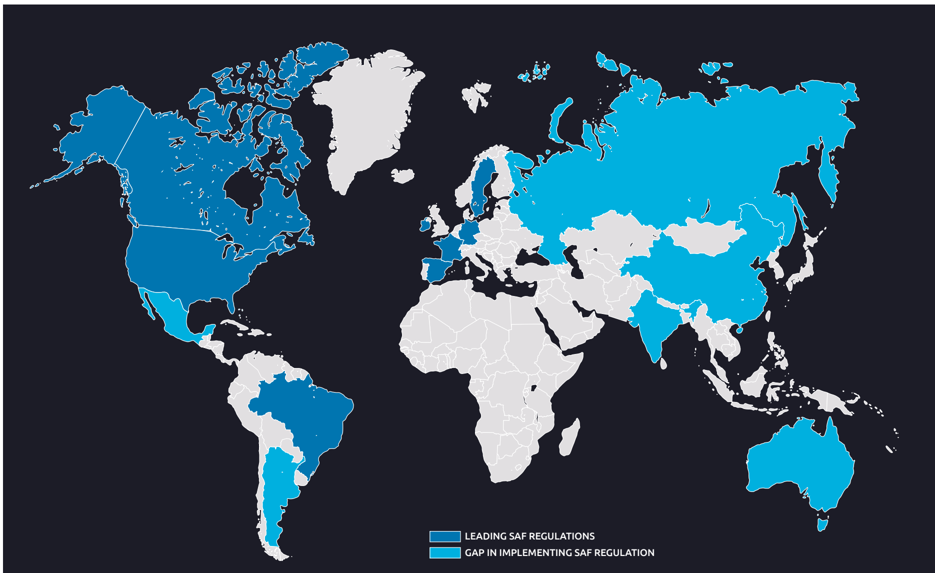


Figure 15: SAF mandate GAP versus leaders

FOCUS ON THE EUROPEAN COMMISSION REGULATORY LANDSCAPE FOR SAF

On 14 July 2021, the European Commission presented the Fit for 55 package – including a number of proposals to help cut emissions from transport. The package includes a proposal to increase the production and use of SAFs, also known as the ReFuelEU Aviation Initiative. This initiative would force fuel suppliers to supply an increasing share of SAFs at EU airports.

The Commission proposal also defines SAF as "drop-in" aviation fuels (fuels substitutable for conventional aviation fuel), which are:

- synthetic aviation fuels (out of the scope of the present study);
- advanced biofuels produced from feedstock such as agricultural or forestry residues, algae, and bio-waste;
- biofuels produced from certain other feedstocks with "high sustainability potential" (e.g., used cooking oil or certain animal fats) that meet the sustainability and GHG emissions criteria.

In April 2023, the Commission acted that feed and food crop-based fuels and fuels derived from palm and soy materials will not be considered green as there negative externalities outweights their benefits.

On the other hand, renewable hydrogen and synthetic low-carbon aviation fuels are considered as part of a sustainable fuel mix.

In addition, the EU has developed sustainability criteria for the production of biofuels from energy crops:

1 GHG EMISSIONS SAVINGS

SAF from energy crops must achieve at least a 70% reduction in GHG emissions compared to fossil jet fuel on a lifecycle basis. This includes emissions from the cultivation and harvesting of energy crops, processing, transportation, and combustion of the fuel.

2 LAND USE AND BIODIVERSITY

The production of energy crops for SAF must not result in the conversion of high-carbon stock land, such as forests or wetlands, or land with high biodiversity value. It should also not have negative impacts on soil quality, water resources, or air quality.

3 HUMAN RIGHTS AND LABOR STANDARDS

The production of energy crops for SAF must respect human rights and labor standards, including the rights of indigenous peoples and local communities, and avoid forced or child labor.

4 SOCIAL AND ECONOMIC IMPACTS

The production of energy crops for SAF should contribute to social and economic development, including rural development, job creation, and poverty reduction.

