ALIGHT
SUSTAINABLE AVIATION

D3.3 Report on environmental and operational benefits of SAF

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Author(s):	Mónica Soria Baledón, Vladimir Borodin, Julie Perovic – IATA Jesper Abery Jacobsen, Helle Holm Clausen, Peter Wiboe Holm – CPH Bastian Rauch, Benedict Enderle – DLR Simone Souza, Blanca de Ulibarri – RSB
Coordinators	Mónica Soria Baledón – soriabalm@iata.org Alejandro Rivera Gil – riveragil@iata.org

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1 Forward: A sustainable recovery from COVID-19

Between 1990 and 2019, global passenger traffic grew at a compound annual rate (CAGR) of 4.5%, primarily driven by micro and macroeconomic factors, changes in the world's demographics, declining airfares, and the liberalization of markets.

In March 2020, the outbreak of the SARS-CoV-2 (COVID-19) pandemic brought unprecedented challenges to the air transport industry in the form of border closures, strict travel controls and a depressed travel confidence. By the end of the year, global passenger traffic had dropped by 65% compared to 2019 (see figure 1) and throughout 2021 and 2022, travel demand remained well below pre-pandemic levels.

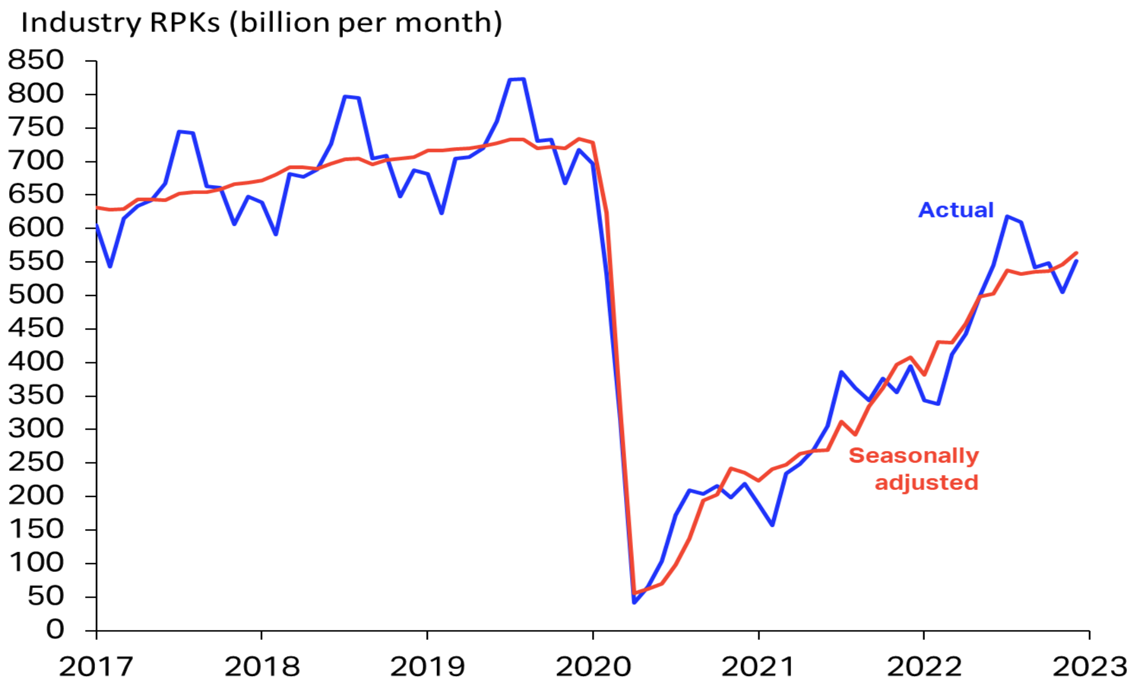

Figure 1. Industry RPKs (billions per month), actual volumes and seasonally adjusted volumes (IATA Economics, Monthly Statistics)

Although the air transport sector has shown great resilience to historical shocks (i.e. 9/11/ terrorist attacks, the SARS outbreak in 2003, the 2009 world's financial recession, etc.), the epidemiological trajectory of the COVID-19 pandemic has unevenly impacted the pace of recovery of domestic and international travel across the world.

In Europe, most countries were affected by the outbreak between April and May 2020, but as of February 2022, the European Economic Area (EEA) had nearly 80% of its population fully vaccinated[1]. Globally, approximately 4.2 billion people have been fully vaccinated, equivalent to 54% of the world's population (Our World in Data, 2022).

[1] Fully vaccinated individuals aged 18 years and over as per the manufacturers' instructions. Typically, this entails the administration of a primary course without considering a booster shot.

Despite the pandemic resurges with new virus variants, notably Delta and Omicron during 2021, the recovery in industry RPKs began to gather pace in 2022 as vaccine rollouts continued, travel restrictions were lifted, and more routes reopened. In some key markets, the opening of borders led to swift rebounds, notably in North America where aviation returned to profitability in 2022 (IATA, 2022). Globally, air travel is anticipated to recover to pre-pandemic levels in 2024 (IATA, 2022) despite the dampening of the global gross domestic product (GDP) in the near to long terms due to the armed conflict between the Ukraine and Russia.

In this context, forecasts associated to climate change are increasingly showing greater impacts over shortened horizons. Rising jet fuel prices and sea levels – along with extreme weather events – expose airlines' near-term profitability, aviation infrastructure and global connectivity.

In November 2021, the aviation industry committed to a carbon neutrality target in 2050, known as Fly Net Zero, where sustainable aviation fuels (SAF) are anticipated to contribute on average 65% to the decarbonization efforts. This contribution is estimated in 330-445 million tonnes of SAF by mid-century and a level of investment between 1 and 1.4 billion US dollars per year to build up the required capacity to attain these volumes (ICF, 2021).

Although airports in the United States and in Europe have been early promoters of SAF usage since 2008, data collected through the ALIGHT project showed that up to October 2021, very few airports had SAF handling experience[2]. This can be attributed mainly to the lack of SAF availability and the low demand from airlines over the past half-decade. Furthermore, there were prevailing concerns among airports and fuel suppliers about the safety of using SAF blends despite their drop-in capabilities.

To address these gaps, Airports Council International (ACI) endorsed in 2021 the World Economic Forum's Clean Skies for Tomorrow 2030 Ambition Statement to accelerate the supply and use of SAF in airports that aims at displacing 10% of the global conventional jet fuel by the end of the decade. Additionally, airports worldwide continue to facilitate SAF inception by partnering with airlines, OEMs, fuel suppliers, academia, and governments to host proof of concept pilot flights, to advance research and innovation in energy and transport, and in some cases, to expand SAF production capacity.

ALIGHT, TULIPS, OLGA and STARGATE are four examples of airport-led projects funded by the European Commission under H2020 to test low-carbon mobility solutions, including the use of SAF, to address the environmental impacts of air transport operations at airports while building industry's resilience to climate change.

[2] See annex 15.1.

2 Executive Summary

This report analysed the environmental and operational benefits of using SAF in the context of the ALIGHT project, as well as it identified outstanding deployment challenges and mechanisms to facilitate and accelerate SAF availability leading up to the entry into force from 2025 of mandated SAF volumes throughout the European Union.

The topics covered in this report were structured into five sections, including mitigation of carbon dioxide (CO_2) and other greenhouse gases (non-CO_2) and particulates, improvements on local air quality around airports, increases in fuel efficiency, costs and financing of feedstock, fuel production, qualification and scale up of operations, and policy mechanisms to stimulate SAF supply, demand and facilitate market dynamics.

In section 1, the Roundtable for Sustainable Biomaterials (RSB) focused on the decarbonization potential of selected conversion pathways for SAF production by using life-cycle assessment (LCA). LCA is a technique used to calculate the environmental impact of a product, process, or system throughout its entire life cycle (from the extraction of the raw material to its end-of-life), and it is based on the review and analysis of inputs and outputs of that system. The GHG emissions performance of SAF depends on a variety of factors, including the feedstock and technology used, the energy inputs, the methodology to calculate GHG intensity, among others.

For this report, the methodology used for calculating the lifecycle GHG emissions for selected SAF production pathways was based on EU Renewable Energy Directive (RED) and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) methodologies. The analyses were conducted for the Hydroprocessing of Esters and Fatty Acids (HEFA), Gasification/Fischer-Tropsch (FT), Alcohol-to-Jet (ATJ) and Power-to-Liquids (PtL) value chains across several scenarios (feedstock, distance, and transport modes). The GHG assessments showed that the lifecycle reduction potential of SAF is highly dependent on the feedstock and the technology combination used. In general, residual biomass yields lower GHG emissions than SAF pathways that rely on crops as feedstocks.

Based on feedback collected during a series of validation workshops organized by RSB, sensitivity analyses were modeled for all pathways considering more than 30 parameters. For the PtL pathway, hydrogen consumption and energy use for CO_2 capture are the key parameters affecting the total LCA GHG emissions. Transport of SAF can be relevant in scenarios where total GHG emissions are already close to the GHG savings threshold for RSB Global and RSB EU RED, which would include technologies using gray hydrogen, for instance.

In the ATJ pathway, we evaluated 13 scenarios. The feedstock, i.e. ethanol, is the most relevant input, followed by ILUC impact. All scenarios for ATJ comply with CORSIA's GHG savings target. All results for CORSIA and RSB EU RED are quite similar.

Even though the ATJ pathways involve the transport of ethanol from the US and Brazil to Europe, the logistic is not as relevant as the impact of ILUC and would not prevent the ATJ-based

SAF from meeting the GHG reduction target. SAF from HEFA technology using palm oil as feedstock is highly affected by direct and indirect land use change emissions.

All scenarios including ILUC would not achieve the CORSIA's GHG savings target. As for used cooking oil and tallow as feedstocks for HEFA-based SAF, both baseline scenarios would comply with the CORSIA savings target. The use of gray hydrogen, however, could prevent the necessary reduction in GHG emissions.

Regarding the impact of the transport steps in the total GHG emissions for HEFA pathways, the transport in the palm oil pathway is irrelevant when compared with ILUC impact. For tallow- and UCO-based SAF, the transport of SAF and residual oil are also not the most GHG impact, even assuming that tallow would be imported from Latin America or the US and a high logistic demand to collect UCO. In the FT pathways, both forest residue- and MSW-based SAF would comply with the CORSIA's GHG savings target, even considering a wide range of variation in the transport distance for residue and SAF.

Section 2 centered in the work conducted by CPH on air quality management. The lighthouse airport has monitored emissions of nitric oxide (NO), nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$) since the year 2000, and other non-CO_2 emissions such as polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC) and particulate organic and elemental carbon, were monitored in a campaign between 2009-2011. Measurements of these pollutants had shown all non-CO_2 emissions have consistently kept within regulatory limits. The campaign also showed high particle count of ultrafine particles (UFP) compared to a busy street in Copenhagen. No limit values are in place for the particle count of UFP.

Emissions of particulate matter, more so of ultrafine particles, result from the combustion of conventional jet fuel and diesel at the airport's apron. To address this, CPH established in 2011 the Copenhagen Airport Air Quality Program, that has expanded its initial scope on local air pollution, to address broader sustainability and climate impacts of the airport's core operations.

The introduction of SAF at the lighthouse airport as part of the ALIGHT project WP3 tasks, whose results will be presented in a dedicated deliverable later in 2023, aims at monitoring local emissions from SAF usage to be measured against the historical data collected at CPH on non-CO_2 emissions from jet fuel combustion. This exercise anticipates reductions in all emissions monitored at CPH, where the progressive uptake of SAF is expected to improve the overall air quality at the airport and of surrounding communities.

In addition to the impact of CO_2 and non-CO_2 emissions on local air quality, aviation affects the climate through atmospheric processes involving emissions at altitude, including water vapour, sulphur dioxide (SO_2), soot particles and oxides of nitrogen (NO_x), collectively known as non-CO_2 effects. In sections 3 and 4, the German Aerospace Center (DLR) conducted a literature review on the benefits of using SAF to avoid contrail formation, to reduce non-CO_2 emissions and to increase fuel efficiency.

Recent research indicates that these effects are responsible for about two third of the total climate impact of aviation. It is important to highlight that even relatively low emissions amounts of non-CO_2 gases and particulate matter in “clean” parts of the atmosphere, can have a disproportionally large impact on the climate. Whereas the science and methods for contrail avoidance require further development, SAF and SAF blends have demonstrated to induce a significant decrease of non-CO_2 emissions during flight, for example of soot, thereby reducing the forcing impact of aviation on the climate. From a performance and fuel efficiency standpoint, SAF offer the potential for an up to 2% fuel consumption reduction effected by a higher energy content than conventional fuels.

Deployment of production capacity for SAF has been challenged by perceived risks and financial constraints to increase the availability of sustainable and cost-effective feedstock, to develop and scale-up novel conversion technologies for SAF, to qualify conversion pathways with high sustainability and decarbonization potential, to optimize supply chains, to enable and facilitate the procurement of SAF, etc. The engagement and support of the financial community – particularly of capital providers – in unlocking the annual requirements estimated in $40 to $50 billion solely for building new SAF plants, is key to materialize the environmental, operational and the broader benefits analyzed in this report.

In section 5, the International Air Transport Association (IATA) conducted a review of the literature on techno-economic analyses (TEA) for three SAF conversion pathways expected to significantly apportion to the volumes needed to comply with mandated quantities in Europe. The analysis compared the cost-breakdown for 3 out of the 4 pathways assessed in this report by RSB using an LCA approach. These include HEFA, Gas/FT, and ATJ pathways, to illustrate the cost variations between them based on selected feedstocks.

Whilst using the latest available figures in the literature, the analysis supported previous studies on the role of HEFA and lipid-based feedstocks to supply most SAF leading up to 2030, seconded by Gas/FT and by ATJ SAF. Considering the amount of time required for de-risking and scaling-up existing technologies, in the short-term, fermentation processes are expected to see incremental yields and higher sustainability, as well as improved technologies will expand the feedstock pool for HEFA. For emerging and less mature conversion pathways that cannot leverage existing capital investments, SAF production is likely to develop in the form of hub-and-spoke models to leverage oil and gas refining capacity for the co-processing of intermediates (i.e. biocrude).

On the procurement side, offtake agreements signed over the past decade have been instrumental to pool voluntary demand for SAF, by allowing to cost-competitively purchase and supply SAF between fuel producers and buyers. Whereas offtake agreements are anticipated to play a major role in accelerating SAF deployment by mitigating some of the financial risk linked to SAF undertakings, chapter 12 compiles and presents policy mechanisms for stimulating supply, demand and enable SAF markets, that need to be implemented in parallel to effectively address the risks and constraints to SAF deployment analyzed in this report.

3 Introduction to WP3: Implementation and uptake of SAF

The aviation industry has long recognized the increasing global need to reduce greenhouse gases (GHGs) and other emissions to adapt to climate change and promote a sustainable future. The development and commercialization of sustainable aviation fuels (SAF) is key to mitigate aviation CO_2 emissions to reach carbon neutrality by 2050.

Copenhagen Airport (CPH) is the lighthouse for the H2020 Smart Airports project ALIGHT where key aviation partners are to collaborate with the mission to develop a best practice guide for SAF handling and logistics – aiming to be demonstrated as an innovative concept for a cost-effective fuel supply chain at CPH. This is to be replicated by fellow airports in Rome, Vilnius and Warsaw.

To implement and use SAF in CPH in an efficient and cost-effective manner calls for an extensive collaboration between all 16 partners of ALIGHT: Copenhagen, Rome, Vilnius and Warsaw airports; Knowledge Institutions: IATA, DLR, DTI, NISA, Hamburg Univ. of Technology, University of Parma, Roundtable on Sustainable Biomaterials and Technology providers: SAS, Air BP, Hybrid Greentech, BKL, BMGI Consulting.

The objective of Work Package 3 is to make the use of SAF more efficient by means of improving the logistics chain and SAF uptake process at airports. Best practices will be defined and described for processes, methods and tools for the supply and usage of SAF.

Within the broad range of activities outlined in WP3, this report aims to provide an overview of the expected environmental and operational benefits of using SAF beyond CO_2 emissions reductions within the European context. The benefits analysed in this report are classified under the following themes: decarbonisation, local air quality, non-CO_2 impacts, and fuel efficiency benefits.

This report will also identify and analyse current barriers for commercial deployment, as well as a variety of mechanisms to facilitate access to the financing SAF production and uptake through dedicated policies and regulations.

The content of this deliverable can be used as an input to:

- sustainability guidelines, including certification,
- strategies to gain extended support for SAF use from customers (passengers, corporates, cargo customers) and the public,
- decision making for the financing of SAF upscaling.

4 Communicating the benefits of SAF usage

The aviation sector has identified several pathways it could take to meet its carbon neutrality target in 2050, known as Fly Net Zero, where sustainable aviation fuels are anticipated to contribute on average 65% to the decarbonization efforts. This contribution is estimated in 330-445 million tonnes of SAF by mid-century and a level of investment between 1 and 1.4 billion US dollars per year to build the required capacity for attaining this target (ICF, 2021).

In 2021, the production of SAF reached 125 million litres, yet still accounting for less than 0.1% of the global jet fuel demand for the same year. This figure contrasts with the aspirational targets that several countries, regions and individual airline operators had set for as early as 2015 where SAF was estimated to average 2% of conventional jet fuel demand.

The shortfalls in global production of SAF have been partially attributed to the lack of dedicated policies and harmonized regulations to stimulate long-term market development, where the capital expenditure required to commercially deploy renewable fuels ought to actively engage decision-makers not typically associated to the value chain of aviation fuels. They include investors, regulators, and corporate end users whom the value proposition of SAF should be conveyed in a meaningful, timely and impactful way.

Developing capacity for SAF production requires on average 4 years from designing to commissioning a commercial-scale plant (ICF, 2021). Although millions of litres of SAF have been committed through offtake agreements in the past years, the existing financial support remains limited compared to the level and duration of capital requirements to bring conversion pathways into maturity and to expand production of already commercial pathways, including HEFA and the co-processing of oils and fats with petroleum intermediates.

For these reasons it is critical to build understanding about the benefits of SAF, particularly for decision-makers who could enable the production of much-needed SAF volumes – including lending and financial institutions and government agencies. Financing the production of SAF means showing decision-makers that the return and contribution to human welfare is positive and worthwhile. Decision-making frameworks are varied, depending on the whether we refer to support for SAF production through grants and loan guarantees, or through financial investors and bank lenders, but each will require an understanding of the benefits and risks of SAF production.

The following chapters will explain and quantify the expected environmental and operational benefits of SAF usage. Within each section of this report, the benefits and the various methods used to estimate them are explained to inform readers about the importance and complexity of measuring SAF benefits. The results contained in this report aim at providing a starting point for practitioners who may wish to use the information in their own analysis and decision making.

SECTION 1: DECARBONIZATION

5 Introduction to aviation and its climate impact

Air transport accounts for ~2.4% of the total manmade CO_2 emissions, but its net contribution to climate change is estimated between 3.5% and 4.9% when emissions at cruise altitude are accounted for. Despite this figure may represent a rather small contribution to global warming, forecasts out to 2050 anticipate emissions from international and domestic aviation to reach 1.82 billion metric tons of carbon dioxide (IEA, 2020); nearly double of those from all aviation commercial operations in 2018 (ICAO, 2019).

Emissions from burning fossil-based jet fuels, commonly known as conventional aviation fuels (CAF), consist of carbon dioxide (CO_2), water vapour (H_2O), nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), soot (PM 2.5), unburned hydrocarbons (HC), aerosols, and traces of hydroxyl compounds (-OH), most of which are released in the atmosphere at cruise altitudes of 8–13 km above mean sea level (Lee, et al., 2021).

The formation of contrail cirrus, the aviation-induced cloudiness (AIC) and the chemical reactions driven by NO_x emissions, are considered to collectively account for the largest warming forcing adding to that of CO_2, yet the scientific understanding of the full non-CO_2 effects on atmospheric chemistry remains incomplete and the methods to monitor and cost-effectively address non-CO_2 emissions from aviation are not yet available to the industry.

Several conversion pathways for SAF show great potential for lifecycle emissions abatement (70%–100%) and production volumes could, in principle, supply the global fleet for commercial operations by mid-century (ATAG, 2020) (WEF, 2020). But the increasing industry and government interest on SAF over the past decade to address the climate impact of aviation, together with the development and diversification of conversion technologies, have not materialized into sufficient volumes to meaningfully displace petroleum-based fuels.

In the following chapters, the Roundtable for Sustainable Biomaterials (RSB) will focus on the decarbonization potential of selected conversion pathways for SAF production by using a life-cycle assessment (LCA) approach. LCA is a tool used to calculate the environmental impact of a product, process or system throughout its entire life cycle (from the extraction of the raw material to its end-of-life), and it is based on the review and analysis of the inputs and outputs of the system to obtain, as a result, its potential environmental impact.

5.1 Calculating the greenhouse gas emissions benefits of SAF

Whilst technology and operational efficiency improvements will play a role in reducing the GHG emissions of aviation, SAF is expected to be the biggest contributor across several scenarios (see figure 2).

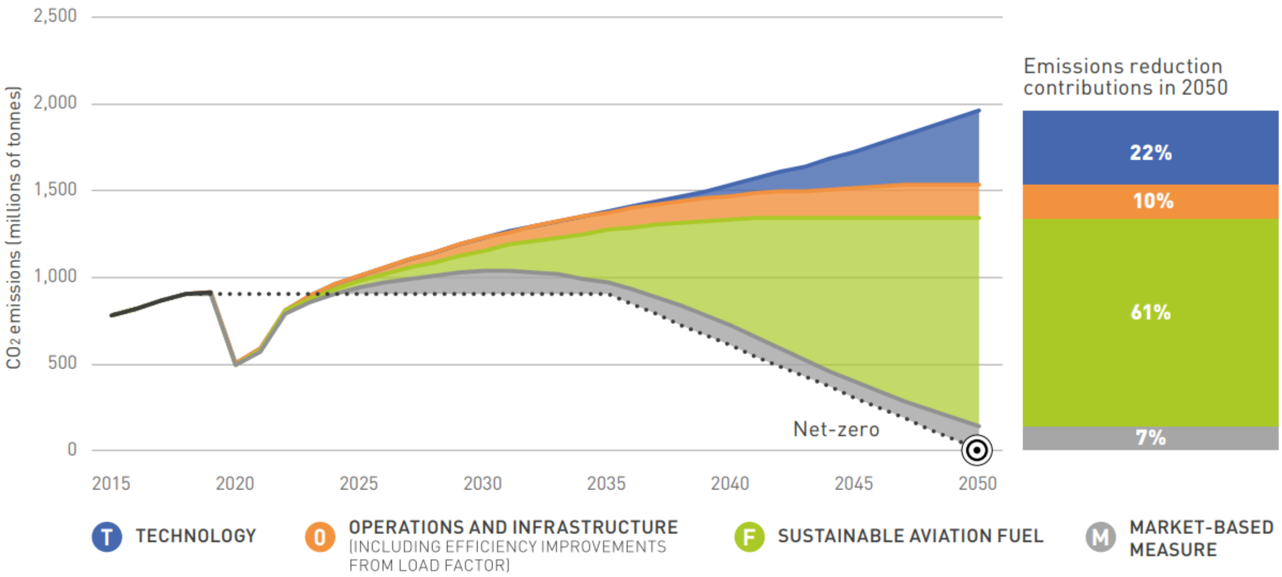

Figure 2. Path towards net-zero emissions for aviation (scenario 1, prioritizing technology and operations) (ATAG, 2021)

The term sustainable aviation fuels (SAF) is used to describe alternative, non-petroleum-based aviation fuels produced from renewable sources of both biological (plant or animal material, from the electrolysis of water) and non-biological origin (e.g., municipal waste or waste CO_2). The chemical and physical characteristics of SAF blends are almost identical to those of conventional jet fuel, thus they can be safely used at up to 50% in existing fueling infrastructure and aircraft engines.

A common tool for measuring the GHG emissions in SAF value chains is the Life Cycle Assessment (LCA); a methodology for assessing environmental impacts associated with all the stages of the life cycle of a product or service.

In this report, the lifecycle emissions of SAF, together with their reduction potential compared to conventional aviation fuels, were calculated using LCA, which includes all activities related to the cultivation and harvesting of the biomass feedstock (or collection of residues), transport, processing stages, SAF production, and distribution to the airport (see figure 3).

Carbon dioxide absorbed by plants during the growth of biomass is roughly equivalent to the amount of carbon dioxide produced when the fuel is burned in a combustion engine, which is returned to the atmosphere. Processing of industrial waste materials and agricultural residues benefit from zero GHG intensity at the point of origin, as the carbon emissions are allocated to the primary products.

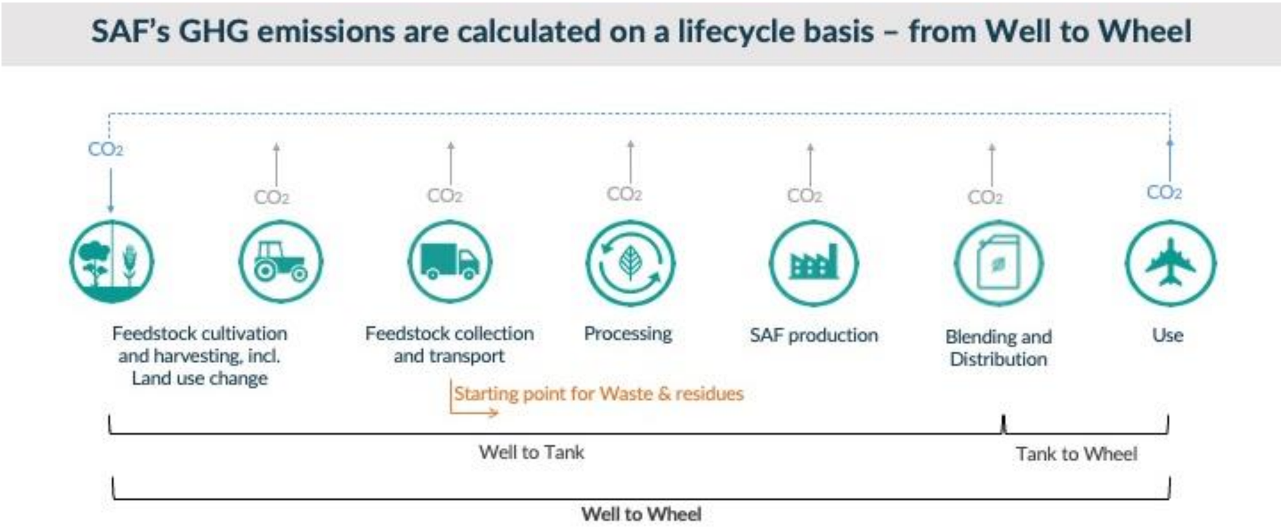

Figure 3. GHG Lifecycle assessment boundary for SAF

When these elements are accounted for, the use of SAF has been shown to provide significant reductions in overall CO_2 lifecycle emissions compared to fossil fuels. Furthermore, SAF contains fewer impurities (such as sulphur), which enables an even greater reduction in sulphur dioxide and particulate matter emissions than present aircraft technology has achieved.

5.1.1 **Regulations and compliance**

Several jurisdictions have developed approaches to support the SAF economy and lowering the SAF price premium while maintaining SAF sustainability integrity. Some are relying on measures such as market-based mechanisms to trade credits generated for the production of low-carbon SAF (e.g. the California Low Carbon Fuel Standard with aviation opt-in) and allowing SAF producers to voluntarily take advantage of programs such as the US Renewable Fuel Standard, US SAF Blender and Producer Tax Credits, and the EU Renewable Energy Directive (REDII).

