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Pathway to net zero: Reviewing sustainable aviation fuels, environmental impacts and pricing

Matthias Braun, Wolfgang Grimme, Katrin Oesingmann *

German Aerospace Center (DLR), Institute of Air Transport, Cologne, Germany

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ABSTRACT

Supporting the pathway to net zero carbon emissions in the aviation industry, sustainable aviation fuels (SAF) will contribute to a large extent to reduce net CO_2 emissions in the next decades to deliver on climate targets. For this reason, the large-scale uptake of SAFs in aviation is on top of the agenda of regulatory policy. However, challenges remain for building the respective infrastructure and supply chains at the appropriate scale to produce and distribute SAF at a reasonable cost. Currently, only one percent of fuels consumed by airlines in Europe are blended with sustainable aviation fuels. The paper examines current SAF production pathways, environmental benefits, and estimated fuel prices from the state-of-the art literature. Further, regulatory policies established by governments, regulatory agencies and industry associations are examined, regarding blending mandates in different regional markets. The authors conclude with the statistical analysis of minimum selling prices for different types of SAF, and discuss their respective availability.

1. Introduction

The transition of air transport toward net zero carbon dioxide (CO_2) emissions by 2050 is a primary goal of the aviation industry, governments, and regulatory agencies. Respective strategies, scenarios, and roadmaps have been suggested at the highest level, for example, the European Green Deal including the Fit-for-55 package, IATA's "Fly Net Zero" strategy, or EUROCONTROL's aviation outlook for 2050 (EUROCONTROL, 2022; European Council, 2022; IATA, 2021). In addition, many global aviation industry forecasts refer to net zero CO_2 targets by 2050.

The majority of studies, reports, and proposals conclude that the net zero target can only be achieved by combining different options for CO_2 emissions reduction, such as improving current aircraft technology, improving airport and air traffic management operations, introducing revolutionary aircraft powered by fuel cells or hydrogen (Grimme and Braun, 2022), by using sustainable aviation fuels, or by introducing effective market-based measures, e.g., the European Emissions Trading Scheme (EU ETS). Among these options, which differ depending on future potential, effectiveness, scalability, time of rollout, and costs, sustainable aviation fuels (SAF) are one of the largest contributors in all net zero strategies. The latest scenario forecast of EUROCONTROL, see Fig. 1., estimates that SAF. will be the largest contributor in two of three outlined European net zero scenarios with 41% and 56% respectively, and the second largest contributor in a third scenario with 34%. Market-based measures and carbon capture will also be a large contributor with 32% as shown in Fig. 1 labelled as "Other".

The reason for this high share is that sustainable aviation fuels can be used as "drop-in" fuels with existing aircraft technology without any modification, and are therefore fully compliant with current aircraft and airport infrastructure. Similar results are found in the Waypoint 2050 study (ATAG, 2021), where SAF would contribute up to 71% to emissions reductions in 2050. It is also well understood how SAF can be produced and blended with conventional fossil fuel kerosene. A range of flight tests have been conducted by major aircraft manufacturers and airlines (The Emirates Group, 2023). Certification is partially completed for blending ratios up to 50%, depending on the SAF type. In addition, sustainable aviation fuels are already commercially available on the market in limited quantities. However, the use of SAF in day-to-day flight operations is still in its infancy, with less than 1% of all European flights being operated with SAF today (EASA, 2022). Reasons for the low utilization rate are related to availability and cost. Production costs and market prices for SAF are substantially higher than for fossil kerosene jet fuel, and the infrastructure and supply chains for efficient large-scale production of SAF are still in their infancy.

* Corresponding author. German Aerospace Center (DLR), Institute of Air Transport, Linder Hoehe, 51147 Cologne, Germany.
E-mail address: katrin.oesingmann@dlr.de (K. Oesingmann).

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However, to leverage the potential of SAF, it is worth reviewing the different types of SAF, their respective production pathways, and feedstocks that are discussed today. SAF can be produced in a variety of different ways and with different feedstocks that serve as raw material inputs to the production process. Examples include biofuels from the hydroprocessed esters and fatty acids (HEFA) conversion pathway, advanced biomass to liquid fuels (ABtL), and power-to-liquid fuels (PtL) from renewable hydrogen and CO_2 as shown in Table 1.

In a competitive market environment, including the availability of fossil jet fuels, SAF competes with other CO_2 mitigation options such as market-based measures and carbon capture but also with various types of sustainable aviation fuels based on different feedstocks and production methods and their respective supply chains. For example, an airline may choose to purchase large stocks of CO_2 allowances to meet CO_2 targets rather than using SAF beyond fuel mandates to gain a competitive advantage. Given a pre-COVID-19 jet fuel price of 690 USD per ton, IEA (2022) estimates the CO_2 price of around 160 USD per ton in 2050, whereas 1 ton of kerosene is equivalent to 3.16 tons of CO_2. Currently, one CO_2 allowance within the EU-ETS is about 85 USD per ton (PwC, 2022).

This paper reviews recent (mainly over the last five years) scientific and economic studies on the production and pricing of SAFs. The aim is to provide up-to-date reference values for SAF pricing that can be used for future economic analysis. The focus of the evaluation is on peer-reviewed articles that considered SAF production pathways and costs from a techno-economic perspective. The analysis only covers the US and European markets, leaving other markets such as those in developing countries or regions in the Far East of Asia, for future research. To the authors' knowledge, no such state-of-the-art review has been undertaken. Based on the data found in the reviewed publications, price ranges are derived from an aggregation and statistical analysis of minimum selling prices (MSP) for sustainable aviation fuels found in 55 peer-reviewed articles. They were selected manually on the basis of a thorough literature review. These derived reference values for SAF pricing can also be used for future market research, scenario planning, and policy option development. In addition, the availability of different SAF types are discussed in more detail, and respective benefits and challenges are revealed. The environmental impacts and non-CO2 effects of air transport emissions regarding SAF utilization are also reviewed. Non-CO_2 effects refer to the climate impact of gases and particles other than CO_2 emitted by aircraft, as well as the formation of contrails and cirrus clouds.

Table 1
Examples of sustainable aviation fuels.

SAF candidates with high market potential	Biofuels - Hydroprocessed Esters and Fatty Acids (HEFA)	Advanced Biomass to Liquids (ABtL)	Power-to-Liquids (PtL)
Feedstock	vegetable oils, residue lipids, and waste, etc.	municipal solid waste, cellulosic cover crops, agricultural and forestry residues, etc.	green hydrogen and a carbon source (e.g. biomass or CO_2)
GHG emissions reduction (compared to fossil jet fuel)	74–84%	66–94%	89–94%
Blending ratio	50%	50%	50%
Certification	yes	yes (for Fischer-Tropsch and Alcohol-to-Jet syntheses)	yes (for Fischer-Tropsch synthesis)
Market availability	yes	–	–

Source: PwC (2022).

The paper is structured as follows: Section 2 reviews different types of SAF, production pathways, and environmental benefits and blending mandates, focusing on the United States and Europe. Section 3 (methodology and results) evaluates SAF prices based on the data found in the reviewed articles and studies. Section 4 specifically discusses SAF availability. Section 5 concludes with a discussion of results.

2. Types, environmental benefits, and regulation of sustainable aviation fuels (SAF)

This section reviews different types of SAF discussed in the literature, and their respective production pathways and feedstocks. The environmental benefits of sustainable aviation fuels in terms of net greenhouse gas emission (GHG) reductions and non-CO_2 effects are examined. In addition, SAF blending limits with fossil jet fuels (kerosene) and regulations regarding mandates for using SAF are reviewed.

