energies

Review

Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review

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Abstract: The Paris Agreement's objectives related to climate change put aviation under great pressure and environmental inspection. In particular, the aviation industry is committed to achieving a 50% reduction in CO_2 emissions by 2050 compared to 2005 levels. A shift to alternative aviation fuels seems imperative. The International Air Transport Association (IATA) has identified the production of drop-in sustainable liquid fuels (SAFs) as the most promising strategy, at least short term, to reduce the environmental impact of the sector. Within this review, a critical summary of the current alternative aviation fuels/pathways is presented and a comparative analysis of the dominant technologies is performed considering techno-economic assessment, environmental evaluation, and future projections. The impact of the 'ReFuelEU Aviation' initiative on the current dominant policies and market incentives is assessed. Hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT) synthesis, alcohol-to-jet (AtJ) conversion, and e-fuel pathways are put under the microscope. A wide range of potential fuel selling prices (0.81–5.00 EUR/L) was observed due to the presence of multiple routes, while some pathways seem able to secure more than 90% emission savings compared to the fossil jet reference. The accelerated scale-up of SAF production is a reasonable demand for the aviation industry. The establishment of a sustainable scale-up framework and the alignment of all of the involved aviation stakeholders is an immediate challenge.

Keywords: SAFs; HEFA; FT synthesis; AtJ; e-fuels; aviation policies; review

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1. Introduction

The global aviation industry has been a constantly and rapidly expanding sector in recent years. The International Air Transport Association (IATA) claims that the request for air connectivity will continue to grow. Indicatively, according to the IATA annual review of 2019, the number of over 4 billion passengers in 2018 is the biggest in history, while the transport of 64 million tons of cargo to markets around the world, for the same year, represents a 3.4% increase compared to the already extraordinary high number of cargo transfers for 2017. The huge decline (~66%) in global revenue passenger kilometers observed in 2020 cannot be considered indicative, since the COVID-19 pandemic delivered the largest shock to air travel and the aviation industry since the Second World War [1,2].

The increasing demands of air traffic has led to increasing demand for aviation fuel (jet fuel). Approximately 80 billion gallons of jet fuel, classified as kerosene-type and naphtha-type, are produced annually worldwide. The extensive use of petroleum-derived jet fuel has resulted in a remarkable decline in petroleum reserves. Furthermore, the large consumption of jet fuel generates notable amounts of greenhouse gases (GHG), making the airline sector responsible for 3% of the total current GHG emissions [3]. The Paris Agreement's objectives related to climate change put aviation, along with other sectors, under great pressure and environmental inspection. In Europe, the pressure is particularly intense and is expected to keep growing. The aviation industry is committed to achieving a 50% reduction in CO_2 emissions by 2050 compared to 2005 levels. While it is important to have a holistic view on climate metrics and to target the parallel reduction of both CO_2 and NO_x emissions via modern aircraft design and improved engine operational measures, the priority for the aviation sector in order to meet its environmental targets is the decarbonization of liquid fuels that are fully compatible with the current infrastructure (drop-in fuels). The slow incremental changes in already-mature engine technology and the long lifetime (>25 years) of existing fleets validate this priority as a much faster and probably cost-efficient way to reduce emissions [4]. Therefore, the present review focuses on the ongoing efforts for the development of low-carbon liquid fuels of the same quality as existing ones without underestimating in any way the importance of parallel advances on aircraft engine operation (i.e., fuel efficiency improvements, engine-out emissions) [5,6].

At present, aviation fuels mainly comprise kerosene fuels (i.e., Jet A or Jet A-1), but as petroleum residues are diminishing and, therefore, their prices are increasing, it is being understood that a shift to sustainable aviation fuels (SAFs) is auspicious and imperative. The IATA has identified the production of drop-in sustainable liquid fuels as the most promising strategy to reduce the environmental impact of the sector, since on the one hand, conventional fuel efficiency improvements are not sufficient to meet the targets for decarbonizing the industry and on the other hand, electrification along with the modern design of aircrafts or hydrogen involvement require extended infrastructure restructuring of the whole industry [3]. Investments are in place to expand SAF annual production from the current 125 million liters to 5 billion by 2025. With effective government incentives, production could reach 30 billion liters by 2030, which would be a tipping point for SAF production and utilization [7]. Relative market-oriented studies seem to confirm the projected SAF rapid evolution within the next several years by claiming that the SAF market is expected to increase from USD 216 million to more than USD 14 billion by 2030 [8].

Within this study, a critical review of the available pathways towards the decarbonization of the aviation industry is attempted. A comparative analysis from the techno-economic and environmental point of view are performed for the identified main technologies. The main objective of this paper is to provide a complete overview of the current alternative aviation fuels as well as to partially decode the 'next day' of aviation.

Even though there are relevant studies in the literature that aim to summarize the latest advances in the field [9–14], the present study is not only powered by them, but also aims to link these advances with the current market status, identify the main ambassadors of each technology, and record the latest key agreements/announcements. The motivation for this approach is the belief on the part of the authors that SAFs have ceased to be considered only as possible future alternatives of mainly research interest, but are already present in the market and there are strong indications that the SAF market will be one of the most active emerging markets of the current decade. Further novel aspects of this work include: (i) the synthesis of the data collected within this study with previous forecasting studies in order to perform future projections regarding the evolution of fuel production costs for the selected technologies; (ii) adhering to data and studies reported after 2015 only in order to draw the most up-to-date conclusions and considerations; (iii) an extensive focus on the current regulatory framework and policy approaches for sustainable aviation [15] along with underlining their importance towards a successful fuel transition; and iv) reference to the progress related to hydrogen and electrification involvement in the aviation sector.

2. Summary of Alternative Aviation Fuels and Current Status

The current tendencies for a more sustainable aviation industry include the so-called 'drop-in' alternative aviation fuels, hydrogen, and the potential aviation electrification (i.e., hybrid or full-electric aircrafts) (Figure 1). The 'drop-in' alternative aviation fuels or sustainable aviation fuels (SAFs) refer to completely interchangeable substitutes for conventional petroleum-derived jet fuel (i.e., Jet A or Jet A-1) that are produced from sustainable resources (e.g., biogenic feedstock, renewable hydrogen + CO_2). The fact that no adaptations are required for the existing fuel systems (i.e., engines, fuel distribution network) establishes SAFs as dominant alternatives towards the decarbonization of the aviation field. Hydrogen is a long-term sustainable fuel option, but requires extended modifications in current fuel infrastructure and overall aircraft design. Finally, aircraft propulsion via electrification in pure or hybrid mode could be an emerging option; nevertheless, energy storage limitations remain a major concern, especially for long-distance applications.

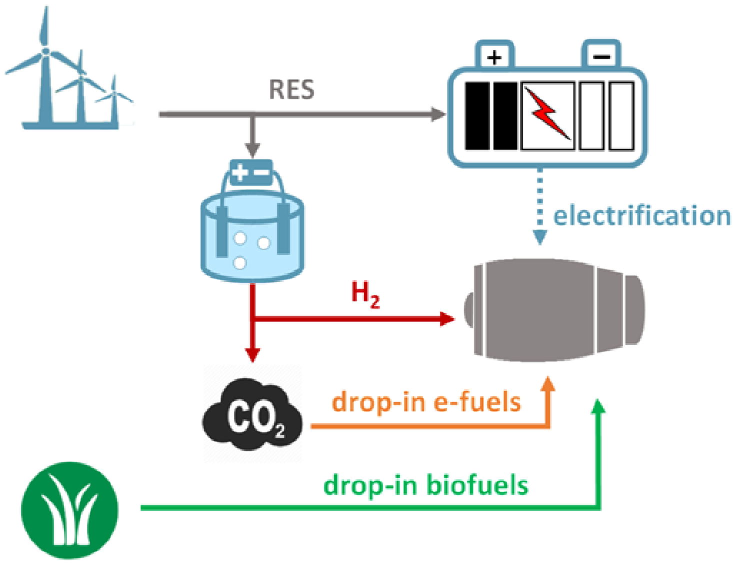

Figure 1. Alternatives towards decarbonization of the aviation field.

2.1. Sustainable Aviation Fuels (SAFs)

SAFs have recently started to attract great interest and have been identified by IATA as the most promising strategy to reduce CO_2 emissions in the aviation sector. Jet fuels, produced from renewable or recyclable feedstock, can deliver up to an 80% reduction in carbon emissions over the complete life cycle of the fuel, while the International Energy Agency (IEA) claims that by 2050, biofuels could provide 27% of the total amount of transport fuel, mainly replacing diesel, kerosene, and jet fuel [16]. Currently, most SAF technologies are still being tested or are at a prototype level, but they are making good progress, with some (e.g., HEFA) already being used in commercial flights as blending components [17]. However, one of the challenges faced in the production of SAFs is creating fuel from renewable sources, such as biomass, at an affordable price. Moreover, the feedstock used for producing the SAFs must not raise the question of food vs. fuel or cause deforestation, or any other environmental/societal harm. Another major concern is producing a fuel that matches the energy density of conventional fuels and their qualities such as a low freezing point and good cold flow properties. The ASTM D7566 specification has been developed over many years following a strict testing regime and approval process dedicated to SAF safety compliance towards their implementation in commercial aviation. The expected scale-up of SAF production in the coming years requires the parallel intensification of quality control in order to ensure that the new fuel technologies introduced are safe [18,19].

