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DECARBONIZING AVIATION WITH SUSTAINABLE AVIATION FUELS: MYTHS AND REALITIES OF THE ROADMAPS TO NET ZERO BY 2050

This paper analyzes the factors influencing present and future sustainable aviation fuels sustainable aviation fuels SAF) market availability – namely resources, technologies, and costs – and attempts to assess the credibility of current SAF development scenarios.

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Decarbonizing aviation with sustainable aviation fuels: Myths and realities of the roadmaps to net zero by 2050

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Abstract

Between 35 and 71% of the decarbonization of aviation is expected to be achieved through sustainable aviation fuels (SAF). This ambition implies that energy production must swiftly start supplying large quantities of SAF, considering the current total dependency on fossil fuels. This paper analyzes the factors influencing present and future SAF market availability – namely resources, technologies, and costs – and attempts to assess the credibility of current SAF development scenarios. Our findings highlight two main challenges: (1) short-term capacity building of an SAF industry still stuck in its infancy, and (2) mid to long-term disproportionate resource requirements. Significant investments from all the industry players, not just energy providers and states, as well as dedicated regulations, are required to overcome the technology, energy, investment, and cost barriers hindering SAF development. Another issue concerns the sustainability of the sector's future demand expansion. The envisioned growth rates will induce excessive biomass, hydrogen, and electricity consumption, jeopardizing other sectors' transition pathways. Overall, the analysis questions the relevance of the resource allocation implicitly used in current industry scenarios for 2050, an assumption with essential environmental, social, and ethical implications. Against this background, policies aimed at lowering demand expansion seem unavoidable if there is any chance of achieving net zero by 2050.

Keywords: Sustainable aviation fuel; Air transport; Biofuel; E-fuel; Decarbonization; Hydrogen; Energy Policy.

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List of abbreviations

APR: Aqueous phase reforming
ATAG: Air Transport Action Group
ATJ: Alcohol-to-Jet
CCS: Carbon capture and storage
CCU: Carbon capture and utilization
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
DAC: Direct air capture
DSHC: Direct sugar to hydrocarbons
EJ: Exajoule
ERF: Effective radiative forcing
EU ETS: European Union Emissions Trading Scheme
FOG: Fat, oils, and greases
FRL: Fuel Readiness Level
F-T: Fischer-Tropsch
GHG: Greenhouse gas
HEFA: Hydroprocessed esters and fatty acids
HPOFS: Hydrotreated pyrolysis oil from straw
HTL: Hydrothermal Liquefaction
IATA: International Air Transport Association
ICAO: International Civil Aviation Organization
ICCT: International Council on Clean Transportation
IPCC: Intergovernmental Panel on Climate Change
LCFS: Low carbon fuel standard
LH_2: Liquid hydrogen
MJSP: Minimum jet fuel selling price
Mt: Megaton
MW_e: Megawatt electrical
PSCC: Point source carbon capture
PtL: Power-to-Liquid
RED II: Renewable Energy Directive
SAF: Sustainable aviation fuel
SIP: Synthesized Iso-Paraffins
TRL: Technological Readiness Level
UCO: Used cooking oil
WEF: World Economic Forum

1. Introduction

According to the 2022 IPCC report, air transport is responsible for 2.4% of worldwide annual CO_2 emissions, and its climate impact is even greater when considering non-CO_2 emissions which amount to 66% of the sector's induced Effective Radiative Forcing (ERF) [1]. These non-CO_2 effects notably include persistent contrails and their development into cirrus clouds, a complex phenomenon that occurs in particular atmospheric conditions and contributes more to aviation-induced ERF than CO_2 [2]. The aviation sector's environmental future impact is expected to worsen as its share in global ERF is on the rise, in a context where post-COVID-19 forecasts anticipate a multiplication of current air traffic by 2.6 to 3 by 2050 (see the central demand growth scenarios published by the International Air Transport Association (IATA), the Air Transport Action Group (ATAG) or the International Civil Aviation Organization (ICAO)) [3–5].

In recent years, the sector has regularly reasserted its net-zero ambition for 2050, built on four pillars: technological progress, optimization of flight operations and infrastructure, sustainable aviation fuels (SAF), and carbon offsets. Of those four, the consensus emphasizes the future importance of SAF – namely low-carbon alternatives to conventional fossil jet fuel following current jet fuel certification standards – as that option is expected to generate between 35 and 71% of the emission reductions by 2050 (compared to a business-as-usual scenario) [4–8]. However, the conditions for that vision to materialize require a rapid and complete reconfiguration of the sector's energy consumption. Today, SAF are almost nonexistent as more than 99.9% of fuels used in the aviation sector are fossil-based [4,6,9,10], most of which are jet fuels (kerosene or naphtha) [11]. Moreover, the sector's continued growth poses another difficulty. Despite the envisioned fuel efficiency gains, the sector's ascending fuel consumption trend is expected to persist in the coming years as the consensus forecast annual growth rates in the range of +3.1–3.6% per year between 2019 and 2050 [3–5]. In fact, aviation has historically displayed strong rebound effects associated with efficiency gains [12,13]. Against this background and given the currently embryonic sate of deployment of these alternative fuels, we urgently need to identify the barriers to SAF deployment and critically evaluate that energy option's ability to meet most of aviation's energy needs by 2050.