Sustainable aviation fuels have been intensively discussed in recent years. For example, Kousoulidou and Lonza (2016), analyze the deployment of biofuels in aviation and outline demand and supply potentials for the European market. Zhang et al. (2020) provide an

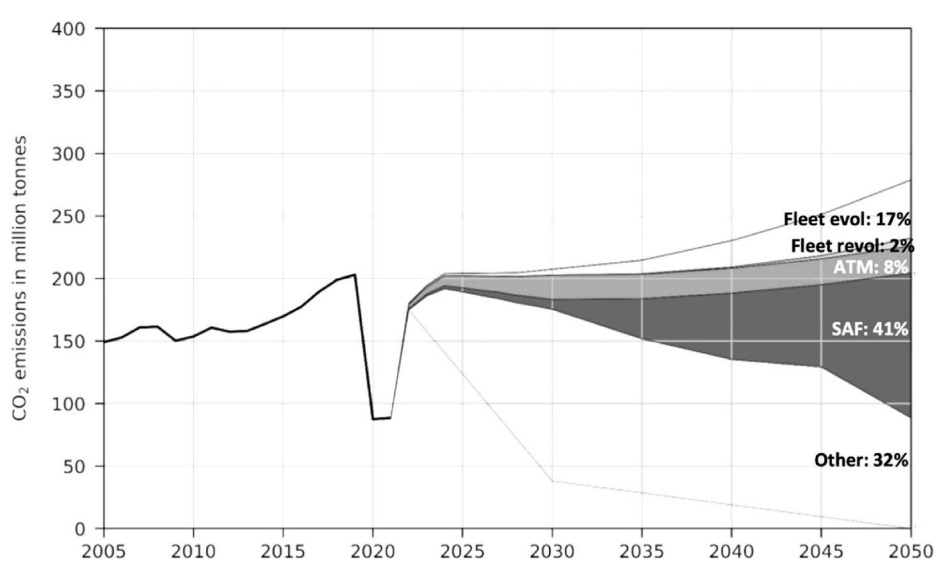

Fig. 1. EUROCONTROL's base scenario towards net zero CO_2 emissions by 2050. Notes: Fleet evol. = Fleet evolution, Fleet revol. = Fleet revolution, ATM = Air traffic management, SAF = Sustainable aviation fuels, Other = Market-based measures, Carbon capture. Source: Figure adopted from EUROCONTROL (2022).

overview of challenges and trends, including certification and availability of SAF regarding the United States (U.S.) domestic market. They state that the U.S. jet fuel market represents approximately 20 billion gallons per year, while global consumption is about four times that amount. Further, Brandt et al. (2022) study impacts of federal policy on minimum selling prices of SAFs, also focusing on the U.S. market. They report that HEFA biofuels could achieve a SAF price that would be competitive to conventional fuels when using a specific feedstock. However, availability of this feedstock is limited and unlikely to support the production of large quantities of SAF. As a result, different SAFs compete not only in terms of market prices but also in terms of their availability including required feedstocks and supply chains.

2.1. Production pathways and feedstocks

The combustion of sustainable aviation fuels in aircraft engines causes nearly the same amount of CO_2 emissions as conventional kerosene-based jet fuel. The CO_2 savings potential is determined by a life cycle analysis of the feedstocks used as raw materials and the required production and conversion processes. For example, biological feedstocks remove CO_2 from the atmosphere during their growth. To produce e-fuels such as Power-to-Liquid fuels, CO_2 previously emitted from other sources is captured from the atmosphere or concentrated sources and then fed into the SAF production process (EASA, 2022; García-Contreras et al., 2022).

Overall, there are several production and conversion pathways to produce SAF and a wide variety of possible feedstocks for biofuels (Karim et al., 2022; Pasa et al., 2022; Vela-García et al., 2022; Zhang et al., 2020). To date, the American Society for Testing Materials (ASTM) has certified seven conversion pathways (García-Contreras et al., 2022; IATA, 2022). The Fischer-Tropsch synthesis (FT or FT-SPK)[1] and the hydroprocessed esters and fatty acids (HEFA) pathway are among the most mature production processes for sustainable aviation fuels, being the first conversion technologies to be approved in 2009 and 2011, respectively. Other pathways include the following processes: Fischer-Tropsch containing aromatics (FT- SPK/A), hydroprocessed fermented sugars to synthetic isoparaffins (HFS–SIP/DSHC), isobutanol and ethanol Alcohol-to-Jet (ATJ), catalytic hydrothermolysis jet fuel (CHJ) and hydroprocessed hydrocarbons (HH-SPK or HC-HEFA) (IATA, 2022). Pathways for drop-in SAF need to be approved by the ASTM to ensure that SAFs are interchangeable with existing infrastructure and jet engines and that they can be blended with conventional fossil kerosene (EASA, 2022; IATA, 2022). Due to their properties, certified SAFs are used as “drop-in” fuels, i.e., they are blended with kerosene and can be used with kerosene-powered aircraft. They can therefore be used in all current and future aircraft designed for kerosene jet fuel. The interchangeability of SAF and fossil-based jet fuel makes SAF a cost-effective solution for reducing CO_2 emissions while scaling up SAF production to gradually replace fossil-based jet fuels. However, the production of SAF is still more expensive than fossil-based jet fuel, and SAF production capacity and quantity is limited. The price of fossil-based jet fuel correlates with the crude oil price.

As outlined by Royal NLR (2022), SAF can be produced from bio- or waste-based feedstocks but also in synthetic form also known as e-fuels or power-to-liquid fuels (see Table 2). For synthetic fuels, hydrogen serves as feedstock and is processed with CO_2 to produce synthetic kerosene. However, direct air capture of CO_2 is at early stage of development and therefore expensive.

Table 2 provides a brief classification of the different types of SAF including potential conversion pathways and costs. Costs refer only to feedstocks supplied from the European Union (EU) or the United Kingdom (UK). According to Royal NLR (2022), the cost of bio- or waste based SAF based on the Fischer-Tropsch (FT) pathway is much lower than the cost of hydrogen in 2020, which is around 8300 EUR/ton of hydrogen. Due to the uncertainty of cost estimations, Section 3 derives estimated SAF cost ranges from a sample of techno-economic studies and papers that have been published in recent years.

[1] The Fischer-Tropsch (FT) process for the production of SAF is also known as gasification-Fischer-Tropsch (GFT).

Table 2
Examples of SAF feedstocks, conversion processes, and costs.

SAF classification	Feedstock	Conversion process	Estimated costs
Bio- or waste based SAF (HEFA, ABtL, etc.)	vegetable oils, residue lipids, municipal solid waste, cellulosic cover crops, agricultural and forestry residues, etc.	Gasification and Fischer-Tropsch synthesis (FT/FT-SPK/A), Hydroprocessed Esters and Fatty Acids (HEFA), Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (DSHC/HFS–SIP) Alcohol-to-jet (AtJ) Catalytic Hydrothermolysis Jet fuel (CHJ), Aqueous phase reforming (APR) Pyrolysis (PYR)	currently about 2550 EUR/ton (Fischer-Tropsch pathway). Expected to decrease to 1350 EUR/t in 2050, about twice as much as expected cost for fossil kerosene (690 EUR/ton)
Synthetic SAF (power-to-liquid, e-fuels, solar-to-liquid)	hydrogen + CO_2	Gasification and Fischer-Tropsch synthesis (FT), Methanol-Synthesis (MeOH) Solar-to-jet (STJ)	currently about 4000 EUR/ton. Expected cost of 1600 EUR/ton in 2050

Source: Own table based on (IEA, 2021b; Royal NLR, 2022).

2.2. Environmental benefits

Sustainable aviation fuels must meet certain sustainability criteria, such as greenhouse gas (GHG) emissions savings, consideration of land use change and avoidance of competition of raw materials with nutrients, in order to comply with European environmental policies. According to the EU’s Renewable Energy Directive (RED III), the life-cycle GHG emissions of biofuels must be 50–70% lower compared to conventional kerosene, and the cultivation of the feedstock must not lead to environmentally or socioeconomically negative changes in land use (European Parliament and Council of the European Union, 2023a). Therefore, emissions from carbon stocks due to land use changes are also considered when calculating life cycle emissions of SAFs.

Feedstocks for biofuels that meet the EU sustainability criteria are defined in Annex IX of RED III. Biofuels produced through the HEFA pathway are limited to sources such as used cooking oil and certain classified animal fats. In contrast to conventional biofuels, the European Union (EU) is focusing on promoting the use of "advanced" biofuels. These advanced biofuels are derived from a specified list of feedstocks, and there are restrictions on biofuels that are considered to pose a high risk of direct and indirect land use change or competition with nutrients. The EU approach aims to ensure the sustainability and environmental benefits of biofuel production. Feedstocks for advanced biofuels can include algae, mixed municipal waste, straw, and others listed by the European Commission. SAFs that can be used under the European Emissions Trading Scheme (EU ETS) and the ReFuel Aviation Regulation must meet the criteria of RED III.