2.1.1. Biofuels

Hydroprocessed Esters and Fatty Acids (HEFA)

Hydroprocessed renewable jet fuels (HRJs or HEFA) are produced by the hydrogenation of vegetable oils, used cooking oils (UCOs), animal fats, waste grease, algal oil, or bio-oil. They are high-energy biofuels that can be used in conventional aircraft engines without further engine modification. Some of their weaknesses (such as low lubricity) are overcome by blending HRJs with other conventional fuels. Using HEFA as an aviation fuel has already been tested by many airline companies in passenger flights. However, it should be mentioned that the feedstock for HEFA is usually costly, often raises the question of food vs. fuel, and its cultivation can cause severe land-use change. Biodiesel is also produced from fatty acids via esterification, but it is considered insufficient as an aviation fuel as its energy density is very low compared to conventional fuels, and its freezing point is very high [10,13].

Fischer–Tropsch Fuels (FT Fuels)

FT fuels are liquid hydrocarbons that are produced by the catalytic conversion of syngas (mixture of CO and H_2), which in turn can be generated from a variety of biogenic feedstock via gasification. They are non-toxic, typically sulfur-free, and contain very few aromatics compared to diesel and gasoline, which results in lower emissions when used in jet engines. Fischer–Tropsch-synthesized kerosene with aromatics (FT-SPK/A) is a variation of the FT process in which a synthetic alternative aviation fuel containing aromatics is produced. The products in the FT process range from methane to long-chain hydrocarbons. The FT process is highly exothermic, meaning that the heat of reaction has to be quickly removed in order to avoid overheating and methane emissions. Like HEFA, FT fuels have low lubricity due to the absence of sulfur [9,10].

Alcohol-to-Jet (AtJ)

The AtJ process turns alcohols into jet fuel through the following reactions: dehydration, oligomerization, hydrogenation, isomerization, and distillation. The involved alcohols can be produced through conventional processes involving the fermentation of sugars deriving from sugar- and starch-rich crops such as sugarcane, corn, and wheat, or through advanced routes from lignocellulosic feedstock (e.g., hydrolysis). Alcohols can also be generated via gas fermentation by utilizing the carbon and hydrogen content of gases such as industrial off-gases. AtJ routes are attractive as they can convert various types of alcohols (so far, ethanol and isobutanol have been approved) from a wide range of sources into jet fuel as well as other hydrocarbons [10,11].

Direct Sugars to Hydrocarbons/Synthesized Iso-Paraffins (DSHC/SIP)

Genetically modified microorganisms (such as algae, bacteria, or yeast) can be used to convert sugar into hydrocarbons or lipids. Currently, biological routes almost exclusively use conventional sugar feedstock, although cellulosic sugars are being tested as well. The complexity and low efficiency of converting lignocellulosic sugars into fuels through DSHC translates into high feedstock cost and high energy consumption, which makes DSHC the most expensive alternative fuel route [10].

Others

The latest additions among the approved technologies (pathways) for SAF production are catalytic hydrothermolysis jet (CHJ) and hydroprocessed hydrocarbons (HC-HEFA). In the CHJ process (also called hydrothermal liquefaction), clean free fatty acid (FFA) oil from the processing of waste/energy oils is combined with the preheated feed water and then passed to the hydrothermal reactor. There, under high temperature and pressure conditions, a single phase is formed consisting of FFA and supercritical water wherein the FFAs are cracked, isomerized, and cyclized into paraffin, isoparaffin, cycloparaffin, and aromatic compounds. The HC-HEFA pathway refers to the hydroprocessing of bio-derived hydrocarbons (unlike the fatty acids or fatty acid esters found in HEFA production) that come from oils found in a specific alga (i.e., Botryococcus braunii). Other also possible pathways for bio-jet fuel production are under various stages of the ASTM evaluation process. A typical example is synthetic kerosene via aqueous phase reforming (APR-SK) [10,20].

So far, only biofuels have secured ASTM certification for commercial use (via blending). SAFs are met as blending components in mixtures with conventional aviation fuels rather than 100% bio-based compounds. Because the penetration of SAFs in the market is still limited and actually HEFA-driven, SAF can be blended at up to 50% with traditional jet fuel and all quality tests are completed as per a traditional jet fuel. However, along with the timely scale-up for the other certified jet fuel pathways, the safety research should be extended to evaluate the miscibility of fuels containing different synthetic compounds as well. The availability of a larger number of alternative certified blends would make possible their simultaneous presence in a fuel tank or aircraft, and in that case, even the slightest alteration in fuel quality should have been anticipated [21].

The SAF technology certification timeline is illustrated in Figure 2.

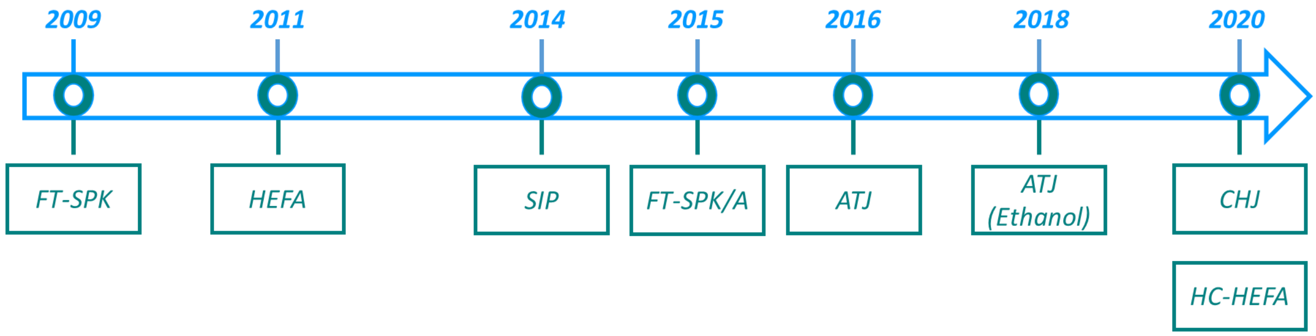

Figure 2. SAF technology certification timeline.

2.1.2. Electrofuels (e-Fuels)

Electrofuels or e-fuels are an emerging class of carbon-neutral drop-in replacement fuels that are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. E-fuels result from the combination of 'green or e-hydrogen', produced by electrolysis of water with renewable electricity, and CO_2, which can be obtained from various sources including biomass combustion, industrial processes (e.g., flue gases from fossil oil combustion), biogenic CO_2, and CO_2 captured directly from the air. E-fuel production routes consist of e-hydrogen reacting with captured CO_2, followed by different conversion routes according to the final desired e-fuel such as the methanization route for e-methane; methanol synthesis for e-methanol, e-DME, e-OME; or the reverse water–gas shift (RWGS) reaction to produce syngas + Fischer–Tropsch synthesis to produce e-liquid hydrocarbons, such as e-gasoline, e-diesel, or e-jet. E-jet production usually refers to the methanol route (e-methanol upgrade to jet) or the FT route (RWGS + Fischer–Tropsch) [10,15].

2.2. Hydrogen

The use of hydrogen in aviation, both as a source of propulsion power and as onboard power, has the potential to diminish noise pollution and GHG emissions and improve efficiency, as long as hydrogen is produced from renewable energy sources. Following thermal and biochemical methods, biohydrogen can be produced from a variety of biomass resources. It can be used either as liquid fuel for turboengines, or in fuel cells (FCs). In the first case, because of hydrogen's low volumetric energy density, major aircraft changes are required in order to accommodate the cryogenic tanks to store liquid hydrogen (LH_2). In addition, storing liquid hydrogen entails risks, as it burns in low concentrations upon mixing with air, and it needs a constant low temperature in order to be kept in the liquid phase. The additional weight of these tanks means extra energy consumption in comparison to kerosene aircrafts. As for the FCs, they can be used to power onboard electrical equipment or an electric propulsion system. They could be used in parallel with or in place of auxiliary power units (APUs), which consist of a small gas turbine supplying power when the aircraft is stationary or while cruising (as backup) [10].

2.3. Electrification (Hybrid or Full-Electric Aircrafts)

Many auxiliary aviation systems are being gradually electrified, because of the relatively lightweight and improved efficiency compared to mechanical systems. In addition, electric propulsion is being investigated given that it can come up with many benefits, such as noise reduction and emission savings. Electric aircrafts are divided into hybrid and full electric. Hybrid aircrafts have an electric motor with a battery and a turbofan (in series or parallel), thereby allowing for the downsizing of jet engines and increased fuel economy. Full-electric aircrafts could lead to zero onboard emissions and noise reduction. However, electric aircrafts face two severe challenges: the low energy density of batteries and the limitations on the distance traveled. Even the most promising batteries have an energy density far short of kerosene, while issues such as battery charging and infrastructure need a considerable amount of consideration [10].

2.4. Market Overview and Technology Readiness Level (TRL)

An overview of the current alternative fuel routes for the aviation sector, as described above, is presented in Figure 3.