Also, the International Civil Aviation Organization (ICAO) adopted in 2016 a global market-based mechanism, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to address CO_2 emissions from international aviation. CORSIA aims to stabilize international civil aviation's net CO_2 emissions at 2019 levels, from 2021, using offsetting programs and the use of eligible fuels, including SAF.

Compliance to CORSIA targets is voluntary until 2026, and from 2027, all international flights will be subject to offsetting requirements[3], representing approximately 90% of all international aviation activity.

[3] States exempt from offsetting requirements, unless they participate on a voluntary basis, include Least Developed Countries (LDCs), Small Island Developing States (SIDS), Landlocked Developing Countries (LLDCs) and States which represent less than 0.5% of international RTKs.

Whilst all policies agree on the fundamental approach to calculating the GHG intensity of SAF, there are some significant differences between LCA methodologies used by different compliance mechanisms. These differences refer primarily to the GHG boundary which sets the limits of the study, a description of the activities within the product's life cycle phases that are included and excluded from consideration. Also, one main difference can be related to the calculation methodology (attributional or consequential) or the fossil baseline used to calculate the GHG savings.

An attributional LCA evaluates the potential environmental impacts that can be attributed to a system (e.g. a product) over its life cycle. A consequential type of LCA, aims at identifying the consequences that a decision in the foreground system has on other processes and systems of the economy, both in the analysed system's background system and on other systems. It models the analysed system around these consequences. Hence, the consequential life cycle model does not reflect the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that is prognosticated along market mechanisms, and potentially including political interactions and consumer behaviour changes (EUCAR, 2020).

This fossil baseline is a reference system from which we compare the new biobased product. In the case of SAF, it is compared to fossil jet fuel and then it is estimated a related reduction percentage, and the reduction threshold for qualifying SAF.

5.1.2 **LCA assessment methodologies**

LCA has been widely used for estimating greenhouse gas emissions of biofuel production under several regulations such as EU RED, ICAO CORSIA, and RFS. Therefore, it is considered as a robust tool that can help to measure and lower environmental impacts in the energy sector.

The following section explains the different methodologies which are used to estimate the environmental impacts of fuels within bioenergy sector.

5.1.2.1 ICAO CORSIA

The scheme is focused in CORSIA eligible fuels, including sustainable aviation fuels, thus the LCA system boundary encompasses the full supply chain of SAF production and use. Total lifecycle GHG emissions values for specific types of SAF are obtained through the sum of 'core LCA' emissions, calculated with an attributional approach and induced land use change (ILUC) emissions calculated with a consequential approach.

As for core LCA, emissions associated with the following stages are accounted for: 1) feedstock production — cultivation, harvesting, collection and recovery — and transportation to processing and fuel production facilities, 2) feedstock processing and extraction, 3) feedstock-to-fuel conversion processes, 4) fuel transportation and distribution, and 5) fuel combustion in an aircraft engine.

Emissions generated during one-time construction or manufacturing activities —e.g. facility construction, equipment manufacturing— are not included. For waste, residue and byproduct feedstocks, GHG emission accountability starts at the point of origin —e.g., collection, leading to zero GHG emissions during the feedstock production step of the lifecycle.

The approach taken for the treatment of the co-products in the carbon footprint analysis is energy-based allocation, in which case lower heating values are associated with each co-product and main product to identify the share of GHG burden that each product receives.

CORSIA LCA methodology calculates carbon dioxide equivalent (CO_2e) emissions based on a 100-year global warming potential (GWP) considering emissions of CO_2, CH_4 and N_2O from well-to-pump activities (stages 1 to 4 above), and CO_2 emissions from well-to-wake (stage 5 above) fuel combustion. 100-year GWP are calculated using the CO_2e values for CH_4 and N_2O from the Intergovernmental Panel on Climate Change (IPCC-AR5) (28 and 265, respectively).

Only non-biogenic CO_2 emissions from fuel combustion shall be included in the calculation of CO_2e emissions. Emission savings —i.e, emission credits that can be deducted from the actual LCA GHG result— are only allowed in two situations: 1) emissions avoided by diverting municipal solid waste (MSW) from landfills, 2) emissions avoided due to additional recyclable material being recovered and sorted during the MSW preparation.

The fossil fuel baseline is set at 89g CO_2e /MJ for jet fuel and 95g CO_2e /MJ for aviation gasoline (avgas). The SAF producer shall demonstrate that the SAF achieves, on a life cycle basis, net GHG emissions reductions of at least 10% compared to the baseline life cycle emissions values. Regarding ILUC, operator shall use default values already calculated by the Committee on Aviation Environmental Protection (CAEP) of ICAO.

5.1.2.2 EU Renewable Energy Directive (EU RED)

The system boundary under this regulation includes emissions from: 1) extraction or cultivation of raw materials, 2) carbon stock changes caused by land-use change, 3) processing, 4) transport and distribution, 5) combustion of the fuel in use, 6) savings from soil carbon accumulation via improved agricultural management, 7) savings from CO_2 capture and geological storage, and 8) savings from CO_2 capture and replacement. Emissions from manufacture of machinery and equipment are not included.

Wastes and residues, which include among others tree-tops and branches, cobs and nut shells, straw, husks, and residues from processing —e.g. crude glycerin and bagasse— shall be considered to have zero life-cycle greenhouse gas emissions at the point of origin (collection) irrespective of whether they are processed to interim products before being transformed into the final product.

The approach taken for the treatment of the co-products in the carbon footprint analysis is also energy-based allocation. Exception is given to the cogeneration unit that supplies heat and/or electricity to a biomass fuel production process for which emissions are being calculated. Where surplus electricity and/or useful heat occurs, the greenhouse gas emissions shall be divided between the electricity and the useful heat according to the temperature of the heat, i.e, an exergy allocation approach.

This approach reflects the usefulness (utility) of the heat. Emissions of CO_2 from fuel in use shall be taken to be zero for bio-based fuels. Emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) from the fuel in use shall be included. The methodology assumes a 100-year GWP calculated using the CO_2e values for CH_4 and N_2O from the Intergovernmental Panel on Climate Change (IPCC-AR5) (28 and 265, respectively).

The fossil fuel baseline for biofuels used as transport fuels is set at 94g CO_2e/MJ. The current GHG savings threshold for biofuels, biogas and bioliquids is at least 50% when produced in installations in operation on or before 5 October 2015, 60% when produced in installations starting operation from 6 October 2015 until 31 December 2020, and 65 % when produced in installations starting operation from 1 January 2021.

The GHG savings from the use of renewable liquid and gaseous transport fuels of non-biological origin shall be at least 70% from 1 January 2021. Under EU RED, operators can take their own GHG calculations if they do not want to use the relatively conservative “default values” for common biofuel pathways.

5.1.2.3 US Renewable Fuel Standard (RFS2)

The system boundary of RFS2 includes feedstock production and transportation, fuel production and distribution, and the use of the finished fuel. GHG emissions associated with co-product use are also included, in which case the emission impacts of their most likely uses and the products they displace in the market are considered.

Therefore, the RFS2 uses the system expansion (also known as displacement) method instead of allocation. Pathways shall be accepted by EPA, which calculates the typical GHG emissions associated with that specific pathway. Only those fuel pathways that meet the appropriate minimum GHG savings target are approved for use in the RFS2. As such, participants in the RFS2 do not have to undertake GHG calculations.

The minimum GHG saving that must be achieved for the pathway to be eligible depends on the fuel type. This ranges from 20% for renewable fuel, to 50% for biomass-based diesel and advanced biofuel and up to 60% for cellulosic ethanol. Cellulosic biofuel must be produced from cellulose, hemicellulose, or lignin. Advanced biofuel can be produced from qualifying renewable biomass (except corn starch). Renewable (or conventional) fuel typically refers to ethanol derived from corn starch.

Economic operators are responsible for reporting the GHG saving of their individual consignments of biofuels and ensuring that they meet the minimum GHG threshold. With regard to land use change (LUC), the GHG saving values quoted in the RFS2 take into account an overall estimate of both “domestic” (i.e. US) and “international” LUC emissions.

A comparative table of the key elements of the LCA methodologies described in this chapter is shown below in table 1.

Table 1. Comparative table of LCA methodologies

	CORSIA	EU RED	RSB CORSIA*	RFS
LCA methodology	Core LCA' emissions calculated with an attributional approach and 'ILUC' emissions calculated with a consequential approach	Following methodology explained in Annex V of REDII	RSB GHG calculator	GREET model
Allocation method	Based on energy content	Based on energy content (lower heating value)	Co-product energy allocation based on lower heating value (LHV)	System expansion (also known as displacement
Fossil baseline (g CO_2e/MJ)	89	94	89	89
Target reduction	10% (core LCA + ILUC)	65% after 1 Jan 2021 70% fuels of non-biological origin	50%; 60% for new installations that started operation after 5 October 2015 (core LCA + LUC)	Dependent on type of fuel: • Renewable fuels: 20% • Advanced &Biodiesel Fuels: 50% • Cellulosic Fuels:60% compared to 2005 petroleum baseline
Type of fuel	Jet fuel and AvGas	Biofuels and Bioliquids	Jet fuel and AvGas	Biofuels

*For RSB CORSIA claims, RSB requires higher GHG reduction than the standard itself.

A GHG intensity target is only as effective as the underlying LCA methodology used to estimate it. For example, British Columbia's LCFS does not include ILUC emissions in its LCA assessment of fuels. Thus, despite ambitious GHG reduction targets, it primarily incentivizes the increased blending of food-based biofuels and has had little impact on the deployment of advanced fuel pathway (Pavlenko & Searle, 2021).

On the other side EU REDII sets limits on high ILUC-risk biofuels, bioliquids and biomass fuels with a significant expansion in land with high carbon stock promoting the use of sustainable feedstocks.

5.1.3 **Opportunities for harmonization**

Sustainability has become an increasingly important strategic consideration across sectors and geographies. Decarbonization is at the forefront of the national and global policy agenda and depends on transformation of development in different sectors, including aviation (Ashrafi, Lister, & Gillen, 2022). Emission reduction potentials of each fuel type as well as other economic, environmental, and social impacts vary significantly, depending on the primary energy source, the fuel processing techniques, and the propulsion technology.

Efforts are being made by ICAO with the development of CORSIA and other examples around the industry. But as a global transportation sector, aviation needs a harmonized standard to ensure that sustainability criteria are equally applied across the industry. The development of an accepted set of globally harmonized standards will help ensure that investment is directed at fuels that meet clearly defined and internationally agreed sustainability criteria, thus minimizing this form of risk (ATAG, 2020).

Furthermore, governments need multi-stakeholder, joint proposals that harmonize environmental goals with financial needs, namely a level playing field among competitors. Additional work is necessary to decide how the blending mandate should be designed considering a particular country's capabilities and how quickly SAF can feasibly be ramped up. The policy package will need to be tied to the feasible ramp-up rate to refrain from any supply shortages and corresponding price volatility.

There is need for harmonization of reduction targets which are used as a baseline for decarbonization of the sector. As it was mentioned earlier in this chapter, there are different methodologies used for estimation of environmental impact of SAF production. Therefore, the use of different methodologies for accounting decarbonization might lead to different values for the same feedstock and technology combination.

6 Assessment of the decarbonization potential of SAF

The decarbonization potential of a SAF can vary largely based on several factors, including the feedstock used, the production method, and supply chain efficiencies, including energy and transport distances. To determine the GHG emission reduction from a given SAF product in relation to fossil fuels benchmarking, a lifecycle assessment approach (LCA) is the preferred technique.

The LCA methodology used in this report is based on the review and analysis of the inputs and outputs of the system to obtain its potential environmental impact. Although LCA is widely used to determine a decarbonization effect, the methodology itself constantly develops and adapts to new production methods and scientific knowledge of applicability.

RSB and NISA engaged with several SAF producers to verify how different practices affect the products GHG performance. The goal of SAF is to achieve a significant GHG emission reduction when compared to conventional fossil jet (i.e., at least 80%) to demonstrate real climate impact. The higher the reduction, the more valuable SAF is in the market. Several policy mandates and incentives, as well as purchase agreements, are linked to the product's GHG performance.

6.1 SAF pathways and supply chain routes

The study evaluated four SAF production pathways: HEFA, ATJ, FT and PtL, across several scenarios (feedstock, distance, and transport modes) summarized in table 2, and validated the input data in close collaboration with ALIGHT project partners and external stakeholders (see table 3)

Table 2. Selected pathways for SAF production

Conversion technologies	Sources
PtL	Electricity from power grid (Europe), wind and PV (Photovoltaic) systems; CO2 from waste gas and direct air capture; hydrogen from natural gas reforming, biogas reforming, ethanol reforming, water electrolysis (PEM and alkaline).
ATJ	**Ethanol sources modelled:** - 1G ethanol from sugarcane juice, - Brazil - 2G ethanol from sugarcane bagasse and trash – Brazil - 1G2G ethanol from sugarcane juice + bagasse and trash – Brazil - Corn ethanol in dry milling – US - Corn ethanol in wet milling – US - Miscanthus ethanol – US - Switchgrass ethanol – US - Forest residue ethanol – Global - Corn stover ethanol (gasification) – US - Waste-gas to ethanol, with and w/o renewable energy (fermentation) – Global - Flue-gas fermentation from steel mill - Global

HEFA	Palm oil, Tallow, Used Cooking Oil
FT	Forestry residues, Municipal Solid Waste

Table 3. Stakeholders involved in the validation workshops

Validation workshop theme	Stakeholders involved in the validation workshop
PtL	Nisa, Arcadia Fuels, Nordic Blue Crude, Shell, Sasol and Riffel Consulting
ATJ	Nisa, Shell, Lanzajet, Lanzatech and Gevo
HEFA and FT	World Energy, Sasol, Nisa, Redrockbio and Shell

6.2 Lifecycle GHG performance of selected pathways

The GHG performance of SAF depends on several factors such as feedstock and technology used, energy input in the system, and methodology used to calculate the GHG intensity.

The criteria considered were feedstock and technology development for SAF production. Four scenarios were developed for four SAF production pathways (HEFA, ATJ, PtL, and FT) based on changes in the following value chain components:

- Type of feedstock (waste vs crops, feedstock yields)
- Energy consumption
- Hydrogen type (grey/green)
- Distance (feedstock to SAF refinery, SAF refinery to airport)
- Transport modes (road, rail, shipping)

The preference was to obtain primary sources, but due to the lack of sufficient commercial data for SAF production and due to confidentiality issues associated to the production data, science-based literature data has been used to do the environmental assessment. The strategy was then taken to:

- Collect a range of primary data from peer-reviewed scientific literature or relevant sources, such science-based reports (e.g., CORSIA, IPCC) and Argonne GREET. Perform sensitivity analyses to evaluate the impact of key inputs from the upstream and down-stream stages on the overall SAF GHG performance, including transportation from SAF producer to CPH.

- Arrange a set of validation workshops with ALIGHT partners and stakeholders from SAF production in order to present the results and validate the data used. One webinar was organised for each one of the four pathways studied.

Validation workshops were carried out to discuss the results obtained from the GHG calculations, discuss the major drivers of the aviation carbon footprint and get feedback from participants on specific questions of importance to develop environmental assessment of SAF. Outputs from the Validation Workshops included, but were not limited to:

- Inclusion of four additional ethanol pathways.
- Inclusion of a pathway for hydrogen production from biomethane.
- Better analysis of the GHG emissions impact from building and maintenance of photovoltaic and wind systems for electricity generation.
- Improvement of the PtX analysis related to the use of electricity.
- Update of the system boundary for PtX technology to better reflect the reality (e.g., conservative approach to the market for oxygen that is unlikely to be sold in the current reality).
- Removal of inconsistent assumption, due to lack of evidence, about emissions displacement from tallow used for SAF production. Attendees also highlighted the risk of double counting when displacement of emissions are included in the final GHG LCA results, and the high availability of some type of residues, which would not displace emissions. In some cases, the use of residues avoids the burning in the field, and therefore avoids GHG emissions. In this case, the emission displacement would benefit the LCA GHG emissions results.
- Update of the technologies adopted for hydrogen production, excluding non-relevant options, improving others, and applying a better treatment to the water used in the electrolyser due to the high purity required in this technology.

Secondary data (e.g., GHG emissions related to inputs such as ethanol production, electricity generation and distribution, palm oil production, etc) for the life-cycle assessment study were retrieved from Ecoinvent database, GREET, EU RED, and CORSIA.

The calendar of the workshop validation data and themes developed were the following:

Workshop	**Date**
PtL	April 22
ATJ	May 22
FT -HEFA	June 22

After the discussion held during the workshop, feedback was considered to further develop the environmental assessment of each pathway. The following sections show the results obtained from the GHG assessment carried out.

6.2.1 **PtL GHG assessment**

Power-to-X technology, (PtX - power to liquid, power to gas or power to ammonia) holds promise as a renewable, non-biogenic technology to produce fuels. PtX uses CO_2, water and renewable electricity to produce synthetic liquid hydrocarbon fuels and chemicals. Electric energy from renewable sources is stored in the chemical bonds of liquid or gaseous fuels to produce the final fuel/chemical. In a straightforward way, PtX technology consists of two main steps: (1) the hydrogen production through an electrolyser using water and renewable electricity as main inputs and (2) a subsequent catalytic conversion of the hydrogen gas with carbon dioxide or nitrogen. In some cases, compounds such as ethanol, methanol, biomethane can also be used as a renewable precursor from hydrogen and carbon in a process of electrochemical synthesis.

Ten scenarios were evaluated for PtL pathway, of which five scenarios consider direct air capture (DAC) as the CO_2 source (F, fig.4), and five scenarios assume waste gases as the source of carbon (G, fig.4). Each of these carbon source scenarios algo varies according to the type of heat, electricity (A, B, or C, fig.4), and hydrogen (electrolysis (D), proton-exchange membrane (PEM, E, fig.4), and natural gas reforming, biogas reforming, and ethanol reforming). For PEM and electrolysis scenarios, hydrogen was also modelled for different sources of electricity, i.e, wind, photovoltaic, and grid.

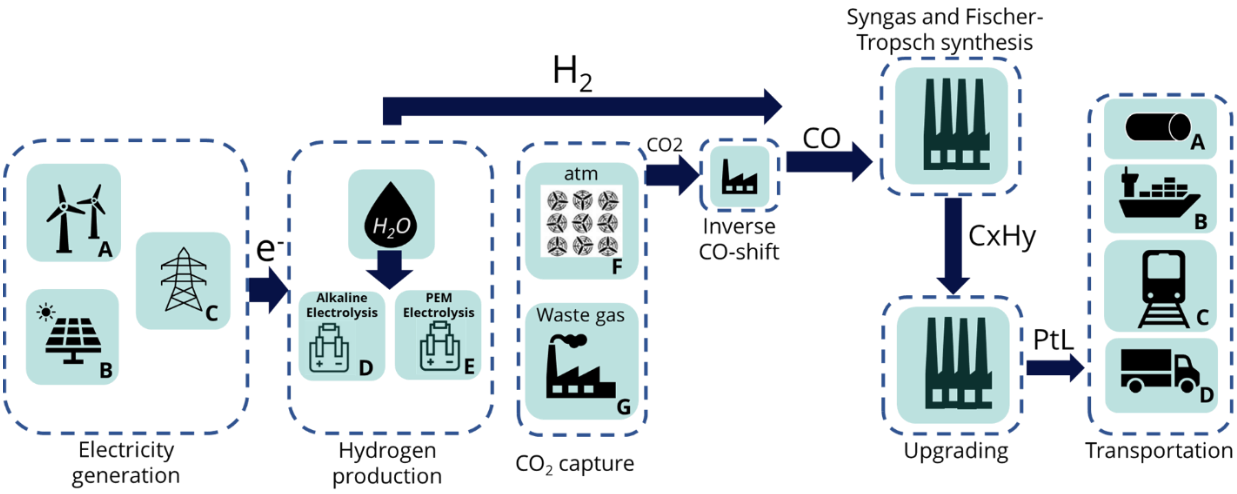

Figure 4. Lifecycle system boundary of the PtL pathway. Cradle-to-gate approach including the final product (SAF) transportation from facility to airport.

The syngas and Fischer-Tropsch (FT) synthesis are all the same across pathways. This report evaluated the sensitivity of key parameters on the final LCA GHG results, that are: hydrogen consumption and technology, amount of electricity and heat used for CO_2/waste gas capture, amount of electricity consumed for FT and electrolysis, hydrogen transportation distance, and energy use for CO_2 compression.

Given the relevance of the hydrogen in the GHG LCA emissions for PtL pathways, as identified in this study, we also applied a sensitivity analysis to better understand the differences between hydrogen production technologies (Figure 5). The production of hydrogen from PEM using the European power grid (average of emission factors from EU countries) has the highest carbon footprint among the pathways evaluated here, even higher than hydrogen from natural gas reforming.

The only pathways, among the ones evaluated here, for hydrogen production that could potentially comply with the EU RED and RSB target reduction for GHG emissions are the PEM and electrolysis of water using wind-based electricity. CORSIA has not defined the GHG savings targeted for hydrogen. Note the GHG savings targets are related to the final fuel, therefore, in this context it applies to the use of hydrogen to power aircraft. Hydrogen as feedstock or input for the production of SAF does not need to meet with the savings target. However, a high LCA GHG emission for hydrogen may impact the SAF LCA GHG emissions (as seen in fig.5).

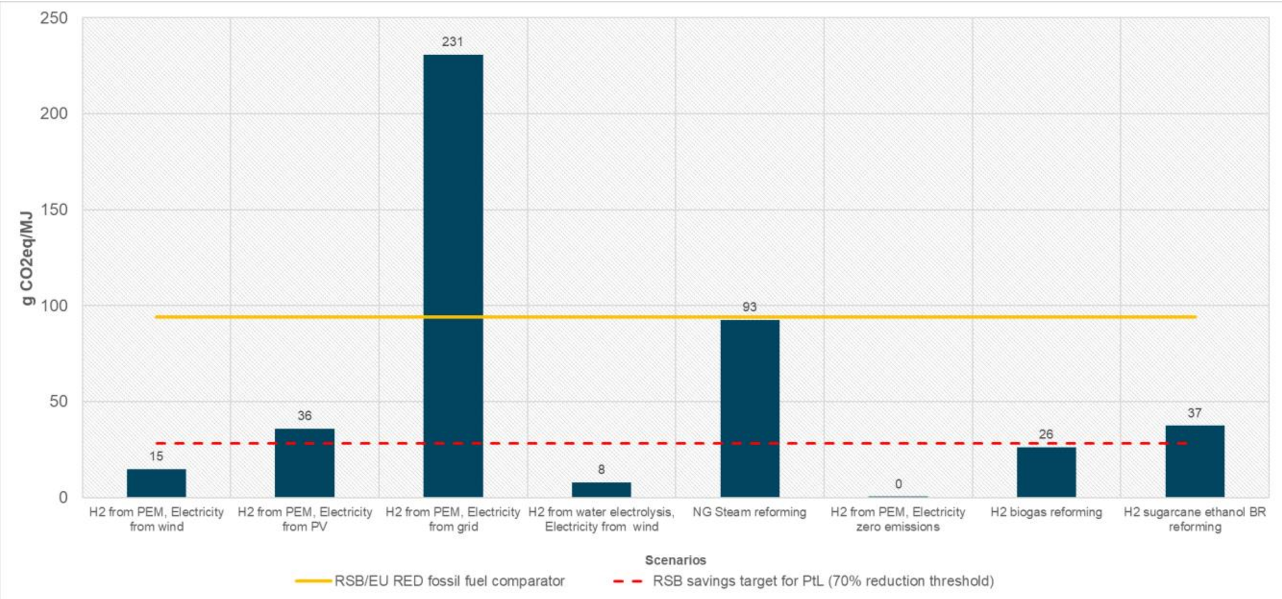

Figure 5. Sensitivity analysis for LCA GHG emissions of hydrogen produced from different pathways.

Baseline scenarios (A) reflect the use of hydrogen with highly intensive LCA GHG emissions, electricity from grid (assuming the average value for emission factor of all European countries), and heat produced from fossil-based sources. Worst case scenario for CO_2 from DAC is not shown in the chart as it represents an LCA GHG emissions factor of more than 750g CO_2e /MJ of SAF. There is a high consumption of heat for direct air capture which ideally should be supplied by waste heat for reducing the GHG impact of such air capture.

CORSIA has not yet established the GHG LCA default values for power-to-liquid technologies, nor has it defined how the ILUC approach will be addressed or if a different GHG saving target will be used for PtL. Therefore, for the PtL analysis we assumed the same fossil fuel comparator (89g CO_2e/MJ) and GHG emissions reduction target (10%) currently used by CORSIA for other pathways. We also assumed zero ILUC for PtL technologies as CORSIA hasn't yet defined whether ILUC emissions from extensive PV and wind systems would be considered.

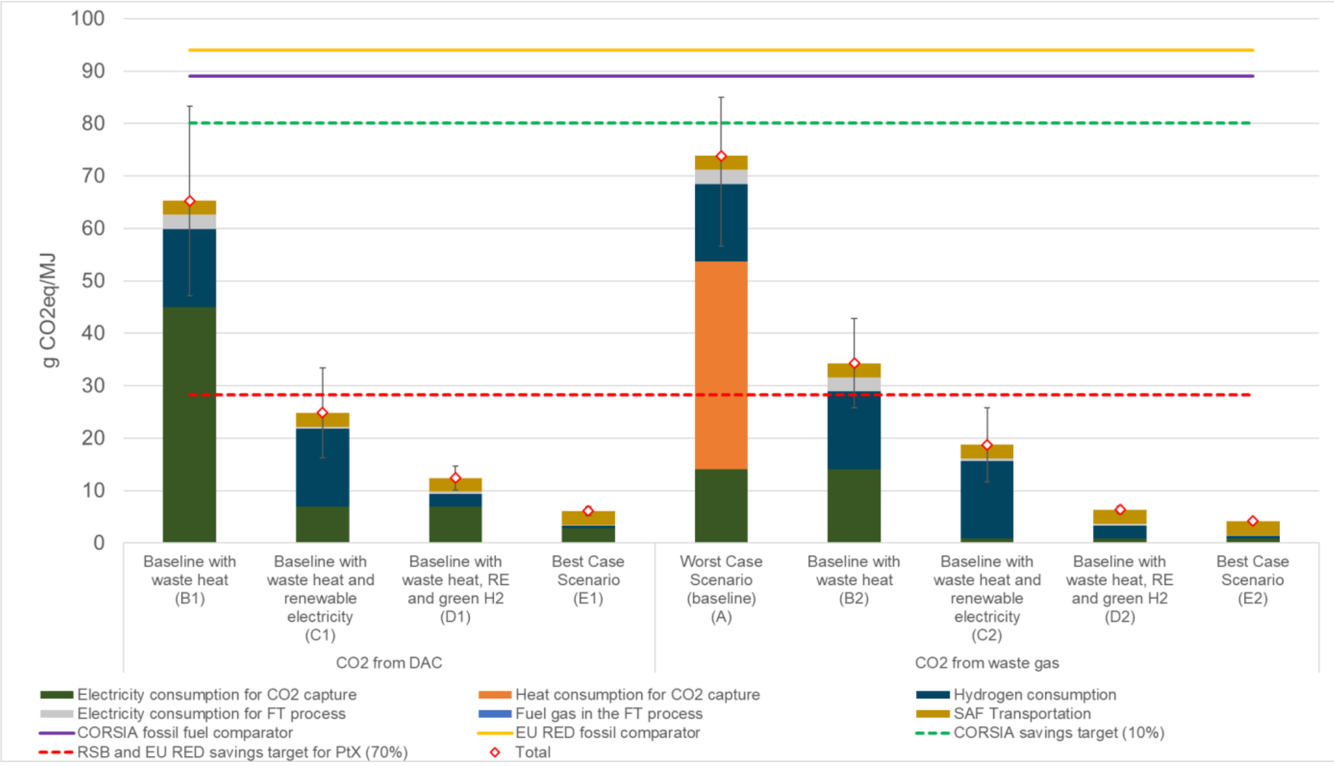

Figure 6. Breakdown lifecycle GHG emissions and sensitivity analysis for PtL SAF production.