ICAO also defines sustainability criteria for SAF to be eligible for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (Efthymiou and Ryley, 2022; ICAO, 2022a, 2022b). The potential to reduce GHG emissions on a life-cycle basis (and including direct and indirect land-use changes) must be at least 10%, and criteria similar to those in the EU Energy Directive apply in relation to biodiversity and carbon stock changes (ICAO, 2022b). ICAO provides a summary of production pathways and raw materials with GHG emissions reported in grams of CO_2 equivalents during each life cycle. In addition to CO_2, the greenhouse gases nitrous oxide (N_2O) and methane (CH_4) are also included in the assessment. The life cycle assessment of GHG emissions is based on "Well to Wake" (WTW), starting with land use and cultivation of the feedstock, transportation of the feedstock, and ending with combustion as jet fuel. To calculate the GHG emission savings potential of biofuels, their life cycle emission factor is subtracted from a reference value of 89 gCO_2 equivalents per megajoule (MJ) of jet fuel (EASA, 2022; ICAO, 2022a; Prussi et al., 2021; Voigt et al., 2021).

Figs. 2 and 3 show the GHG emissions saving potentials by production pathway and by feedstock on a life cycle basis. As mentioned above, the life cycle emissions factor (LSf) includes direct and indirect land use change. While some production processes may result in higher emissions than the fossil baseline, e.g., when life cycle emissions and land use changes are included, a wide range of biomass feedstocks and conversion processes can reduce carbon dioxide equivalents.

Among advanced biofuels, SAF globally produced using the Fischer-Tropsch process from miscanthus - also known as silver grass - forestry and agricultural residues, and municipal solid waste, offers the highest potential to reduce greenhouse gas emissions by more than 90%–100%, based on lifecycle emissions. In some regions, emissions savings could be as high as 125%. The median reduction potentials of alcohol-to-jet conversion pathways are about 60%, while those of HEFA are almost below 60%. In terms of feedstocks used to produce biofuels, e.g., miscanthus, jatropha oil, and municipal solid waste generally offer the highest GHG reduction potential. Palm oil and corn kernels show almost no potential, with an average savings potential of around zero, and even net negative emissions are possible.

Palm oil and corn grains in this case can have a negative impact on emissions due to land use change. GHG emissions savings potentials of less than 50% would not be eligible for the EU sustainability criteria for biofuel plants starting operations before October 2015, nor would they be eligible for financial support from public authorities. The GHG savings threshold increases to 65% for biofuel plants starting operations after January 2021.

In contrast, synthetic fuels have the potential to reduce direct emissions by up to 100% and achieve carbon neutrality if electricity is generated from renewable resources and the required CO_2 is extracted from the air by direct capture. However, due to GHG emissions from transport supply chains, full carbon neutrality will not be achieved based on a life cycle analysis. EASA (2022) defines synthetic fuels as renewable liquid transportation fuels of non-biological origin; other terms include electro-fuels, e-fuels, and power-to-liquid (PtL) fuels. The production pathway is based on the Fischer-Tropsch technology, and there are several ways to obtain the CO_2 needed for the PtL process. Technically, the CO_2 could be extracted from industrial waste gases, biomass or directly from the atmosphere (EASA, 2022), but the EU restricts the origin of the CO_2 to non-biological sources (European Parliament and Council of the European Union, 2023a)

In addition to reducing life-cycle GHG emissions, the use of SAF can also reduce other direct climate impacts of aviation (García-Contreras et al., 2022). In addition to carbon dioxide (CO_2), planes emit water vapor (H_2O) and aerosol particles (particulate matter) like soot. Under certain atmospheric conditions, the water vapor emissions from an aircraft engine become visible as contrails and cirrus clouds. In addition, the soot particles alter the cloud formation. However, this effect is concentrated on a small percentage of flights that are particularly responsible for the formation of the warming contrails (Teoh et al., 2022). The climate effect is measured using the concept of radiative forcing. A positive radiative forcing means that less solar radiation is reflected back into space from the Earth's atmosphere, resulting in a warming of the Earth (Lee et al., 2021). Although research in this area is ongoing, recent studies have found that SAF reduce contrail lifetime and its radiative forcing because sustainable aviation fuels are typically low in aromatics and sulfur, and thus will emit less particulate matter (Beyersdorf et al., 2014; Durdina et al., 2021; EASA, 2020; Lobo et al., 2012; Moore et al., 2017; Teoh et al., 2022; Voigt et al., 2021). Since the formation of contrail clouds is highly dependent on the particular flight route and weather conditions, climate researchers suggest using SAF primarily for flights that form highly warming contrails in order to more effectively reduce the climate impact of air traffic (Teoh et al., 2022).

To comply with regulatory sustainability criteria, the GHG savings potential is particularly important also regarding future investments and public financial support. Regulations are covered in the next section. Minimum selling prices for SAFs are evaluated in Section 3.

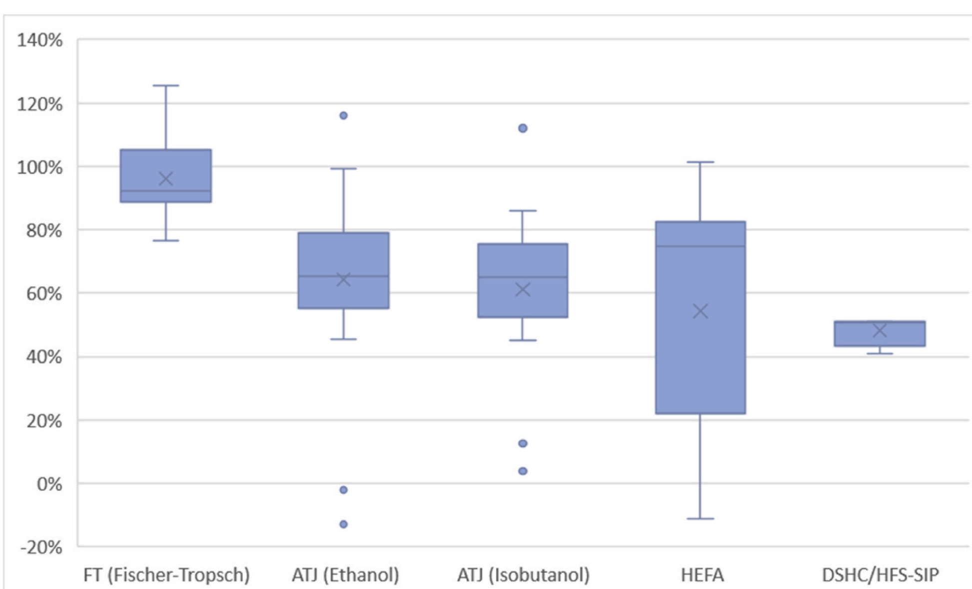

Fig. 2. Greenhouse gas (GHG) emission saving potential of biofuels by conversion process compared to kerosene baseline. Source: Based on data from ICAO (2022a). Note: GHG emissions savings based on life cycle emissions including land use change. ATJ = Alcohol-to-Jet, HEFA = hydroprocessed esters and fatty acids, DSHC/HFS–SIP = hydroprocessed fermented sugars to synthetic Isoparaffins.

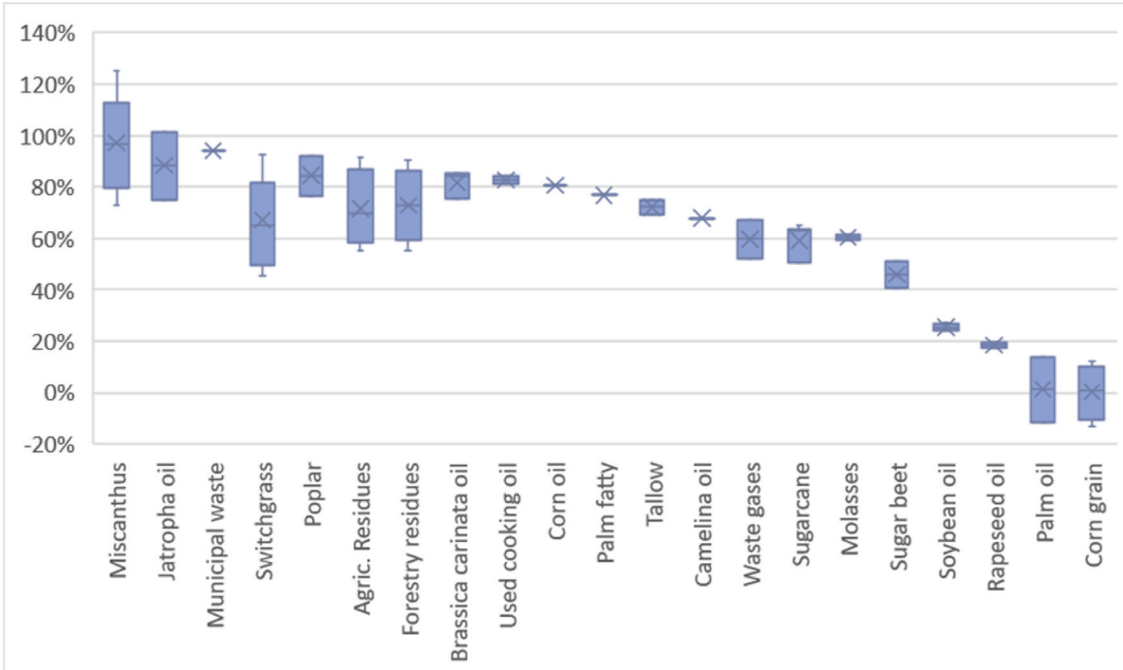

Fig. 3. Greenhouse gas (GHG) emission savings potential of biofuels by feedstock compared to kerosene baseline. Source: Table is based on data from ICAO (2022a). Notes: GHG emissions savings based on life cycle emissions including land use change. Palm fatty = Palm fatty acid distillate.