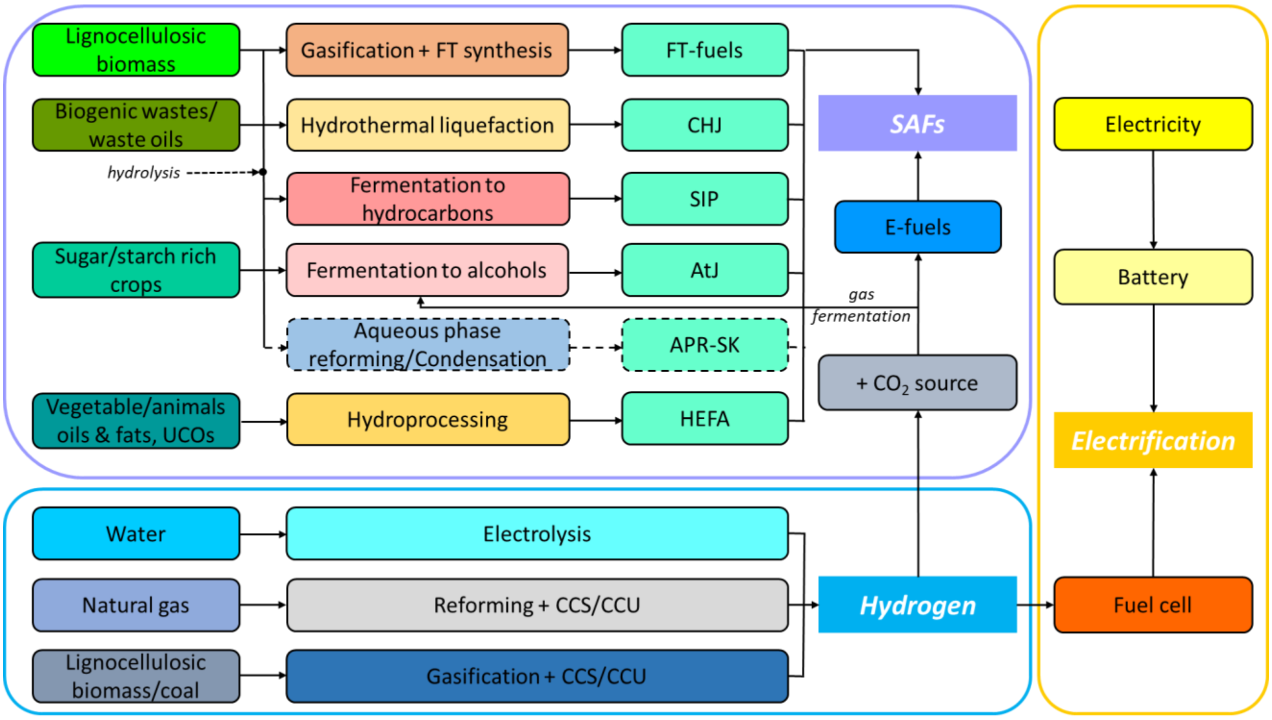

Figure 3. Overview of alternative fuel routes for the aviation sector.

Concerning the technological maturity of the current tendencies in aviation, each route has seen different growth. Starting with SAFs, while HEFA is the only alternative fuel in commercial use, the FT and AtJ market developments are also particularly intense.

The HEFA technology is currently the most mature, with HEFA fuels being the only alternative already used commercially (TRL 9) [10]. HEFA-jet is produced on a batch basis by several commercial-scale facilities worldwide [22]. It can be blended up to 50% with conventional fuel, but flight trials have recently been performed with 100% HEFA. In particular, aviation leaders such as Airbus, Rolls Royce, and the German Aerospace Center (DLR) launched the first 100% SAF commercial passenger jet flight with the HEFA-fuel provided by Neste [23].

Neste reaches an annual capacity of 100 kt SAF and production will increase to 1.5 million tons annually by the end of 2023. Neste's SAF is available at many major airports, including San Francisco International Airport (SFO), Heathrow Airport (LHR), and Frankfurt Airport (FRA) and is currently being used by many leading commercial airlines including KLM, Lufthansa, Delta, and American Airlines [24]. There are also synergies with leading fuel distributors that provide Neste's SAF to the market [25,26].

As for the Fischer–Tropsch fuels, the bio-based gasification with FT synthesis is now just approaching commercialization (TRL 7-8), while the jet fuel produced through the FT route has been certified and can be blended up to 50% with fossil kerosene. The collaboration between British Airways and Velocys [27] aims to establish the first commercial Fischer–Tropsch BtL plant in the UK. Other notable commercial plants that are based on FT liquid production using sustainable feedstock are found in the USA (i.e., Red Rock Biofuels, Sierra Biofuels) [28].

Alcohol-to-jet fuels have been certified by ASTM (i.e., from ethanol and isobutanol) and can be blended up to 50%. This is another route that is approaching commercialization (TRL 7-8) [10]. In 2018, Virgin Atlantic completed the first commercial flight with AtJ fuel produced by Lanzatech [29]. Lanzatech is also the technology provider of the project FLITE that targets the installation of Europe's first of its kind AtJ production plant at pre-commercial scale. In 2012 and 2014, both the US Air Force and the US Navy used bio-jet fuel produced by the AtJ pathway to conduct the first tests [30].

Lanzatech, via a spin-off called LanzaJet, aims to be amongst the leaders in the emerging SAF market. LanzaJet AtJ technology can process any source of sustainable ethanol, including ethanol produced from municipal solid waste, agricultural residues, industrial off-gases, and biomass. British Airways will purchase SAF from LanzaJet's US plant in Georgia to power a number of the airline's flights from late 2022. The deal also involves LanzaJet conducting early-stage planning for a potential large-scale commercial SAF biorefinery in the UK [31]. Another key player in the AtJ pathway is the Colorado renewable fuels producer Gevo. The Oneworld Alliance members will use Gevo's SAF for operations in California including San Diego, San Francisco, San Jose, and Los Angeles International airports. Delivery of the fuel is expected to commence in 2027 for a five-year term [32].

Regarding SIP, there are two different production routes. The first, using conventional sugar feedstock, is at the pre-commercial level (TRL 7), while the second, based on cellulosic feedstock, is still at the prototype level (TRL 5). The certified route includes sugar fermentation to farnesene, which, after hydroprocessing to farnesane, can be blended up to 10% with fossil kerosene [10]. Lufthansa performed a commercial flight with a 10% farnesane blend from Amyris/Total in 2014 [33]. However, at present, potential SIP developers tend to target the chemical, pharmaceutical, food, and feed markets [10].

The technological maturity of e-fuels, or power-to-liquid (PtL) routes as they are also called, depends mostly on the maturity of the single components and the design configuration chosen. For example, routes where the CO_2 comes from concentrated sources, such as CO_2 waste streams from industrial processes, biogas upgrading, or beer brewing, are available for commercial use, while others such as CO_2 captured directly from the air remain at an earlier level (TRL 5–7) [10]. In general, PtL can be characterized by a relatively high technological maturity, since the majority of the individual process steps for kerosene synthesis via PtL are proven technologies with high TRLs. E-fuel routes are already being implemented in over 40 pilot and demonstration projects in Europe [34]. The barriers towards full commercialization are the amount of capital-intensive equipment to deploy the technology, the need for a substantial increase in renewable electricity production, and the rather low energy efficiency due to the inherent thermodynamic conversion losses that occur during e-fuel production. Technologies at the lowest level of development include electrolytic or electro-photocatalytic CO_2 conversion.

There are also commercial applications, such as Carbon Recycling International, which has produced over 4 kt of methanol per year since 2012 and aspires to commission the world's first 110 kt/year recycled carbon methanol production plant after 2021 [35]. Energy supplier Uniper, Siemens Energy, and aircraft manufacturer Airbus are teaming up with chemical and energy company Sasol ecoFT to realize a commercial project to produce SAF for Germany named 'Green Fuels Hamburg'. From 2026, the production facility in its initial configuration is projected to produce at least 10,000 tn of PtL-SAF annually [36].

Table 1 summarizes the current technology status of SAFs and the latest highlights of each route.

Table 1. Current technology status of SAFs.

SAFs	Fuel	Technology Readiness Level (TRL)	Highlights
Biofuels	HEFA	9	Commercial passenger jet flight test with 100% HEFA fuel [23] Projection for annual production of 1.5 million tons by the end of 2023 (Neste) [24]
	FT-fuels	7–8	Establishment of the first commercial Fischer–Tropsch BtL plant in the UK (Velocys) [27]
	AtJ	7–8	First commercial flight with AtJ fuel [29] British Airways will purchase SAF from LanzaJet's US plant from late 2022 [31] Oneworld Alliance members will utilize Gevo's SAF for operations in California from 2027, for a five year-term [32]
	DSHC/SIP	5–7 (depending on the sugar type)	Commercial flight with 10% farnesane blend from Amyris/Total (2014) [33]
E-fuels	e-jet, e-methanol *	5–8 (depending on the CO_2 source)	World's first 110 kt/year recycled carbon methanol production plant [35] 'Green Fuels Hamburg' [36]

* considering methanol upgrade to SAF.

Although hydrogen aviation is not a new concept, it will require significant research and development (R&D), investments, and accompanying regulations to ensure safe, economic H_2 aircrafts and infrastructure mastering the climate impact [37]. Airbus has performed a study called 'Cryoplane' in order to examine the concept of hydrogen-fueled turbo-engines, which led to the adoption of a minimal-change approach to the wing configuration and engine design [38]. However, the main research activities of hydrogen involvement in aviation are related to the development of hydrogen fuel cell aircrafts, as it is a much lighter way to power the electric airplanes than batteries. Fuel cell systems are tested as auxiliary power units in commercial aircrafts, even though they have not been deployed in serial production. H_2 propulsion with fuel cell systems is also tested for urban air mobility (unmanned air vehicles and 'taxi'-drones) [37]. One such project is the HY4, a four-seater hydrogen fuel cell aircraft, developed by DLR, which completed its first flight in 2016 [39]. Moreover, ZeroAvia USA has launched the HyFlyer project, which aims to decarbonize medium-range, six-seater aircrafts by replacing the conventional propeller with a fuel cell system [40]. In general, the immediate priorities for hydrogen aviation R&D are the development of lightweight tank systems, reliable fuel distribution components, H_2 propulsion turbines with low NO_x emission and long lifetimes, and high-power fuel cell systems [41].