To add value to the analysis, the GHG emissions saving targets from EU RED and RSB were also evaluated as the European Commission and RSB have already established targets for PtL technologies. According to EU RED and RSB requirements, the SAF producer shall demonstrate that the SAF achieves, on a life cycle basis, net GHG emissions reductions of at least 70% when compared to the fossil baseline. Incorporating the Land Use Change impact of PtL technologies has also been discussed by RSB.

The breakdown of GHG emissions for the SAF pathways and the sensitivity analysis show that the electricity consumption for carbon capture plays an important role in the GHG emission impact, followed by the hydrogen consumption. From the sensitivity analysis, we identified that small variations in the electricity consumption for direct air capture may lead to an increase of 16% in the LCA GHG emissions for PtL-based SAF production in Scenario B1. For the capture of waste gas in Scenario B2, this impact is up to 10% on the final LCA GHG emissions for PtL-based SAF.

The high variation identified in Scenarios B (error bars in fig. 6) are related to the hydrogen type, which can be green or natural gas-based, and to the type of source used for electricity production consumed to capture CO2 (DAC). In Scenario C, the high variation is mainly related to the type and consumption of hydrogen. Once hydrogen is switched to green (Scenario D), the potential variation is associated to the electricity for DAC (Scenario D1, fig.6)). Scenarios C and D assume for renewable electricity the use of PV systems. Scenario E, the best-case scenario, uses a wind-based system to supply the electricity demand for carbon capture and FT process.

Results show that the GHG emissions savings target for CORSIA would be easily achieved by most of the scenarios, except for scenario B (Figure 6) in which case the electricity demand for CO_2 capture is supplied by the power grid. The emission factor of the power grid refers to the average value of all European countries. Considering the RSB and EU RED savings target, only pathways using renewable electricity and green hydrogen (D, E, fig.6) would easily reach the target. Pathways not using green hydrogen (B and C, fig.6) could be affected by the high LCA GHG emissions related to hydrogen or high uncertainty of the other parameters, which was captured in the sensitivity analysis (error bars in fig.6).

6.2.1.1 SAF transport impact for PtX pathways

SAF transportation (dark yellow portion in figure 6) accounted for 4% (B1) to 62% (E2) of the LCA GHG emissions depending on the SAF pathway. Pathways with low GHG emissions due to improvements in the energy source (Figure 6, scenarios E) have a greater impact from SAF transport as other categories become irrelevant. The distance and mode of transport, however, may make a SAF technically unfeasible in terms of reducing life-cycle greenhouse gases considering the RSB and EU RED saving targets for PtX (Figure 7). As scenarios A and B (Figure 6) would not achieve the GHG savings target, we evaluated scenarios C, D, and E considering the transport of SAF from different regions of the world to Europe.

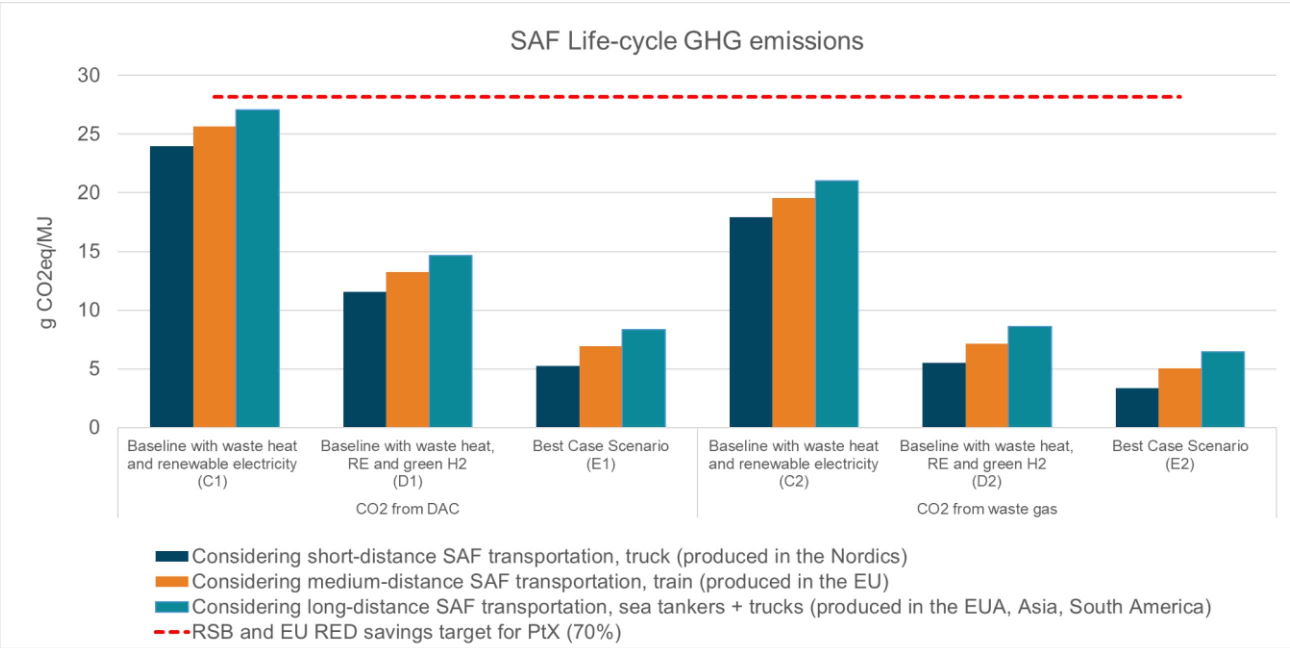

Figure 7. Lifecycle GHG emissions for SAF PtX pathways considering different transport distances.

Transporting SAF from South America or USA to Europe (Figure 7, green bars) would only be critical, in terms of achieving the GHG savings target, for scenario C1, whose LCA GHG emissions for the base case scenario (medium-distance transport) were already critical (Figure 6). For the other scenarios, even transporting SAF over long distances would not compromise the potential to achieve the GHG savings target. It is important to note that variations in other parameters (e.g., hydrogen type, energy consumption) are more likely to reduce the attractiveness of reducing the GHG emissions, as indicated in the error bars in Figure 6.

6.2.2 **ATJ GHG assessment**

ATJ technology consists of converting alcohols into an alternative jet fuel, diesel, and naphtha, by using a process where alcohol molecules are dehydrated, oligomerized, and, finally, hydrogenated to suitable hydrocarbon chains.

The ATJ pathway was evaluated for thirteen scenarios, which varies according to feedstocks and ethanol production technologies. The scopes are indicated below (Figure 8). Ethanol-to-SAF processes are all the same across the pathways. We evaluated, however, the sensitivity of key parameters associated with the SAF refinery on the final LCA GHG results.

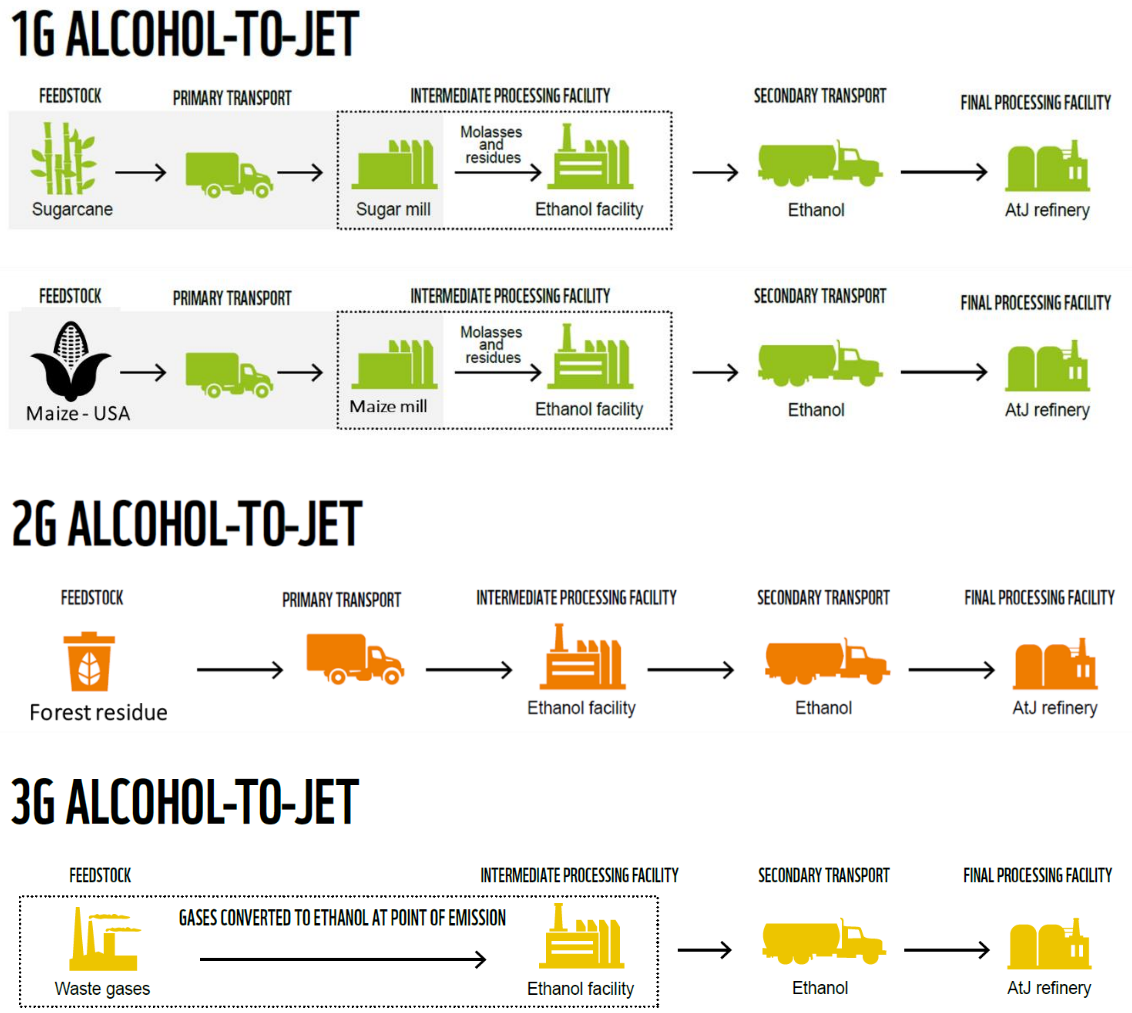

Figure 8. Lifecycle system boundary for ATJ pathways.

The analysis used the 89g CO_2e/MJ as fossil comparator and evaluated the GHG reduction based on the CORSIA and RSB CORSIA saving targets. We included the ILUC impact in accordance with CORSIA default values and the location of each feedstock evaluated. The SAF producer shall demonstrate that the SAF achieves, on a life cycle basis, net GHG emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel. To comply with RSB CORSIA, in addition to the 10% CORSIA requirement, the SAF producer shall also achieve an LCA GHG emission reduction of 60% relative to the jet fuel fossil baseline (new installations). The RSB CORSIA requirement does not include ILUC. SAF producers under RSB CORSIA shall also include GHG emissions from direct land use change.

Results show that the GHG emissions savings target for RSB CORSIA (green markers in fig.9) would be easily achieved by ATJ pathways based on ethanol from forest residues, miscanthus, switchgrass, from fermentation of waste gas, in addition to 2G ethanol from sugarcane bagasse and trash. Regarding the GHG emissions savings target for CORSIA, only, all pathways would easily attend the threshold, except ethanol from corn produced through wet milling.

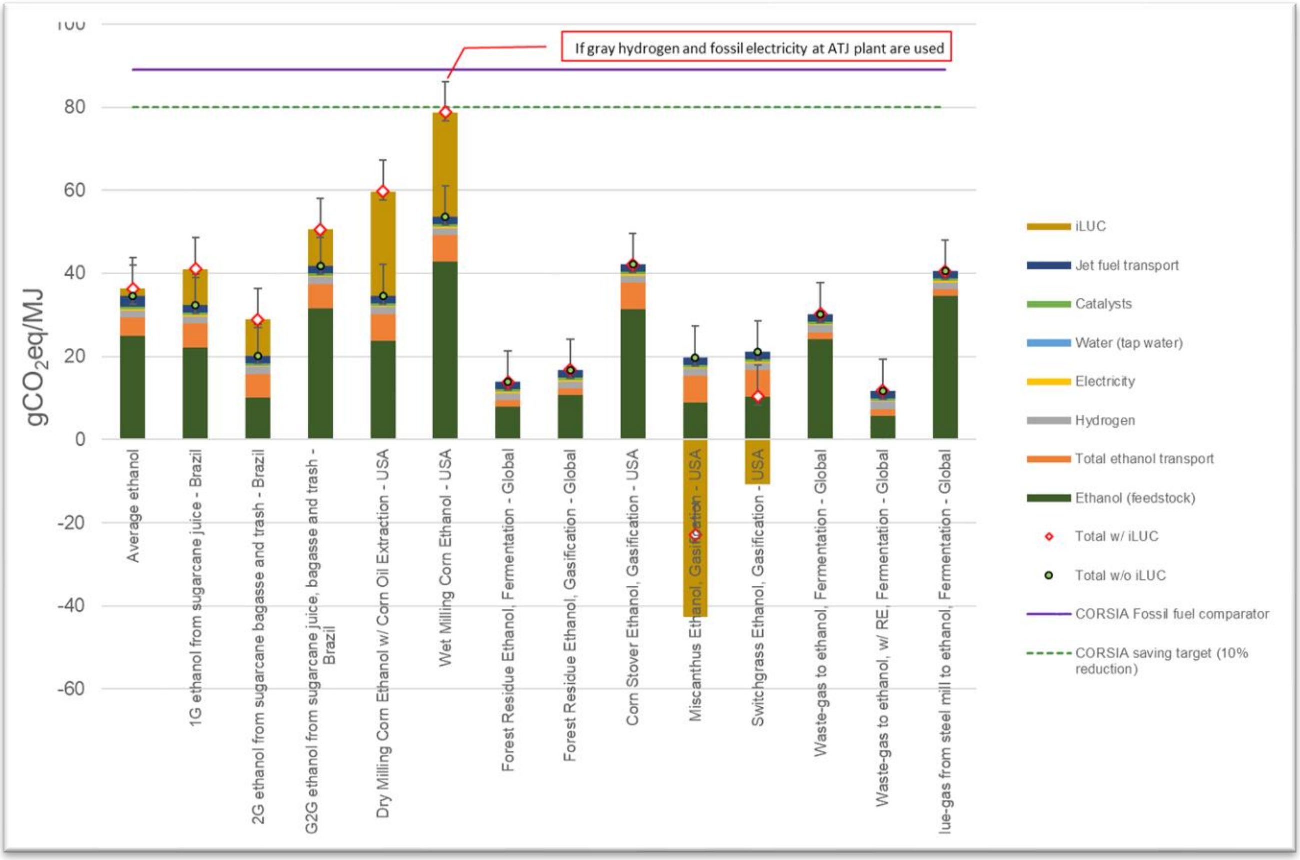

Figure 9. Breakdown lifecycle GHG emissions and sensitivity analysis for alcohol-to-jet SAF production using different ethanol types.

The sensitivity analysis identified that the ethanol carbon footprint is the most relevant factor affecting the GHG LCA results for SAF, which can vary from 12 to 54g CO_2e/MJ without accounting for ILUC, and -22 to 79g CO_2e/MJ including ILUC. Parameters related to the feedstock-to-SAF conversion stage were also evaluated, including transportation distances and modes for SAF and ethanol, use of grey hydrogen versus green hydrogen, and fossil electricity at the ATJ plant versus renewable electricity.

In the worst-case scenario, where grey hydrogen and fossil electricity is used at the SAF facility, additional 7.5g CO_2e/MJ can be added to the final GHG LCA results for SAF (bars indicated in fig.9). Given the negative ILUC attributed to the miscanthus pathway, the final GHG LCA results is also negative. Final negative values, however, are not accepted by CORSIA yet, in which case a zero-carbon footprint value would be considered.

6.2.2.1 *SAF transport impact for ATJ pathway*

To produce SAF from ATJ pathways in Europe, the lack of feedstock availability could require importing ethanol from Brazil and the US, for instance. The transportation of ethanol from these regions, however, would add to the total LCA GHG emissions only around 6g CO_2e/MJ. The worst-case scenario for transportation would add around 8g CO_2e/MJ, which would still result in all pathways, except ATJ SAF from corn ethanol (dry milling), achieving the CORSIA target (Figure 10).

The SAF transportation accounts for 1 or 3.5g CO_2e/MJ for short- and medium-distances, respectively. We assumed truck for short-distance (300 km) and train for medium-distances (3000 km) (Figure 8). The impact by transporting SAF over different distances across Europe is not as relevant as transporting ethanol, and even less relevant when compared to potential impacts from ILUC or GHG emissions related to the feedstock, ie ethanol.

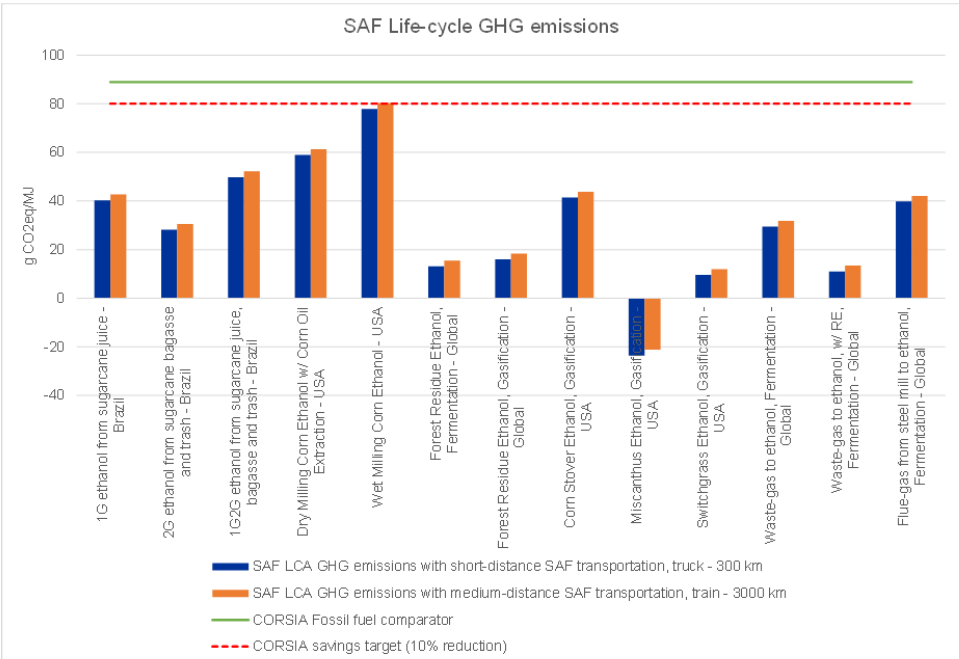

Figure 10. Life-cycle GHG emissions for SAF ATJ pathways considering different transport distances.

6.2.3 **HEFA GHG assessment**

The HEFA process is currently the best-known process for alternative jet fuel production. In this process, the oleaginous feedstock undergoes hydrotreatment with hydrogen in the presence of a catalyst. Unsaturated carbon-bonds are saturated, and oxygen is removed. Subsequently, the hydrocarbon chains are hydrocracked in different ranges, isomerized and, finally, fractioned, thus producing jet fuel and other products, such as diesel, naphtha, and light streams, such as propane.

Three oil feedstocks were evaluated for HEFA technology, these being palm oil, used cooking oil (UCO), and tallow. For palm oil pathways, the scope starts at the palm oil cultivation up to the SAF use, including transportation of feedstock, oil and SAF, oil extraction process, and oil-to-SAF conversion. For UCO and tallow, which are classified as wastes according to CORSIA, the GHG emissions start at the point of origin, i.e., point of collection.

6.2.3.1 HEFA from palm oil

Palm tree is cultivated in Malaysia or Indonesia, processed into crude oil locally, transported to Europe and then converted into fuels. The LCA GHG emissions related to SAF production were retrieved from CORSIA documents. The approach used by CORSIA takes into account that the palm oil is transported from the mill to the HEFA conversion facility using trans-oceanic transportation of 8,800-10,000 nautical miles. The palm oil is thus produced in Asia and transported to Europe.

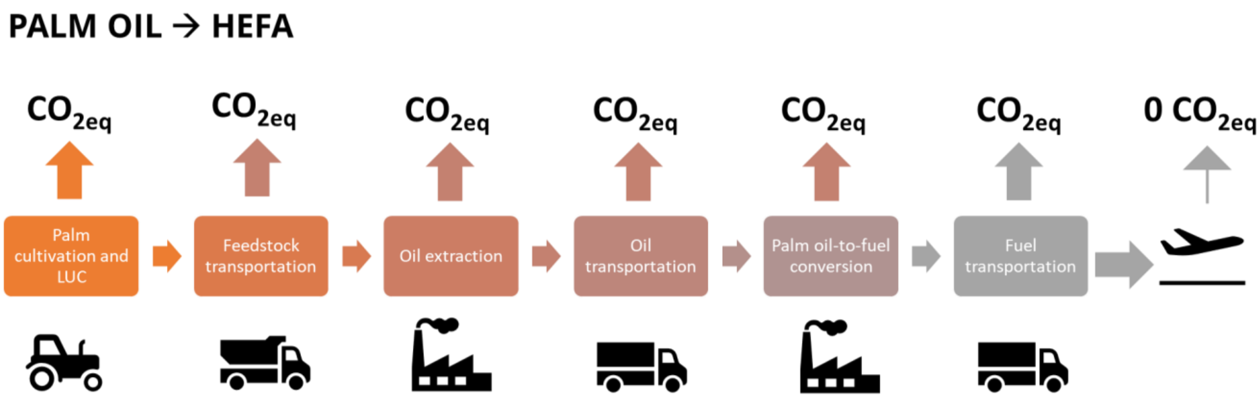

Figure 11. Lifecycle system boundary for tallow-based and UCO-based SAF using HEFA technology.

Results for palm oil-based SAF show that the land use change may either contribute to high LCA GHG emissions or negative LCA GHG emissions depending on the type of land replaced to grow oil palm, climate region, and tillage regime in the reference land and actual land use. The assumptions adopted in each scenario for LUC are indicated in table 4.

Table 4. Scenarios evaluated for Land Use Change.

Scenarios	Reference Land use	Climate Region	Reference tillage regime	Actual tillage regime
Best case scenario	Grassland	Tropical, moist/wet	Tropical, moist/wet - Severely degraded, medium inputs	Tropical, moist/wet - No till, high inputs with manure
Middle scenario	Grassland	Tropical, moist/wet	Tropical, moist/wet - Nominally managed, medium inputs	Tropical, moist/wet - Reduced tillage, medium inputs
Worst case scenario	Forest	Tropical, moist/wet - shifting cultivation - shortened fallow	Forest land-tropical rain forest (South America)	Tropical, moist/wet - Full-tillage, Low inputs

The analysis used the 89g CO_2e/MJ as fossil comparator and evaluated the GHG reduction based on the CORSIA and RSB CORSIA saving targets. We included the Induced Land Use Change (ILUC) impact in accordance with CORSIA default values and the location of each feedstock evaluated. The RSB CORSIA requirement does not include ILUC. SAF producers under RSB CORSIA shall also comprise GHG emissions from direct land use change. For LUC evaluation, we used default values from EU RED based on climate conditions and carbon balance per types of land use and land management.

Notably, in 2022 the European Commission officially approved a measure to gradually phase out palm oil-based biofuel by 2030 under the scope of the RED II. Member states' maximum share of palm oil-based biodiesel that can be counted toward EU renewable transport targets for national governments (and hence be eligible for subsidies) will be capped at 2019 levels until 2023. After that, it will be progressively phased out of renewable targets to zero percent.

The annualized GHG emissions from land use change may lead to a final LCA GHG for SAF ranging from -44g CO_2e/MJ (best case scenario) to 200g CO_2e/MJ (worst case scenario) (Figure 12). The SAF producer under CORSIA regulation shall demonstrate that the SAF achieves, on a life cycle basis, net GHG emissions reduction of at least 10% compared to the baseline life cycle emissions values for aviation fuel. To comply with RSB CORSIA, in addition to the 10% CORSIA requirement, SAF producers shall also achieve an LCA GHG emission reduction of 60% relative to the jet fuel fossil baseline (new installations).

Results show that both best case and middle scenarios can comply with RSB CORSIA threshold. The CORSIA threshold, however, would not be reached under any of the baseline scenarios unless better technology is used at the palm oil plant, such as the capture of methane emitted from the thermophilic fermentation in the treatment of palm oil mill effluent (POME). This is the case for the lower values indicated in the error bars in figure 12.

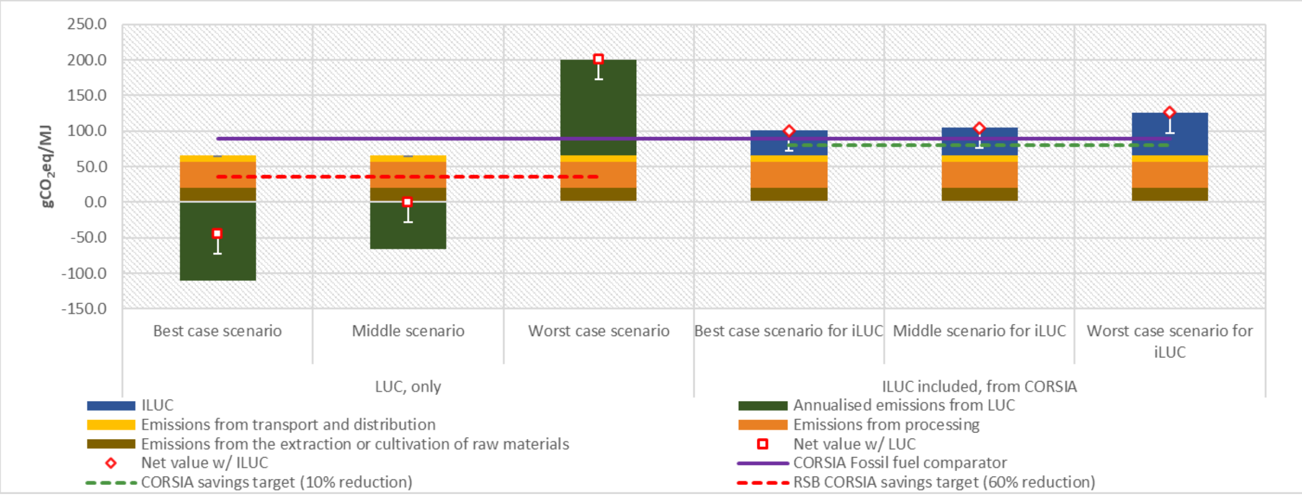

Figure 12. Breakdown lifecycle GHG emissions and sensitivity analysis for HEFA SAF production using palm oil from Malaysia and Indonesia.

In summary, the pathways evaluated here for palm oil-based SAF would hardly achieve RSB and CORSIA requirements unless degraded grasslands, no till system, and use of manure as inputs are implemented.