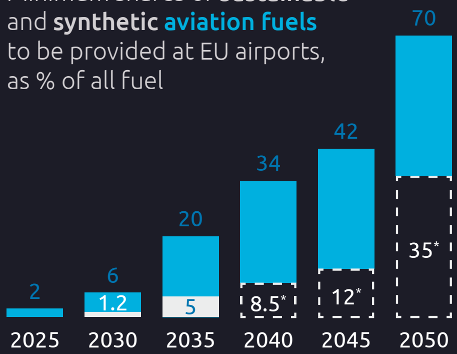
5 TRANSPARENCY AND TRACEABILITY

The supply chain for SAF from energy crops must be transparent and traceable, with information on the origin, production, and processing of the feedstock and fuel.

However, the ReFuelEU Initiative should contain the following objective: a minimum share of SAF supplied at each EU airport

2% in 2025
6% in 2030
20% in 2035
34% in 2040
42% in 2045
70% in 2050

Minimum shares of **sustainable** and **synthetic aviation fuels** to be provided at EU airports, as % of all fuel



*Capgemini extrapolation based on previous EU commission proposals

Figure 16: Minimum share of SAF to be supplied according to the EU Commission proposal

FOCUS ON THE US SAF GRAND CHALLENGE ROADMAP

In the past few years, many regulations in the US were set up, such as the following:

- The Alternative Fuel Transportation Program (AFTP)
- The Aviation Fuel Tax Exemption for Sustainable Aviation Fuel
- The Renewable Fuel Standard (RFS)
- Guidance from Federal Aviation Administration (FAA)
- A support program from the Department of Energy (DOE)

Following these regulations, an SAF plan was built and published in 2022 by the US government in order to accelerate the development and implementation of SAFs: **the SAF Grand Challenge Roadmap.**

The roadmap outlines a whole-of-government approach with coordinated policies and specific activities that should be undertaken by the federal agencies to support the achievement of both the 2030 and 2050 goals of the SAF Grand Challenge.

It also ensures the alignment of government and industry actions and coordinated government policies to achieve the goals of the SAF Grand Challenge.

The roadmap aims to achieve three main objectives:

1 EXPANDING SAF SUPPLY AND END USE

- **Three billion gallons per year of domestic SAF production by 2030**
- **35 billion gallons by 2050** (100% of the projected aviation jet fuel use)
- Maximize sustainable lipid supply for 2030 by investing in lipid production pathways like HEFA
- Increase production of purpose-grown biomass resources and collection of wastes and residues to achieve 2050 objectives
- Improve existing process such as ETJ

2 REDUCING THE COST OF SAF (THANKS TO THE 2022 INFLATION REDUCTION ACT)

- **A two-year tax credit** is accorded **for SAF blending**
- A subsequent **three-year tax credit** is accorded **for SAF production**
- A **grant program of $290 million** is set up over four years to carry out projects that produce, transport, blend, or store SAF, or develop, demonstrate, or apply low-emission aviation technologies
- The **tax credit** – which **starts at $1.25/gallon** of neat SAF – increases with every percentage
- point of improvement in lifecycle emissions performance of **up to $1.75/gallon**

3 ENHANCING THE SUSTAINABILITY OF SAF

- **SAFs that achieve a 50% reduction** in lifecycle GHG emissions compared to conventional jet fuel by 2030

6.6 ENVIRONMENT ASSESSMENT OF FEEDSTOCK

For a holistic assessment of feedstock, our study will focus on two main parameters related to environment. These parameters are the impact on soil quality and CO2.

- **SOIL HEALTH IMPACT**
  This measures the impact to the quality of soil for the next batch of feedstock production.
- **IMPACT ON CO2 EMISSIONS**
  This measures the reduction in CO2 emissions when SAF produced by this feedstock is blended with jet fuel.

6.6.1 ASSESSING SOIL IMPACT

FEEDSTOCK AND SOIL HEALTH ASSESSMENT

FEEDSTOCK	S NO	IMPACT TO SOIL?	IMPACT INTENSITY
Agricultural residues	1-18	−	MEDIUM
Forestry residues	2-19	−	MEDIUM
Municipal solid waste (MSW), 0% NBC	3	NOT APPLICABLE	NOT APPLICABLE
Poplar (short-rotation woody crops)	4	+	LOW TO NO IMPACT
Miscanthus (herbaceous energy crops)	5-22	−	LOW
Switchgrass (herbaceous energy crops)	6-23	+	MEDIUM
Sugarcane	7-20	−	MEDIUM
Sugarbeet	8	+	HIGH
Tallow	9	NOT APPLICABLE	NOT APPLICABLE
Used cooking oil (UCO/WCO)	10	NOT APPLICABLE	NOT APPLICABLE