2.3. Regulation and blending limits

Due to the significance of SAF for the overall strategy towards net zero 2050, governments are promoting the adoption of SAF by airlines and air transport operators. The certification of SAFs also defines the maximum blending limits with kerosene. The maximum blending limit is currently up to 50% by volume for the Fischer-Tropsch, HEFA, AtJ and CHJ pathways, and 10% for the other certified pathways.[2] In addition to SAF blending limits, which may increase in the future with ongoing SAF certification, several directives in the EU and in other regions have been released to encourage investments in sustainable aviation fuels (Efthymiou and Ryley, 2022). These include, for example, mandates for fuel suppliers to deliver SAF blended fuels to all European airports with more than 800,000 passengers or 100,000 tons of cargo per year, ensuring that airlines operate a certain number of their flights with sustainable aviation fuels (European Parliament and Council of the European Union, 2023b).

The ReFuelEU Aviation Regulation (European Parliament and Council of the European Union, 2023b) (Quelle) requires SAF mandates (shares) of between 2 and 70% for jet fuel starting in 2025, whereas the share is gradually increasing in 5-year increments (European Parliament and Council of the European Union, 2018; Seo Amsterdam Economics, NLR, 2022). The regulation also requires jet fuels to meet specific quotas for synthetic (power-to-liquid) fuels as shown in Fig. 4.

Similarly, the IEA Net Zero proposal (IEA, 2021a) suggests SAF mandates of 2–75% from 2025. These quotas are higher than those in the ReFuelEU directive, and are therefore more likely to support the 1.5-degree climate target. In addition, the European Energy Tax Directive (ETD) has been revised, including the removal of an exemption for a European kerosene tax (European Parliament and Council of the European Union, 2021).

In contrast to the EU ETS and the ETD, the SAF mandate of the ReFuelEU Aviation directive will apply to all flights departing from European airports including those arriving at non-EU airports (European Parliament and Council of the European Union, 2018).

In the U.S., the Biden administration announced the goal of replacing all fossil jet fuel with SAF by the year 2050, including the plan to increase SAF production to 3 billion gallons annually by 2030 in coordination with Airlines for America. This goal is supported by the Sustainable Skies Act, which was passed in the US Congress in May 2021 (U.S. Congress, 2021). The act introduces a dedicated blender's tax credit of 1.50–2.00 USD per gallon to accelerate commercial-scale production of SAF. California's Low Carbon Fuel Standard (CA-LCFS) is restricted to the U.S. regional state but also gives credits for reducing the GHG intensity of California's transportation fuels by 20% by 2030 (U.S. State of California, 2009).

In Australia, the Sustainable Aviation Fuels Alliance (SAFAANZ) of Australia and New Zealand published a proposal in 2022 with the goal of 2.5% emissions reduction from jet fuel by 2025, 3% by 2030, and 10% in 2050 (Bioenergy Australia, 2022). These quotas are much weaker than the European directives.

ICAO has conducted feasibility studies for the introduction of SAF in smaller, less economically developed countries as part of its capacity-building and assistance to member states. Four studies have been conducted for the Dominican Republic (Gomez Jimenez, 2017), Kenya (White, 2018), Burkina Faso (Weber, 2018) and Trinidad and Tobago (Serafini, 2017).

Despite these regulatory efforts, the widespread adoption of SAF will depend on competitiveness in the marketplace against other CO_2 reduction alternatives such as cap-and-trade systems. Airlines and decision makers are developing their own roadmaps to reduce their air transport emissions while meeting customer needs. In the EU, the enforcement of the blending quota will be monitored for aviation fuel suppliers and aircraft operators: First, in the event of non-compliance, the SAF aviation fuel suppliers will be subject to a fine not less than twice as high as the amount resulting from the multiplication of the difference between the yearly average price of conventional aviation fuel and SAF per ton by the quantity of aviation fuels not complying with the minimum shares. In addition, the fuel supplier will be obliged to deliver the missing SAF amount in subsequent years on top of the respective obligations for these years (European Parliament and Council

[2] HH-SPK, HC-HEFA and SIP.

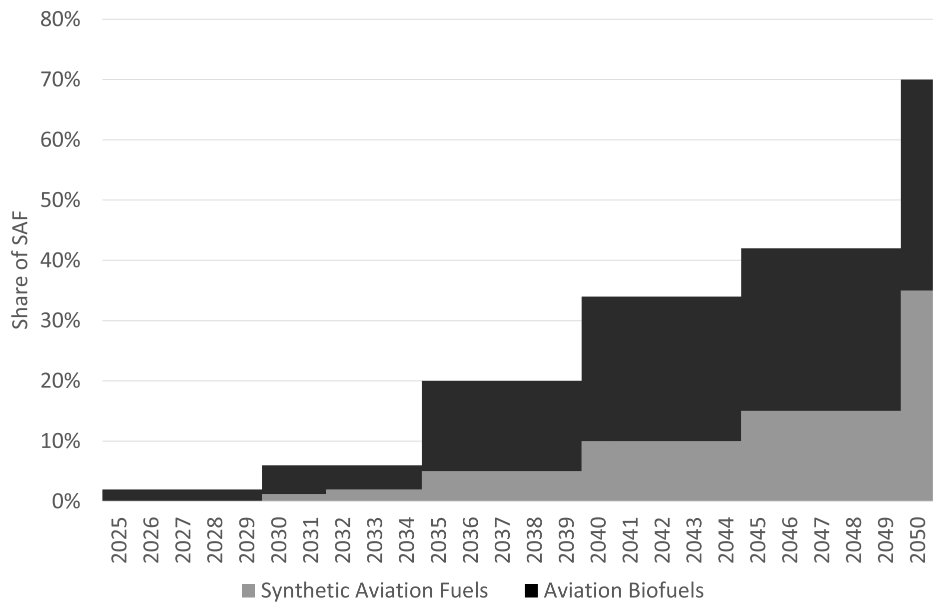

Fig. 4. SAF mandates of the ReFuelEU Aviation Regulation for increasing the share of SAF in the aviation sector. Mandates for synthetic (power-to-liquid) fuels are shown in light grey. Source: Based on Regulation (EU) 2023/2405, Annex I.

of the European Union, 2023b).

Airlines will risk penalties at least twice the average annual price of kerosene per ton multiplied with the total yearly non-tanked quantity if airlines fail to comply to uplift at least 90% of the fuel required for flights from each respective EU airport. This provision shall limit tankering to a minimum to avoid potentially higher fuel costs at EU airports as a consequence of the blending mandate (European Parliament and Council of the European Union, 2023b). And to avoid double-counting of CO_2 emission reductions, airlines may only claim the benefits of SAF utilization once - under the EU ETS for intra-EU flights or under CORSIA for extra-EU flights.

For the timeframe 2025 to 2034, fuel suppliers will not be required to deliver the minimum amounts of SAF to all airports physically. For compliance purposes, they can prove an average share of SAF delivered to all EU airports. For these reasons, reliable cost estimates for sustainable aviation fuels including their availability are important for decision-making in a competitive market environment.

3. Market prices for SAF derived from reviewed studies

In this section, a meta study on SAF prices is presented. In a competitive environment, prices will have a relevant impact on future air transport and passengers. Stakeholders may fear substantial cost increases compared to the current use of fossil jet fuel, which could lead to a reduction in demand and, subsequently, profits for many stakeholders in the air transport value chain. Airlines may also decide to pass on to customers the add-on costs for SAF. Therefore, expectations on future SAF prices are of interest for the aviation industry and regulators alike. Also, for air transport forecasts typically relying on the relationship between fuel prices, airline ticket prices and demand development, future prices of sustainable aviation fuels are of considerable interest.