6.2.3.2 HEFA from tallow and used cooking oil

The system boundary for tallow-based HEFA starts at the rendering plant. The distance from the collection and transportation points of tallow to the rendering plants was assumed to be 100 km. At the rendering plant, used cooking oil (UCO) is filtered for the removal of solid particles and then heated to reduce the moisture content and to obtain yellow grease. The rendering process for tallow involves crushing/grinding, cooking, pressing and centrifuging the animal fat. The outputs comprise tallow, meat and bone meal (MBM) and water (mass fraction of 55%).

As for UCO-based HEFA, the system boundary starts at the point of collection. The distance from the collection and transportation points of UCO to the rendering plants was assumed as 50 km.

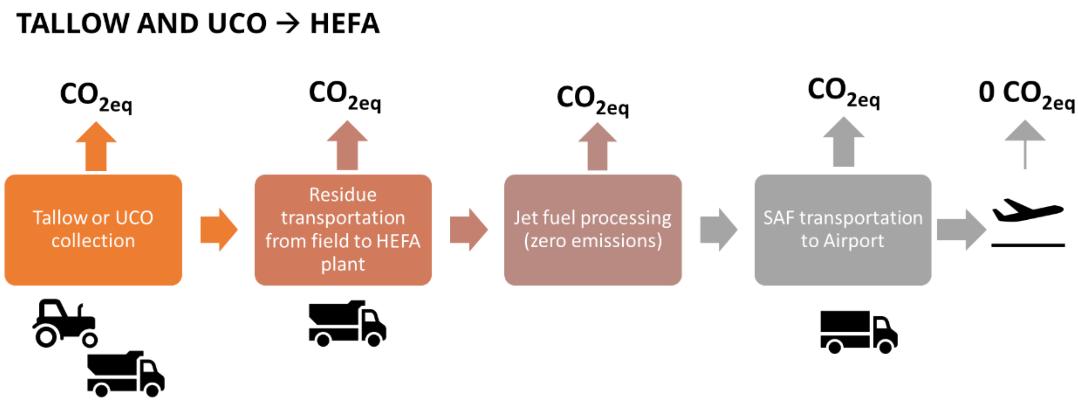

Figure 13. Lifecycle system boundary for tallow-based and UCO-based SAF using HEFA technology.

Results for tallow-based HEFA indicate that the LCA GHG emissions for SAF production is 22g CO_2e/MJ for the baseline scenario, but higher values may occur if the hydrogen for the oil-to-fuel conversion process is derived from PEM technology using electricity from the European power grid (average emission factor between EU countries) (Figure 14).

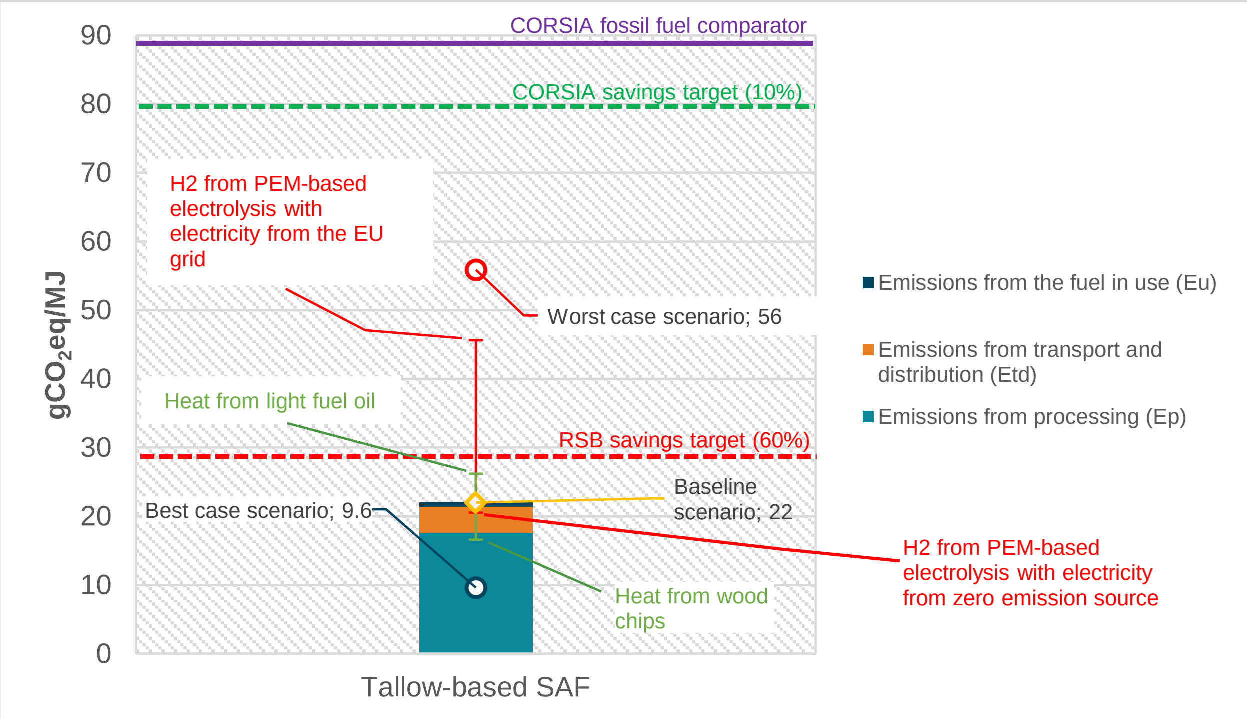

Figure 14. Breakdown lifecycle GHG emissions and sensitivity analysis for HEFA SAF production using tallow; point of origin is defined at the rendering plant.

Under this condition, the GHG savings target would not reach the RSB CORSIA threshold. Note that even achieving the CORSIA savings target, SAF producers would not be eligible to get RSB CORSIA certification without also achieving RSB savings target.

The best-case scenario refers to the use of hydrogen derived from PEM technology using zero emission electricity (0.5g CO_2e/MJ), and heat for oil-to-fuel conversion plant derived from wood chips (18.6g CO_2e/MJ). The worst-case scenario indicates the use of high carbon intensity hydrogen, produced from PEM technology using the grid power technology (7.9g CO_2e/MJ), and heat for oil-to-fuel conversion plant derived from light fuel oil (91.5g CO_2e/MJ).

The LCA GHG emissions for SAF produced from UCO using HEFA technology resulted in 15.2g CO_2e/MJ, which would comply with both RSB and CORSIA threshold GHG savings. UCO collection accounts for 17% of the total GHG emissions (an average of 50 km was considered), but higher contribution may occur if a non-appropriated logistic is in place. The main driver of the GHG emissions is the oil-to-fuel conversion step, which account for 60% of the total GHG emissions. At this step, half of the GHG emissions (i.e, 30% of the total SAF GHG emissions) is derived from natural gas used at the conversion, and hydrogen accounts for 18% of the conversion step. Hydrogen with lower LCA GHG emissions can lead to an overall reduction of the SAF carbon footprint in the UCO-based HEFA process.

6.2.3.3 SAF transport impact for HEFA pathways

To evaluate the GHG emissions impact of transporting SAF across Europe, we assumed the extreme distance in the region at 3000 km, using train, and a short-distance scenario at 300 km, using truck. Results showed that that opting for shorter or longer logistics does not significantly affect the results (see Table 5 and figure 15).

Transporting the feedstock plays a more relevant role for palm-based SAF because palm oil is transported from the mill, where it is extracted, to the HEFA facility through a trans-oceanic transportation of 8795 nautical, coming from Malaysia and Indonesia (in accordance with CORSIA methodology). Even with the trans-oceanic transport, this stage accounts for only 6% of the total LCA GHG emissions for palm-based SAF.

For tallow- and UCO-based SAF, the transport of SAF and oil are also not the most relevant portion of GHG emissions (Table 5), even assuming that tallow would be imported from Latin America or the US and considering the high logistic demand to collect UCO.

Table 5. Impact on GHG emissions from transporting SAF (in grams CO_2e/MJ)

	Feedstock		
	Palm, including ILUC	Tallow	UCO
Feedstock collection (tallow, UCO) / production (palm)	19.8	0.5	2.4
Oil processing	0.0	5.9	1.1
Oil to HEFA plant transport	5.9	2.5	2.2
SAF production at HEFA plant	37.1	12.4	12.7
SAF transport - 300 km, truck	1.4	1.6	1.6
SAF transport, 3000 km, train	3.5	3.7	3.8
ILUC	39.1	0.0	0.0
TOTAL, short distance, 300 km, truck	103.3	22.8	20.0
TOTAL, medium distance, 3000 km, train	105.4	24.9	22.2

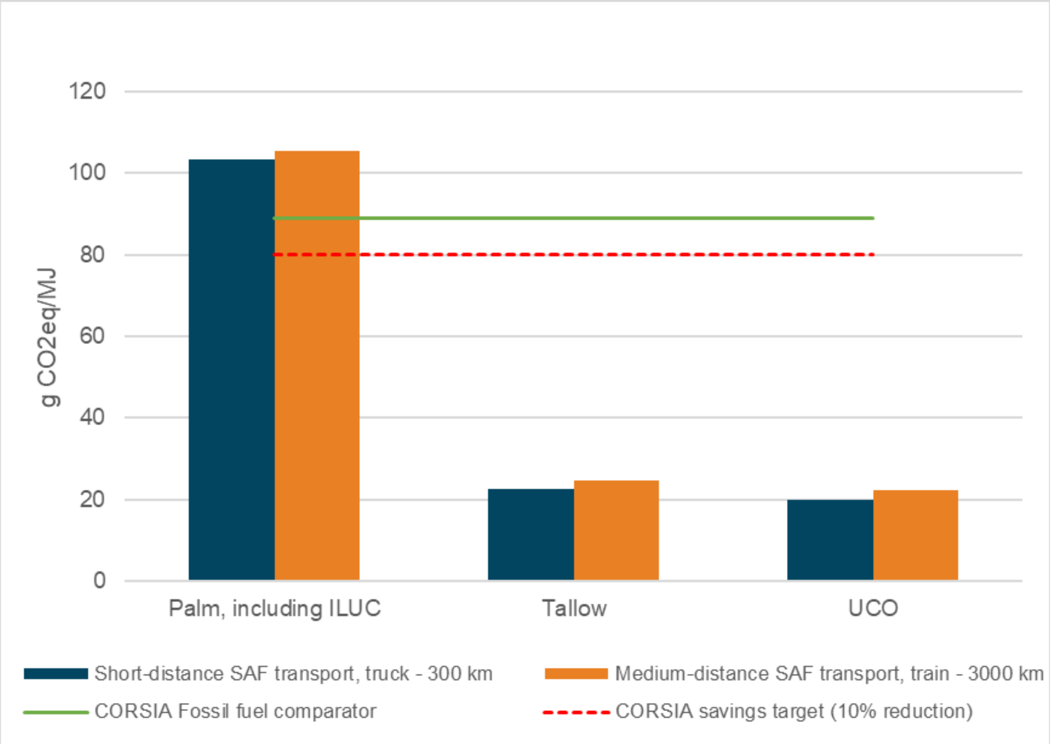

Figure 15. Lifecycle GHG emissions for SAF HEFA pathways considering different transport distances.

6.2.4 FT GHG assessment

In the Fischer-Tropsch (FT) process, biomass is gasified into syngas. After the clean-up process, syngas goes to the Fischer-Tropsch reactor, where it is catalytically converted into liquid long-chain hydrocarbons, which are then cracked, isomerized and fractioned into drop-in jet fuels and other products (Figure 16).

6.2.4.1 FT from forestry residue

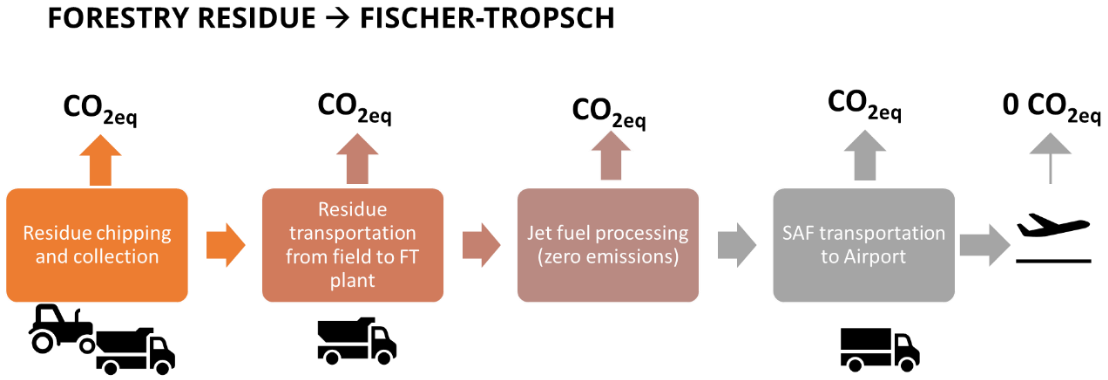

Figure 16. Lifecycle system boundary for forestry residue-based SAF using Fischer-Tropsch technology.

The LCA GHG emissions for SAF produced from FT technology using forestry residue resulted in the lower carbon footprint, with value at 5.1g CO_2e/MJ, which would comply with both RSB and CORSIA threshold GHG savings. The majority of the LCA GHG emissions are related to transport and distribution from FT plant to the airport, which account for over 60% of the total emissions. Displacement emissions from diverting forestry residues from other users were not considered in the analysis as this residue is still widely available (feedback received from the workshop validation). However, this could be a consideration for future studies if this feedstock pathway is scaled significantly in the future.

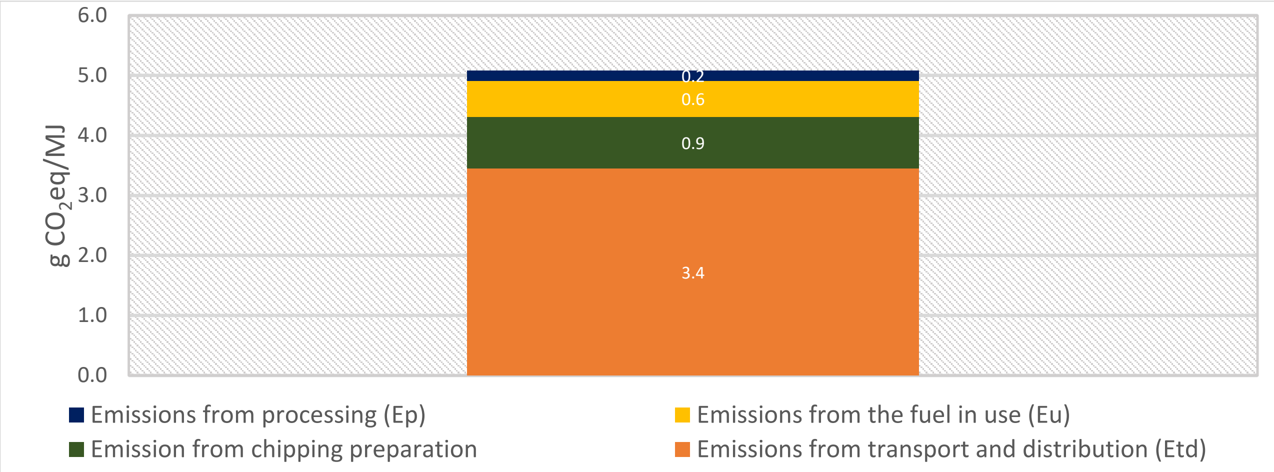

Figure 17. Breakdown lifecycle GHG emissions for FT-based SAF derived from forestry residue; point of origin is defined at the field.

6.2.4.2 *FT from municipal solid waste*

In this case study, the conversion of an MSW-derived feedstock into a liquid hydrocarbon, similar to crude oil, has been assessed via the gasification and Fischer-Tropsch (FT) pathway. Figure 18 shows the steps considered in the evaluation of the environmental impacts for the whole process.

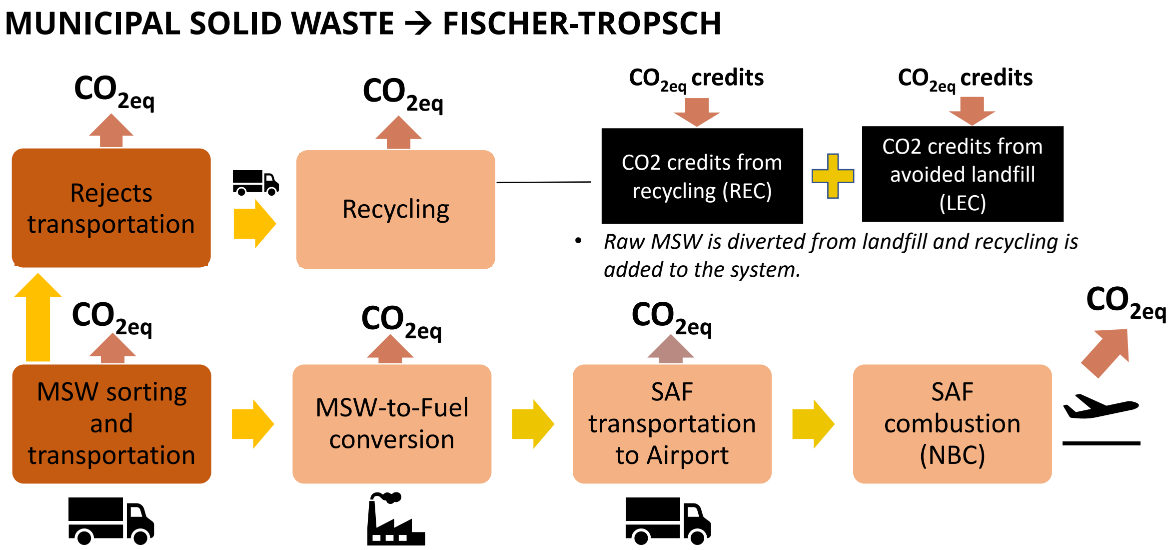

Figure 18. Lifecycle system boundary for municipal solid waste-based SAF using Fischer-Tropsch technology.

Unsorted MSW is supposed to be diverted from landfill, therefore no upstream emissions are considered. Moreover, as covered in supplementary materials to the CORSIA implementation elements, credits for avoided emission from landfill (LEC) and additional material recovery (REC) are calculated.

The LCA GHG emissions for SAF produced from FT technology using MSW resulted in a negative value of –163g CO_2e/MJ, which would comply with both RSB and CORSIA threshold GHG savings. The negative result of the process is associated to the carbon credits from MSW materials diverted from landfill and recycling process.

However, it is important to note that during the pilot phase of CORSIA, and until additional requirements and guidance have been developed to (a) ensure that emission credits for SAF generated under CORSIA are of an equivalent quality and quantity to emission units, and (b) resolve concerns regarding double counting, after the subtraction of the LEC and/or REC applicable to a SAF, the total LCA GHG emissions value cannot be smaller than 0g CO_2e/MJ (as per current approach defined by CORSIA that total LCA GHG emissions value cannot be negative). The majority of the LCA GHG emissions are related to processing and the fuel use, but these emissions are offset when taking into account the credits from LEC and REC.

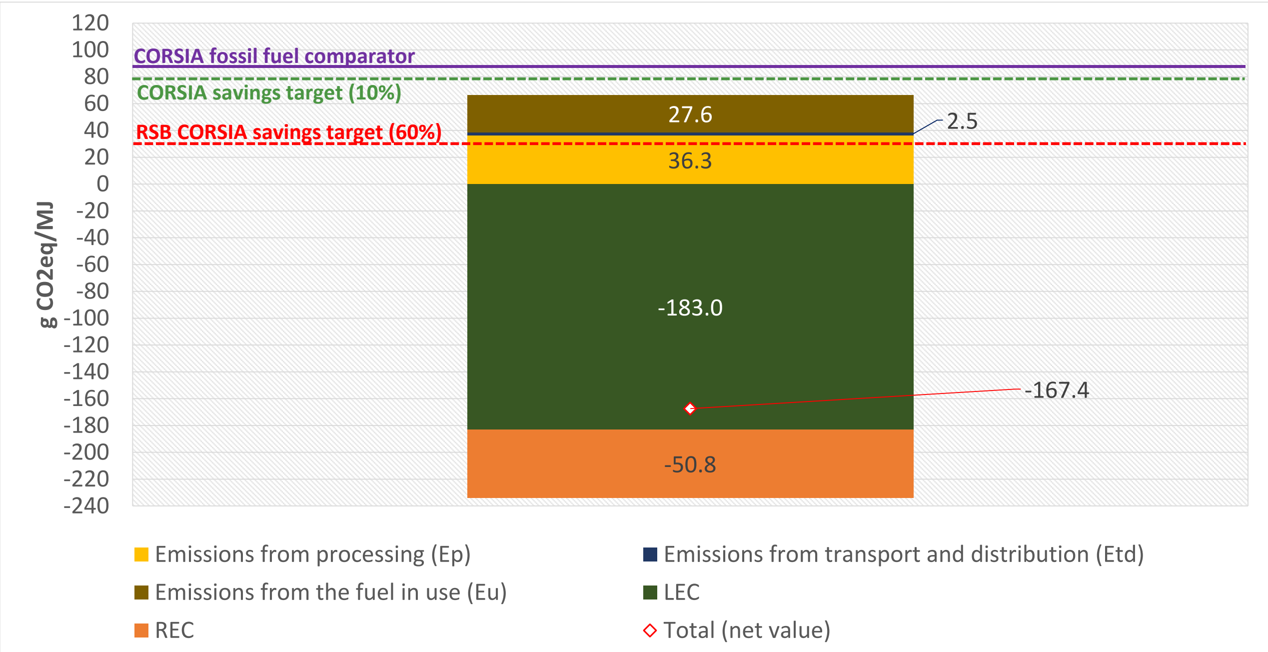

Figure 19. Breakdown lifecycle GHG emissions for FT-based SAF derived from municipal solid waste.

Furthermore, a sensitivity assessment was conducted to identify to which extent some parameters affect the LCA GHG emissions result. It was identified that credits from LEC, which is associated with the MSW composition, can play an important role in the result. MSW with a higher non-biogenic carbon content will result in higher GHG emissions, but in the evaluated scenario the results would still be below zero (Figure 20).

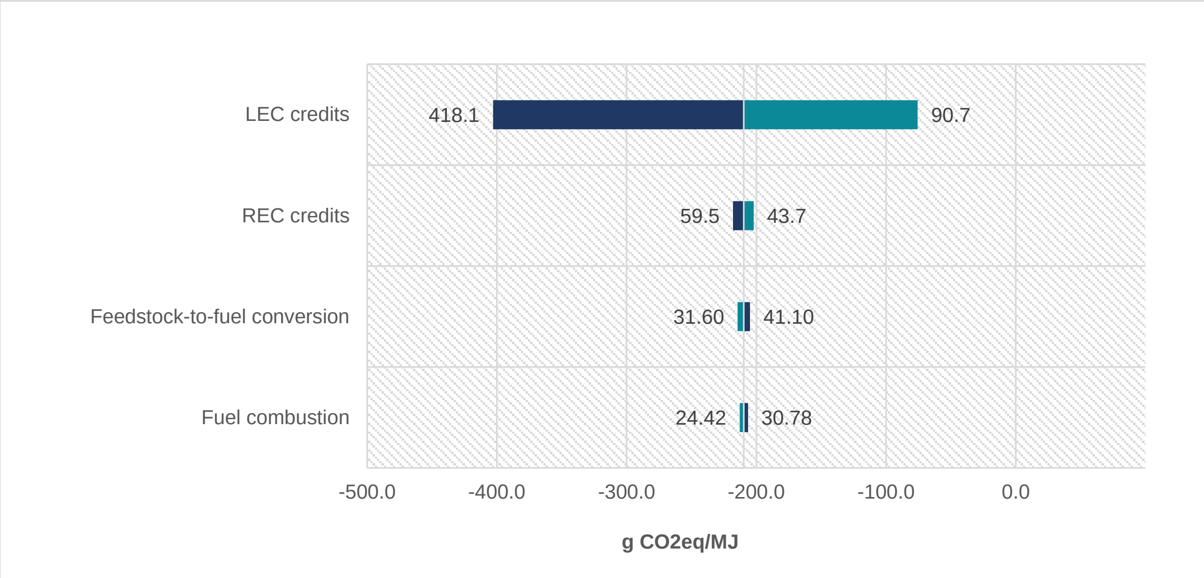

Figure 20. Sensitivity analysis for FT-based SAF derived from municipal solid waste.

6.2.4.3 *SAF transport impact for FT pathways*

The transport stage on the FT pathways was evaluated considering different diesel consumption for the steps of 1) residue collection, 2) waste transport, and 3) transport of SAF from the industry to the airport.

Transport of forest residues at different distances can impact the baseline result (i.e., 5.1g CO_2e/MJ) with a range of 3.4 to 7.2g CO_2e/MJ. SAF transport, which was modelled to range from short-distance (baseline scenario; 300 km using truck) to long-distance (3000 km, using train), can lead to a 40% increase in the LCA GHG emissions result (Figure 21). In the worst-case scenario, with higher diesel consumption for residue collection and transport and a long-distance scenario for SAF logistics, the result can reach up to 9.4g CO_2e/MJ.

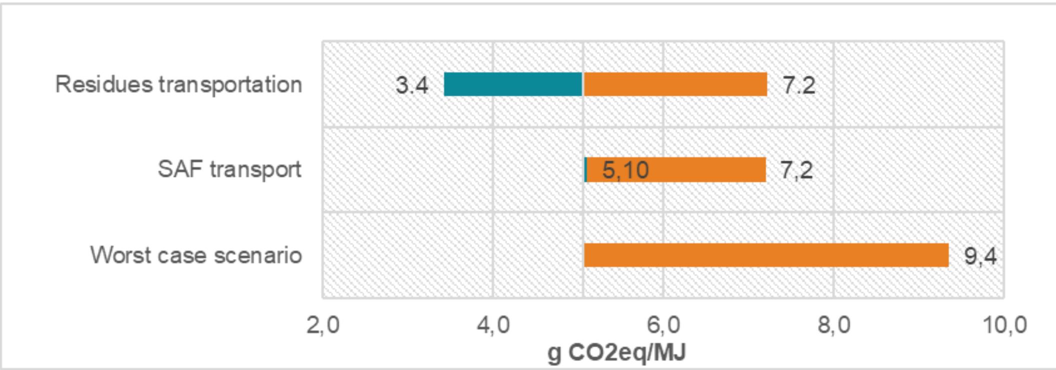

Figure 21. Sensitivity analysis of transport stages for FT-based SAF derived from forest residue.

As for MSW-derived SAF, RSB evaluated the impact of collecting and transporting MSW and SAF without considering the LEC and REC benefits. The impact of these credits, in the scenario evaluated here, always leads to very negative final values that prevent capturing the sensitivity of transport-related parameters. The baseline result without LEC and REC is 32g CO_2e/MJ.

Since transporting MSW from one country to another one entails legal restrictions, we assumed that MSW would be collected in the US, processed in the US, and SAF would be transported from the US to Europe (and then up to the airport). Despite the long distance to transport SAF, the most critical aspect in terms of logistics is the MSW collection, which can add 2g CO_2e/MJ (Figure 22).

This impact, however, does not play an important role in the overall LCA result. For example, the non-biogenic content of MSW affects not only the LEC but also the GHG emissions associated with fuel combustion, where this parameter has a higher impact on the result. Up to these results (Figure 22), however, a credit of 234g CO_2e/MJ can be discounted when LEC and REC are considered, leading to a negative total LCA GHG emissions value.