Since the 1960s, many aviation auxiliary systems have gradually been electrified, while electric propulsion systems have seen development as well. However, concerning the latter, they all remain at a demonstration level [42]. Regarding the development of hybrid electric aircrafts, Airbus, Rolls-Royce, and Siemens AG collaborated to launch the flight demonstrator E-Fan X [43]. In addition, Boeing and NASA have partnered up in order to develop a hybrid electric aircraft, named 'SUGAR Volt', with twin engines designed to burn fuel when the power demand is high (e.g., take-off) and to run on electricity while traveling [44]. Other industries have experimented with building full-electric aircrafts, mostly for civil non-commercial aviation and urban air-taxis, such as Kitty Hawk USA that developed a two-seater to be used by Air New Zealand as an air-taxi [45]. Moreover, Airbus has taken on an air-taxi project called Vahana [46], while Lilium GmbH and Eviation Aircraft Ltd. have produced full-electric, five- and nine-seater aircrafts, respectively, meant for regional commuting [47–49]. In order for electric aircrafts to be more commercially available, challenges such as the plane's mass reduction or the expansion of the batteries' energy density must be faced. As already mentioned, there is a limitation in the envisaged travel distance and in order to tackle this, electric aircrafts could be used for commercial regional flights or for pilot training. Such an aircraft is the Pipistrel Alpha Electro, which is a two-seater, full-electric aircraft with a range of about 160 km on a single charge [50]. Concerning the endeavor to increase the energy density of batteries, OXIS Energy has made significant progress in developing solid-state lithium–sulfur batteries, which have an increased density and can be used in electric buses, electric trucks, aircraft, and marine trials [51].

In general, it can be observed that SAFs are technologically in a favorable position towards the decarbonization of the aviation industry. Their compatibility with the extended current infrastructure is a great advantage that is able to offer instant industrial compliance with the international policies and regulations. Hydrogen aviation or electrification require deep and comprehensive changes in the industry and can only be considered as long-term alternatives.

3. Comparative Analysis and Insight

Taking into account the already-mentioned dominant position of SAFs in comparison with hydrogen aviation or electrification at least for the near future, a comparative analysis is performed among the most active SAF technologies on the market in terms of cost and environmental efficiency. The latest EU proposal, 'ReFuelEU Aviation' [15], identifies the key role of HEFA, Fischer–Tropsch, AtJ, and e-fuels in the emerging jet fuel market and therefore the focus of the present study is on these routes as well. The selected metrics for the comparison are: minimum jet fuel selling price (MJSP), expressed in EUR/L, for the techno-economic assessment and GHG emissions, expressed in gCO_{2eq}/MJ of produced fuel, for the environmental assessment.

Due to the intense activity in the SAF sector from the market, research, and legislative point of view, there is a wealth of data available in the literature concerning the main characteristics of each technology. The differences among the examined studies in terms of system boundaries, economic and life cycle assumptions, and processing steps sometimes made direct comparisons challenging. However, the large volume of collected data and the inclusion of studies only after 2015 allowed the extraction of solid conclusions and relevant future projections.

3.1. Techno-Economic Assessment (Literature Review)

Aiming to make the present review as up-to-date as possible, only techno-economic studies after 2015 have been taken into consideration. A wide collection of predictions concerning SAF MJSPs via multiple feedstocks has been carried out for HEFA, FT, AtJ, and e-jet pathways and is presented in Table 2.

The HEFA process envisages the hydroprocessing of various oils to produce jet fuel as the primary product. Studies that involve first-generation (i.e., palm oil, soybean oil) as well as second-generation (i.e., UCOs) feedstock oils have been identified and an MJSP range of 0.81–1.84 EUR/L was obtained. UCO-driven cases appear to be the most cost-competitive HEFA options, with values below 1 EUR/L seeming possible. It was noticed that the feedstock cost accounts for more than 50% of the levelized production costs in every relative techno-economic study, leading to the conclusion that HEFA costs are driven mainly by the costs of the purchased oils.

Table 2. Techno-economic studies concerning SAFs potential MJSP for HEFA, FT, AtJ, and e-jet routes.

Route	Year	Feedstock	MJSP
HEFA	2019	Vegetable oil	1.39 EUR/L [52]
	2016	Vegetable oil	1.84 EUR/L [53]
	2015	UCOs	1.03 EUR/L [54]
	2018	Jatropha oil Palm oil	1.60 EUR/L 0.81 EUR/L [55]
	2017	UCOs Tallow Soybean oil	0.94 EUR/L 1.10 EUR/L 1.23 EUR/L [56]
	2017	UCOs	1.29 EUR/L [57]
	2019	UCOs Soybean oil	0.88 EUR/L 1.09 EUR/L [58]
	2018	Jatropha oil Palm oil	1.44 EUR/L 1.04 EUR/L [59]
FT	2022	Municipal solid waste Agricultural residues	1.55 EUR/L 2.01 EUR/L [60]
	2022	Rice husk	2.22 EUR/L [61]
	2015	Wood chips	1.24 EUR/L [62]
	2016	Lignocellulose feedstock	1.97 EUR/L [53]
	2019	Municipal solid waste Agricultural residues	1.34 EUR/L 1.80 EUR/L [58]
	2022	Forestry residues	2.47 EUR/L [63]
	2022	Lignocellulose feedstock	2.22 EUR/L [64]
	2021	Municipal solid waste Agricultural residues Forestry residues	1.55 EUR/L 2.00 EUR/L 1.82 EUR/L [65]
	2022	Rice husk Pyrolysis bio-oil	2.22 EUR/L 2.34 EUR/L [66]
	2021	Corn stover	3.64 EUR/L [67]
AtJ	2016	Corn grain (1-G ethanol) Corn stover (2-G ethanol)	1.21 EUR/L 1.71 EUR/L [68]
	2022	Corn grain (1-G ethanol) Lignocellulose (2-G ethanol)	0.90 EUR/L 2.30 EUR/L [69]
	2016	Sugarcane (1-G ethanol) Lignocellulose (2-G ethanol) Lignocellulose (2-G ethanol)	2.02 EUR/L 1.98 EUR/L 2.75 EUR/L [53]
	2015	Forestry residues (2-G ethanol) Wheat straw (2-G ethanol)	1.98 EUR/L 2.72 EUR/L [54]
	2015	Woody biomass (2-G mixed alcohols)	1.28 EUR/L [62]
	2020	Sugarcane (1-G ethanol) Lignocellulose (2-G ethanol) Steel off-gases (2-G ethanol)	1.27 EUR/L 1.71 EUR/L 1.53 EUR/L [70]

Table 2. *Cont.*

Route	Year	Feedstock	MJSP
E-jet	2022	$CO_2 + H_2$ (FT route/Methanol route)	2.10–2.30 EUR/L [71]
	2020	$CO_2 + H_2$ (FT route/Methanol route)	2.13 EUR/L [72]
	2021	$CO_2 + H_2$ (FT route)	2.77–4.89 EUR/L [73]
	2022	$CO_2 + H_2$ (FT route)	2.33–3.17 EUR/L [74]
	2021	$CO_2 + H_2$ (FT route/Methanol route)	2.25–5.00 EUR/L [75]
	2021	$CO_2 + H_2$ (FT route)	3.39 EUR/L [76]
	2019	$CO_2 + H_2$ (FT route/Methanol route)	2.94 EUR/L [77]
	2018	$CO_2 + H_2$ (Methanol route) $CO_2 + H_2$ (FT route)	2.45–3.28 EUR/L 2.60–3.37 EUR/L [78]

The FT process is based on the promotion of residue-based biofuels (or so-called advanced biofuels). In particular, a wide variety of biogenic residues is appropriate feedstock for the gasification process that subsequently feeds the FT pathway with syngas. The gasification-driven FT process incurs high capital expenses (i.e., more than 50% of the production costs), but as already mentioned, is flexible regarding the type of feedstock used. This flexibility involving multiple feedstocks (e.g., forestry residues, agricultural residues, municipal solid waste) results in a relatively wide range of production costs, as also observed in the present review (1.24–3.64 EUR/L). The lowest obtained MJSPs refer to the involvement of municipal solid waste (MSW) as feedstock, since MSW is usually available free of charge and has the potential for negative costs [79,80].

AtJ production costs depend mainly on ethanol costs. While first-generation (1-G) ethanol, which is obtained via the fermentation of sugar/starch crops (e.g., sugarcane, corn grain), is a merchandised and mature product, the conversion of lignocellulosic feedstock via hydrolysis and subsequent fermentation or the conversion of off-gases via gas fermentation to ethanol (2-G) is a more complex and usually more costly pathway. However, multiple AtJ pathways based on sustainable feedstock (2-G ethanol) also appear to result in affordable or at least competitive production costs. A group of techno-economic studies involving 1-G as well as 2-G ethanol was gathered and an MJSP range of 0.90–2.75 EUR/L was obtained for the AtJ route.

Concerning e-fuels, the main routes identified for e-jet production are the FT route and the methanol route. The FT route encompasses the RWGS or co-electrolysis followed by FT synthesis, while the methanol route involves methanol formation and subsequent upgrade to jet. A wide MJSP spectrum of 2.10–5.00 EUR/L was obtained from the identified power-to-liquid (PtL) studies. E-jet fuels exhibit the greatest uncertainty due to the wide range of potentially involved technologies including CO_2 capture from concentrated sources or direct air capture (DAC), solid oxide electrolyzer cell (SOEC) or RWGS, and, of course, the diverging prices of green electricity. Green hydrogen and its associated costs (i.e., hydrogen plant, green electricity) account for more than 70% of the levelized e-jet production costs in most of the studies.