FEEDSTOCK	S NO	IMPACT TO SOIL?	IMPACT INTENSITY
Palm fatty acid distillate	11	−	LOW TO MEDIUM
Corn oil	12	+	NOT APPLICABLE
Soybean oil	13	+	MEDIUM
Rapeseed oil	14	+	MEDIUM
Sunflower oil	15	+	MEDIUM
Brassica carinata oil	16	NO IMPACT	NOT APPLICABLE
Camelina oil	17	NO IMPACT	NOT APPLICABLE
Corn grain	21	+	MEDIUM
Molasses	24	NO IMPACT	NOT APPLICABLE

− *Reduces Soil Quality for next round of production*
\+ *Enhances Soil Quality for next round of production*
NO IMPACT *No or little impact to Soil Quality for next round of production*

WHAT PARAMETERS MEAN?

IMPACT TO SOIL	IMPACT INTENSITY	RESULT
+	HIGH, MEDIUM	Soil quality remains good even when entire feedstock is used for SAF production
+	LOW, LOW TO NO IMPACT	Soil quality tends to be good even when entire feedstock is used for SAF production
NO IMPACT	NOT APPLICABLE	Soil quality remains same even when entire feedstock is used for SAF production
−	LOW	Soil quality mildly degrades when entire feedstock is used for SAF production
−	MEDIUM, HIGH	Soil quality degrades when entire feedstock is used for SAF production

Figure 17: Soil impacts assessment

The feedstock soil impact assessment was done by considering the impact of producing the feedstock using agricultural and forest soils. Feedstocks like MSW, animal fats like tallow, and used cooking oil were not considered for this assessment as they are not direct products grown from soil.

Using entirely forest and agricultural residues is not good for soil health. The residues from crops are considered "the greatest source of soil organic matter" for agricultural soils. Completely diverting agricultural residues for producing biofuels will have an adverse impact on soil quality. Similarly, forest residue removal can reduce the amount and quality of soil organic matter (SOM). SOM plays an important role in the soil's chemical (cation exchange capacity, metal complexation, and nutrient availability), physical (soil structure and water holding capacity), and biological (microbial activity) properties, especially in highly weathered soils. While both agricultural and forest residues are good feedstock sources, they cannot be used entirely for environmental reasons.

Crop rotation plays a major part in preserving soil quality. Feedstocks like corn, soy, rapeseed, sunflower, sugar beet, sugarcane, and miscanthus, when grown in rotation with compatible crops, increase soil quality retention. In many cases they are even known to improve soil quality.

6.6.2 ASSESSING CO2 EMISSION REDUCTION

	FISCHER TROPSCH PROCESS	ATJ PROCESS
AGRICULTURAL WASTE	High reduction in emission of 91%	Medium reduction in emission of 67%
FOREST WASTE	High reduction in emission of 90%	High reduction in emission of 73%
MISCANTHUS	High reduction in emission of 95%	High reduction in emission of 77%
SWITCHGRASS	High reduction in emission of 92%	Medium reduction in emission of 45%

KEY POINT TO NOTE..

The reduction in emission varies by process and feedstock

The same feedstock when supplied to different processes yield different results for emissions

The SAF produced from Fischer Tropsch process results in much lesser CO_2 emission then the SAF produced from ATJ process

In cases of switchgrass the emission reduction delta % varies by ~47% between ATJ and FT process

Hence a careful selection of pathways and feedstock must be made

Figure 18: CO2 emission reduction assessment

The reduction in CO2 emissions varies with SAF production pathways and the feedstock supplied to each pathway. Lifecycle assessment (LCA) emission results compiled by the ICAO clearly demonstrate that, when feedstocks like agricultural and forest residues, miscanthus, and switchgrass undergo the FT and AtJ processes, the resultant SAF has varied LCA emission parameters. The SAF produced by the standard FT process has lesser LCA emissions than that produced by the AtJ process.

If we categorize the emissions reduced by these processes into high, medium, and low, we can ascertain that, out of 24 feedstock and pathways combinations that we are assessing, 14 are capable of high reduction in CO2 emissions, six of medium reduction in CO2 emissions, and three of low reduction in CO2 emissions.