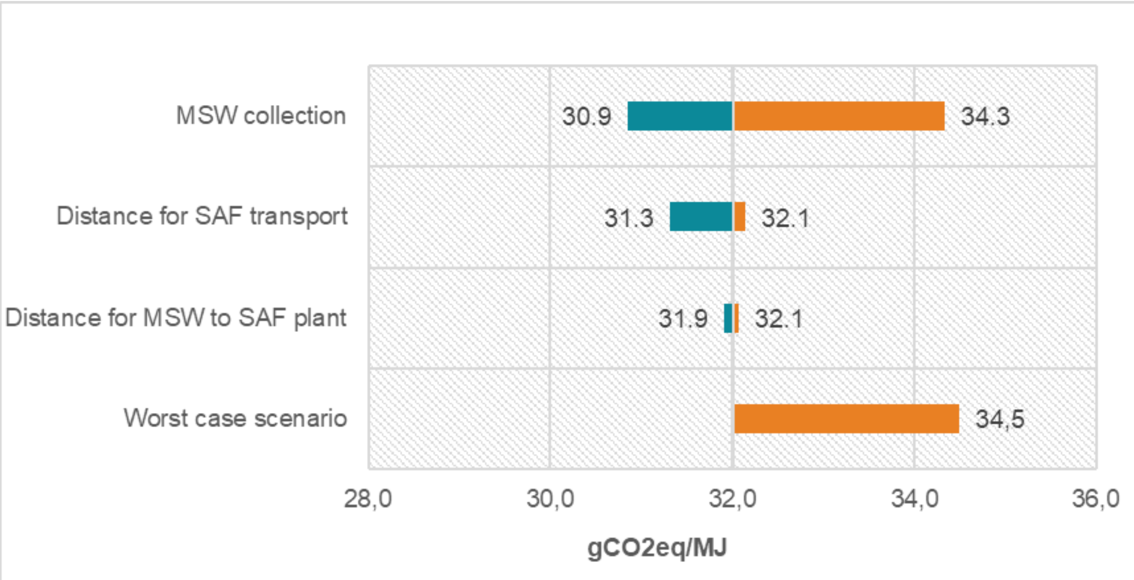

Figure 22. Sensitivity analysis of transport stages for FT-based SAF derived from municipal solid waste.

SECTION 2: LOCAL AIR QUALITY

7 Aviation and local air pollution at the lighthouse airport

Like many other airports, CPH has been working with air quality management for several years. Focusing on the airport's possible impact on workforce and the neighboring communities, CPH has monitored the air quality at the airport fence since 2000. The monitoring program has been focusing on particles ($PM_{2.5}$), NO and NO_2. Results have always been well below regulatory limit values.

Based on the air quality monitoring program, CPH was doing quite well in terms of air quality. However, after a study of polycyclic aromatic hydrocarbons (PAH) at the Airports in Rome (Carvallo, et al., 2006), the air quality in terms of working environment gained more focus among staff as well as management in both partners and airport companies.

With the aim of taking a fact-based approach to this challenge, a thorough survey of air pollution was conducted from 2009 to 2011 by the Danish Centre for Environment and Energy, Aarhus University (DCE). The findings were published in the scientific report titled: Assessment of the air quality on the apron of Copenhagen Airport Kastrup in relation to working environment (Ellermann, et al., 2012).

The aim of the survey was to improve the working environment of airport staff by mapping air pollution at the apron – consisting of nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$), polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), particulate organic and elemental carbon, determine its sources and measure the air pollution levels to which staff is regularly exposed.

The main conclusion of the study was that for all but one air pollutants analyzed, the concentrations at the apron were below the comparable levels measured at H.C. Andersens Boulevard (HCAB), one of the busiest streets in Copenhagen (approximately 60,000 vehicles per day). Also, all measured pollutants were below air quality limits, where such exist.

Measurements on particulate matter where the exception to these findings. The levels measured at the apron showed that the particle number (6 – 700 nm) was about two to three times higher at the apron than at HCAB and 85-90% of the particle number consisted of particles with a diameter between 6 and 40 nm. This particle fraction accounted for the difference between the particle number at the apron and HCAB.

The ultrafine particles (particles with a diameter less than 100 nm) originated from the combustion of conventional jet fuel and diesel at the apron. At the outskirts of the airport, the particle number was about 20 – 40 % lower than at HCAB. It is important to note that there is no air quality limit value for particle number in ambient air.

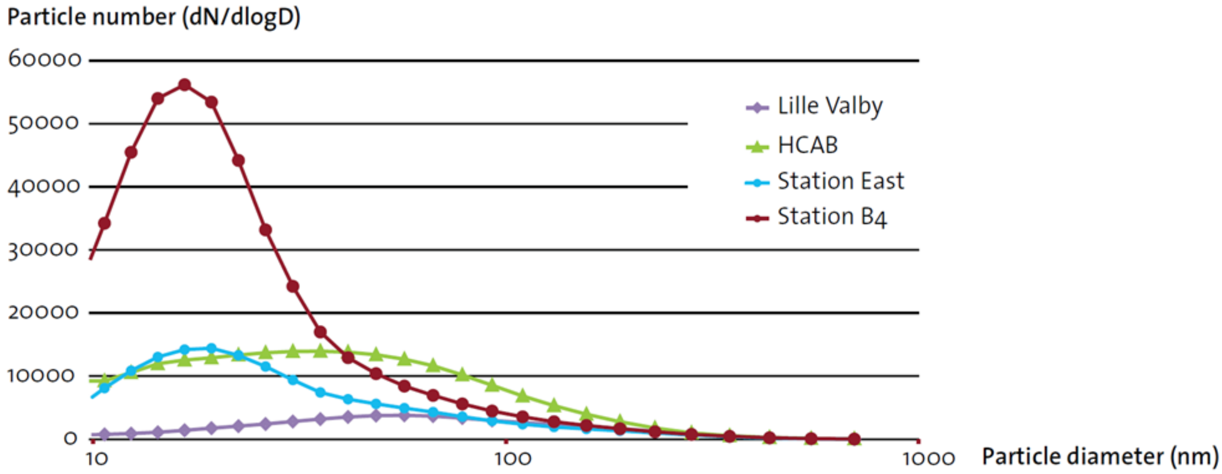

Figure 22. DCE study on particle count. Particle count on y-axis and size on the x-axis at 4 different locations: Copenhagen Airport, Station East, Station B4, HCAB and Lille Valby (Rural area) (Ellermann, et al., 2012)

As a result of this study, CPH has voluntarily established continuous monitoring stations for ultrafine particles at two locations: at the central apron (B4) and at the western boundary close to residential areas (see fig.21 and fig.22). Measurements started in August 2010 and are conducted 24/7 on an ongoing basis. Since 2019, CPH also supplemented these with measurements for black carbon (BC), since it is regarded as a potential carcinogenic substance from combustion sources. Altogether, CPH has been continuously measuring air quality for more than 12 years and it will continue measurements in order to collect data for documenting the effects of various remediation initiatives.

For particle count, CPH is using a CPC for the stationary monitoring stations and furthermore using 2 types of handheld equipment, the TSI P-Trak and DiSCmini from Testo. The latter has more or less taken over from the P-trak when it comes to ad hoc measurements with handheld devices – used for ad hoc measurements to detect various air pollution sources.

The DCE study highlighted that the most prevalent air pollutant at the apron area were ultrafine particles and, on this basis, CPH established the Copenhagen Airports Air Quality Program. The program is organized across the airport companies with personnel on the apron, with the common goal of minimizing the exposure of air pollutants, especially Ultrafine particles, to employees.

The Copenhagen Airport Air Quality Program is managed by CPH, but the strength of the program lies in the cross organizational setup and the fact that representatives in the program include both employees and management, also from handling companies, union representatives, main carriers, ANSPs and authority representatives. The work is voluntary, based on collaboration and an open dialogue between the partners, where the success of the program is highly dependent on this partnership.

At first, the program centered on mitigation of local air pollution but with increasing climate awareness over the years, there is greater societal demand and a drive within the aviation industry to make the sector more sustainable. This had led CPH to ambitious climate goals and to the engagement in numerous initiatives to address the impact of aviation and airport core operations to make them more sustainable.

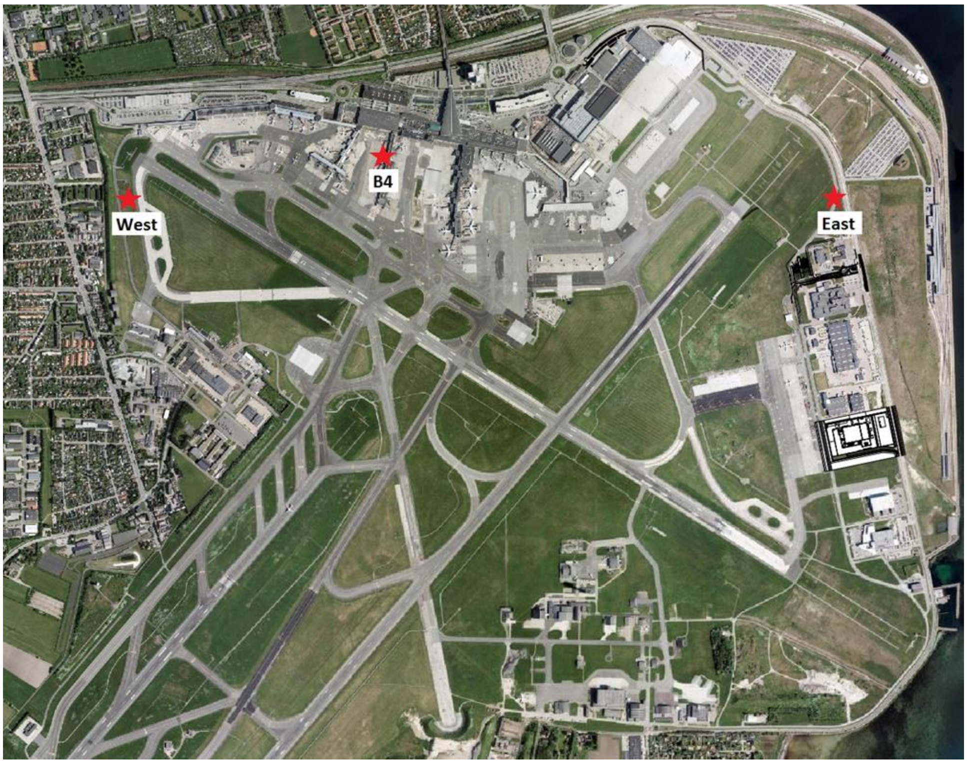

Figure 23. Copenhagen Airport and the locations of the airport's air quality monitoring stations (red stars): Station West (NO, NO_2, $PM_{2.5}$, BC and UFP), Station East (NO, NO_2, $PM_{2.5}$) and the apron station, Station B4 (NO, NO_2, BC and UFP) (Ellermann, et al., 2012).

7.1 SAF benefits on local air quality

Airports are at the intersection among a wide range of aviation and non-aviation stakeholders, hence, to tackle the sustainability challenges faced by the industry calls for partnerships – and new type of collaboration models. The ALIGHT project is an example of the latter, where all stakeholders involved acknowledge the anticipated benefits of using SAF for local air quality and climate change.

As part of the activities within WP3, the ALIGHT project aims at reducing harmful emissions and improve local air quality where the CPH monitoring stations and the measurements collected since 2010 will help to benchmark "normal" airport operations, particularly since the pre-COVID19 dataset is very comprehensive. The benchmarking of airport operations using historical data will be used to define the baseline against which new measurements using SAF at CPH will be compared and reported separately in a dedicated deliverable under WP3.

This exercise anticipates improvements in local air quality at CPH, and it will be conducted using the existing setup for monitoring airport air quality plus additional mobile measurement equipment as per DLR's data requirements.

The progressive uptake of SAF, together with enhancements in ground traffic are expected to reduce the amount of air pollutants affecting both the airport workforce and of surrounding communities. These include significant health improvements due to reduced exposure to $PM_{2.5}$, ultrafine particles (UFP), BC and ground-level ozone (O_3) from aviation emissions, linked to approximately 16 000 premature deaths from lung cancer and cardiopulmonary disease every year in Europe (European Commission, 2015), whose main source at the airport level is the operation of aircraft.

Jet engines mainly emit particles in the range below 100 nm. These particles are not regulated in environmental monitoring and are not a strong contributor to PM10 values due to their low mass. However, they are relevant to human health because they can penetrate the deep areas of the lungs; thus exposure to these particles should be lowered at a technically achievable minimum.

For this reason, dwellings in the vicinity of airports are particularly vulnerable to changes in local air quality. Several monitoring studies have been performed or are ongoing (e.g., in Frankfurt, Munich, Zurich and soon also at Copenhagen) to address this issue. Some of these studies have found that particles from jet engines may be transported over significant distances due to their small size and high mobility. It must be noted, though, that the particles in the aircraft plume undergo changes in size distribution and chemistry (e.g., due to the evaporation of particles and interaction of particles with humidity and other pollutants).

7.2 Regulations and standards

Although there is no specific EU legislation in relation to aviation emissions, the general EU regulation establishing limit values for the air pollutants analyzed in this section is Directive 2008/50/EC on Ambient Air Quality and Cleaner Air for Europe, applicable at and around airports as they do everywhere else in the EU.

Air quality standards for the EU were revised in September 2021 and proposed dividing by 2 the annual guide values for fine particles and by four for nitrogen dioxide (NO_2), to align with the recommendations of the World Health Organization (WHO). The proposed revision to the Ambient Air Quality Directive will set interim 2030 EU air quality standards to support the EU efforts to achieve zero pollution for air by 2050 at the latest.

The proposed annual limit would be set as follows:

- from 25 µg/m3 to 10 µg/m3 for $PM_{2.5}$
- from 40 µg/m3 to 20 µg/m3 for PM_{10} and NO_2

SECTION 3: CONTRAILS AND OTHER NON-CO_2 BENEFITS

In addition to the direct CO_2 emissions, aviation affects the climate through other emissions and atmospheric processes, summarized as non-CO_2 effects. Recent research indicates that these effects are responsible for about two third of the total climate impact of aviation (Lee, et al., 2021). It is important to point out that despite relatively low emissions compared to other sources, aviation's non-CO_2 emissions in comparably clean parts of the atmosphere can have a disproportionally large impact (EASA, 2020).

Aviation's non-CO_2 emissions of importance to climate include water vapor (H_2O), sulphur dioxide (SO_2), soot particles (PM) and oxides of nitrogen (NO_x). Emission of water vapor directly stems from the combustion of jet fuel in the jet engines. Emitted water vapor condensates in clouds and is removed from the atmosphere through rainfall. The lifetime of water vapor emissions depends on emission location and is between some hours at the surface and some weeks in the upper atmosphere.

Emissions of sulphur dioxide are the result of the combustion of jet fuels whose composition includes hydrocarbons containing sulphur. The fuel sulphur content has a strict regulatory limit and hence the global emissions of sulphur from aviation are estimated to be small compared to surface anthropogenic sources. Soot particles are largely the result of incomplete combustion of fuel. The general term *soot* refers to combustion particles that exist in the engine plume and may undergo further chemical and physical processes (EASA, 2020).

From a technological point of view, soot emissions depend on the power setting of the engine as well as the engine technology. From a general point of view, especially the number of emitted soot particles shows a significant dependency on the aromatic content of the fuel, since aromatics are a major precursor of soot formation.

Emissions of nitric oxide are formed in the engine combustor as a natural byproduct of technical combustion. The formation rate is determined by the temperature of the flame and the system pressure and thus depends on the engine and combustor technology.

8 Contrails and their climate impact

The most notable atmospheric effect resulting from these non-CO_2 emissions is the formation of contrail cirrus. Contrail cirrus is an artificial cirrus-like cloud produced in the upper atmosphere (approximately 10 to 12 km above ground) because of aircraft emissions of water vapor and soot particles into very cold atmospheres that are supersaturated with respect to ice (EASA, 2020).

Local conditions of the atmosphere dictate whether linear contrails form behind the aircraft and persist to produce larger-scale spreading of the linear contrails into contrail cirrus. The lifetime of contrails and contrail cirrus is between minutes for non-persisting contrails up to several hours for long persisting contrail cirrus (Dahlmann, Grewe, & Niklab, 2020). As contrails reflect solar short-wave radiation and trap outgoing long-wave radiation their overall radiative impact of is mainly dependent on their coverage and optical depth.

8.1 Contrail formation and opportunities for SAF

During the EU JETSCREEN project, the effect of different conventional and alternative jet fuels on soot emissions was measured in a detailed experimental measurement campaign and correlations for different SAF blend rates were derived (Christie, et al., 2020). Various combustor configurations were tested under laboratory conditions, going from academic ones (for better understanding) to more representative ones (e.g. APU).

Figure 23 shows results from the APU measurement demonstrating a clear decrease in the number of emitted soot particles with increasing hydrogen content of the fuel. Since SAF and SAF blends have a higher hydrogen content than conventional fuels, this resembles a reduction in soot through the use of SAF and SAF blends.

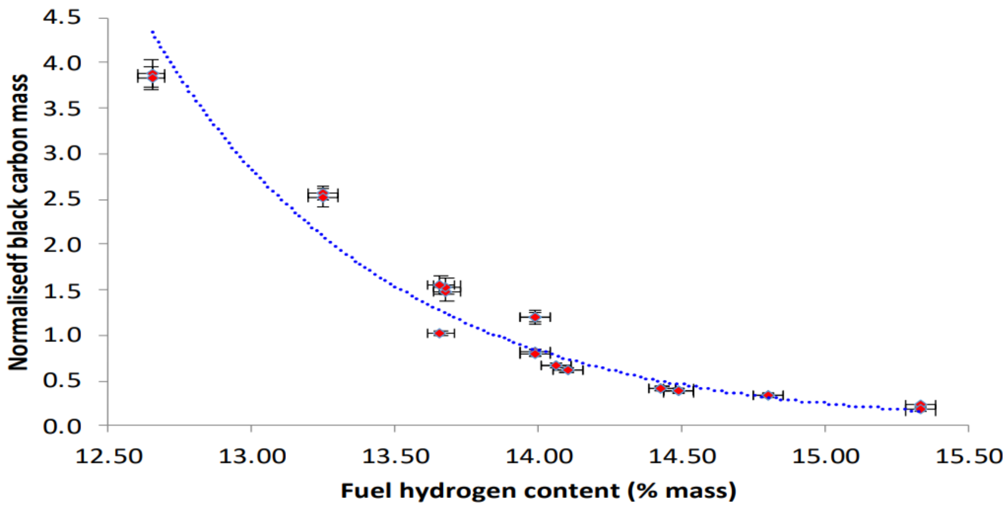

Figure 24. Normalized black carbon mass emissions for the JETSCREEN and ECLIF fuels (Christie et al., 2020)

Measurements behind aircraft (Bräuer, et al., 2021) (Voigt, et al., 2021) verify that the combustion of a SAF blend induces a decrease in the mass and number of emitted soot particles. This results in a lower number of nucleated ice crystals and in a higher survival rate of ice crystals during the contrails' vortex phase. The change in the ice crystal number after the vortex phase has an impact on the evolution of contrail cirrus. This leads eventually to a decrease in the mean optical depth and lifetime of contrail cirrus.

Hence, a direct option for mitigating the contrail formation from aviation is reducing aviation's soot emissions by using SAF. Figure 24 shows exemplary results from the DLR-NASA aircraft campaigns that measured exhaust and contrail characteristics of an Airbus A320 burning either standard jet fuels (reference value) or low aromatic SAF blends (alternative fuels). Clearly, the soot particle number is reduced when using SAF.

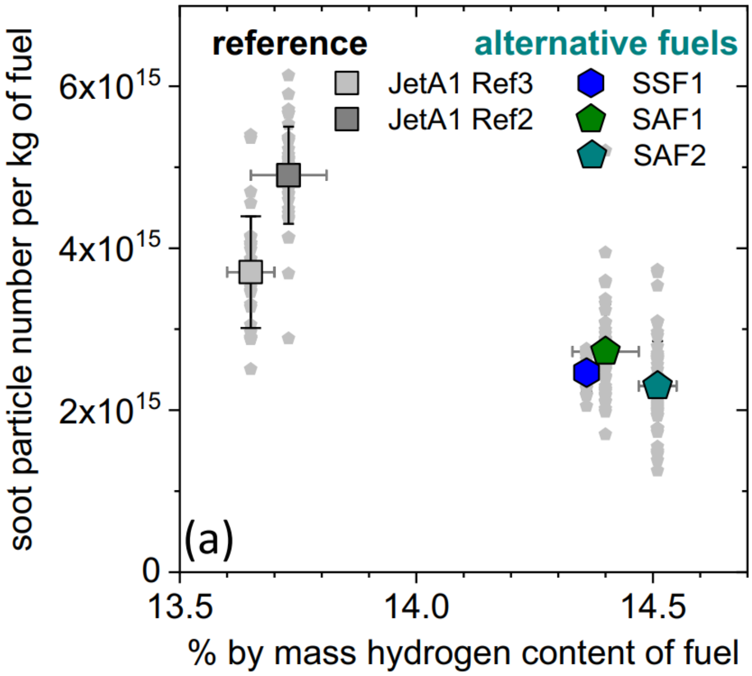

Figure 25. Soot particle emissions at cruise conditions for a conventional Jet A-1 fuel and low-aromatic SAF blends

SECTION 4: FUEL EFFICIENCY

9 SAF properties and fuel efficiency

Current crude oil-based fuels as well as sustainable aviation fuels have different chemical characteristics that lead to non-negligible variation of the performance and emissions emitted on flight missions. The most notable characteristic is the chemical composition, since jet fuels are always a mixture of different hydrocarbons, i.e., groups of molecules composed of hydrogen and carbon. These groups include normal-alkanes, iso-alkanes, cycloalkanes, and aromatics. A comparison of the chemical composition of a conventional and a fully synthetic fuel is given in figure 25.

While conventional fuel consists of a wide range of hydrocarbon groups, synthetic fuel differs drastically, with a composition dominated by a distinct number of a few molecular groups. As a result of the varying composition, physical properties of the fuels vary within a given specification range. These physical properties, like density or surface tension, are relevant for different aspects of a flight mission, for example fuel consumption or emissions.

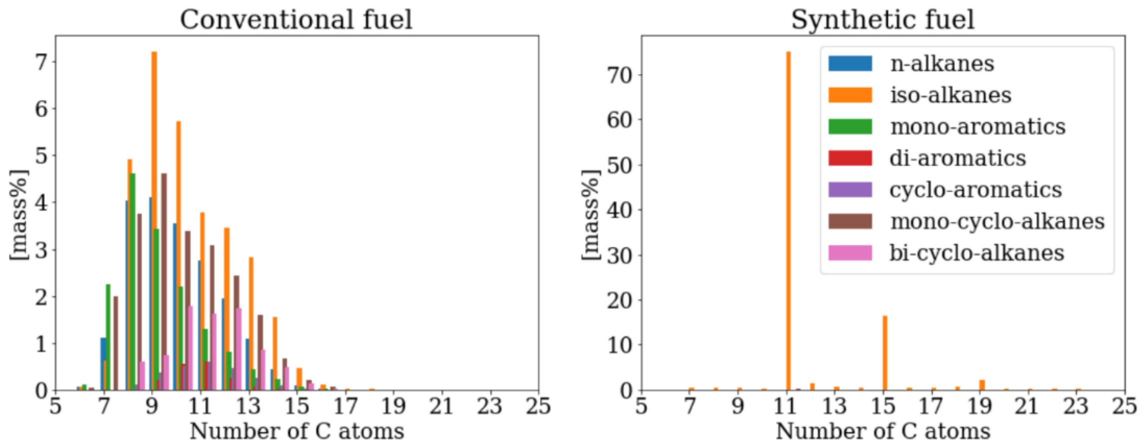

Figure 26. Comparison of the chemical composition of conventional and synthetic fuel.

The utilitarian performance of a fuel – what an airline is likely willing to pay more for – can be derived from at least the specific energy and density of a fuel (U.S. DOE, 2020). Specific energy and density improvements have the potential to be used by an airline immediately. All flights benefit from increases in specific energy, as the flight can achieve the mission at a lower total weight and hence reduced fuel burn. On payload-limited flights or flights that are limited in range by a maximum weight, high specific energy might enable carrying an additional payload and thus become more profitable (U.S. DOE, 2020).

Because sustainable aviation fuels have very low or zero aromatics and a higher n-alkane content, they have a potentially higher energy density than conventional, crude oil-based jet fuels. To illustrate this, figure 26 shows the density and the net heat of combustion for fuels from the DLR fuel database. Three main categories are visible: Conventional crude oil-based Jet A-1 from a worldwide data acquisition (black dots, where each dot is an individual fuel), neat SAFs (green dots) and approved blends of SAF and Jet A-1 with blend ratios up to 50% (orange dots). The crude oil-based fuels already demonstrate a significant variation in both density and heat of combustion, highlighting that there are differences in the performance of conventional jet fuels, although they are all denoted and certified as Jet A-1.

All shown neat SAFs have a considerably higher net heat of combustion and thus energy content than the conventional fuels, reducing the required fuel mass for the same flight mission. However, it must be pointed out that these fuels are currently not approved for 100% utilization but must be blended with conventional fuels to comply with ASTM D 1655. For this reason, approved blends are included in the figure. As a result of the blending their performance with respect to energy density ranges between the neat SAFs and the conventional fuels.

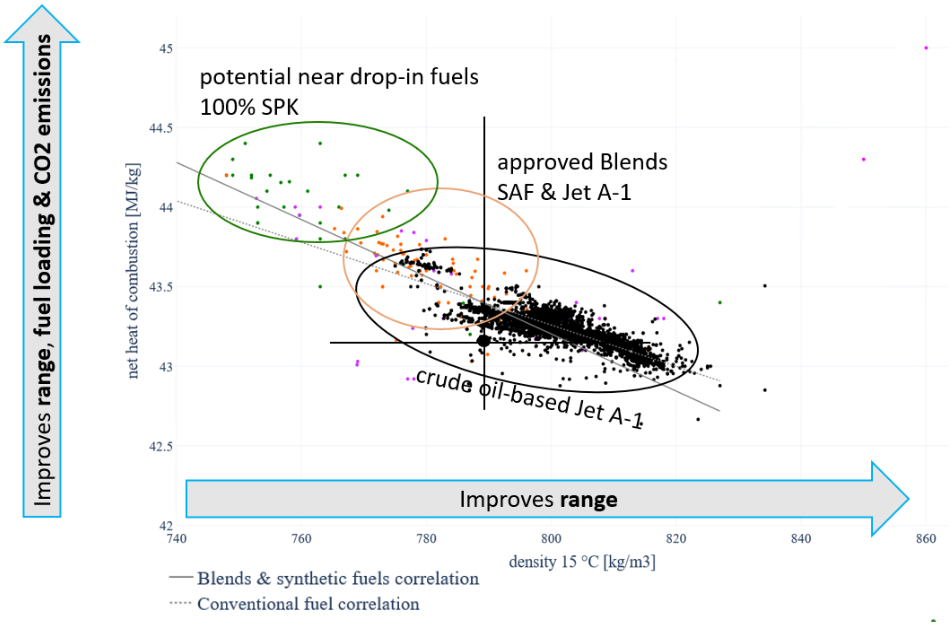

Figure 27. Net heat of combustion over density for a wide range of conventional jet fuels (black), SAF blends (orange) and neat SAFs (green)

9.1 Example and best practices

The added value of SAF regarding fuel efficiency for real flight missions was demonstrated during the BurnFAIR research project. Within the project, one engine of a Lufthansa A321 was fueled with 50% SAF blend for half a year during normal airline operation. 1187 flights were successfully completed, burning approximately 1160 metric tons of SAF blend. The fact that one engine was supplied with SAF blend while the other was supplied with conventional Jet A-1 allowed for a direct comparison of the fuel consumption in the operational context.