The purpose of this paper is to provide an exhaustive review of the elements hindering SAF deployment and the implications behind the massive use of SAF to replace fossil jet fuel, in order to determine policy options. To that end, our research carefully compares documentation issued by industry and industry-linked sources to academic literature and evaluates the consistency of the sector's hypotheses and the academic estimates on elements such as biomass availability, feedstock prices, or political priority given to aviation. The paper has four objectives: (1) to review the various factors affecting the availability of SAF inputs (resources, energy, technology), to identify, when possible, the main challenge for each pathway, (2) to evaluate the cost implications of these factors, (3) to analyze the recent dynamics in SAF development and discuss the credibility of SAF development prospects, and (4) to examine implemented policies and possible complementary measures.

A rapidly blossoming literature is now emerging on the topic of sustainable aviation fuels. A tentative clustering of these contributions certainly includes the papers discussing recent technological developments [10,11,14–19], feedstock availability [19–21], environmental benefits [20–24], cost and investment perspectives [11,21,24–28], and policy possibilities [29–32]. To the best of our knowledge, most of these studies typically focus on one or two of these issues in detail, but none provide a comprehensive review of the challenges faced in the deployment of SAF. However, such a thorough analysis can provide valuable and timely guidance to policymakers overseeing future air transportation and its environmental impacts. Another noticeable feature of that recent literature is its contemporary nature that merely reflects current conceptions of aviation decarbonization. Yet, a broader historical perspective aimed at gaining insights from earlier decarbonization attempts and identifying long-term trends could provide the lantern on the stern needed for navigation ahead.

This paper is organized as follows. Section 2 provides a concise presentation of the two main SAF categories (bio and synthetic) and reviews their latest developments and environmental impacts. Section 3 examines the availability of SAF. That analysis successively discusses the multifaceted constraints that can affect the development of SAF: resource availability and accessibility, technology readiness, and adaptation of the infrastructure. Section 4 then reviews the cost implications. Section 5 revisits SAF challenges and attempts to contextualize them by delving into earlier literature.

2. Background: The essentials of sustainable aviation fuels

2.1. SAF: A fancy but blurry definition

Fuzzy and variable definitions

SAF, produced from biomass or synthetic materials, make up less than 0.1% of the fuels now utilized by airplanes globally [9]. These fuels are "drop-in," *i.e.*, they must be fully compatible with the existing aircraft technologies. The International Civil Aviation Organization (ICAO) defined several sustainability criteria, notably a 10% greenhouse-gas (GHG) emissions reduction compared to conventional fuel, evaluated on a life-cycle assessment basis [33].

However, the details matter when it comes to normatively defining what qualifies a fuel as an SAF, and these details vary substantially. For instance, through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the United Nation's ICAO imposes several criteria on land use, the impacts on water, air, and soil quality, on biodiversity, on waste management, and several social criteria, but does not explicitly prohibit SAF produced from dedicated food crops [33].

The United States follows ICAO norms through a large definition including any hydrocarbon derived from “sources of hydrogen and carbon not originating from unrefined or refined petrochemicals,” yet said fuel must achieve a 50% GHG emissions reduction [34]. In contrast, the European Union is currently working on a more rigorous definition, which only includes synthetic fuels and biofuels produced from waste or non-food material (*i.e.*, advanced biofuels), and raises the GHG emissions reduction threshold to 65% [35]. The ReFuelEU proposal also contains minimum incorporation rates of SAF in European airports, starting at 2% in 2025 and up to 65% in 2050 (including 28% of synthetic fuel).

Different pathways with heterogeneous technological maturities

Another challenge is the wide range of Technology Readiness Levels (TRL) achieved by the different SAF pathways, as shown in Table 1.