HIGH-REDUCTION CATEGORY

SAF produced from these pathways and feedstock combinations can reduce CO_2 emissions by 68–95%. These include pathways like Fischer-Tropsch, HEFA, and AtJ. Feedstocks such as agricultural and forest residues, miscanthus, switchgrass, and used cooking oil fall under this category.

MEDIUM-REDUCTION CATEGORY

SAF produced from these pathways and feedstock can reduce CO_2 emissions by 36–67%. These include pathways like SIP and AtJ. Feedstocks like sugarcane, sugar beet, and molasses generally fall under this category.

LOW-REDUCTION CATEGORY

SAF produced from these pathways and feedstock can reduce CO_2 emissions by less than 35%. These pathways include HEFA and AtJ with feedstocks like soy oil, rapeseed oil, and corn grain oil.

FISCHER-TROPSCH AND HEFA PROCESSES ARE LEADING CO2 EMISSION REDUCTION RATE

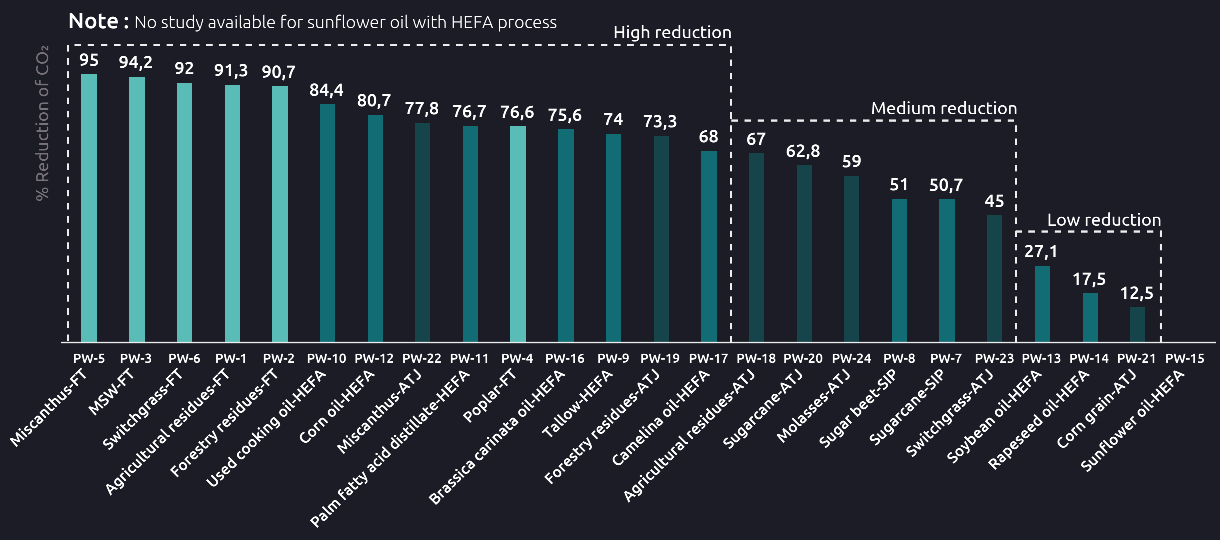


Figure 19: Environmental assessment of pathways

6.7 ECONOMIC ASSESSMENT OF FEEDSTOCK

The economic assessment of SAF produced from feedstock is necessary to understand the impact to the overall aviation value chain. Thus, we assessed the four ASTM-approved process (HEFA, SIP, FT, and AtJ) by focusing on the feedstocks that are already used by these technologies in order to have a clear view of the actual costs of SAF production.

Compared with the classic jet fuel (in March 2023), all of the pathways taken in consideration are more expensive. However, production process like HEFA will allow for the production of SAF at around 1$/L, which is not far from the actual price of jet fuel.

Among the four processes assessed, it appears that HEFA is the cheapest one, with a high level of accuracy and confidence. In fact, HEFA is one of the most mature processes today for SAF production.

Fischer-Tropsch and AtJ are the second- and third-cheapest process, respectively, as the maximum blend of these technologies is around 50%, although these technologies are the least mature (commercial pilot).

Lastly, the SIP process is actually the most expensive way to produce SAF, due to a maximum blend level of only 10% and a medium level of maturity.