In recent years, a plethora of techno-economic analyses on SAF production have been carried out, describing feedstocks, conversion processes and associated costs of production or minimum selling prices, respectively. In total, 55 peer-reviewed studies were considered for the analysis presented in this paper. The studies have been searched at various sources (ScienceDirect, Google Scholar, Springer Link and Wiley Online Library) using search terms closely related to the topic, such as "techno-economic study", "sustainable aviation fuel", "power-to-liquid", "biofuel" or "jet-fuel". Additionally, the list of references of studies found in a first round of search were analyzed for further relevant studies. Fig. 5 shows the distribution by publication year, revealing a growing scientific interest in techno-economic analysis. The studies describe production processes from a technological and bio-chemical point of view, additionally it is the purpose to determine the minimum selling price (MSP) of SAF. This is done by estimating required capital expenditure (CAPEX) and operating expenditure costs (OPEX) over the life of the plant. For finance costs, assumptions on interest rates are made. At the minimum selling price, the net present value of the overall project is zero. Hence, the variations in minimum selling prices are a result of different conversion pathway efficiencies and different assumptions on costs of feedstock, facility construction, energy and interest rates. In economic terms, this corresponds to the long-term average cost.

Several studies analyzed multiple conversion pathways, feedstocks or input cost scenarios. Overall, 230 observations on minimum selling prices (MSPs) and production costs were included in the analysis. In order to improve the comparability, the results of different years and different currencies have been normalized to USD_{2020}, using the average exchange rate of the base year of each study and OECD's producers price index. For aggregation and to allow a better interpretation of results, typical descriptive statistics (mean, median, lower quartile and upper quartile) have been calculated on the basis of the normalized mean selling price in USD_{2020}. Table 3 lists analysis results grouped by conversion pathway and respective minimum selling prices based on production costs.

The HEFA conversion pathway is the most intensively studied production process with 23 studies and 81 observations on MSP/production costs. HEFA results in the lowest price range, when considering the lower quartile, but not according to the mean and median indicators. The reason for this is that several studies have analyzed this production process with algae as feedstock. Oil extraction from algae is considered to be more expensive than with vegetable oils, producing several outliers with production costs above 2000 USD_{2020}/t SAF, as also shown in Fig. 6. The Fischer-Tropsch (FT) conversion pathway with biogenic feedstocks, the initially approved production process for SAF, is more cost-intensive compared to other pathways, except for the production of power-to-liquid (PtL) fuel. This is mainly due to the capital-intensive nature and operational complexities associated with the FT production pathway. The feed mass and energy balances are lower for the FT

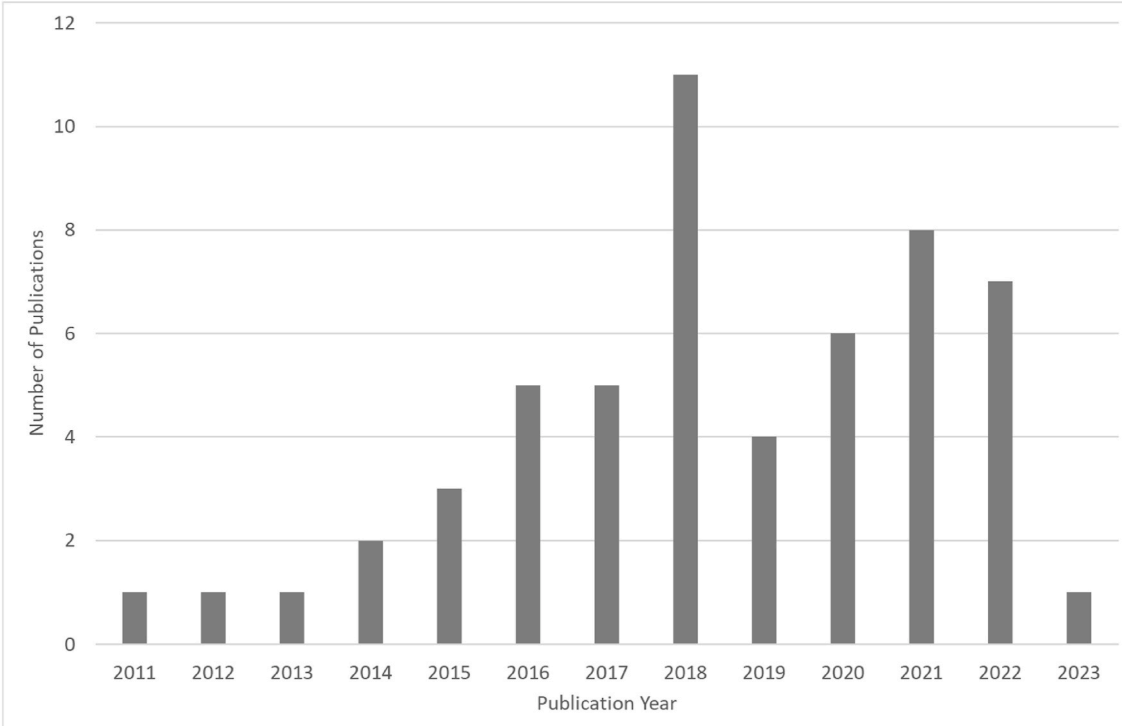

Fig. 5. Distribution of techno-economic studies on SAF analyzed in the meta study by publication year. Source: Own compilation.

Table 3
Descriptive statistics of the SAF minimum selling price/production cost meta study.

Conversion pathway	Number of studies	Number of observations minimum selling price (MSP)/production costs	Mean (MSP in USD_{2020}/metric ton SAF)	Median (MSP in USD_{2020}/metric ton SAF)	Lower quartile (MSP in USD_{2020}/metric ton SAF)	Upper quartile (MSP in USD_{2020}/metric ton SAF)
HEFA	23	81	1942.5	1544.0	1068.5	2141.2
AtJ[a]	16	36	2116.7	2004.9	1325.4	2655.7
FT	14	24	2233.3	2169.5	1513.7	2872.0
DSHC/SIP	3	6	3191.3	3700.8	1715.5	4307.6
APR	6	12	1663.9	1553.7	1073.6	2489.0
CHJ	6	19	1467.3	1349.3	1166.1	1637.4
PYR	10	19	2001.2	1972.2	1585.1	2483.9
PtL[b]	5	28	3216.3	2821.2	2023.6	3708.6
StL[c]	3	5	2538.4	2527.2	1928.6	3153.8

[a] Includes Alcohol-to-jet (ATJ) based on ethanol, isobutanol and others.
[b] Includes the production pathways Fischer-Tropsch (FT) and methanol-synthesis.
[c] StL = Sun/Solar-to-liquid, which uses direct solar energy for hydrogen production and the provision of process heat.
Source: Own modelling results.´

synthesis, and the ratio of jet fuel to feed energy is half that of hydroprocessed esters and fatty acids (HEFA) pathway, for instance (Diederichs et al., 2016). Studies focusing on aqueous phase processing/reforming (APR) with furfural and/or levulinic acid as intermediate products also feature relatively low production cost estimates, and thus, lower minimum selling prices.

Power-to-liquid (PtL) fuels have the highest production costs, both in the mean (3126.3 USD_{2020}/t), median (2821.2 USD_{2020}/t) and lower quartile (2023.6 USD_{2020}/t). The variation in production costs can be attributed to several factors. For relatively highly advanced conversion pathways, technological uncertainty about the efficiency of processes (e.g. conversion yields) is low, but assumptions about feedstock prices play a major role in SAF price modelling. For instance, Barbera et al. (2020) assume a used cooking oil price of only 150 USD/t, resulting in a SAF price of 564 USD_{2020}/t. Due to the high demand for used cooking oil as feedstock for both SAF and biodiesel, prices increased on the international commodities market to more than USD 1200 in the year 2022 (Matsuura, 2022). For PtL fuels, electricity prices determine the minimum selling prices to a large extent. Assumptions on electricity prices themselves vary across different studies, therefore also impacting the model results in the respective studies. Drünert et al. (2020) use a price range between 4.4 and 7.2 euro cents per kWh in 2030 and 3.5 to 5.5 euro cents per kWh in 2050. Schmidt et al. (2018) assume an electricity price of 4 euro cents per kWh, while Gonzalez-Garay et al. (2022) assume a price of 3 €-cents per kWh during the day and 8 euro cents per kWh during the night. The provision of sufficient electricity from renewable sources is an enormous challenge in the upscaling of PtL production, as it requires substantial capital expenditures. Electricity generation capacity used for PtL production should be additional, in order not to compete with alternative uses required in the transformation of power systems. It also favours locations where an efficient combination of different renewable power sources (such as photovoltaics and wind) could be realized in order to buffer fluctuating power generation.