Utilizing any available cost breakdown from the identified techno-economic studies, a general range was set regarding the CAPEX (capital expenditures), OPEX (operational expenditures), and feedstock contributions to the production costs of each technology (Table 3). The dependence of HEFA technology on the feedstock cost has already been mentioned, while the feedstock flexibility of the FT and AtJ pathways leads to wide ranges with CAPEX as the main cost indicator. Concerning e-jet, the securement of green hydrogen, which is considered feedstock, is clearly the most influential cost parameter and is driven by renewable electricity prices and electrolyzer hardware [81]. The average values from Table 3 are used for the cost allocation of each technology, presented in Figure 4.

Table 3. CAPEX, OPEX, and feedstock range of contribution to the production costs.

	HEFA *	FT	AtJ	E-Jet **
CAPEX range (%)	22–40	54–81	45–75	5–20
OPEX range (%)	8–10	12–21	2–14	5–15
Feedstock range (%)	51–69	0–32	20–44	70–85

* hydrogen-associated costs are considered CAPEX- and OPEX-related costs within HEFA process. ** hydrogen-associated costs are considered feedstock-related costs within e-jet process.

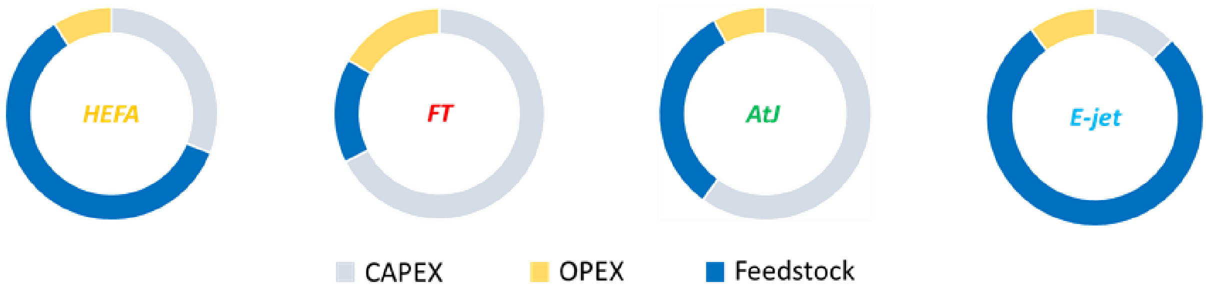

Figure 4. Average CAPEX, OPEX, and feedstock range of contribution to the MJSP formation.

All of the reported MJSPs of Table 2 have been imported into Figure 5 along with the generated trend lines of each route sourced from the corresponding set of prices. Moreover, the global average price evolution of conventional jet fuel (Jet A-1) in recent years was added, as extracted from [82].

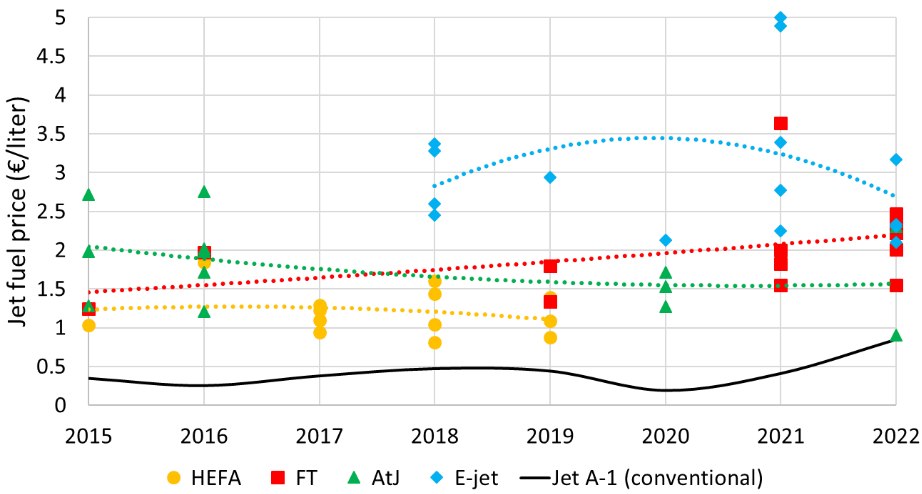

Figure 5. MJSP predictions for SAF and Jet A-1 global average price evolution in recent years.

It is clear that HEFA-produced SAF is the most cost-competitive option and the only route so far that can consistently compete with conventional jet fuel prices. Moreover, the fact that the relevant literature (HEFA) after 2019 is sparse is another indicator that HEFA has already penetrated the market and can be considered the only state-of-the-art commercial SAF. The respective trend lines for the FT and AtJ routes lie well within the range of 1.50–2.00 EUR/L. As already mentioned, FT and AtJ are two technologies that have approached commercialization, subsequently causing intense research and market interest. The feedstock flexibility of these two routes results in potential deviations regarding the assessment of their exact production costs, but it is rather safe to claim that cost-effective feedstock (e.g., MSW, residues) can lead to cost-competitive FT and AtJ implementations. The ongoing technological advances and the inherent scale effect are expected to further reduce production costs and turn the FT and AtJ routes into viable choices. The e-jet generated trend line moves around 3 EUR/L and illustrates the already-mentioned current uncertainty that characterizes this kind of fuel due to the dynamic cost diversity of the potentially involved technologies. Almost every identified techno-economic study struggles to determine affordable e-jet production costs at present, but they all highlight the significant cost reduction potential in the future, driven mainly by lower-cost electrolyzers and scale effects.

In general, it can be safely posited that technological advances and favorable legislative frameworks have drastically assisted SAFs in terms of closing the gap with conventional jet fuel in terms of production costs. There is a sense that the envisaged intensification of carbon costs and blending mandates will eventually enable a break-even between SAF and fossil jet fuel. The latter is expected to be the decisive step for the direct unlocking of SAFs in the fuel market.

3.2. Environmental Assessment (Literature Review)

Although the techno-economic assessment of SAF technologies reveals that these pathways are yet to consistently compete with fossil jet fuel in financial terms, their environmental advantage over conventional fuels cannot be disputed. Life cycle analysis (LCA) is crucial for the environmental assessment of these pathways, since it can quantify the GHG emissions to the environment of each technology, including all stages from feedstock production to end product use. The GHG emissions attributable to each technology are typically measured in grams of carbon dioxide equivalents per megajoule of the produced fuel (g CO_2eq/MJ).

Conventional jet fuel produced from petroleum resources has a carbon intensity within the range of 85–95 g CO_2eq/MJ. About 80% of the mentioned carbon intensity comes from the combustion of fossil fuel, while the remaining GHG emissions are attributed to the fuel extraction, the processing of the fuel in refineries, and its subsequent transportation. Given that the calculations of the GHG emissions of conventional jet fuel differ between the conducted studies, the International Civil Aviation Organization's (ICAO) policy for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has decided to use a baseline of 89 g CO_2eq/MJ [83].

HEFA jet fuel, as stated previously, is one of the most prominent alternatives to replace conventional jet fuel in the near future. At present, its price is the lowest compared to the other existing SAFs. However, as for its environmental analysis, the GHG emissions attributed to its use vary depending on the feedstock involved in its production. For example, HEFA jet fuel produced from waste fats, oils, and greases (FOGs) generally has significantly low life-cycle GHG emissions, given that this process avoids the GHG emissions attributed to crop production. On the other hand, the production of HEFA from vegetable oils typically has higher GHG emissions. It should be noted that in the HEFA conversion process, a large volume of the emissions comes from the production of the required hydrogen [83]. Thus, depending on the source of hydrogen or the source of electricity at the regional grid, the GHG emissions of the HEFA fuel can vary greatly. CO_2 emission savings from HEFA fuels are estimated to be around 25–85% of the corresponding conventional jet fuel emissions [84], forming an average of 10–66 g CO_2eq/MJ, which is in general accordance with the emission savings for HEFA reported in the recent dominant proposal 'ReFuelEU Aviation' [15].

Jet fuels produced through the gasification–FT pathway from agricultural residues, non-food energy crops, or solid waste generally achieve the lowest GHG emissions among the approved fuel technologies for SAFs. The CO_2 emission savings are estimated to be approximately 85–91% of the corresponding conventional jet fuel emissions, leading to an average of 5–16 g CO_2eq/MJ [15,84]. It should be noted that the utilization of MSW for FT fuels can lead to a wide range of emissions depending on their biogenic content. The conversion step is considered the most environmentally intense for the FT pathway [85].

AtJ pathways generally have higher GHG emissions than HEFA and FT fuels, mainly due to the energy- and GHG-intensive biochemical processes for the production of alcohols. Depending on the feedstock, a wide range of GHG emission savings can be found in the literature, varying from 26% to 73% of the petroleum jet baseline [15,84]. For example, sugary crops (e.g., sugar beet, sugarcane) show a better emission mitigation potential compared with starch crops such as maize and cereals, since this type of feedstock is more efficient to grow and process. Jet fuel produced from lignocellulosic crops and residues also has a relatively low carbon footprint because of the low GHG emissions related to fertilizer use, feedstock cultivation, and collection [86]. Carbon-containing waste gases (e.g., steel mill off-gases) are also environmentally good candidates for AtJ, since no emissions linked to feedstock cultivation/collection are included, thus providing a high emission reduction. However, a large portion of the GHG emissions of these pathways is attributed to the electricity required for gas compression.