On average, the required fuel flow rate on the engine using SAF was reduced by approximately one percent compared to the engine burning conventional fuel. This directly relates to the chemical analysis of the used SAF blends which showed that the mean specific energy of the SAF blends was roughly one percent higher than for the conventional Jet A-1.

SECTION 5: ACCELERATING SAF DEPLOYMENT

Presently, production capacity for SAF has not been deployed at the pace and scale needed to supply the volumes for achieving aviation's Net Zero target in 2050. In this section, the International Air Transport Association (IATA) provides an overview of the challenges for SAF deployment including the availability of sustainable and cost-effective feedstock, the variety and magnitude of costs associated with fuel development, scaling up of operations, qualification of novel conversion pathways for SAF, etc.

This exercise has the objective of highlighting the perceived risks and the financial constraints to accelerate SAF production, but also to give an overview of the mechanisms available for financing the energy transition of the air transport sector through dedicated policies and regulations.

10 Overview of the broader benefits of SAF

In the decades ahead, SAF will be key to the aviation industry's overall decarbonization progress. Depending on the location, applicable policies and regulations, and the available technologies and feedstocks, SAF production could offer many benefits in addition to the environmental and operational benefits analyzed in this report.

Some of these include creating employment opportunities, protecting the land, air and water by reducing the amount of waste in landfills and illegal dumps (WEF, 2020), increasing soil organic carbon through the use of selected crops with the potential to yield food, feed and fuel, enhancing local energy security, and providing a steady new source of income for the agricultural and forestry sectors, etcetera.

In Europe, regional and multilateral development and investment banks can play a proactive role in developing a SAF industry by helping to finance production for commercially ready feedstocks and technologies[4]. Of particular importance to the multilateral development banks are the opportunities for job creation within the renewable energy sector, that foster synergies with local, national and supranational climate mitigation and adaptation efforts (ATAG, 2020).

The investment in developing a SAF industry is anticipated to create and sustain approximately 13.7 million jobs across the global economy. Compared to other renewable energies, investments in bioenergy over the last decade have shown that for every $1 million invested 23 jobs are created, whereas only 2.7 jobs have been created per $1 million invested in solar power and 1.1 jobs in wind power, respectively (ICF, 2021).

SAF production has greater potential to create new jobs than other renewable energy industries due to the labor required to support the wider supply chains from well-to-tank[5]. SAF supply chains entail feedstock production, collection and distribution to production facilities; the

[4] For example, the European Central Bank requires banks to consider ESG risks in their risk models.
[5] Covering from feedstock production to the delivery of fuels for consumption.

conversion of feedstock to fuel, transport of intermediates to blending and storage facilities, and the transport of finished SAF for delivery to aircraft.

Still a nascent industry, SAF supply chains are immature, some may be regionally unique, and will require significant resources and investment to establish. The aviation industry as well as governments worldwide have committed to the achievement of a carbon-neutral sector by 2050, where the engagement and support of the financial community in unlocking the annual capital requirements of $40-$50 billion per year in SAF plants and upstream energy infrastructure is essential.

Capital providers are particularly relevant for ramping up SAF development and uptake because the steering of financial flows to environmentally sustainable business activities, has a major impact on the projects and companies financed. At the same time, the production and use of SAF offers new green assets to these key players who are increasingly required to disclose the proportion of their sustainable investments and loans, where SAF could represent a future-proof business field.

To this end, the following chapters focus in identifying and analysing the financing challenges for SAF development and deployment, and to discuss a variety of mechanisms and policy options for mitigating and/or avoiding financial risk.

11 Risk and challenges for SAF deployment

Global SAF production is expected to reach between 240 and 380 thousand tonnes by the end of 2022, equivalent to 0.1% of total jet fuel demand at 254 million tonnes. Meeting the mid-century decarbonization aviation targets require ramping up production to approximately 450 million tonnes of SAF per year using all the feedstock and conversion pathways available then. In the EU and the UK, the total mandated demand for SAF based on proposed regulations is projected to be 40 million tonnes in 2050.

Several countries that have adopted or proposed SAF policies to support the decarbonization efforts of the air transport sector, have set intermediate targets leading up to 2050 to be fulfilled based on obligations (i.e. mandates), incentives (i.e. tax credits), market-based measures (i.e. carbon markets) or a combination thereof. However, broadening the availability and cost-effective production of SAF to achieve targeted volumes ought to address the following limitations:

1. Availability of sustainable, cost-effective feedstock for SAF
2. Higher cost of production for SAF than for conventional aviation fuel
3. High procurement cost of SAF for airlines
4. Lack of infrastructure for feedstock processing, fuel conversion and SAF supply.

Considering these limitations, Strategy& has estimated HEFA to peak production in Europe at 7 million tonnes per year from 2030, equivalent to 15% of projected conventional jet fuel demand. From 2040 onwards, European production of SAF from ATJ and FT pathways will peak at

14.5 million tonnes per year (approximately 30% of yearly jet fuel demand), with increasing contributions from PtL SAF starting at 1 million tonnes per year from 2030 up to 12.7 million tonnes in 2050 (Strategy&, 2022).

Whereas the figures from Strategy& for ATJ and FT are more optimistic than those modeled by EASA in relation to the targets in the ReFuelEU proposal[6] – amounting to 8 million tonnes per year by 2050, the figures projected for PtL converge at 12.7 million tonnes. It should be noted that forecasts from EASA and Strategy& are much lower than those modeled by ATAG on its Waypoint 2050 analysis for Europe, that anticipate 31.3 million tonnes per year from ATJ and FT, and 26.3 million tonnes per year from PtL (ATAG, 2020).

11.1 Availability of sustainable and cost-effective feedstock

As of November 2022, 46 million tonnes of renewable fuel capacity[7] spanning 30 countries have been publicly announced (Figure 27), with a theoretical maximum fraction of 31 million tonnes of SAF output by 2027[8]. In its Waypoint 2050 analysis, the Air Transport Action Group (ATAG) identified 24 million tonnes of SAF output by 2030 – equivalent to 6.5% of global jet fuel volume, as the point of reference for production ramp up.

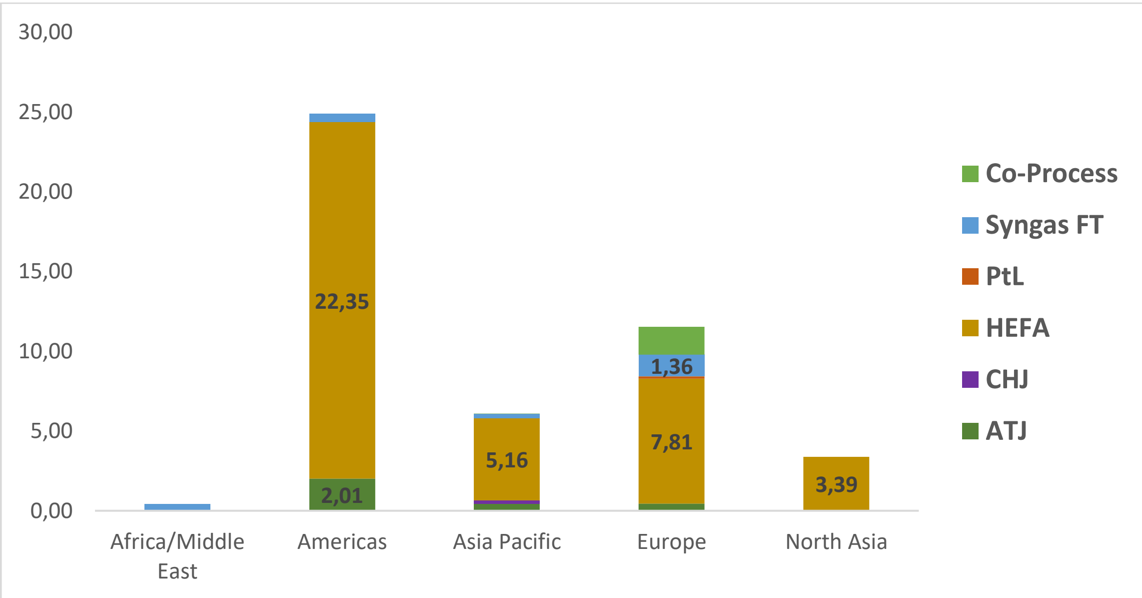

Figure 28. Expected renewable fuel capacity in 2027 in million tonnes (IATA Env., January 2023)

The primary source of SAF volumes leading up to 2030 will be lipid-based (i.e. fats, oils and greases), but meeting the climate targets of the aviation sector in 2050 requires a variety of feedstocks that are not commercially available today. Therefore, ensuring feedstock of

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[6] Current landscape and future of SAF industry | EASA Eco (europa.eu)
[7] Renewable fuel capacity refers to a biorefinery's total output. This output, called product slate, consists of yields of products such as renewable diesel, naphtha, neat SAF, etc. in varying proportions.
[8] Projects typically have a 3 to 5 year lag effect from announcement to commercialization.

sufficient quality and quantity, demonstrating their performance and commercial viability, validating process economics, and quantifying GHG reductions are all essential activities for mitigating the financial risk of new SAF developments.

In the U.S., the Commercial Aviation Alternative Fuels Initiative (CAAFI), the U.S. Department of Agriculture (USDA) and the Federal Aviation Administration (FAA) developed an assessment tool for the production, market and policy maturity of feedstocks for SAF production, called the Feedstock Readiness Level (FSRL).

Whether on its own or in conjunction with other tools for evaluating a fuel's readiness level (FRL) or measure environmental progress, the FSRL facilitates producers to benchmark the maturity and commercial readiness of a variety of second and third-generation feedstocks (see figure 28) for SAF, to pinpoint opportunities for cost-effective near production as well as to identify gaps where further research, development and/or investment is needed.

In addition to the FSRL, there are a variety of activities promoted by CAAFI to mitigate the financial risk of feedstock production, to create new opportunities and co-benefits for farmers and feedstock producers, and to accelerate their commercial availability for producing SAF. These include dedicated crop insurance programs, integration of cover and of novel crops into current rotations, research and development programs and projects for creating synergies between feedstock production and environmental protection (i.e. increase in the soil organic carbon through dedicated crops), among others.

The integrated approach to feedstock production and commercialization in the U.S. could be adopted at the EU level, to facilitate the cost-effective availability of feedstock for SAF production in European countries, as well as for informing domestic SAF policies and regulations for GHG reduction target-setting. On the latter, the emission reduction potential of SAF pathways is particularly relevant for financing SAF developments since the cost of abating carbon emissions provides an indicator of the real value of the fuel produced.

For example, the blenders and producers tax credits recently launched under the U.S. Inflation Reduction Act of 2022, require SAF to achieve at least 50% reduction in GHG emissions on a life cycle basis compared with conventional jet fuel. These tax credits – that start at $1.25 per gallon of neat SAF – increase with every percentage point of improvement in the fuel's life cycle emissions performance up to $1.75 per gallon (U.S. DOE, 2022).

Although the carbon reduction potential of SAF depends on a variety of factors, the type of feedstock used significantly apportions to the overall benefits from a particular feedstock and conversion pathway combination. Figure 28 schematically depicts the feedstock generations that can be used for bio-based fuels and intermediates, where they are compared using four criteria: emissions reduction potential, sustainability, cost, and the investment required to reach commercial readiness.

Most first-generation feedstocks, notably agricultural crops that are defined in Figure Y, are commercially available, typically utilize existing infrastructure and technologically mature processing and conversion processes, and can derive significant GHG reductions; however, they have been progressively phased-out as eligible feedstocks under international (i.e. ICAO CORSIA), domestic (i.e. SAF mandates in France) and regional (i.e. EU ETS) regulations as well as under voluntary sustainability schemes (i.e. RSB, ISCC) due to risk of competition with local food security and impacts on biodiversity[9].

With few exceptions (i.e. palm fatty acid distillate or PFAD), second-generation feedstocks typically meet robust sustainability requirements for SAF production, but their availability and quality are limited by the complexity of collection logistics, pre-treatment and for their competing uses in other markets (i.e. feed).

Feedstock Type	Emissions Reduction Potential	Sustainability	Cost	Investment for Commercial Readiness
1st Generation Feedstocks	Mid	Low	Mid	Low
2nd Generation Feedstocks	High	Mid	High	Low
3rd Generation Feedstocks	High	High	Low	High

Figure 29. Overview of feedstocks for bio-based renewable fuels (IATA Environment)

Feedstocks classified as 3rd generation (see figure 28), primarily comprise residual streams that can achieve carbon reductions of over 80% on a life cycle basis. However, residual streams also entail the greatest financial risk to investors because they are the least commercially ready of

[9] Eligible feedstocks within the first-generation category that demonstrate adherence to robust sustainability criteria can provide opportunities for rural development and diversification of farmers' income, while leading to investment in agricultural productivity and resilience.

all feedstock generations depicted above, and the technologies to collect, pre-treat and condition them for use in SAF production have not reached maturity.

To illustrate this, a report from NNFCC suggests that the utilization of residual streams (mostly of 3rd generation feedstocks) could create between 56,000 and 133,000 additional permanent jobs in the EU agricultural and forestry sectors, together with 4,000 to 13,000 permanent jobs in plant (i.e. biorefineries) operations, and 87,000 to 162,000 temporary jobs during the construction phase of feedstock processing and fuel conversion infrastructure.

According to these figures, this would provide a net value of up to €5.2 billion to the EU rural agricultural economy and up to €2.3 billion to the EU rural forestry economy, assuming equal access to these feedstock streams compared to other competing sectors (i.e. heat and power). In the European context, SAF production could leverage existing harvesting, transport and processing infrastructure, as well as the human capital thereof, of declining markets in the pulp and paper industry in Norway[10], Sweden and Finland.

In the U.S., ongoing research under the SAF Grand Challenge aims at quantifying the full economic benefits of feedstock production for SAF, that presently are accounted within the estimated revenues of up to $250 billion per year from their domestic bioeconomy (U.S. DOE, 2022).

11.2 The cost of producing SAF

11.2.1 **Fuel qualification**

Since 2009, the air transport sector has qualified SAF from a variety of feedstock and pathway combinations for use in civil aviation. Presently, there are 7 approved pathways for SAF production compiled as annexes to ASTM D7566 "Standard specification for aviation turbine fuel containing synthesized hydrocarbons". Currently, the industry is in the process of assessing and qualifying new pathways to increase the availability of SAF over the upcoming years.

Additional fuel qualifications can facilitate SAF deployment by reducing the cost of production with conversion processes that have lower capital and operating expenses, utilizing lower-cost feedstocks, conversion technologies with reduced carbon intensities and higher carbon utilization, as well as technologies that allow producing a wider range of hydrocarbons to potentially eliminate blending requirements, etc.

However, fuel qualification is a resource-intensive process that is often overlooked when assessing the economic and financial barriers for SAF deployment. In the U.S., fuel qualification for SAF is an iterative process that requires a candidate SAF developer to test fuel samples to measure properties, composition, performance and to periodically review those results with engine and aircraft manufacturers (OEMs).

[10] In Norway, the forestry section provides employment to approximately 4,000 people, the sawn-wood industries to 16,000 and the pulp and paper sector to 6,500 people (NNFCC, 2013).

This process is governed by ASTM D4054 "Standard practice for evaluation of new aviation turbine fuels and fuel additives", and it comprises 4 rigorous and comprehensive testing tiers that SAF candidates must undergo to be approved and incorporated to an existing annex as a new annex in ASTM D7566. Table 6 summarizes the cost and fuel volumes required per tier under ASTM D4054 guidelines:

Table 6. Cost of fuel qualification for neat SAF

Tier no.	Type of testing	Approximate cost (USD)	Fuel requirements (litres)
1	Basic specification properties	$5,000	Up to 45
2	Fit-for-purpose properties	$50,000	Up to 450
3	Engine/aircraft systems rig and component testing	Up to $1.5M	Between 1,130 to 68,200
4	Full-scale engine testing or aircraft flight testing	Up to $1M	Up to 909,220

Source: adapted from (Rumizen, 2021).

Additional to the testing costs summarized above, D4054 typically requires demo-scale production capability to supply the candidate fuel volumes needed to undergo the evaluation process. To reduce the barriers for producers of candidate SAF that fall within the compositional and performance range of conventional aviation fuel, D4054 introduced in 2020 a Fast Track process as an annex to the guidelines. The Fast Track imposes a 10% maximum blending limit with petroleum-based jet fuel as a trade-off with the reduced testing requirements.

The FAA also supports fuel testing efforts for civil aircraft through the ASTM D4054 Clearinghouse at the University of Dayton Research Institute. The Clearinghouse provides an entry point for SAF candidates to begin evaluation, where the Institute facilitates fuel testing and research report review, and it assists SAF producers throughout the D4054 process.

11.2.2 **Demonstration operations**

Presently, commercial volumes of SAF for civil aviation have only been produced using 2 of the 7 approved conversion pathways[11] under ASTM D7566, and by fewer than a dozen refineries/biorefineries worldwide.

This mismatch between the pursuit of SAF pathway qualification and actual SAF production has been driven by several factors, including changing priorities of the technology developer or producer since qualification, additional technical discovery or shifting market conditions that

[11] HEFA and ATJ.

lessen interest in the pathway, and/or a reflection of the difficulty (e.g., cost, effort, permitting, financing, acquiring offtake) to scale-up plant operations.

On the latter, deployment of SAF technologies – notably for first-of-kind, requires stepped scaling-up for avoiding process configuration changes at the commercial scale that could render an entire project uneconomical. By validating process performance metrics, progressive scaling up of SAF production – from pilot process to demonstration, can significantly mitigate financial risk while delivering a return on investment to companies and investors.

However, demonstration-scale operations of SAF pathways shall comprise the entire supply chain from feedstock collection through delivery of SAF blends to airports, thus typically requiring significant investment of private capital. This has created significant challenges for SAF demonstration projects to access debt financing for building out new capacity[12], despite the increasingly numerous offtake agreements signed off by airlines for at least a decade.

This challenge has been somewhat addressed through public funding for SAF innovation covering research and development activities up through technology scale-up and demonstration, that has been made available in North America and selected European countries through cooperative agreements and grant programs under EU Horizon 2020, Canada's The Sky's the Limit Challenge, UK Jet Zero Strategy, among others.

Additional funding sources include owner equity, venture capital, corporate investors, green funds, institutional investors, and various philanthropic investments, that can be complemented with public funds as those mentioned above, to help develop interest and confidence in supporting early, mid-stage, and long-term industry growth.

For example, the U.S. Department of Energy has funded several integrated biorefinery demonstrations and the Inflation Reduction Act (IRA) of 2022 established a grant program of $290 million over four years to carry out projects to produce, transport, blend, or store SAF, or develop, demonstrate, or apply low-emission aviation technologies under the Fueling Aviation's Sustainable Transition through Aviation Fuels (FAST-SAF) program and the Low-Emissions Aviation Technology (FAST-Tech) program.

11.2.3 **Commercial-scale production**

For full-scale production, commercial arrangements that provide more certainty around revenue can also increase the financeability of SAF undertakings. These include pooled offtake agreements that mitigate off-takers' credit risk, book-and-claim systems that allow corporate buyers to enter into long-term agreements with producers for the Scope 3 environmental attributes associated with SAF[13], or financial products that decrease the perceived risk associated

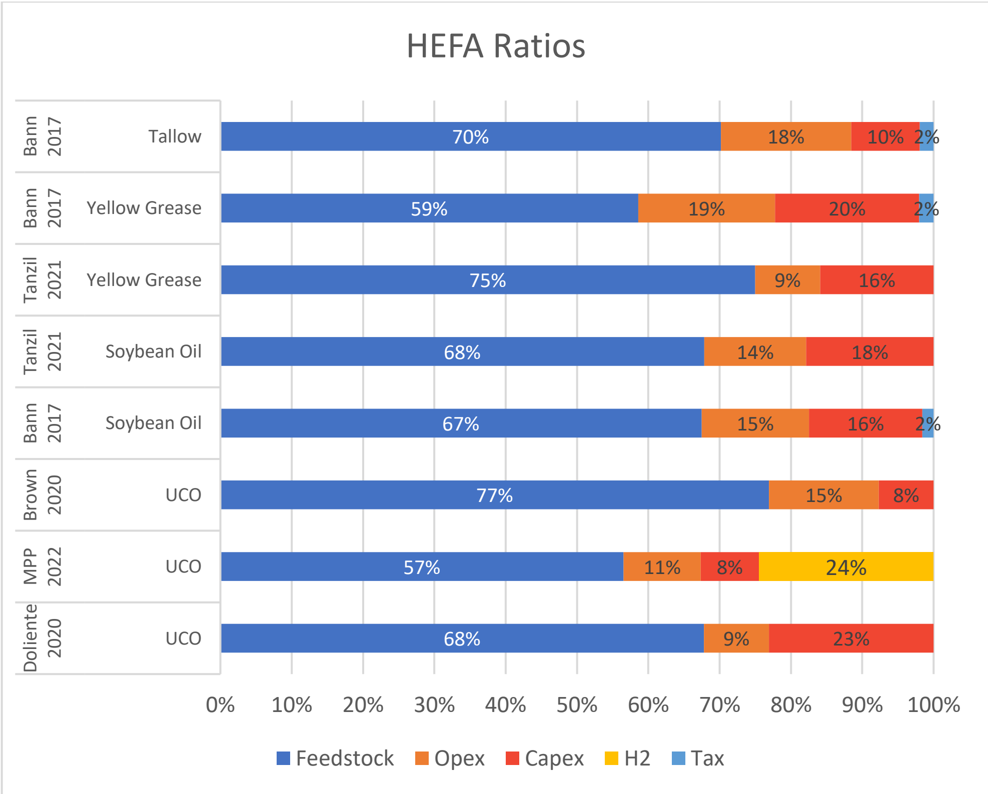
[12] SAF project development in the U.S. is largely equity-financed, thus entailing a high cost of capital when debt is involved that can strain project economics, and drive prices up for the end purchasers of SAF (U.S. DOE, 2022).

[13] Refer to the accounting and reporting deliverable within ALIGHT WP3 or separate reference material as appropriate.

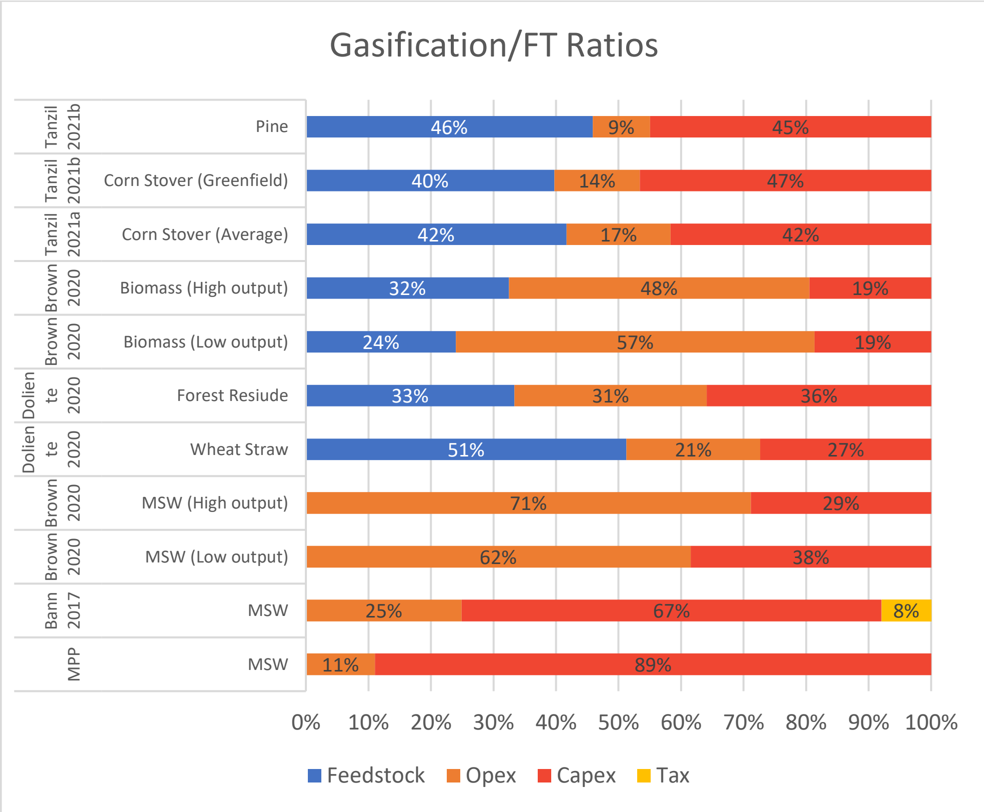
to market-based incentive schemes (e.g. California's Low Carbon Fuel Standard (LCFS) and EPA's Renewable Fuel Standard's renewable identification number credits in the U.S).

Production costs vary significantly between SAF conversion pathways, where market prices are forecast to remain higher than for conventional jet fuel in years to come. Out of the 7 approved conversion pathways[14] for producing SAF, lipid-based pathways (fats, oils, and greases) are anticipated to supply most SAF volumes worldwide to meet intermediate targets leading up to 2030, with a smaller contribution from waste, forest and agricultural residues, and alcohol pathways (U.S. DOE, 2022).

To illustrate the significant cost variations between SAF production pathways, a cost-breakdown analysis[15] was done for HEFA, FT and AJT, respectively (figure 29).



[14] As well as co-processed fuels certified under ASTM D1655.
[15] The methodology as well as the knowledge gaps for this analysis are detailed in appendix 15.2



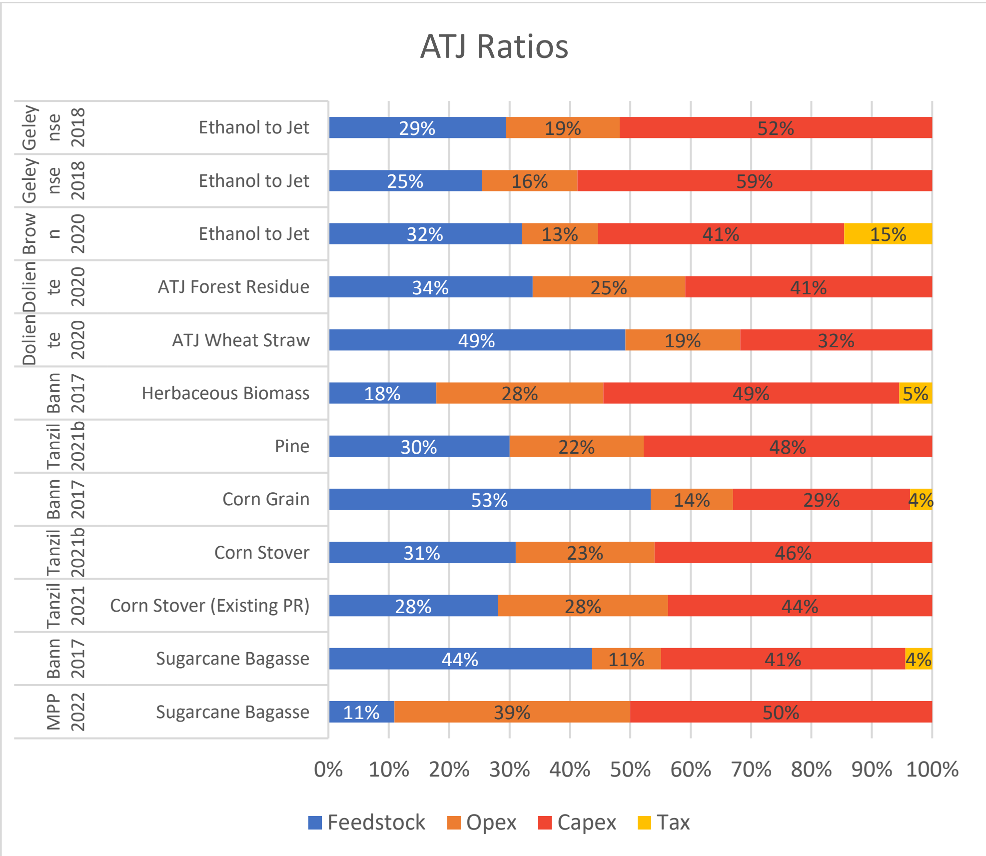


Figure 30. Cost breakdown ratios for HEFA, FT and ATJ SAF (IATA Environment, December 2022)

The amount of time required to properly de-risk and scale up existing and novel conversion technologies indicate that, in the short-term, fermentation processes will see incremental yields and sustainability improvements, new technologies will expand the feedstock pool for HEFA processing, and a growing oil and gas refining capacity will be utilized for the co-processing of intermediates. In this scenario, strong demand signals in the form of policies and regulations will be critical to reduce the overall production costs of these SAF pathways and co-processed fuels, and for enabling efficiencies of scale, technology maturation and supply chain optimization to achieving SAF competitiveness in the mid-term.