Table 1 – Summary of TRL and scale of production of drop-in jet fuels. Source: [10]

Route	Technology status	Largest plant, kt·year^{-1} [a]
Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (HEFA-SPK)	Commercial (TRL 8)	1653 (planned)
Alcohol-to-jet SPK (ATJ-SPK)	Demonstration (TRL 6-7)	82 (planned)
Hydroprocessing of fermented sugars-synthesized isoparaffins (HFS-SIP)	Prototype (TRL 5, lignocellulosic sugars), pre-commercial (TRL 7, conventional sugars)	81 (operational)
Fischer-Tropsch-SPK (FT-SPK)	Demonstration (TRL 6)	225 (planned)
Pyrolysis	Demonstration (TRL 6)	138 (planned)[b]
Aqueous phase reforming (APR)	Prototype (TRL 4-5, lignocellulosic sugars), demonstration (TRL 5-6, conventional sugars)	0.04 (operational)[c]
Hydrothermal liquefaction	Demonstration (TRL 5-6)	66 (planned)
Power-to-liquid FT (PtL FT)	Demonstration (TRL 5-6)	8 (planned)[e]

[a] *Here, ton refers to a generic ton of liquid fuel and not specifically to jet fuel*
[b] *Pyrolysis oil*
[c] *Bio-crude*
[d] *Blue-crude*

The industry uses a variant, the Fuel Readiness Level (FRL) scale, to characterize the technological maturity of a given SAF pathway. That notion is derived from the TRL with a broader perspective: not only does the fuel need to be chemically operational, but the technological context (*i.e.*, the aircrafts and the fueling infrastructures) must also allow for its use. Thus, FRL 8 and 9 go beyond system qualification in an operational environment by adding business model robustness and level of consensus to the GHG assessment [36]. Both indicators contain flaws and, as such, are not consensually accepted by all studies. A handful of them retain TRL as their prime indicator [10], whereas others use TRL and FRL [11]. Despite their limitations, we retain these indicators as convenient tools to evaluate the efforts and investments required to fulfill development plans.

2.2. Pathway#1: Biofuels or biomass-to-liquid

Generations of biofuels

The first category of SAF gathers the fuels derived from biomass processing. That category is reputed to be the closest to technological maturity. The different biofuels are usually clustered into three generations, depending on the feedstock used [37].

First-generation biofuels are produced from dedicated cultures (*e.g.*, soy, palm, rapeseed), which deliver oil, sugar, or starch. Most of these fuels are already commercialized (FRL 9) [37]. However, depending on the jurisdiction, they may not qualify as SAF.

The second generation is derived from lignocellulose (e.g., straw, forest residue) or waste such as used cooking oil (UCO) or animal fat. That category includes a variety of processing technologies with different levels of maturity. Depending on the feedstock used, the FRL indicator ranges from 9 for UCOs or 7–8 for some lignocellulose, to 4–6 for several other processes [17,37,38].

The third generation of biofuels is processed from microalgae species cultivated in dedicated plants. The FRL for these biofuels does not exceed 5, since only few pilot plants were launched but many processes remain at an early stage of development [17,39,40].

One can wonder about the limitations of this traditional delineation as current developments reveal the presence of blurred boundaries between these generations. For example, the biofuels processed from intermediate energy crops, UCOs, and other oily residues are *de facto* classified as second generation, whereas the processing technology used for the refining processes is already mature and well characterized as it is based on the ones already developed for first-generation biofuels [41]. To *circumvent* that, the term “advanced biofuel” is sometimes used to encompass second and third generation and biofuel processed from feedstock with limited land-use change impacts [42]. Nevertheless, that notion remains vague and, to the best of our knowledge, has so far not been universally accepted.

Technological readiness and GHG emissions

To explain the FRL differences among same-generation fuels, one must closely examine the conversion pathways. Today, seven SAF production pathways are qualified for commercial use, and six more are currently undergoing the qualification process [27,43]. Among those, two have already achieved a significant level of development (Table 1), namely HEFA and Fischer-Tropsch. HEFA is already used for soy- and palm-based biofuels. The Fischer-Tropsch pathway relies on an adaptation of the well-known Fischer-Tropsch process that was used to process fossil hydrocarbon feedstocks into liquid fuels during WWII or in South Africa.

Regarding GHG emissions, the environmental assessments presented in the literature consistently point to favorable results obtained with lignocellulosic biofuels and UCOs [22,23,37,44]. Some of these biofuels generate negative GHG emissions, whereas biofuels emanating from dedicated cultures, especially palm, have either limited benefits or negative impacts (see Figure 1). Other methods can be used to compute GHG emissions, which yield approximately the same results [23]. When considering the impact of land-use conflicts, first-generation biofuels are further penalized: we refer to Figure 3 of the ICCT study by El Takriti *et al.* [45], which suggests that their GHG impact can be seven times higher than their fossil counterparts.