E-fuels can make a significant contribution to reducing GHG emissions in the aviation sector. Studies indicate that the overall direct GHG emissions of an e-fuel production pathway from renewable electricity and CO_2 are approximately 1 g CO_2eq/MJ of final fuel [87], delivering more than 95% emission savings related to the fossil jet reference. This estimation only accounts for transportation, distribution, and dispensing, since only renewable sources are involved in the production of the fuel. However, due to the large amount of renewable electricity that is required for the production of this type of fuel, LCA studies often include the emissions deriving from the construction of the production facilities and power stations. According to [88], the carbon footprint of the e-jet pathway via the FT route, including GHG emissions from asset construction, is estimated to be from 5 to 10 g CO_2eq/MJ of the final fuel when using electricity from offshore wind in Norway and a wind/PV hybrid power station in Germany, respectively. It can be conceived that the environmental performance of e-fuels is highly dependent on the source of electricity generation. Indicatively, if grid-average electricity were used for the production of e-fuels, the GHG emissions could exceed the fossil jet baseline (approx. 130 g CO_2eq/MJ) [83]. The use of renewable electricity is a clear prerequisite for the achievement of GHG reductions.

For sustainability reasons, according to the Renewable Energy Directive (RED), first-generation biofuels produced from edible energy crops, such as sugar, starch, and oil crops, should not be supported [15]. When the cultivation of crops for biofuels replaces traditional crops for food production, a change in how the land is used occurs, which can have dire environmental impacts. In order to meet the growing demand for aviation fuel, agricultural land is often expanded to places with high carbon stock, such as forests, peatland, and wetlands. This induced land-use change (ILUC) releases carbon from disturbed biomass and soil, causing further GHG emissions and raising concerns about the loss of biodiversity in these areas. Even though HEFA is the most technologically ready alternative to petroleum jet, its use is bound by environmental concerns related not only to high direct GHG emissions, but also to significant ILUC emissions. ATJ pathways can also release considerable amounts of ILUC emissions, especially when produced from food crops. In some cases, ILUC emissions can completely negate the GHG emission savings, surpassing even the baseline for conventional petroleum jet fuel [83,85]. Land-use change can also be caused by some second-generation biofuels that are produced from energy crops, such as switchgrass, but with low GHG intensity. FT fuels are mostly produced from lignocellulosic crops or residues and wastes, thus leading to low or zero ILUC emissions. Negative ILUC emissions can also be generated if marginal areas are used for cultivation, causing an increase in carbon stock in the soil [89]. Under RED II, crop-based biofuels with significant ILUC emissions are capped at the 2019 level and will be phased-out by the year 2030 [15]. It should also be stated that the magnitude of the ILUC emissions depends greatly on the feedstock used, the economic model used for their calculation, and the modeler's assumptions, which highlights the uncertainty in the assessment [90].

Except for the ILUC emissions associated with the crop-derived biofuels, there are also indirect emissions linked with the use of by-products, residues, and wastes as feedstock, as well as renewable electricity. In fact, many of these materials have valuable existing uses and their diversion from these uses can sometimes generate indirect emissions from the materials that will be used in their place. Some of these materials can be substituted by crops or fossil fuels resulting in higher GHG emissions. For instance, the displacement of FOGs, such as animal fats, corn oil, and palm fatty acid distillates, from their existing uses in other markets (e.g., oleochemicals, heat and power, animal feed) would be likely to cause high indirect emissions when replaced by virgin vegetable oils or fossil fuels. Generally, lignocellulosic feedstock, such as agricultural and forestry residues, if collected in quantities that do not affect soil quality, can be diverted with less indirect emissions compared with FOGs, since fewer markets exist for these materials. Carbon-containing industrial flue gases, such as steel mill off-gases, also entail some indirect emission risks since many industries use them for onsite energy generation. Therefore, substituting these gases with other energy sources may lead to higher GHG emissions. Electrofuels may also cause displacement effects if renewable electricity is diverted from existing uses and replaced by a marginal source of electricity. For this reason, it is important to ensure that the renewable electricity used for e-fuel production is both new and additional. On the other hand, when MSW from landfills are used as feedstock, negative displacement emissions may occur due to the avoidance of methane emissions from anaerobic digestion at some landfills [83].

Figure 6 illustrates the Well-to-Wing emissions (i.e., emissions over the entire life cycle of fuels, from production to combustion) of the SAF production pathways from various feedstock types. The data for the direct emissions were extracted from [70,78,83,84]. For the ILUC emissions, values estimated by ICAO were used [84]. Displacement emissions were not included since they are extremely sensitive to assumptions about the uses from which the materials are diverted, and are therefore difficult to estimate.

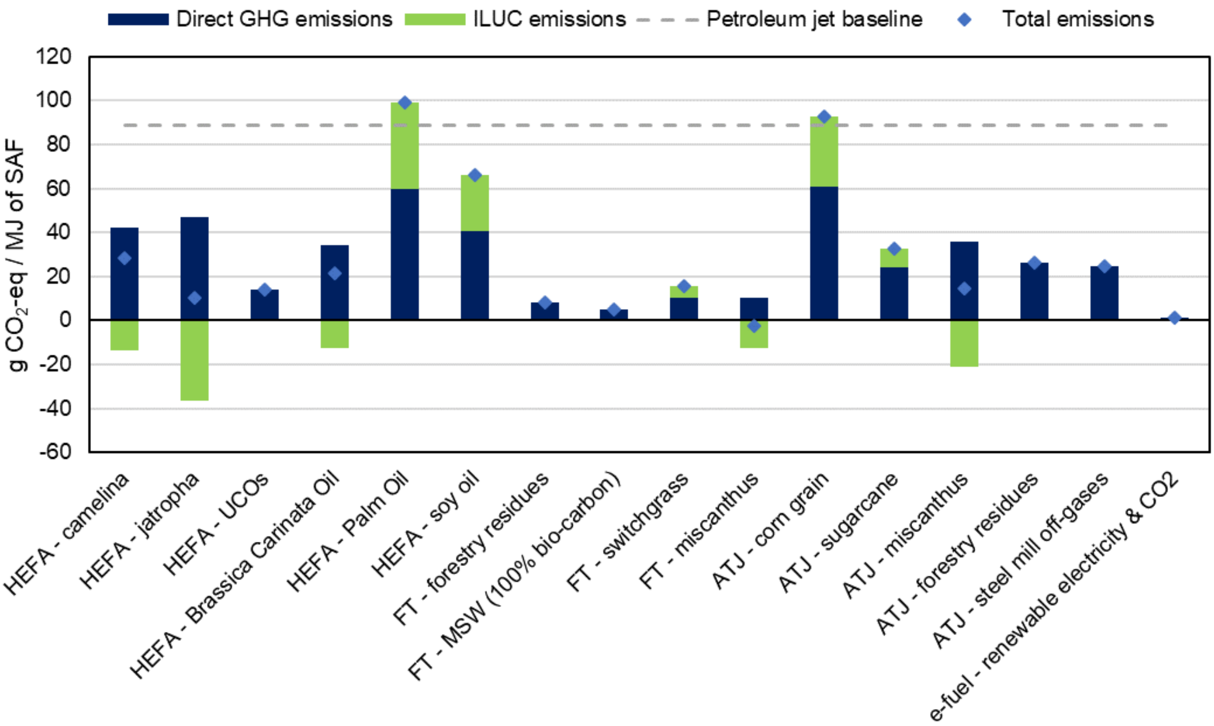

Figure 6. Well-to-Wing GHG emissions of the SAF pathways from various feedstock types relative to petroleum jet baseline.

3.3. Future Projections

Forecasting regarding a newly emerging market, such as SAFs, that is not yet fully formed is quite a challenging task. However, the key characteristics of each technology allow for some cautious predictions regarding their development and their margins of competitiveness [91,92]. Therefore, this section deals with the future projections of the HEFA, FT, AtJ, and e-jet pathways based on the available forecasting studies. At this point, it should be noted that as research on the SAF technologies progresses and more data are collected over the years, strategies such as big data analytics (BDA) could be useful to improve the performance of these technologies and accelerate their scale-up [93].

HEFA jet fuel is the most cost-competitive option and is expected to remain the most efficient pathway, at least through to 2030. Nevertheless, its dependence on feedstock costs is an inhibiting factor towards a decisive reduction in the overall production costs since HEFA feedstock (i.e., oils) is a factor with low cost-reduction potential. The limited supply of feedstock and lack of cultivation areas turn HEFA into a feedstock-constrained pathway. Indicatively, HEFA facilities use the majority of their capacities to produce biodiesel. A rather stiff selling price is expected for HEFA jet fuel in the coming years due to the absence of any obvious aspect for cost improvement. Hydrogen (green) seems to be the only variable from the HEFA production route with remarkable cost-reduction potential and is by no means sufficient to drastically affect the production costs [13,94–96].

FT and AtJ technologies involve intense capital expenses and at first glance, their cost-reduction potential seems rather moderate. However, on the one hand, the feedstock constraints that do not let HEFA meet the accelerated SAF scale-up requirements on its own, and on the other hand, the high feedstock flexibility of the AtJ and FT routes, are expected to speed up the commercial establishment and subsequently the beneficial scale effect of these technologies. While almost all SAF production is currently sourced from the HEFA pathway and waste FOGs are expected to constitute the largest source of feedstock until 2030, there are claims that the next two decades will be dominated by technologies handling advanced feedstock (e.g., MSW, biogenic residues) such as FT and AtJ. Agricultural residues constitute the largest quantities of the available feedstock, but their exploitation will be delayed due to the time lag associated with the commissioning of such new large-scale biorefineries. Of course, the inhibiting factors for the extended reduction of production costs, such as the high costs related to gasification for FT or lignocellulosic ethanol for AtJ, will continue to question the financial competitiveness of these routes. Already-announced investments in new AtJ and FT facilities raise confidence that SAF's competitiveness from these routes can be significantly increased [94,97–100].