For emerging and less mature conversion pathways (i.e. first-of-kind) that are technically complex and cannot leverage existing capital investments, SAF production may develop in the form of hub-and-spoke models, consisting of segmented supply chains where feedstock processing, fuel conversion and fuel finishing take place in separate facilities (i.e. SAF from forestry residues) versus a vertically integrated biorefinery (i.e. SAF from sugar cane).

In a hub-and-spoke model, bio-intermediates are transferred between entities before finally being delivered to a blending and storage site or an airport as finished SAF. These bio-intermediates are typically stable and can easily be stored and transported, therefore facilitating the supply chain logistics. Examples of bio-intermediates include cellulosic sugars, alcohols from fermentation or synthesis, stabilized bio-oils from pyrolysis, or biocrude from hydrothermal liquefaction.

The utilization of bio-intermediates in existing capital assets can contribute to achieving larger SAF quantities by using them as drop-in substitutes for lipidic feedstocks in petroleum hydrotreaters, as most SAF conversion pathways require hydroprocessing or other fuel-finishing steps that traditionally entail high capital costs. Thus, leveraging existing petroleum-refining assets such as hydrotreaters, hydrocrackers, and alkylation units can significantly lessen the capital intensity and financial risk of investments, while creating synergies with industry partners for identifying insertion and blending points, and working with industry partners to determine critical material attributes of these bio- intermediates (i.e. oxygen, nitrogen and sulphur content).

11.3 The cost of procuring SAF for airlines

As for conventional fuel, SAF prices are constantly fluctuating and are affected by a variety of factors. Presently, SAF remains at least twice as expensive as its petroleum-counterpart due to higher production costs, the addition of a markup by fuel producers and suppliers, and the influence of policies and regulations on market dynamics. Despite this price differential, all SAF produced until now has been sold, thus signaling greater constraints on supply than on demand.

Economies of scale, feedstock availability and technology maturation for current and novel production pathways will bring down future costs for SAF, however, they are to remain more expensive than conventional jet fuel until 2040. Price parity may not be achieved until 2050 unless the environmental costs of petroleum-based fuels are reflected in the price via fiscal measures (i.e. cost of carbon emissions) and through incentives for alternative fuels that demonstrate environmental benefits (i.e. lifecycle carbon emissions reductions) (Strategy&, 2022).

Figure 30 shows illustrates this by comparing prices for lipid-based SAF (HEFA), bio-based SAF (primarily via ATJ and FT), and e-fuels (via FT or methanol synthesis), against cost baseline scenarios for conventional jet fuel.

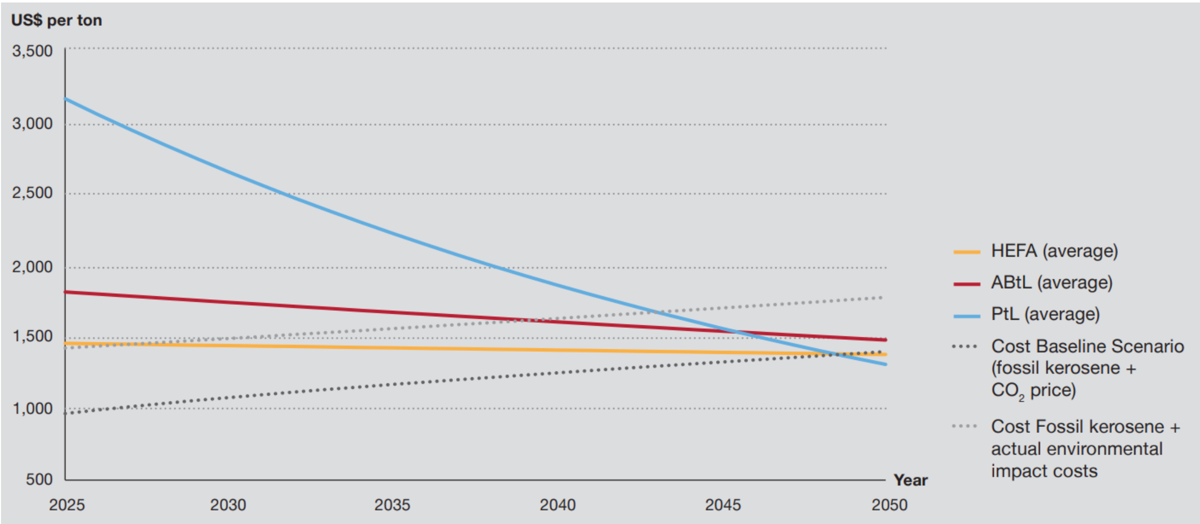


Figure 31. Price evolution of selected SAF pathways versus conventional jet fuel (Strategy&, 2022)

Although the price gap between SAF and conventional fuel is commendable, an increasing number of commercial arrangements – mostly in the form of offtake agreements – have allowed the cost-competitive procurement and supply of SAF between fuel producers and SAF buyers. This means that while still small quantities of SAF are used by airlines today (equivalent to 0.1% of total jet fuel demand), significant quantities are already committed for offtake in the future.

Thus far, offtake agreements have been a mechanism to pool voluntary demand for SAF, where they are anticipated to play a major role in accelerating global SAF deployment leading up to 2030 and beyond, by mitigating financial risk of SAF undertakings. Notably for pooled offtake agreements, this type of commercial arrangement can facilitate obtaining financing to build or expand SAF production capacity while securing advantageous fuel pricing (i.e. hedge) for airlines and their corporate customers.

The first SAF offtake agreement dates to 2013, when United Airlines agreed to purchase 56.8 million litres from AltAir Fuels (now World Energy) over a 3-year period. Since then, nearly 30 million tonnes of SAF have been purchased by major airlines under contracts spanning durations between 6 months and 20 years. Out of that volume, almost over 60% were signed off between 2021 and 2022, following the announcement of major decarbonization industry targets and government commitments to reach net zero emissions by 2050.

Figure 31 shows volumes traded by the top ten SAF producers and figure 32 shows volumes contracted by the top ten SAF buyers among commercial carriers as of December 2022.

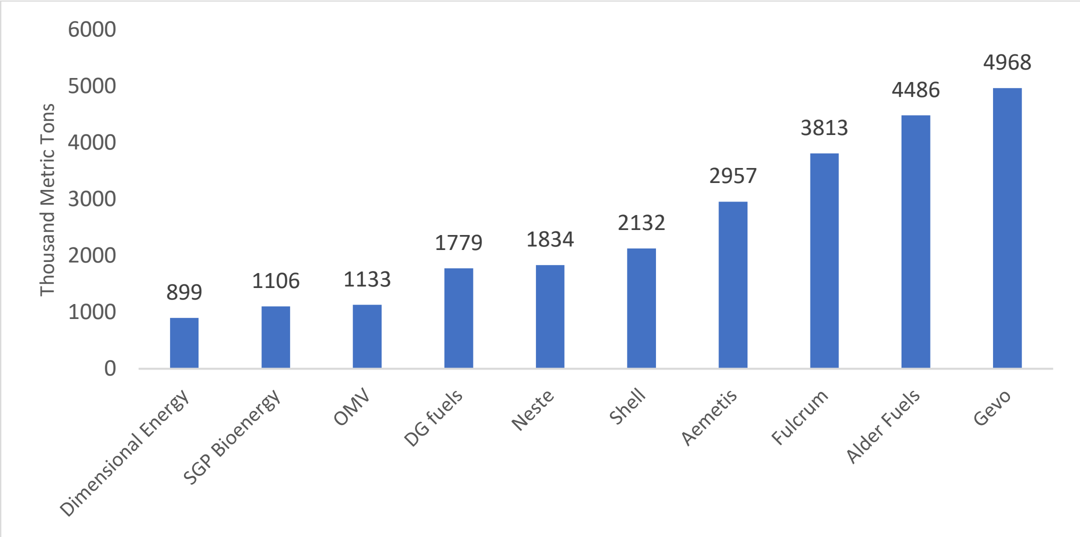


Figure 32. Top 10 SAF producers by published offtake volume[16] (in thousand metric tonnes) (IATA Env., December 2022)

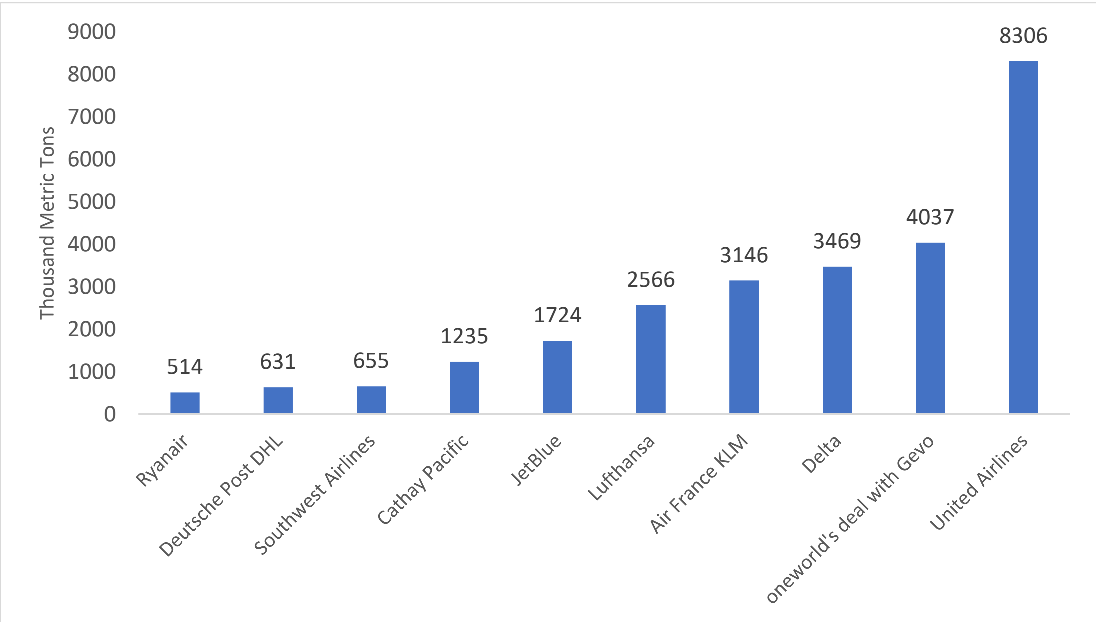
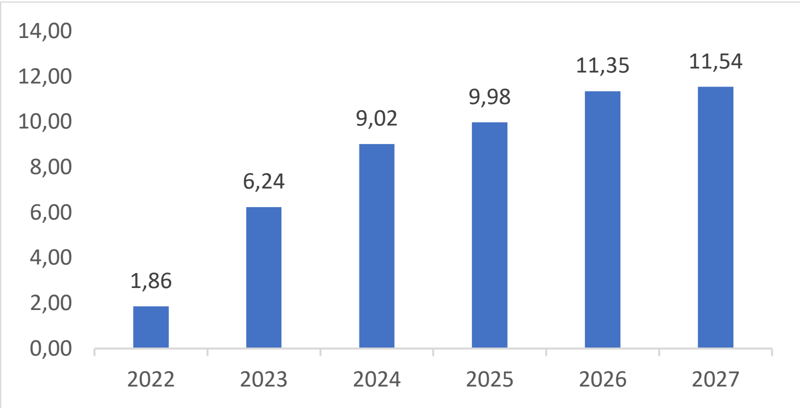


Figure 33. Top 10 SAF airline buyers by published offtake volume (in thousand metric tonnes) (IATA Env., December 2022)

[16] This only includes sales to airlines, excluding sales to OEMs and other SAF buyers (i.e. corporations, traders, etc.). Note that offtake volumes do not reflect actual renewable capacity production.

From the SAF volumes shown in the figures above, 9.36 million metric tonnes have been traded in Europe through 35 offtake agreements of varying lengths. Although the total number offtake agreements signed in North America is slightly lower than in Europe at 32 contracts, the SAF volumes traded are more than double, equivalent to nearly 20 million metric tonnes.

Today, less than 1% of aviation fuels used in Europe are SAF, yet the cumulative renewable fuel capacity[17] in 2027 is anticipated to reach 11.5 million tonnes, split among 4 conversion pathways and the co-processing of fuels (see fig.33 and fig.27).



Technology	Capacity (Mt)
ATJ	0.46
HEFA	7.81
PtL	0.15
Gasification/FT	1.36
Co-processing	1.76
Total	**11.54**

Figure 34. Cumulative ren. fuel capacity 2022-2027 for Europe, in million tonnes (IATA Env., Nov. 2022)

Most of this renewable fuel capacity, will be deployed in selected European countries, including Sweden, the UK, Germany, the Netherlands, France, Spain, Finland, Italy, Norway, Austria and Poland, where SAF – as a percentage of the total renewable fuel capacity expected in 2027, is likely to reach main and some secondary airports where the transport of fuel can leverage existing infrastructure (i.e. multiproduct pipelines).

SAF is regularly supplied at selected European airports since 2016, where the commingled infrastructure at major hubs makes it increasingly challenging to measure the amounts of SAF delivered to specific aircraft without the use of a fuel bowser. Furthermore, SAF production and/or blending facilities might not often be located in the vicinity of an airport, which will demand flexible accounting and reporting mechanisms for airlines to report their SAF usage.

To address these constraints, several industry and non-governmental organizations[18] are developing guidelines and systems to ensure the integrity of SAF transactions, while taking into account different types of feedstocks for SAF, supply chains, and production technologies. When fully developed, these guidelines and systems will guarantee that SAF environmental

[17] As explained earlier, renewable fuel capacity refers to a biorefinery's total output. This output, called product slate, consists of yields of products such as renewable diesel, naphta, neat SAF, etc.
[18] Including the Council on Sustainable Aviation Fuel Accounting (CoSAFA), the Roundtable on Sustainable Biomaterials (RSB), the International Sustainability & Carbon Certification (ISCC), the World Economic Forum's Clean Skies for Tomorrow (CST) initiative, and other private initiatives such as Avelia.

attributes incorporate accurate lifecycle analyses and verifiable transaction data, with the appropriate safeguards to prevent fraudulent claims or double counting. Presently, some of these programs are being successfully pilot-tested with the potential for broader use within the next 12 months.

For example, in 2021 the Roundtable on Sustainable Biomaterials (RSB) launched a book-and-claim pilot test with Air bp, United Airlines, and Microsoft, that allows airlines and their corporate customers to report their scope 1 and scope 3 emissions reductions – respectively – from SAF usage by decoupling its environmental attributes from the physical supply of fuel (see figure 34). This mechanism allows airlines to get equal access to purchase SAF and to claim the environmental benefits even if they do not operate at a particular airport where SAF is physically available.

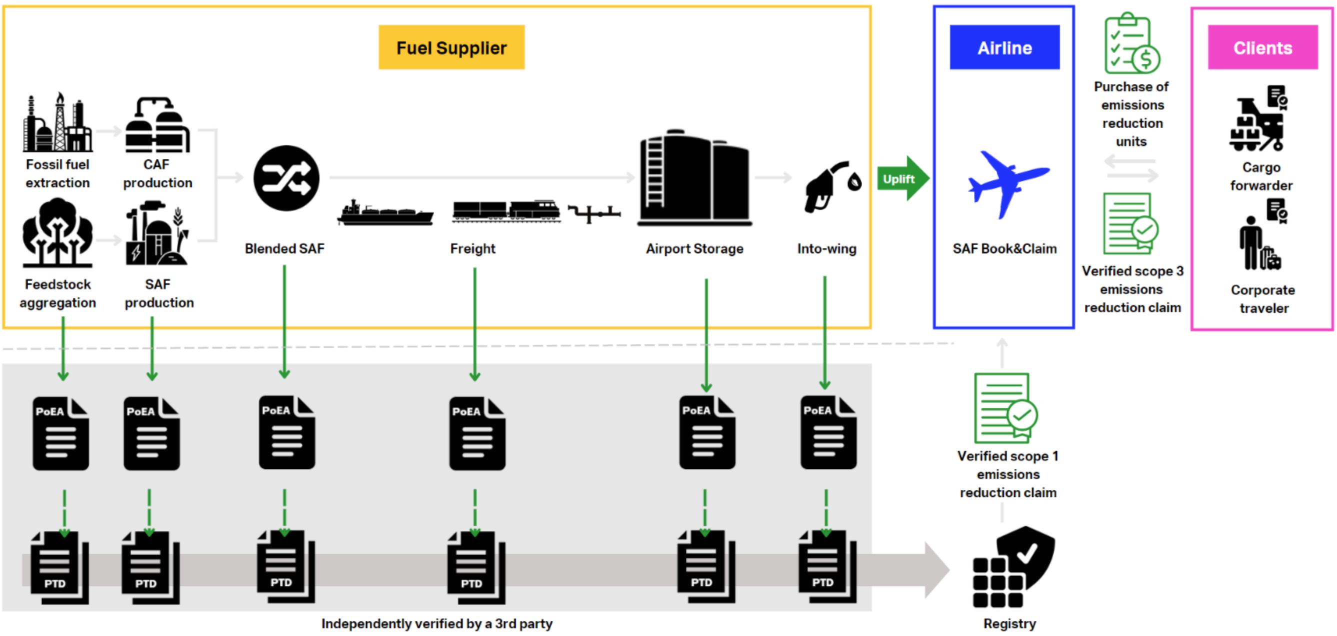


Figure 35. Chain-of-custody for SAF using a book-and-claim approach (IATA Environment, November 2022)

Whilst book-and-claim is not recognized for compliance under the ReFuelEU Aviation proposal at present, adopting this approach to account for the environmental benefits of SAF would facilitate and accelerate SAF production and uptake by:

- Enabling and promoting SAF production where it is most efficient
- Stimulating SAF uptake where demand would not justify local SAF production (i.e. notably in smaller airports and/or remote locations), or where physical supply is too expensive or otherwise inefficient
- Minimizing costs of logistics, such as transport and use of intermediate storage facilities
- Avoiding additional greenhouse gas emissions from transport

- Reaching many more customers than with physically segregated supply, thus providing clear market signal to ramp up SAF production
- Promoting competition in a broader marketplace

Moreover, the climate targets of corporate airlines' customers and the increasingly intensified efforts to achieve greater carbon emissions reductions, signal a potential willingness to pay for SAF that could be facilitated by a book-and-claim approach and leveraged through long-term offtake agreements.

12 Financing mechanisms for SAF

The Paris Agreement's goal to limit global warming to 1.5 degrees Celsius compared to pre-industrial levels is very influential in terms of capital markets and the flow of funds toward activities that support this target. This means that the Paris Agreement objectives will have an impact on capital providers in terms of which projects and companies they will finance.

To that end, capital providers are well-placed to support the increase in SAF supply that will be needed. Capital providers must disclose what proportion of their investments and loans are sustainable. This is leading to increasing requirements with respect to Environmental, Social, and Governance (ESG) criteria for the companies they finance. In addition, the European Central Bank requires banks to consider ESG risks in their risk models. The production and use of SAF offers new green assets that can be financed by financial institutions, which is why they can also find a future-proof business field here (Strategy&, 2022).

While the context for funding SAF supply seems promising overall, the type of financing depends on the maturity of the technology and the size of the company, and this can present various challenges. These factors will influence the financing instruments that are best suited to enable new investments in low-carbon technologies like first of a kind (FOAK) and second of a kind (SOAK) SAF plants. The Mission Possible Partnership (MPP, 2022) gives examples of financing options:

- High technological maturity (e.g. HEFA)
  - Institutional investors to provide green bonds
  - Banks to provide green loads for projects
- Low technological maturity (e.g. power to liquids, and others where reducing costs and risk is essential for supply ramp-up)
  - Consortium of capital providers to share risk
  - Public sector banks to de-risk projects (e.g. anchored blended finance, concessional loans, low interest loans, capital grants, or long term guarantees)
  - Insurers to insure the risk of uncertain technological development (e.g. the risk of SAF producers not being able to produce at a certain SAF price point by 2030 to de-risk offtake agreements).

Further to the consideration of level of technology maturity, financing options will also vary with respect to which phase of the SAF supply process funding is needed, meaning if it is for initial research or the establishment of a demonstrative pilot production facility.

12.1 Policy mechanisms to stimulate and accelerate SAF development

Broadening the availability and cost-effective production of SAF remains a great challenge, where policy intervention is required to address deployment barriers. Some of these include significantly higher production costs (contingent on selected feedstock and pathways) compared to conventional jet fuel, limited availability of commercially ready feedstocks, insufficient infrastructure for feedstock processing, fuel conversion, blending and supply to airports, etc.

Policy frameworks for scaling up SAF production require a considered and customized approach that acknowledges the differences in climate, agricultural systems, resources, economic factors, regulatory structures, and opportunities for SAF that are unique to a country. To enable the development of a sustained SAF industry, these frameworks ought to set clear criteria on targets of SAF to be deployed, sustainability requirements, commercial parameters, timeframe, and a legal foundation. Similarly, policies that consider, respect and address social and economic factors are likely to deliver broader benefits that those focused solely on the attainment of environmental targets.

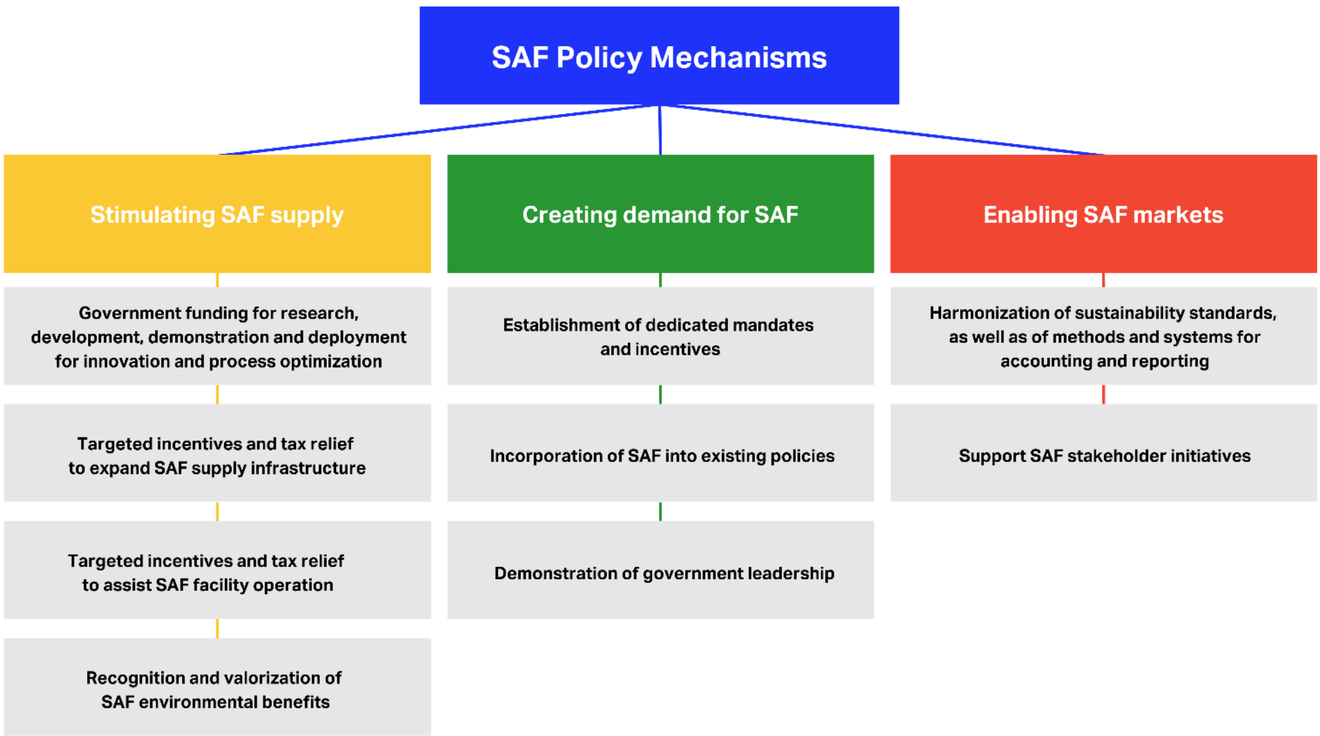


Figure 36. SAF policy mechanisms (source: IATA Env., adapted from ICAO)

Based on the work of ICAO's Committee on Aviation Environmental Protection (CAEP), Figure 35 compiles SAF policy mechanisms classified per objective that can: 1) stimulate growth of SAF supply, 2) create demand and 3) enable the marketplace, and that ought to be adapted to the uniqueness of a country's needs, ambitions and potential for SAF deployment.

12.1.1 Policies for stimulating SAF supply

This type of policies aims at stimulating and increasing feedstocks and infrastructure for SAF production and distribution through incentives for research and development, scale-up, commercialization and uptake.

1. **Government funding for innovation and process optimization** can support new feedstock and technologies across the SAF supply chain, centered in reducing production costs, enhancing the sustainability profile of feedstock and products (i.e. neat SAF and blends), improving production yields, optimizing conversion processes and supply chain logistics, and support technology demonstration and commercialization. Mechanisms under this policy category include:

    i. Government directed research and development activities, where support is provided through dedicated programs (public and private) and/or through academic and research institutes (i.e. EU Horizon 2020).

    ii. Government directed demonstration and deployment activities, where support to feedstock producers and technology providers through dedicated programs intended to mitigate the financial risk of supply chain scale-up (i.e. Canada's Sky the Limit Challenge).

2. **Targeted incentives and subsidies to expand SAF supply infrastructure** facilitate access to financing for building new capacity and, notably, for upscaling fist-of-kind feedstocks and technologies for SAF. Creating programs and tax policies that reduce the financial risk of SAF projects, can support private sector capital investment in SAF production through the following mechanisms:

    i. Capital grants given by governments to an entity to build or purchase infrastructure for SAF production, transportation, blending and refuelling (i.e. UK Dft's Green Fuels, Green Skies).

    ii. Government-backed loan guarantee programs facilitate access to equity financing and lower the cost of capital while reducing the financial risk of SAF developments (i.e. USDA's 9003 Loan Guarantee Program).

    iii. Eligibility of SAF projects for tax-advantaged business status (i.e. master limited partnerships in the U.S.)

    iv. Accelerated or bonus depreciation to reduce the amount of tax-owing over the life of a SAF project.

v. Business Investment Tax Credit (ITC) for SAF investments to reduce the amount of tax-owing over the life of a project by allowing deduction of construction and/or commissioning costs of a qualifying asset.

vi. Performance-based tax credit for SAF projects that meet certain conditions. The credit could use a sliding scale and should have a defined timeframe (i.e. U.S. Sustainable Aviation Fuel Credit).

vii. Bonds/green bonds can be issued by public or private entities, supranational institutions to provide low-interest rate and tax-exempt financing to build infrastructure for SAF.