THE MOST MATURE PRODUCTION PROCESS IL ALSO THE CHEAPER TO PRODUCE SAF IN 2023

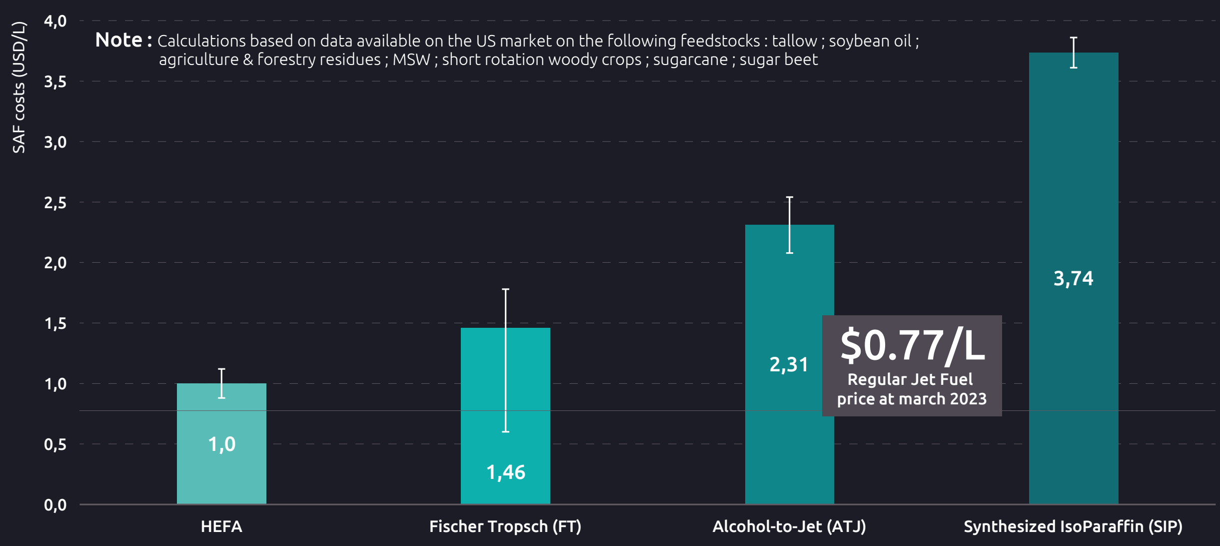


Figure 20: SAF production cost comparison by process

7 CONCLUSION

SAF is clearly the best bet in the near term to decarbonize the aviation sector – however, not all pathways can achieve this goal. Not all pathways and feedstocks are available in all regions. Hence, regional compatibility must be considered when deciding on the SAF production pathways and feedstock selection. We have also taken into account the latest EU regulations excluding certain pathways for SAF production, linked to feed and food crops.
The intention of this document is to study the different feasibility options. However, due to limited data availability, the research recommendations only cover Europe and the USA.

7.1 RECOMMENDATIONS FOR THE USA

Feedstock availability is obviously the main factor to select the appropriate feedstock: it must be available in a sustainable way. It must also not compete with agriculture and have low competition with other industries. In case the feedstock is competing with other industries and the impact is too high, the feedstock will lead to an economic paradox.

Comparing the feedstocks based on a two-by-two matrix of agricultural availability and industrial competition, we found that three feedstocks perform best in the USA: forest residue, tallow, and used cooking oil. Other probable options include MSW and agricultural residues.