In several cases where hydrotreatment is a process step in the conversion pathway (e.g. HEFA, pyrolysis (PYR) or APR), a trade-off

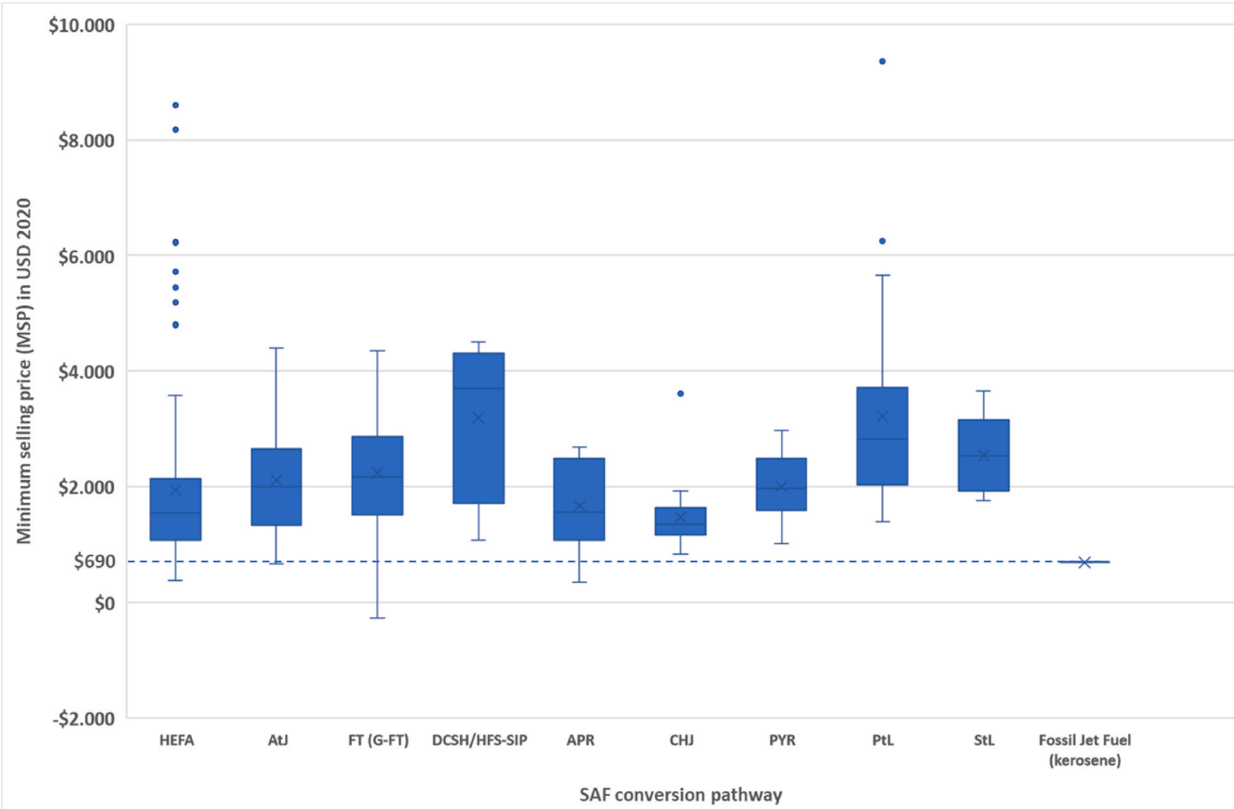

Fig. 6. Analysis results, showing a box-plot of SAF price ranges based on estimated minimum selling prices/production costs in USD_{2020}. For comparison, the authors assumed an average fossil jet fuel price (2010–2021) of 690 USD_{2020}. Source: Own modelling results.

between production costs and GHG reduction potential can be observed. When the required hydrogen originates from steam methane reforming (SMR), lower costs for the provided hydrogen can be achieved, while SMR releases substantial amounts of CO_2. Water electrolysis can provide hydrogen with minimal lifecycle GHG emissions if renewable electricity is used, but costs are substantially higher.

The MSPs calculated for SAF in techno-economic studies also depend on the assumptions made for revenues from co-products. Most, if not all, conversion pathways produce other chemicals and fuels in addition to SAF, and in some cases, electricity and heat. For plants not focused on SAF, this could even lead to negative prices for SAF if the costs of operation are already covered by other products (e.g. in the studies conducted by Alam et al., 2021; Klein et al., 2018).

Assumptions on plant sizes and capacity have a direct impact on minimum selling prices due to economies of scale. The studies examined clearly show that there is a correlation between the capacity of biorefineries and decreasing costs per fuel production unit. Atsonios et al. (2015) show that the increase in plant size for a facility with gasification of biomass and methanol synthesis can reduce the MSP from initially 2470.7 USD_{2020}/t for a plant with 400 tons/biomass feedstock per day to 2291.6 USD_{2020}/t for 864 tons feedstock/day and 1772.4 EUR/kg for 2000 tons feedstock/day. Similar findings are observed by Li et al. (2018), where an increase in plant capacity from 1.3 million liters per year to 13 million liters per year for a facility utilizing corncobs as feedstock with aqueous phase reforming (with Furfural and Levulinic acid as intermediates) reduces the MSP from 1853.6 USD_{2020}/t to 1342.2 USD_{2020}/t.

Techno-economic studies typically focus on the engineering dimension of SAF productions, making assumptions on feedstock prices, capital costs and process efficiency to estimate minimum selling prices. However, selling and market prices can differ substantially, depending on market structure. On the one hand, given the high number of different feedstocks and production pathways, there is likely to be a low level of concentration in supply of SAF, potentially leading to competitive pricing in the SAF market. From an economic perspective, it would be welfare enhancing to have a global market for feedstock, intermediary products and SAF. However, differing sustainability criteria may impede global trading. For instance, SAF made from corn or sugar in North America is not eligble under the ReFuel EU regulation, as food and feed crops from agricultural land will not be accepted. On the other hand, blending quotas combined with the obligation to uplift 90% of the fuel required at each respective airport will lead to a reduction in price elasticity of demand. This, together with the likely limited supply of SAF has the potential to drive up SAF prices well above production costs.

4. Availability and production outlook

Production cost, availability and selling price are highly interconnected. Production cost, or minimum selling price as defined by techno-economic studies is mainly determined by the prices of the input factors (feedstocks and energy) and production (conversion processes, realization of economies of scale of industrial-sized facilities, and capital cost). However, airlines as future operators of SAF should be aware of the potential discrepancy between production costs and the customers' willingness to pay. In a classic microeconomic setting, SAF prices will be determined by the interplay between supply (production cost and availability) and the demand. Blending mandates (see Section 2.3) are likely to lead to inelastic demand, as aircraft operators have no choice but to comply with the quota imposed. This can lead to high prices and supernormal profits for the suppliers of SAF, if the quantity supplied is inelastic. If supply reacts elastic to changes in price, high prices will normally send out a price signal that leads to an increase in the supplied quantity. However, when feedstocks, energy or process technology are constrained, stakeholders are not able to increase quantities. Hence, a systemic analysis of SAF production processes with an outlook on potential future quantities that can be supplied are important when evaluating policy objectives on blending mandates.

4.1. Biomass-to-liquid availability

The availability of SAF produced from biomass feedstocks is constrained by the availability of natural resources. For first-generation biomass feedstocks competing for food use, such as vegetable oils, wheat grain or corn, typical constraints are the availability of agricultural land and harvest results. Moreover, due to sustainability issues, it is questionable whether some of the first-generation biogenic feedstocks should be actively promoted for SAF usage. For some feedstocks, when indirect land use changes are considered in the life-cycle assessment, total emissions (as measured in CO_{2eq}) can be even higher than fossil jet fuel as outlines in Section 2.2.