3. **Targeted incentives and subsidies to assist SAF production facilities** facing high operating costs and risks. The following mechanisms intend to reduce the cost differential between SAF and conventional jet fuel, and they are linked to a specific quantify of fuel produced and made available to the market:

   i. Blending incentives targeted at fuel suppliers and/or blenders, typically provide a credit against the entities' taxes, therefore reducing the price gap between SAF and jet fuel.

   ii. Production incentives also reduce the gap between SAF and conventional fuel by providing a credit against producers' taxes.

   iii. Excise tax credit for SAF where domestic jet fuel consumption is taxed. This mechanism also stimulates demand for SAF while lowering its price, by eliminating or lowering the tax burden in proportion to the quantity of SAF consumed.

   iv. Support for feedstock supply establishment and production that can address the risks and costs of feedstock (i.e. new crops). This mechanism includes subsidy payments as well as insurance programs.

4. **Recognition and valorisation of SAF environmental benefits** and ecosystem services in existing and new policies. These could include improvements in air quality, contrail reduction and others that may be identified going forward. Policy mechanisms can include:

   i. Recognition of SAF emission reductions under carbon taxation, where rating is contingent to the life cycle benefit of fuel, thereby subject to reduced tax.

   ii. Recognition of SAF benefits under cap-and-trade systems, where the obligations of the regulated party would be reduced or exempt (i.e. CORSIA, EU ETS).

iii. Recognition of additional SAF benefits by setting programs and incentives in place based on the air quality benefits and/or contrail reduction potential that SAF may be able to provide.

12.1.2 Policies to create demand for SAF

These policies focus in creating and sustaining demand for SAF based on a combination of obligations and incentives.

a. **Establishment of dedicated mandates and incentives.** SAF obligations can be set either as volumetric and/or emission reduction targets; however, this approach shall be complemented with incentives to cost-effectively address potential constrains on supply, as well as by robust sustainability frameworks to avoid negative impacts on natural resources, biodiversity and local food security.

   i. Mandating volumetric requirements in the fuel supply on a multi-year schedule, creates an incentive for SAF production that can also include life cycle emissions reduction requirements (i.e. Norway and Sweden SAF Blending Mandates, ReFuelEU Aviation proposal).

   ii. Mandating reductions in the carbon intensity (CI) of SAF on a life cycle basis and multi-year schedule incentivize production of SAF with higher sustainability profile that deliver greater environmental benefits (i.e. BC Low Carbon Fuel Standard in Canada).

b. **Incorporation of SAF into existing policies** as eligible fuels at national, sub-national and local levels, aims at stimulating demand and also contributes to SAF economic viability if incentives can be "stacked" at multiple levels (i.e. opt-in option within US Renewable Fuel Standard (RFS2) and California's LCFS where SAF production can receive credits in both programs at once).

c. **Demonstrated government leadership** establishes policy direction by setting aspirational goals for SAF production and/or use (i.e. Canada's Low Carbon Fuel Procurement Program) that are typically linked to comprehensive SAF policy measures and implementation plans (i.e. 2021 U.S. Aviation Climate Action Plan and SAF Grand Challenge Roadmap). Particularly, this policy mechanism can create a strong demand signal for SAF due to the ability of governments to commit to long-term contracts supported by strong credit ratings.

12.1.3 Enabling SAF markets

While complementary, these policies are critical to support market development for SAF since they bring certainty and clarity to the requirements and components of those described above. They include:

a. **Harmonization of sustainability standards, life cycle emissions methods and systems for the accounting and reporting of SAF usage** that rely on:

    i. Recognition of standards for life cycle emissions calculation and sustainability of feedstock and SAF production and supply, that ensure their environmental integrity along the supply chain (i.e. Canada's Clean Fuels Regulation, EU RED, CORSIA, RSB, etc.)

    ii. Standardize process and systems for purchasing SAF, including "book and claim" transactions. The latter could facilitate and promote a more efficient use and uptake of SAF by decoupling the physical use of fuels from their environmental attributes.

b. **Support for SAF stakeholder initiatives and consultation groups.** These can be led by governments, industry or NGO with the purpose of aligning the diverse stakeholders along the SAF supply chain, coordinating efforts and provide timely information and feedback to policymakers (i.e. Nordic Initiative for Sustainable Aviation (NISA), the Aviation Initiative for Renewable Energy (Aireg), etc.).

13 General conclusions

This report provided an overview of the environmental and the operational benefits of using SAF to improve local air quality around airports and to reduce the climate impact of aviation. The GHG assessment conducted by RSB on selected conversion pathways, showed that the lifecycle reduction potential of SAF is highly dependent on the feedstock and the technology combination used. In general, residual biomass yields lower GHG emissions than SAF pathways that rely on crops as feedstocks.

The production costs of SAF vary significantly among conversion pathways, where market prices are forecast to remain higher than for conventional jet fuel in years to come. The review conducted by IATA on TEAs for HEFA, FT and ATJ pathways using a variety of feedstock/technology configurations, supported previous analyses on the role of HEFA and lipid-based feedstocks to supply most SAF leading up to 2030, seconded by Gas/FT and by ATJ SAF.

It is important to highlight that this report did not analyze the availability, quality and accessibility of feedstocks considered in the LCA and review assessments, as this exercise was out of the scope of WP3 activities and was conducted within WP2.

While also out of the scope of this report, the measurements on local air pollutants to take place at CPH during January and February 2023 within WP3 activities, are anticipated to demonstrate reductions when using SAF compared to the baseline set with conventional jet fuel using historical data that the airport has been collecting for over a decade.

On the potential for reducing the climate impact of aviation, neat SAF and SAF blends have demonstrated to induce a significant decrease of non-CO_2 emissions, thus potentially reducing their non-CO_2 effects, for example, linked to contrail formation. Additional CO_2 and non-CO_2 reductions can be achieved through SAF usage due to improvements in fuel efficiency effected by the higher energy content in SAF compared to conventional jet fuel.

Deployment of production capacity for SAF requires addressing perceived risks to stimulate innovation targeting feedstock development, processing, and novel fuel conversion pathways but foremost, for leveraging the capital to scale-up existing technologies, to optimize supply chains and to increase the access to sustainable feedstock sources.

Materializing the environmental, operational and the broader benefits of SAF analyzed in this report, demand an active role from governments for putting in place the mechanisms to stimulate supply, demand and to enable SAF markets.

14 References

Ashrafi, M., Lister, J., & Gillen, D. (2022). Toward a harmonization of sustainability criteria for alternative marine fuels. *Maritime Transport Research, 3*, 100052. doi:https://doi.org/10.1016/j.martra.2022.100052

ATAG. (2020). *Waypoint 2050.* Retrieved from https://aviationbenefits.org/media/167187/w2050_

ATAG. (2021, September). *Waypoint 2050. Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century.* Retrieved from https://www.atag.org/our-publications/latest-publications.html

Bräuer, T., Voigt, C., Sauer, D., Kaufmann, S., Hahn, V., Scheibe, M., . . . Anderson, B. (2021). Reduced ice number concentrations in contrails from low-aromatic biofuel blends. *Atmospheric Chemistry and Physics, 21*(22), 16817-16826. doi:https://doi.org/10.5194/acp-21-16817-2021

Carvallo, D., Ursini, C., Carelli, G., Iavicoli, I., Ciervo, A., Perniconi, B., . . . Iavicoli, S. (2006). Occupational exposure in airport personnel: characterization and evaluation of genotoxic and oxidative effects. *Toxicology, 223*(1-2), 26-35. doi:https://doi.org/10.1016/j.tox.2006.03.003

Christie, S., Ahmed, I., Ling, C., Wijesinghe, C., Khandelwal, B., Dunstan, D., & Hemstock, A. (2020, October 26). *D7.3 - Report and analysis of APU emission measurements.* Retrieved from JETSCREEN H2020: https://cordis.europa.eu/project/id/723525/results

Dahlmann, K., Grewe, V., & Niklab, M. (2020, July). *Integration of Non-CO2 effects of aviation in the EU ETS and under CORSIA. Part A: Suitable climate metrics for assessing the relation of non-CO2 and CO2 climate effects.* Retrieved from German Environment Agengy - Climate Change: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2020-07-28_climatechange_20-2020_integrationofnonco2effects_finalreport_.pdf

EASA. (2020, November). *Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4).* Retrieved from https://www.easa.europa.eu/en/downloads/120860/en

Ellermann, T., Massling, A., Lofstrom, P., Winther, M., Nojgaard, J., & Ketzel, M. (2012). *Assessment of the air quality at the apron of Copenhagen Airport Kastrup in relation to the working environment. Technical report no.15.* Aarhus University. Danish Centre for Environment and Energy DCE. Retrieved from https://www2.dmu.dk/Pub/TR15.pdf

EUCAR. (2020). *Attributional vs. consequential LCA methodology overview, review and recommendations with focus on well-to-tank and well-to-wheel assessments.* Retrieved from https://www.eucar.be/wp-content/uploads/2020/08/20200820-EUCAR-Attributional-vs-Consequential-updated-2.pdf

European Commission. (2015, July 16). *Long-term exposure to aircraft emissions causes premature death*. Retrieved from https://www.environmental-expert.com/news/long-term-exposure-to-aircraft-emissions-causes-premature-death-564469

IATA. (2022, December). *Global Outlook for Air Transport: Sustained Recovery Amidst*. Retrieved from https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---december-2022/#:~:text=Traffic%20is%20forecast%20to%20grow,pace%20in%202023%20and%20beyond.&text=travel%20restrictions%20which%20are%20still,the%20201

IATA. (2022, June). *Global Outlook for Air Transport: times of turbulence.* Retrieved from https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---june-2022---report/

ICAO. (2019). *Destination Green: The Next Chapter.* Retrieved from https://www.icao.int/environmental-protection/Documents/ICAO-ENV-Report2019-F1-WEB%20%281%29.pdf

ICF. (2021). *Fueling Net Zero: how the aviation indsutry can deploy sufficient sustainable aviation fuel to meet climate ambitions. An ICF report to ATAG Waypoint 2050.* London.

IEA. (2020). *CO2 Emissions from fuel combustion.* Retrieved from IEA Atlas of Energy: http://energyatlas/

Lee, D., Fahey, D., Skowron, A., Allen, M., Burkhardt, U., Chen, Q., . . . Wilcox, L. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 117834.

NNFCC. (2013, November). *Use of sustainably-sourced residue and waste streams for advanced biofuel production in the European Union: rural economic impacts and potential for job creation.* Retrieved from https://www.nnfcc.co.uk/publications/report-sustainable-residue-waste-advanced-biofuel

Our World in Data. (2022, February 9). *Share of people vaccionated against COVID-19*. Retrieved from Coronavirus (COVID-19) Vaccinations: https://ourworldindata.org/covid-vaccinations

Pavlenko, N., & Searle, S. (2021, March). *Assessing the sustainability implications of alternative aviation fuels. ICCT Working Paper 2021-11.* Retrieved from https://theicct.org/sites/default/files/publications/Alt-aviation-fuel-sustainability-mar2021.pdf

Rumizen, M. (2021). Qualification of Alternative Jet Fuels. *Frontiers in Energy Research, 9*. doi:doi: 10.3389/fenrg.2021.760713

Strategy&. (2022). *The real cost of green aviation. Evaluation of SAF ramp-up scnerios and cost implications for the European aviation sector.* Retrieved from https://www.strategyand.pwc.com/de/en/industries/aerospace-defense/real-cost-of-green-aviation.html

U.S. DOE. (2020, September 9). *Sustainable Aviation Fuel: Review of Technical Pathways Report.* Retrieved from Energy Efficiency & Renewable Energy: https://www.energy.gov/sites/default/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf

U.S. DOE. (2022, September 23). *SAF Grand Challenge Roadmap. Flightplan for Sustainable Aviation Fuel.* Retrieved from Energy Efficiency & Renewable Energy: https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf

Voigt, C., Kleine, J., Sauer, D., Moore, R., Bräuer, T., Le Clercq, P., . . . Anderson, B. (2021). Cleaner burnin aviation fuels can reduce contrail cloudiness. *Communications Earth & Environment, 2*(114). doi:https://doi.org/10.1038/s43247-021-00174-y

WEF. (2020, November 11). *Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.* Retrieved from Clean Skies for Tomorrow: https://www.weforum.org/reports/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation

15 Annexes and appendices

15.1 Results of ALIGHT airport survey

IATA conducted a survey between August 9 to October 29, 2021, with the objective of assessing airports and fuel suppliers' needs and immediate concerns about SAF integration in downstream operations. The survey was distributed through Airports Council International (ACI) and data were collected using an online polling site (Survey Monkey) and via e-mail in Word format.

The survey comprised 32 questions covering the following themes: handling, safety and quality, accounting and reporting, and other general aspects related to SAF.

At total of 54 responses were collected from airport operators and fuel suppliers primarily located in Europe (n49). European respondents represented 48% of passenger traffic in 2019 in the region.

The analysis done by IATA and Hamburg University of Technology (TUHH) showed that in 2021:

1. There was an information gap across European stakeholders on the basics of sustainable aviation fuels across all the topics covered in the survey, notably related to the accounting and reporting of SAF usage.

   On the latter, respondents were unfamiliar and/or had little understanding of the role of airports (versus fuel suppliers and airlines) regarding the scope and eligibility of carbon reductions from SAF usage, as well as the interplay of multiple schemes (i.e. compliance with national and/or supranational regulations versus voluntary programs such as ACI Airport Carbon Accreditation).

2. Due to constraints in supply as well as the perceived lack of demand for SAF from airlines, most respondents had no experience handling SAF[19] (43 out of 54), and had no clear short-term (i.e. by 2025) plans to supply volumes. By 2030, most respondents anticipate enough SAF quantities available to supply at least the mandated volumes under ReFuelEU.

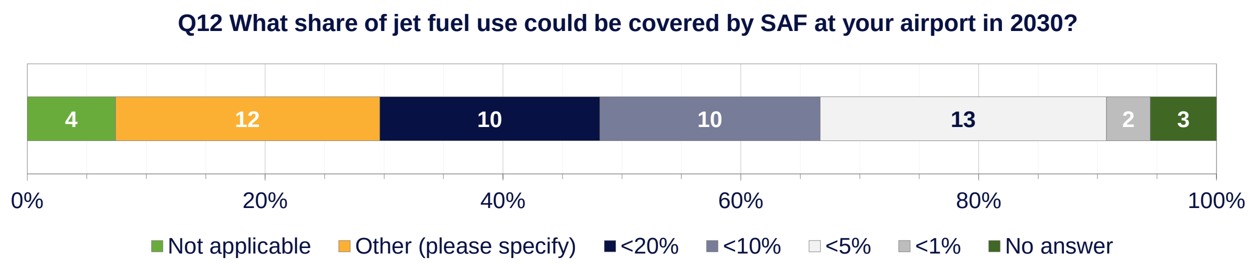


Figure 37. Expected share of SAF supplied in airports by 2030

[19] One or more of the following instances counted towards experience with handling SAF: flight demonstrators, proof of concepts, limited-time supply, and regular supply of SAF.

3. Despite the drop-in capabilities of SAF, some survey respondents expressed concerns around safety and performance of using SAF as replacement for conventional jet fuel.

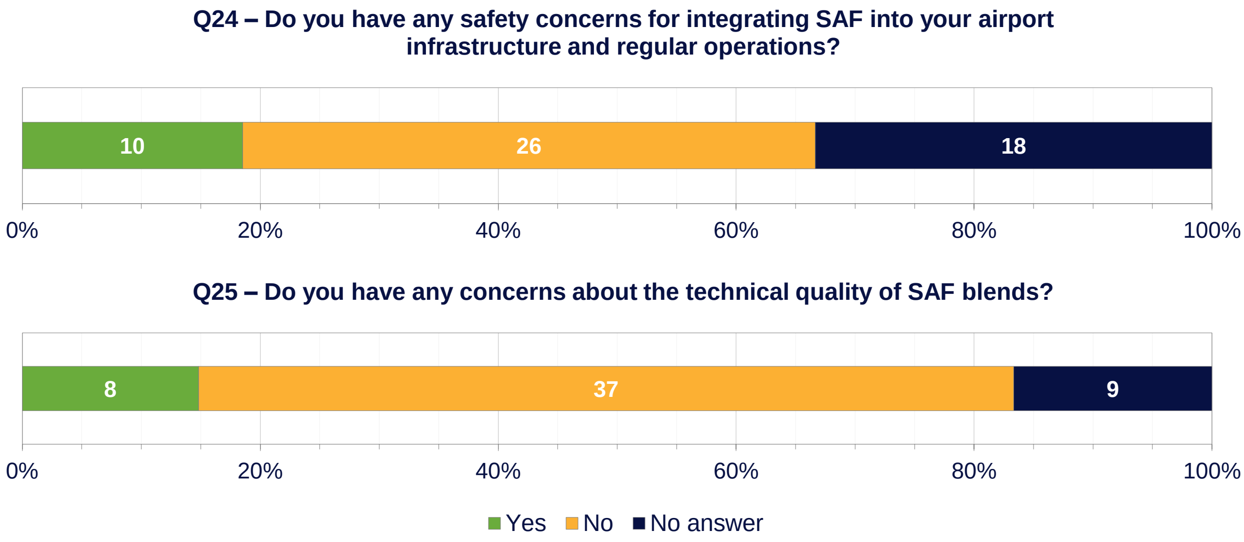


Figure 38. Airports' perception on safety and performance of SAF

The concerns expressed above were primarily shared among airports with no handling experience, where need for technical guidance on the following topics was identified:

- SAF handling as per current standards (i.e. Energy Institute / Joint Inspection Group)
- Guidance on testing requirements for SAF
- Risk of and response to SAF contamination
- Feasibility of SAF blending on airport premises
- Handling of SAF multi-blends and 100% SAF (neat SAF)
- Product quality assurance and reputational risk of SAF producers

The feedback collected through this survey has been used by the ALIGHT consortium to guide the work of partners within Work Package 3, to contribute to the mission of developing relevant guidance material for making the most efficient and sustainable use of SAF at Copenhagen Airport Kastrup (CPH).

The knowledge gained through this Horizon 2020 funded project, and the best practices identified through this exercise are to be replicated by fellow consortium airports in Rome, Vilnius and Warsaw.

15.2 Knowledge gaps to the cost-breakdown assessment for SAF pathways

The cost-breakdown assessment presented in chapter 11.2.3 (Figure 30) was based on a review of the literature on techno-economic analyses (TEAs) for selected SAF production pathways. These included only feedstock/technology combinations for the alcohol-to-jet (ATJ), gasification/Fischer-Tropsch (FT) and Hydroprocessing of Esters and Fatty Acids (HEFA) pathways, to keep consistency with the scope of the LCAs conducted by RSB in chapter 23. However, there was not enough literature on the Power-to-Liquids (PtL) to include them in the assessment.

15.2.1 Estimating CAPEX & OPEX

A wealth of studies on SAF production costs use prices for capital, labor, taxes, and feedstocks that were originally compiled from previous analyses, and that oftentimes require to be updated to the year or publication or a reference year. For example, Doliente et al. (2020) used values from De Jong et al. (2015) adjusted to 2019 levels using the Chemical Engineering Plant Cost Index (CEPCI).

The CEPCI can be used to adjust equipment costs shared by most refineries such as hydrocracking units, distillation towers, etc., up to the present year, where the Total Purchased Equipment Cost (TPEC) makes up the bulk of CAPEX. Unfortunately, there is not a standard method to conduct TEAs across the literature, so the meaning of TPEC and the consequent Total Capital Investment (TCI) are not always the same.

To illustrate this, some methods consider TPEC inside battery limits (ISBL), comprising all the equipment directly related to the production process, while other methods also include the cost of Outside Battery Limits (OSBL), that is, equipment such as waste treatment and utility equipment that may be on the refinery grounds but not related directly to the production of the final products. Other methods for conducting TEAs include the Percent Equipment Deliver method (Peters et al. 2004) and the Standardized Cost Estimation for New Technologies (SCENT) (Ereev and Patel 2012).

The fixed capital investment (FCI), defined as the cost of the equipment and the cost of installing it, can be estimated from the TPEC using an installation factor, commonly known as Lang factor**,** which is oftentimes a multiple of the TPEC. However, the actual costs of installation, piping, buildings, service facilities, etc. are dependent on the location of the plant/refinery under study, and thus the same TPEC can lead to different FCIs in different areas. The total CAPEX is, in most studies, computed by adding the required working capital (assumed to be a percentage of FCI) to the FCI.

Operational Expenditure (OPEX) is calculated from mass balances and utility requirements for each pathway, including electricity, water and hydrogen. Additionally, factors based on other assumptions in the literature, include maintenance, repairs, local taxes and insurance; each of which is calculated as a percentage of FCI.

Even within the same pathway, changes to the process design can affect the ratio between CAPEX and OPEX. For example, on-site production of hydrogen or enzymes (for fermentation in the ATJ process) and bio-crude upgrading (for pyrolysis and hydrothermal liquefaction), add to CAPEX at the expense of OPEX since these additional inputs and/or upgrading steps are handled by the plant itself. Most TEAs perform Discounted Cash Flow / Rate of Return (DCFROR) models to arrive at a minimum selling price of jet fuel (MSP) that would set the Net Present Value (NPV) of the project to 0 (zero).

One of the most important financial parameter to consider when comparing TEAs is the base year of calculation. When performing comparisons, a reference year should be set, and financial values adjusted to said year to account for inflation. The final estimated MSP in many studies often does not incorporate costs of transportation from the plant to the retail location nor any localized fuel taxes, and thus represents an “at-gate” price instead of the “at-pump” price of SAF. While the yield of jet fuel produced from a unit of feedstock can be referenced in the literature, the size of the plant can vary and can therefore affect the MSP.

All the studies reviewed for this report assumed a rate of inflation of 2% per year and a construction period of 3 years with spending (and construction progress) assumed to be 8% of total FCI for the first year, 60% the second year, and 32% the third year. The financial assumptions used in the literature reviewed are compiled in Table 7.

Table 7. Assumptions in selected literature for estimating the cost of SAF production

	Doliente 2020	**Diederichs 2016**	**Bann 2017**	**Tanzil 2021**	**Geleynse 2018**
Reference Year	2019	2014	2015	2017	2015
Plant Lifetime (years)	25	20	20	20	20
Debt to equity ratio	80 / 20	60 / 40	80 / 20	70 / 30	70 / 30
Interest rate	8%	8%	10%	8%	Unspecified
Corporate tax rate	22%	35%	16.9%	17.2%	16.9%
Discount Rate	10%	10-20%	3.2-22%	10-20%	10%
Capacity Factor	90%	90%	95%	Unspecified	90%
Capacity Factor in hours	7884	7884	8400	Unspecified	7884
Assumed Refinery Capacity (Mg product/year)	Variable	61,000	89,000	50,000	Up to 49,000

15.2.2 **Estimating feedstock costs**

A major limitation to the TEAs reviewed in this report is the lack of standardized prices for lignocellulosic feedstocks like corn stover, miscanthus, jatropha, among others. While, the U.S. Department of Agriculture and the EU Directorate on Agriculture and Rural Development provide updated prices for various oils, like rapeseed, palm, and sunflower oil, the markets for certain SAF feedstocks (as those mentioned above) are not developed enough to find timely and reliable pricing information for lignocellulosic biomass.

Therefore, price estimates for some ATJ, DSHC, and Gas-FT pathways are not easily comparable from one study to another, where typically local prices are used. For example, Mupondwa and Li (2016) conducted a TEA for HEFA using data published by the Saskatchewan Provincial government on prices for camelina, which cannot be extrapolated to TEAs for HEFA produced elsewhere.

It is noteworthy that feedstock prices refer to the delivery cost, which is split between the unit price of feedstock plus the various costs associated with delivering and storing it. All these factors are affected by location, especially if the refinery is importing its feedstock, as that will add customs duties and tariffs. Also, the DCF modelling done in most TEAs assumes that feedstock prices remain static throughout the lifetime of the plant. Only the study conducted by Bann et al. (2017) applied stochasticity to simulate a dynamic changing in the price for feedstocks in the various pathways considered.

15.2.3 **Literature reviewed for the cost-breakdown assessment of SAF**

Bann, S.J. (2017). "The costs of production of alternative jet fuel: a harmonized stochastic assessment." MIT. Accessed at: https://s3.wp.wsu.edu/uploads/sites/192/2018/01/Bann-Seamus-Endres-2016-17.pdf.

Brown, A., et al. (2020). "Advanced Biofuels – Potential for Cost Reduction." IEA Bioenergy. Task 41 IEA Bioenergy Technology Cooperation Program. Available at: https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf.

Danish Energy Agency. (2017). "Technology Data – Renewable Fuels." Available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

Diederichs, G.W., et al. (2016). "Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice." *Bioresource Technology* 216. 331–339. http://dx.doi.org/10.1016/j.biortech.2016.05.090.

Doliente, S.S., et al. (2020). "Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components." *Front. Energy Res.* 8:110. http://dx.doi.org/10.3389/fenrg.2020.00110.

De Jong, S., et al. (2015). "The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison." *Biofuel, Bioprod. Bioref.* http://dx.doi.org/10.1002/bbb.1613.

Ereev, S.Y., and M.K. Patel. (2012). "Standardized cost estimation for new technologies (SCENT) – methodology and tool. *Journal of Business Chemistry*. 9 (1):31-48.

Geleynse S., et al. (2018). "The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation." *ChemSusChem*. http://dx.doi.org/10.1002/cssc.201801690.

Mupondwa, E., et al. (2016). "Technoeconomic analysis of camelina oil extraction as feedstock for biojet fuel in the Canadian Prairies." *Biomass & Bioenergy 95.* http://dx.doi.org/10.1016/j.biombioe.2016.10.014.

Peters MS, Timmerhaus KD, West RE. (2004). Plant Design and Economics for Chemical Engineers. 5th ed. McGraw-Hill Chemical Engineering Series. 1221 Avenue of the Americas, New York, NY 10020: McGraw-Hill.

Tanzil A.H. et al. (2021). "Strategic assessment of sustainable aviation fuel production technologies: Yield improvement and cost reduction opportunities." *Biomass & Bioenergy 145.* https://doi.org/10.1016/j.biombioe.2020.105942.

Seufitelli et al. (2022). "Techno-economic analysis of an integrated biorefinery to convert poplar into jet fuel, xylitol, and formic acid." *Biotechnology for Biofuels and Bioproducts* 15:143. https://doi.org/10.1186/s13068-022-02246-3

16 Acronyms and abbreviations

ATAG	Air Transport Action Group
ATJ	Alcohol to jet
CAF	Conventional aviation fuel
CPH	Copenhagen Airport Kastrup
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DCE	Danish Centre for Environment and Energy, Aarhus University
DLR	German Aerospace Center
FT	Fischer Tropsch
FOG	Fat, oil and grease
GHG	Greenhouse gas
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILUC	Induced land use change
LCA	Lifecycle assessment
MJ	Megajoules
NO_x	Nitrogen oxides
OEM	Original Equipment Manufacturer
PAH	Polycyclic aromatic hydrocarbon
PtL/X	Power-to-Liquids

RED	Renewable Energy Directive
RFS	Renewable Fuel Standard
RPK	Revenue passenger kilometer
RTK	Revenue tonne kilometer
RSB	Roundtable of Sustainable Biomaterials
SAF	Sustainable aviation fuel
TEA	Techno-economic analysis
UCO	Used cooking oil
VOC	Volatile organic compounds

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