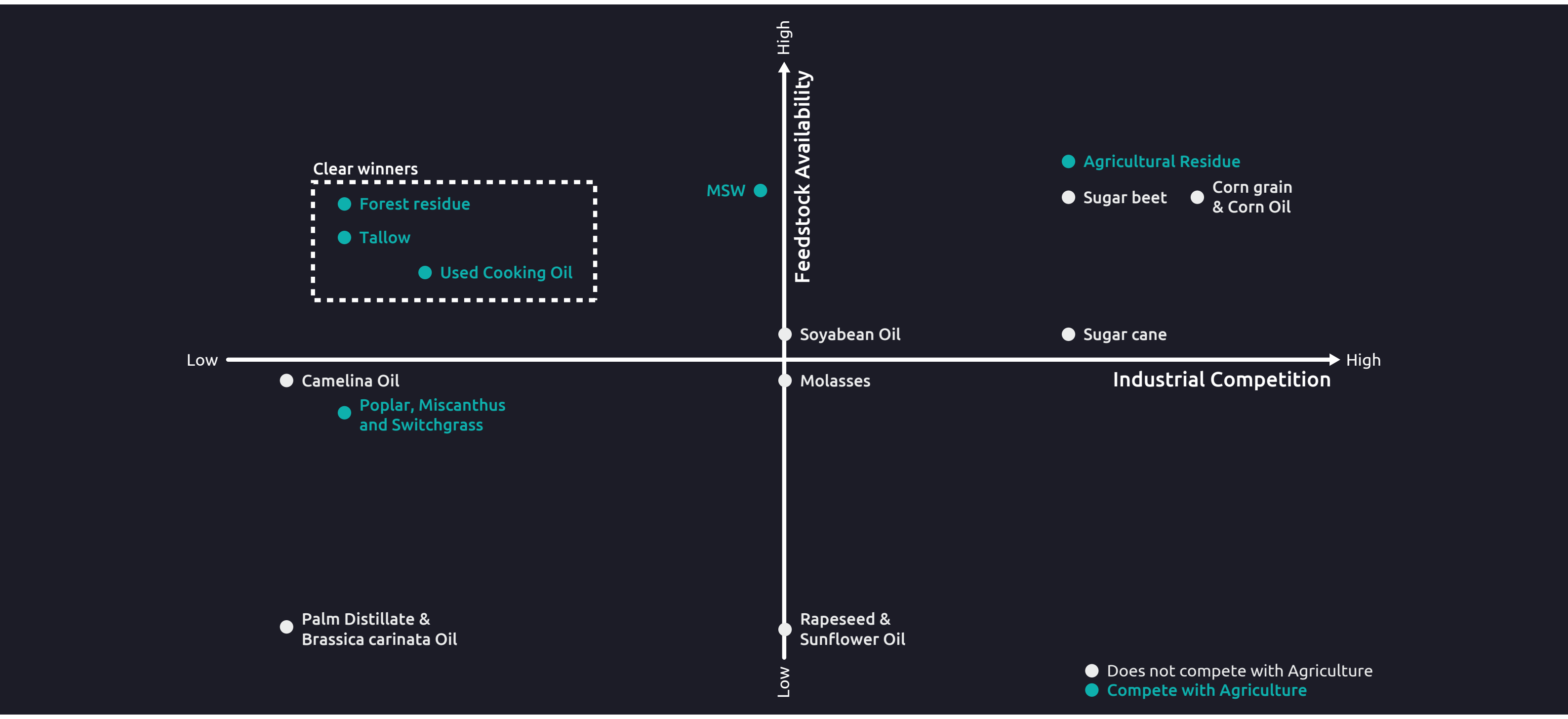


Figure 21: SAF opportunity matrix for the US

Lastly, using miscanthus, switchgrass, and poplar can be considered when cultivated in a sustainable way.

The winners at this stage were compared against the emission reduction parameters and process yield percentages. This clear winners at this stage were FT with forest residues and HEFA with used cooking oil. Other combinations present in the chart were all good options to consider by the industry.

Since SAF production from forestry residues by the FT process and used cooking oil by the HEFA process are the final winners of this assessment for the US perimeter, the development of these pathways in the US should be increased for several reasons:

S NO	PROCESS	FEEDSTOCK	EMISSION REDUCTION %	PROCESS YIELD %
PW-1	FISCHER-TROPSCH	Agricultural residues	**91.3 %**	MEDIUM
PW-2		Forestry residues	**90.7 %**	HIGH
PW-3		Municipal solid waste (MSW), 0% NBC	**94.2 %**	MEDIUM-HIGH
PW-9	HEFA	Tallow	**74.0 %**	HIGH
PW-10		Used cooking oil (UCO/WCO)	**84.0 %**	HIGH
PW-20	ATJ	Agricultural residues	**67.0 %**	LOW-MEDIUM
PW-21		Forestry residues	**73.3 %**	LOW-MEDIUM

Figure 22: Final recommendations for the US

USED COOKING OIL COMBINED WITH AN HEFA PROCESS:

- fits into the targeted pathways of the US SAF Grand Challenge Roadmap. The roadmap clearly aims to maximize sustainable lipid supply for 2030 by investing in lipid production pathways.
- provides an opportunity to plan efficient waste oil collection and leads to a positive social impact circularly.