Non-food agricultural crops on marginal farmland, waste and residues have a potentially high emissions reduction potential and are also available in large quantities. Estimations of biomass availability have been conducted both in the context of SAF production, as well as in a more general context of the transition to renewable energies. Brosowski et al. (2019) have estimated the mobilizable potential of biomass in Germany. Agricultural by-products, such as animal manure or cereal straw have a potential in a range of 11.1–26.2 million tons and forestry by-products range from −0.8 to 10.9 million tons. DBFZ (2023) estimates a technical potential of 4.3 million tons of cereal straw that could be mobilized in Germany. It should be noted, however, that the conversion rates of feedstock-to-SAF from biomass are relatively low. Estimated conversion rates from biomass to jet fuel are listed in Table 4. For residues and lignocellulosic biomass, most of the conversion pathways yield in less than 200 kg per ton of input biomass.

Further issues can be caused by a competition for biogenic feedstocks, which could be either used for electricity, heating, and for fuels used in ground transport next to aviation. Hence, studies providing information on biomass availability does not necessarily impose that the biomass estimated will be fully available for aviation (see Table 5).

4.2. Power-to-liquid availability

At least in theory, power-to-liquid based fuels are unlimited in terms of feedstock availability, as they require electrical energy, hydrogen (e.g. from water electrolysis) and carbon (e.g. from carbon dioxide through direct air capture or concentrated streams). In practice, the availability of electricity from renewable sources is likely to limit PtL production. It is estimated that 1 kg of PtL fuel requires 42 kWh of electricity, assuming a mix of pure and scrubbed CO_2 from point sources and a 20% share of direct air capture (Drünert et al., 2020). Subsequently, the electricity demand for the production of a high share of PtL fuels would be enormous: for the production of 10.3 Mt of jet fuel (which equals 2019 aviation fuel demand in Germany), Drünert et al. (2020) estimate an electricity demand of 440 TWh, which corresponds to about 80 % of the total electrical energy production of Germany in year 2022 (Fraunhofer ISE, 2023). Results in a similar order of magnitude were found by Gonzalez-Garay et al. (2022), estimating 298–361 TWh of Spain's current jet fuel demand could be met with power-to-liquid fuels.

The price of PtL fuels depends largely on the price for electricity, but also depends on the capital cost of building PtL refineries and the efficiency of the different process steps (such as electrolysis and the provision of carbon through direct air capture or concentrated streams).

5. Conclusion

Sustainable aviation fuels (SAF) will contribute to a large extent to the net zero CO_2 roadmap in the aviation industry. In addition, SAF can also reduce other significant direct climate impacts of aviation such as the formation of cirrus clouds and contrails. However, in a competitive market environment, sustainable aviation fuels compete with other CO_2 mitigation options such as hydrogen or carbon offsetting regimes. In addition, different types of sustainable aviation fuels (SAF) compete with each other in terms of market prices due to different production processes and raw materials. This paper has reviewed a wide range of scientific studies to determine price ranges for different types of sustainable aviation fuels based on minimum selling prices. These price estimations could potentially support market research and policy option development with respect to SAF blending mandates or future investments.

Regarding SAF production, the Fischer-Tropsch (FT) conversion pathway has the highest average greenhouse gas (GHG) savings potential (almost 100%) compared to fossil-based jet fuel, followed by Alcohol-to-Jet (slightly above 60%), and HEFA (slightly below 60%). Among advanced biofuels, SAF produced from feedstocks of miscanthus, forest and agricultural residues, or municipal solid waste, and combined with the FT process can potentially reduce GHG emissions of about 90% to more than 100%. However, this legislative position in the EU (European Council, 2022) is likely to be particularly challenging, as SAF production processes with a highly advanced technology readiness level and reasonable production and feedstock costs favoured e.g. in North America are explicitly ruled out in Europe, such as alcohol-to-jet from sugar- or starch-rich crops (sugar beet or corn) or HEFA from vegetable oils. In the EU, only agricultural feedstocks from waste or residues are acceptable for accounting as SAF under the ReFuel EU Aviation regulation.

Market prices for SAF are likely to remain well above the price for fossil jet fuel. Therefore, regulatory policy and respective incentives will have an impact on future price competitiveness. SAFs produced with the HEFA process are expected to achieve the lowest prices with a minimum selling price of 1068 USD_{2020}/t in the lowest quartile of studies but still well above the 2010–2021 average for fossil jet fuel of 690 USD_{2020}/t. However, cost reductions for HEFA-based fuels are expected to be limited as their technology readiness level is relatively high, so prices

Table 4
Exemplary physical conversion rates of biomass to jet fuel.

Conversion pathway	Feedstock	Physical conversion rate jet fuel in tons per ton of biomass	Source
AtJ (Ethanol)	Corn	0.111–0.147	Wang and Tao (2016)
AtJ (Ethanol)	Switchgrass	0.08–0.09	Wang and Tao (2016)
AtJ (Ethanol)	Sugar	0.207	Alves et al. (2017)
AtJ (Butanol)	Corn Stover	0.207–0.234	Wang and Tao (2016)
AtJ (Methanol)	Woody Biomass	0.127–0.143	Wang and Tao (2016)
HEFA	Jatropha Seeds	0.167–0.189	Wang and Tao (2016)
HEFA	Vegetable Oils	0.494	Pearlson et al. (2013)
FT	Hardwood	0.179–0.202	Wang and Tao (2016)
DSHC	Sugarcane Bagasse	0.137–0.155	Wang and Tao (2016)
CHJ	Food Waste	0.393	Farooq et al. (2020)
CHJ	Sewage Sludge	0.439	Farooq et al. (2020)
PYR/Hydroprocessing	Rice Husks	0.109	Chen et al. (2020)

Source: Own compilation.

Table 5
Overview on biomass availability in the context of SAF production.

Conversion pathway	Feedstock	Geographical scope	Feedstock availability Mt/a	SAF availability Mt/a	Source
CHJ	Algae	UK	7.18	1.01	Farooq et al. (2020)
CHJ	Food Waste	UK	10	1.14	Farooq et al. (2020)
CHJ	Sewage Sludge	UK	6	0.78	Farooq et al. (2020)
Integrated G-FT/CHJ/HEFA	Manure, MSW, Jatropha	Qatar	Jatropha Fruits: 0.454 MSW: 0.530 Manures: 0.689	0.26	Alherbawi et al. (2023)
HEFA	Camelina Oil	Saskatchewan/Canada	0.17–1.29	0.085–0.638	Mupondwa et al. (2016)
Various	Various biomass crops	Brazil		0-149 (2015) 28-182 (2030)	Cervi et al. (2020)
Various	Various biomass crops + municipal solid waste	Global		30.2–850.3	Staples et al. (2018)

Source: Own compilation.

will likely be more dependent on feedstock costs. power-to-liquid fuels have an availability advantage that is basically only constrained by the provision of green electricity but minimum selling prices well above 2000 USD_{2020}/t are currently not competitive. Nevertheless, several studies suggest a high cost reduction potential. Schmidt et al. (2018) estimate production costs of 1393 USD_{2020}/t for PtL fuels in 2050 based on a concentrated CO_2 source with the methanol synthesis pathway. Drünert et al. (2020) estimate minimum selling prices for PtL fuels of 1610 USD_{2020}/t in 2050, also assuming a concentrated CO_2 source.

An essential factor in the decarbonization of aviation through the use of sustainable aviation fuels (SAFs) is the availability of SAFs to meet environmental policies and achieve established climate goals. Although several projects are in the planning stages to scale up production capacities, SAF production is still in its early stages. The SAF dashboard by Boeing (2023) offers a summary of projected SAF capacities per region or country, relative to the expected consumption of jet fuel. This highlights potential shortfalls and gaps between the need for SAF and the production capacities that may arise. To prevent shortages in SAF supply, collaboration among various stakeholders in the aviation industry is crucial. Underwriting memorandums of understanding (MoU) for joint SAF production, (Airbus, 2022) can be a strategic approach. Cooperation between different stakeholders, including the aviation industry and institutional stakeholders, is particularly important in the early stages, as the adoption of new technology demands significant investment for ramping up SAF production.

In addition, the aviation sector needs to be mindful of potential demand competition from other transport modes. In particular, maritime transport is increasingly turning to sustainable fuels, given that there are limited alternatives to decarbonize large container ships. This highlights the importance of considering broader inter-sectoral dynamics when planning and implementing sustainable fuel strategies within the aviation industry. Future research could address pricing strategies for SAF based on co-products, the in-depth analysis of regional markets, or pricing impacts of policies and tax incentives.

CRediT authorship contribution statement

Matthias Braun: Conceptualization, Investigation, Validation, Writing – original draft, Writing – review & editing. **Wolfgang Grimme:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Katrin Oesingmann:** Conceptualization, Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

None.