PtL costs are almost entirely driven by the costs of purchased hydrogen. Therefore, the great cost-reduction potential of hydrogen, primarily due to remarkably decreased renewable electricity prices and secondarily due to electrolyzer hardware cost reductions, is able to decisively upgrade the future competitiveness of e-jet pathways. Their undisputed beneficial environmental impact along with their independence from bioenergy availability are expected to rapidly reduce their current, admittedly non-affordable, production costs. The pace of cost reductions will depend on the speed of the global shift to sustainable energy, but considering that the price of renewable electricity continues to decline, e-fuel pathways are set to start producing significant volumes after 2035. Of course, e-fuels are unlikely to achieve steady establishment in the SAF market without dedicated policy support, such as a sub-target within the overall blending mandate [13,94,98,101].

Within the present review, the average MJSPs for each technology (HEFA, FT, AtJ, and e-jet) were calculated based on the reported values in Table 2 and were assumed to be representative of the financial status of each pathway at the beginning of the current decade (2020). Thus, 1.21 EUR/L for HEFA, 1.91 EUR/L for FT, 1.81 EUR/L for AtJ, and 2.99 EUR/L for e-jet are considered the current average prices, while the applied future projections were mainly based on [13,94] (Figure 7). The low cost-reduction potential of HEFA reflects on the rather optimistic forecast for a price reduction of only up to 23% over a 30-year period. FT technology's heavy dependence on CAPEX due to gasification and usually intense gas-cleaning requirements does not leave much room for bold predictions regarding drastic improvement of production costs (25% price reduction forecast over a 30-year period), but extended feedstock flexibility combined with great capabilities of GHG reduction promise competitiveness. The even greater feedstock flexibility, also involving industrial off-gases, for the AtJ routes allows forecasts for a price reduction of up to 33% over a 30-year period. The most optimistic forecasts concern e-fuels (up to a 67% price reduction over a 30-year period), directly linked to the equally optimistic forecasts for green electricity costs that include 50% reductions by the end of the current decade. Moreover, the expected beneficial, but difficult to accurately predict, scale effect for FT, AtJ, and e-fuels should be noted since these technologies have not yet reached their full-scale potential. On the other hand, the technology risk is low for the mature HEFA technology, but higher for the other pathways. In general, there are a number of uncertainties when forecasting for the next 10 years, let alone 30 or more. Producing SAF will almost certainly continue to be more expensive than refining fossil jet fuel, but the necessity for SAFs for the immediate environmental compliance of the aviation sector indicates a continuous concerted effort to ensure they become as competitive as possible.

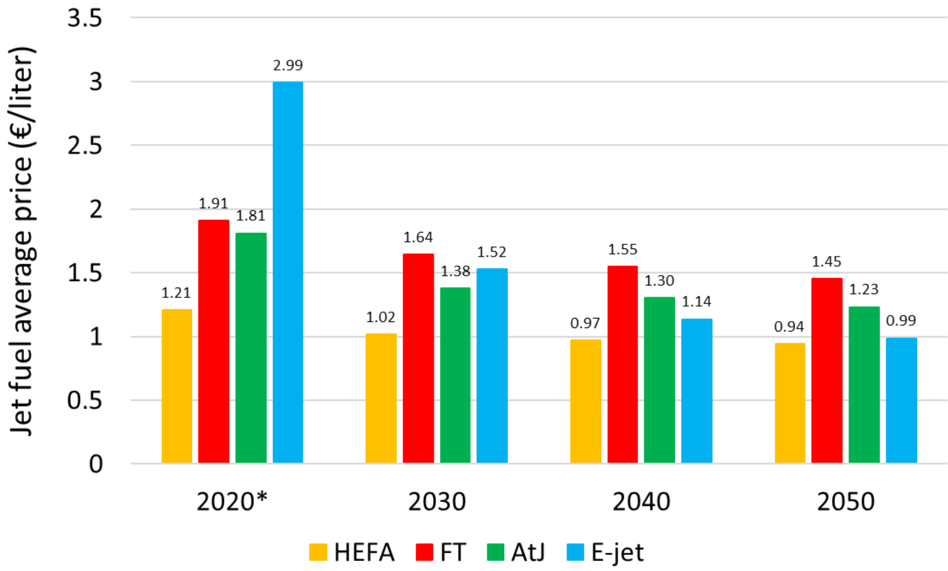

Figure 7. Future projections for the average selling price of HEFA, FT, AtJ, and e-jet pathways (* the average selling price for each pathway, extracted from Table 2, was assumed to be representative for 2020).

4. Current Regulatory Framework and Policy Approaches for Sustainable Aviation Transport

4.1. Background

In December 1997, the Kyoto Protocol [102] was signed and came into force later in 2005, with a commitment to reduce GHG emissions. According to the Kyoto Protocol, CO_2 was the only GHG emission considered for reduction, requiring signatory countries to take action to limit or reduce international aviation CO_2 emissions. In 2009, the Renewable Energy Directive (RED I), also known as Directive 2009/28/EC, was signed, which was a European Union Directive mandating specific levels of the use of renewable energy. The directive required that 20% of the total energy consumption in the EU must derive from renewable energy sources. Besides this, it also stated that the transport sector must be supplied with 10% of renewable energy by 2020, either from transport biofuels or from the electrification of the sector, although there was no specific target for aviation. In 2015, the Paris Agreement was signed, a pledge of the world's governments to further reduce emissions in a response to climate change, which set a target to 'hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' [103].

To ensure that the EU will meet its emissions reduction commitments under the Paris Agreement and keep the global leadership in renewables, the European Commission released a proposal for a revised Renewable Energy Directive (RED II) in 2016, which finally entered into force in December 2018. This recast, covering the period from 2021 to 2030, raised the overall share of energy from renewable sources to 32% by 2030 [104]. For the first time, the RED II established a multiplier factor for renewable aviation fuels to incentivize their uptake. The use of SAF has also been encouraged by the implementation of two market-based measures, namely, the EU ETS for aviation (2012) and CORSIA (2021) at the EU and international level, respectively. However, these policy actions were rather insufficient to drive SAF into the aviation market.

On 14 July 2021, the European Commission published the 'Fit for 55' package, which is a set of policy proposals to deliver the EU's ambition of reducing net GHG emissions by at least 55% by 2030 and achieving climate neutrality by 2050. Among these proposals, an amendment of the RED II directive, as well as a dedicated regulation for sustainable aviation transport, namely, 'ReFuelEU Aviation' [15], have been included. The latter aims to provide the aviation industry with clear and consistent measures that will strengthen SAF production and use, and will contribute significantly to mitigating the carbon intensity of the air transport sector.

4.2. RED II: Current EU Energy Policy Framework

With regard to the transport sector, RED II raised the minimum share of renewable road and rail transport fuels to 14% by 2030. To promote the use of 'advanced' biofuels, a sub-target of 3.5% by 2030 was introduced for biofuels deriving from algae, biowaste, manure, sewage sludge, lignocellulosic materials, etc. (as defined in Part A of Annex IX). Transport fuels produced from used cooking oil or animal fats (as defined in Part B of Annex IX) are capped at 1.7% to cope with the limited availability of feedstock. The feedstock types reported in parts A and B of Annex IX are both double-counted towards the 14% target. A cap for food and feed crop-based biofuels (1G) is also imposed in each member state, freezing their consumption at the 2020 national level (plus 1%), without exceeding 7% [105]. The consumption of high-ILUC-risk biofuels, such as palm oil-derived fuels, should be limited to 2019 levels until 2023 and gradually phased out to 0% in 2030, while biofuels produced from low-ILUC-risk feedstock are exempted from this restriction [106,107].

Although the aviation sector is excluded from the 14% obligation of RED II, a multiplier of 1.2 for renewable fuels supplied to the aviation industry was introduced (not applying to food- and feed-based fuels) to stimulate the deployment of SAFs in the EU. This means that SAFs can contribute 20% more of their energy content towards the renewable energy targets. However, this multiplier only represents a very limited incentive for the industrial production of SAFs since it does not close the price gap between SAF and fossil jet fuel. To achieve economic sustainability for the substitution of fossil jet with SAF and create a profitable business case, additional measures should be taken (e.g., co-funding, lending guidelines), otherwise producers and suppliers cannot push volumes to the aviation sector [106,108,109].

Under the 'Fit for 55' package, the revision of the RED II has been proposed. The key element of the proposal is to increase the target for the share of renewable energy sources in the EU energy mix to 40% by 2030. Changes to transport fuel submandates, caps, and multipliers are also being discussed. Concerning the aviation sector, it is proposed to keep the 1.2 multiplier, applying not only to advanced biofuels, but e-fuels as well [110].

4.3. Other Existing International and EU Policy Actions for Sustainable Aviation

The use of SAF is also encouraged by other global and EU policy actions. For example, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a market-based emission mitigation mechanism for the global airline industry that was developed by the International Civil Aviation Organisation (ICAO) and started in 2021. This plan focuses on the concept of compensating emissions that are above a certain threshold by financing a reduction in emissions elsewhere or by using SAF. CORSIA is now going through a voluntary pilot phase (2021–2023), which will be followed by a voluntary first phase and a mandatory second phase (2027–2035). CORSIA intends to offset over 80% of air traffic growth after 2020 [111]. Although CORSIA and RED II aim to achieve different goals, it is likely that EU Member States may implement aspects of these measures in a conflicting way (e.g., carbon accounting). For this reason, the compatibility of the RED II sustainability framework with that of CORSIA has to be reconsidered in order to avoid overlaps and uncertainty for producers and investors.