FORESTRY RESIDUES COMBINED WITH A FISCHER-TROPSCH PROCESS:

- also fits into the targeted pathways of US SAF Grand Challenge Roadmap as it aims to increase production of biomass resources especially from residues collection to achieve 2050 objectives.
- brings an opportunity to plan efficient residue collection that can provide extra income to improve the forestry management and lead to a positive social impact.

FINALLY, THE COST WILL BE THE LAST DRIVER OF DEVELOPMENT:

- In the Fischer-Tropsch process, the production cost is mainly driven by capital costs as gasifier building is cost-intensive.
  On the other hand, the HEFA process is mainly driven by feedstocks and H2 prices, which depend on the market.
- Several funding mechanisms are or will be set up by the US government to develop the sector (tax credits and grants for SAF blending and production especially).

7.2 RECOMMENDATIONS FOR THE EUROPEAN UNION

Using the same approach to identify the best pathways for the EU, we find that forest residues are the clear winner when it comes to comparing feedstock availability versus industrial competition. Since it is the single winner in this matrix, we wanted to explore more options for the EU. Hence, we relaxed our criteria for this matrix to include all feedstock in the high and medium zone of agricultural availability. Thus, forest residues, MSW, used cooking oil, poplar, miscanthus, and switchgrass were found to be better suited as feedstock for SAF production in the EU. Moreover, feed and food crop-based fuels and fuels derived from palm and soy materials are not considered in this metrics since they are outlawed by EU regulations.