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Appendix. Table of studies considered in the meta-study

Author(s)	Journal	Year of publication	DOI	Conversion pathways	Feedstocks
Agusdinata et al.	Environmental Science & Technology	2011	10.1021/es202148g	HEFA, FT	Camelina, Algae, Corn Stover, Short Rotation Woody Crops, Switchgrass
Atsonios et al.	Applied Energy	2015	10.1016/j.apenergy.2014.10.056	AtJ, FT	Woody biomass
Alam et al.	GCB Bioenergy	2021	10.1111/gcbb.12888	HEFA	Carinata
Bann et al.	Bioresource Technology	2016	10.1016/j.biortech.2016.12.032	HEFA, AtJ, FT, APR, CHJ, PYR	Yellow Grease, Tallow, Soybean Oil, Herbaceous Biomass, Corn Grain, Sugar Cane, MSW, Woody Biomass, Corn Stover
Barbera et al.	Renewable Energy	2020	10.1016/j.renene.2020.06.077	HEFA	UCO
Bittner et al.	Biofuels, Bioproducts & Biorefining	2015	10.1002/bbb.1536	PYR	Corn Stover
Bond et al.	Energy & Environmental Science	2014	10.1039/c3ee43846e	APR	Red Maple Wood
Chu et al.	Applied Energy	2016	10.1016/j.apenergy.2016.12.001	HEFA	Camelina, Carinata, UCO

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Author(s)	Journal	Year of publication	DOI	Conversion pathways	Feedstocks
Colling Klein et al.	Applied Energy	2018	10.1016/j.apenergy.2017.10.079	HEFA, AtJ, FT	Palm Oil, Macauba Oil, Soybean Oil, Sugarcane, Eucalyptus
Crawford et al.	Biotechnology for Biofuels	2016	10.1186/s13068-016-0545-7	AtJ	Poplar Wood
de Jong et al.	Biofuels, Bioproducts & Biorefining	2015	10.1002/bbb.1613	HEFA, AtJ, FT, CHJ, PYR	UCO, Forestry Residues, Straw
del Monte et al.	Fuel	2022	10.1016/j.fuel.2022.124602	HEFA	Camelina
Diederichs et al.	Bioresource Technology	2016	10.1016/j.biortech.2016.05.090	HEFA, AtJ, FT	Vegetable Oil, Lignocellulosic Biomass, Sugarcane Juice
Diniz et al.	Biotechnology for Biofuels	2018	10.1186/s13068-018-1158-0	HEFA	Camelina, Carinata, Jatropha
Drünert et al.	Applied Energy	2020	10.1016/j.apenergy.2020.115578	PtL	CO2/water
Eswaran et al.	Renewable and Sustainable Energy Reviews	2021	10.1016/j.rser.2021.111516	CHJ	Soybean Oil, Carinata, Yellow Grease, Brown Grease
Falter et al.	Environmental Science & Technology	2016	10.1021/acs.est.5b03515	StL	CO2/water
Falter et al.	Sustainable Energy & Fuels	2020	10.1039/D0SE00179A	StL	CO2/water
Falter et al.	Energies	2020	10.3390/en13040802	StL	CO2/water
Farooq et al.	Cleaner Engineering and Technology	2020	10.1016/j.clet.2020.100010	CHJ	Algae, Food Waste, Sewage Sludge
Gonzalez-Garay et al.	Energy & Environmental Science	2023	10.1039/d1ee03437e	PtL	Air/concentrated CO2 source, water
Habermeyer et al.	Frontiers in Energy Research	2021	10.3389/fenrg.2021.723774	FT	Forest Residue Chips
Hsu et al.	Journal of Cleaner Production	2021	10.1016/j.jclepro.2020.125778	HEFA	UCO
Klein-Marcuschamer et al.	Biofuels, Bioproducts & Biorefining	2013	10.1002/bbb.1404	HEFA, DSHC/SIP	Microalgae, Pongamia pinnata, Sugarcane
Kreutz et al.	Applied Energy	2020	10.1016/j.apenergy.2020.115841	FT	Woody biomass
Kumar et al.	GCB Bioenergy	2018	10.1111/gcbb.12478	HEFA	Lipid-producing sugarcane
Li et al.	Applied Energy	2018	10.1016/j.apenergy.2017.07.133	APR	Corncob
Liu et al.	Applied Energy	2021	10.1007/s11367-021-01914-0	HEFA	Castor, Jatropha
Martinez-Hernandez et al.	Chemical Engineering Research and Design	2019	10.1016/j.cherd.2019.03.042	HEFA	Palm Oil
McGarvey and Tyner	Biofuels, Bioproducts & Biorefining	2017	0.1002/bbb.1863	CHJ	Brown Grease, Yellow Grease, Carinata
Michailos	Environmental Progress & Sustainable Energy	2017	10.1002/ep.12840	DSHC/SIP	Sugarcane bagasse
Michailos and Bridgwater	International Journal of Energy Research	2019	10.1002/er.4745	PYR	Forest residues
Neuling and Kaltschmitt	Fuel Processing Technology	2018	10.1016/j.fuproc.2017.09.022	HEFA, AtJ, FT, PYR	Jatropha, Palm Oil, Wheat Straw, Wheat Grain, Manure, Biogas, Willow
Nguyen and Tyner	Biofuels, Bioproducts & Biorefining	2022	10.1002/bbb.2258	CHJ	Carinata
Olcay et al.	Energy & Environmental Science	2018	10.1039/c7ee03557h	APR	Red Maple Wood
Park et al.	ACS Sustainable Chemistry & Engineering	2022	10.1021/acssuschemeng.2c03853	AtJ	Bioethanol
Pearlson et al.	Biofuels, Bioproducts & Biorefining	2012	10.1002/bbb.1378	HEFA	Soybean Oil
Rojas Michaga et al.	Energy Conversion and Management	2022	10.1016/j.enconman.2022.115346	FT	Forest residues
Santos et al.	Renewable Energy	2018	10.1016/j.renene.2017.05.011	AtJ, PYR	Sugarcane/Bagasse & Juice
Schmidt et al.	Chemie Ingenieur Technik	2018	10.1002/cite.201700129	PtL	CO2/water
Shila and Johnson	Applied Energy	2021	10.1016/j.apenergy.2021.116525	HEFA	Camelina
Silva Braz and Pinto Mariano	Bioresource Technology	2018	10.1016/j.biortech.2018.07.102	AtJ	Eucalyptus
Staples et al.	Energy & Environmental Science	2014	10.1039/c3ee43655a	AtJ	Sugarcane, Corn Grain, Switchgrass
Tanzil et al.	Biomass and Bioenergy	2021	10.1016/j.biombioe.2020.105942	HEFA, AtJ, FT, DSHC/SIP, APR, PYR	Soybean Oil, Yellow Grease, Stover, Pine
Tanzil et al.	Fuel	2022	10.1016/j.fuel.2022.123992	AtJ, FT, DSHC/SIP, APR, PYR	Molasses, Switchgrass, Bagasse

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Author(s)	Journal	Year of publication	DOI	Conversion pathways	Feedstocks
Tao et al.	Biotechnology for Biofuels	2017	10.1186/s13068-017-0945-3	HEFA	Jatropha, Camelina, Pennycress, Castor, Yellow Grease
Tao et al.	Green Chemistry	2017	10.1039/C6GC02800D	AtJ	Corn Mill, Corn Stover
Tongpun et al.	Journal of Cleaner Production	2019	10.1016/j.jclepro.2019.04.014	HEFA	Jatropha
Trinh et al.	Energies	2021	10.3390/en14217194	FT, PtL	Forest residues, CO2/water
Wang	Energy	2019	10.1016/j.energy.2019.04.181	HEFA	Jatropha, Palm Oil, Algae, Soybean Oil, Rapeseed, Castor Oil, Corn, Yellow Grease, Edible Tallow, Inedible Tallow, Brown Grease, Lard
Wang et al.	Energy	2022	10.1016/j.energy.2021.121970	FT, PYR	Rice Husks
Wassermann et al.	Applied Energy	2022	10.1016/j.apenergy.2021.117683	PtL	CO2/water
Yang et al.	Energy	2018	10.1016/j.energy.2018.04.126	PYR	Hybrid Poplar
Yao et al.	Biotechnology for Biofuels	2017	10.1186/s13068-017-0702-7	AtJ	Sugarcane, Corn Grain, Switchgrass
Zech et al.	Applied Energy	2018	10.1016/j.apenergy.2018.09.169	HEFA	Jatropha, Rapeseed, Palm Oil, UCO

Source: Own compilation.

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