At the EU level, there is the EU Emissions Trading System (ETS), launched in 2005, which constitutes the first and largest international emissions trading system. The EU ETS is based on the 'cap and trade' principle, meaning that an upper limit is placed on the GHG emissions of certain sectors covered by this system. This limit is gradually being reduced over the years, so that the total number of GHGs emitted in the atmosphere is slowly decreased. Every year, companies must surrender as many allowances as their annual emissions, otherwise they will be subject to heavy fines. Emission allowances are given for free or auctioned off to companies, which can later be traded between one another if needed. Despite the ETS being set up in 2005, aviation CO_2 emissions have only been covered by it since 2012. The EU ETS provides economic incentives to airlines if SAF is used for their flights, thereby allowing them to qualify as 'zero-emissions'. More specifically, airlines do not have to surrender any emission allowances for CO_2 when SAFs are used to substitute for conventional jet fuel. This practice could potentially boost the uptake of SAFs in flights if the profit from having to buy fewer allowances, or selling the extra ones, equals or even exceeds the additional cost of the SAFs [112].

4.4. ReFuelEU Aviation Initiative

As already mentioned, the current regulatory framework on renewable energy, as well as the EU ETS and CORSIA policy actions, may not be sufficient to motivate airlines to adopt SAFs [113,114]. Thus, the Commission released the 'ReFuelEU Aviation' initiative, as part of the 'Fit for 55' package, to secure the long-term growth of sustainable air transport [15]. With 'ReFuelEU Aviation', it will be the first time that the EU has mandated SAF blending at European airports. Fuel suppliers will be obliged to ensure that all aviation fuel supplied to aircraft operators includes a minimum share of SAF with a submandate referring to e-fuels. According to the draft regulation proposed by the Commission, these mandates will start with a minimum volume of SAF at 2% in 2025, increasing in five-year intervals to eventually achieve a minimum volume of 63% in 2050, of which 28% will consist of electrofuels (Figure 8). Feed and food crop-based fuels are not eligible for these mandates. A transitional period of 5 years (until the end of 2029) is envisaged, during which, for each reporting period, fuel suppliers may supply the minimum share of SAF as an average over all of the aviation fuel they supplied to EU airports [114].

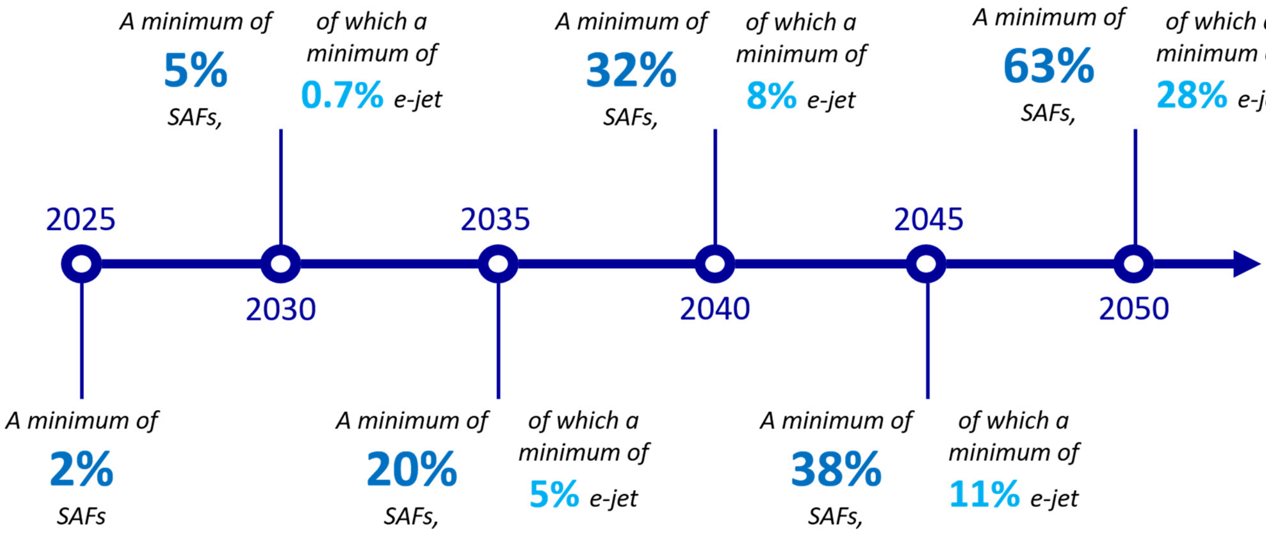

Figure 8. Proposed timeline of SAF mandates as reported in ReFuelEU Aviation (draft regulation).

The proposal also aims to battle fuel tankering practices and ensure a level playing field for sustainable air transport. 'Fuel tankering' occurs when aircraft operators uplift more jet fuel than necessary at a given airport where prices are low, avoiding partial or full refueling at destinations with more expensive fuel. Excessive amounts of fuel lead to increased fuel consumption due to the extra weight on board, which, in turn, leads to additional emissions. Except for the detrimental environmental effects, fuel tankering undermines fair competition between airlines or airports. To prevent these practices and ensure that the SAF mandates will not harm the EU aviation market because of the expected higher fuel costs, ReFuelEU proposes a clear and uniform obligation for all airlines (EU and non-EU) departing from EU airports to uplift jet fuel prior to departure. The uplifted amount of jet fuel will be limited to the amount required for the safe operation of the planned flight. According to the draft regulation, the yearly quantity of fuel uplifted by aircraft operators at a given EU airport must be at least 90% of the yearly aviation fuel required. Reporting obligations are also set for both aircraft operators and fuel suppliers, as well as noncompliance financial penalties.

In addition, ReFuelEU approves the envisaged amendments to the existing form of ETS. First, the total amount of emission allowances for aviation must be solidified at current levels and gradually minimized using the linear reduction factor. Moreover, the auctioning of the allowances must be strengthened, instead of free allocation. Currently, about 85% of the emission allowances are given for free to European airlines, which constitutes a significant loss of revenue that could be provided for the decarbonization of the sector [113]. Furthermore, it must be guaranteed that airlines face equal treatment when operating on the same routes. Finally, EU ETS should continue to apply for flights taking place within Europe, while the rest (extra-European) should be subject to the regulations of CORSIA.

The Council of the European Union and the European Parliament have assessed the original Commission's proposal for 'ReFuelEU Aviation' and have suggested amendments. Negotiations are ongoing [114]. SAF mandates accompanied by appropriate policy measures to ensure that a competitive market will offer a great opportunity to accelerate the deployment of SAF technologies and boost SAF uptake in the next decades. Relying on the sustainability framework of RED II and being in alignment with the EU ETS and CORSIA policy actions, ReFuelEU will manage to drive the EU to the decarbonization of the aviation sector.

5. Conclusions

This review presents and evaluates the available pathways towards the decarbonization of the aviation industry. The performed analysis is based on the admission that SAFs (drop-in biofuels and e-fuels) are the only available option for instant compliance of the aviation industry with the international policies and regulations. Hydrogen aviation or electrification require deep and comprehensive changes in the industry and can only be considered long-term alternatives. The already-announced investments and agreements indicate that SAFs are a recognized and well-accepted necessity, and the challenge now is to scale up their production and gradually penetrate the market with a lasting and beneficial impact.

HEFA, FT, AtJ, and e-jet are the identified leading technologies towards the targeted fuel transition of the aviation sector. While HEFA is currently the only market-proven pathway and the most cost-competitive option, its feedstock constraints and the questionable environmental contribution (GHG emissions reduction) of some of these fuels raise skepticism. Indicatively, some of the HEFA feedstocks that offer the greatest environmental benefit and financial competitiveness, such as UCOs, are also among the most limited. In any case, HEFA jet fuel is expected to remain the most efficient pathway, at least through to 2030. Fuels derived from biogenic wastes and residues (lignocellulosic feedstock) via the FT and AtJ routes usually provide solid reductions of GHG emissions, but the corresponding conversion processes seem quite costly. However, it is anticipated that the wide feedstock flexibility of these technologies and the related technological advances will limit their production costs and will keep pace with future SAF demand that is expected to arise due to HEFA constraints. Finally, e-jet pathways currently struggle to present affordable production costs, but their undisputed environmental benefits combined with the projections for rapid reductions in hydrogen and green electricity prices form a well-oriented and promising future.

The authors envisage the involvement and accelerated scale-up of all SAF pathways. Supportive public policies are necessary in this regard. The existing policy frameworks (RED, EU ETS, CORSIA) have done little to urge SAF deployment. The 'ReFuelEU Aviation' initiative, released by the Commission in July 2021, is the first policy proposal that speaks clearly for mandatory SAF blending at European airports and shows an intention for decisive institutional support of SAFs. While neither policy on its own is the solution to scaling SAF production, the correct and concerted combination of incentives could provide a strong long-term signal for a smooth transition away from fossil jet fuel. Stakeholders across the aviation sector agree that SAFs are a critical component in the industry's decarbonization efforts. An effective harmonized system should be designed in order to achieve not only the commercial uptake of SAFs, but also deliver economic benefits to the industry and beyond.

Finally, this study aims to emphasize that SAFs represent a reasonable and valuable perspective that requires a framework of sustainable establishment from the technical, financial, environmental, and sociopolitical points of view. The successful and timely formation of this framework will rely on the agility and commitment of all of the involved stakeholders within the aviation industry to ensure the safe and effective fuel transition of the sector.

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