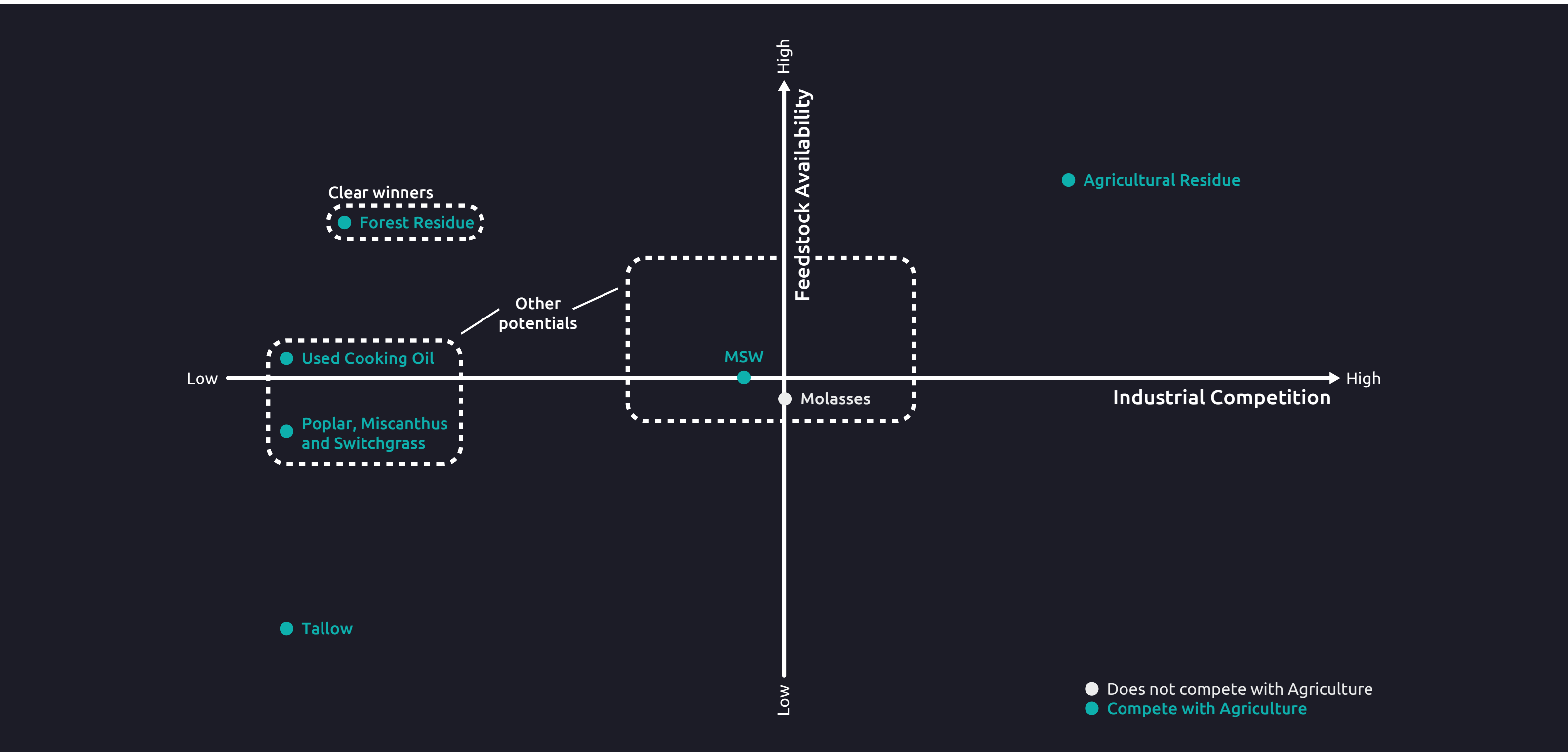


Figure 23: SAF opportunity matrix for the EU

The winner and other potentials at this stage were compared against the emission reduction parameters and process yield percentages. The winners at this stage were FT for forest residues, FT for used cooking oil, and FT for MSW. Other combinations present in the chart were all good options to consider by the industry.

Moreover, these three feedstocks and pathways fit into EU regulations for SAF production.

They also do not have a negative social impact as there is no land competition and using these feedstocks respects human rights and labor standards.

S NO	PROCESS	FEEDSTOCK	EMISSION REDUCTION %	PROCESS YIELD %
PW-2	FT	Forestry residues	**90.7 %**	HIGH
PW-3		Municipal solid waste (MSW), 0% NBC	**94.2 %**	HIGH
PW-5		Miscanthus (herbaceous energy crops)	**95 %**	MEDIUM-HIGH
PW-6		Switchgrass (herbaceous energy crops)	**92 %**	MEDIUM-HIGH
PW-4		Poplar	**76.6 %**	MEDIUM-HIGH
PW-10		Used cooking oil (UCO/WCO)	**84 %**	HIGH
PW-21	AtJ	Forestry residues	**73.3 %**	LOW-MEDIUM
PW-22		Miscanthus (herbaceous energy crops)	**77.8 %**	LOW-MEDIUM
PW-23		Switchgrass (herbaceous energy crops)	**45 %**	LOW-MEDIUM

Figure 24: Final recommendations for the EU

SAF production from forestry residues, MSW, and used cooking oil by the Fischer-Tropsch process are the final winners of this assessment for the EU perimeter. Thus, the development of these pathways in the EU should be increased, for several reasons:

USED COOKING OIL AND MSW COMBINED WITH A FISCHER-TROPSCH PROCESS:

- fits into the targeted pathways of the ReFuelEU Aviation Initiative and RED II as allowed biofuels produced from certain other feedstocks with "high sustainability potential" that meet the sustainability and GHG emissions criteria (70% reduction in GHG emissions compared to fossil jet fuel on a life-cycle basis).
- brings opportunity to plan efficient waste oil collection and leads to a positive social impact as it circularly reduces MSW deposits in landfills.

FORESTRY RESIDUES COMBINED WITH A FISCHER-TROPSCH PROCESS:

- also fits into the targeted pathways of the ReFuelEU Aviation Initiative and RED II as allowed advanced biofuels produced from feedstock such as agricultural or forestry residues, algae, and bio-waste.
- brings opportunity to plan efficient residue collection that can provide extra income to improve the forestry management and lead to a positive social impact.

FINALLY, THE COST WILL BE THE LAST DRIVER OF DEVELOPMENT:

- For the Fischer-Tropsch process, the production cost is mainly driven by capital costs as gasifier building is cost intensive.
- In July 2022, the European Parliament proposed the creation of a Sustainable Aviation Fund from 2023 to 2050 to accelerate the decarbonization of the aviation sector and support investment in sustainable aviation fuels, innovative aircraft propulsion technologies, and research for new engines. The fund would be supplemented by penalties generated by the enforcement of these rules.

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