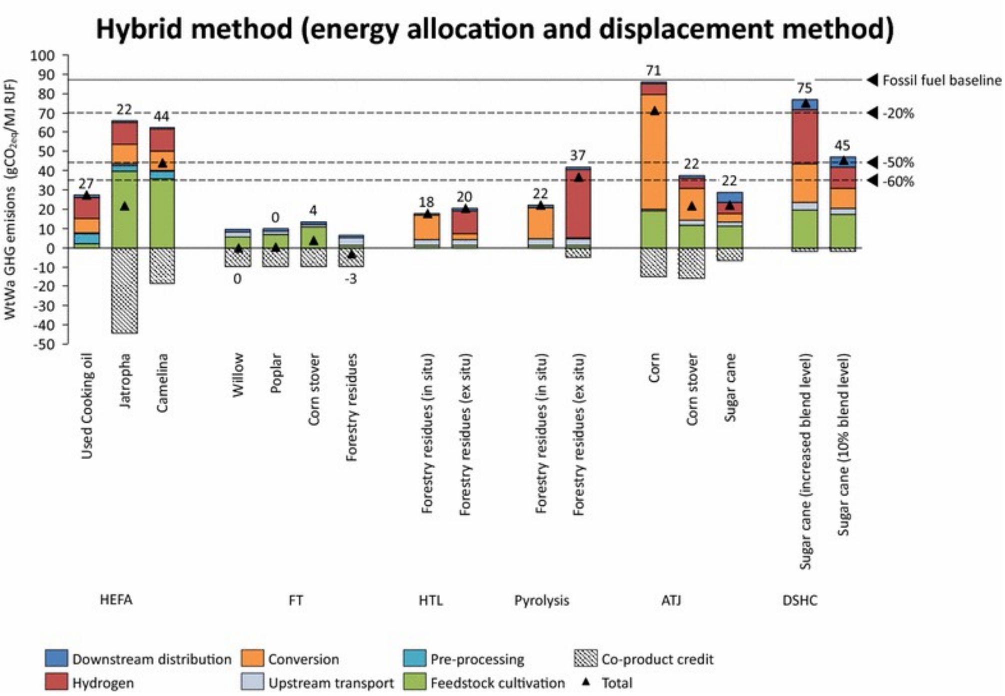

Figure 1 – WtWa GHG emission performance of SAF conversion pathways. Source: [23]

2.3. Pathway#2: E-fuels or power-to-liquid

E-fuels – also known as synthetic fuels – are recurrently presented as the main alternative to biofuels on the mid to long-term horizons. That category is broadly defined as it also encompasses non-drop-in fuels, such as liquid hydrogen, liquid methane, or ammonia. However, the present study adopts a narrower definition as we concentrate solely on drop-in fuels. Indeed, the utilization of liquid hydrogen, liquid methane, or ammonia in aviation requires significant infrastructure change and breakthrough technological development (*e.g.*, to develop the engines, to fully characterize the behavior of these fuels in air applications). Given the stringent requirements associated with the certification process, the industry does not consider them to be credible full-scale technological options for net zero in 2050.

For drop-in fuels, there are two main processes, relying on a similar principle: combining hydrogen obtained through water electrolysis and carbon dioxide, either through the Fischer-Tropsch process, or with an intermediate methanol stage [37]. Carbon dioxide can be obtained from point-source carbon capture (PSCC) at industrial facilities (TRL 6–9), geothermal sources, or biomass processing plants (*e.g.,* biofuel production) [19], or from Direct Air Capture (DAC) in the atmosphere (TRL 6) [11]. The ICCT figure mentioned above [45] demonstrates a clear benefit of Power-to-Liquid solutions over fossil jet fuel in terms of GHG emissions when the electricity is decarbonized.

Before COVID-19, only a handful of academic studies had discussed e-fuels as a decarbonization solution for aviation, most of which were published in the mid-to-late 2010s [16,19,31,46,47]. In contrast, drop-in e-fuels are gaining momentum in the literature [11].

3. Assessing the future availability of SAF

3.1. Resources: Potential and cost considerations

3.1.1. Biomass

Global biofuel production in 2021 was 3.92 EJ for the whole transportation sector, an insignificant portion of which was bio-jet fuel [48]. Furthermore, only 7.6% of biofuels produced were advanced [48], an essential criterion for qualifying as SAF, whether required explicitly, as it will be in the EU, or implicitly, as it is in the US where the 50% GHG emissions reduction restricts the use of most first-generation biofuels [49].

Turning a largely untapped potential into an economically efficient resource

Bio feedstock is limited in theory, yet the potential remains largely untapped to this day. The evaluation of the bioenergy technical potential is difficult, and can range from 30 EJ/year to over 1,000 EJ/year by 2050 (cf. Figure 2) [41]. The IPCC considers 100 EJ/year in 2050 a relatively consensual minimum among the different studies [50]. The same report also points out the estimates' sensitivity to various variables, including price, regulations, technological readiness, land allocation, and policies.

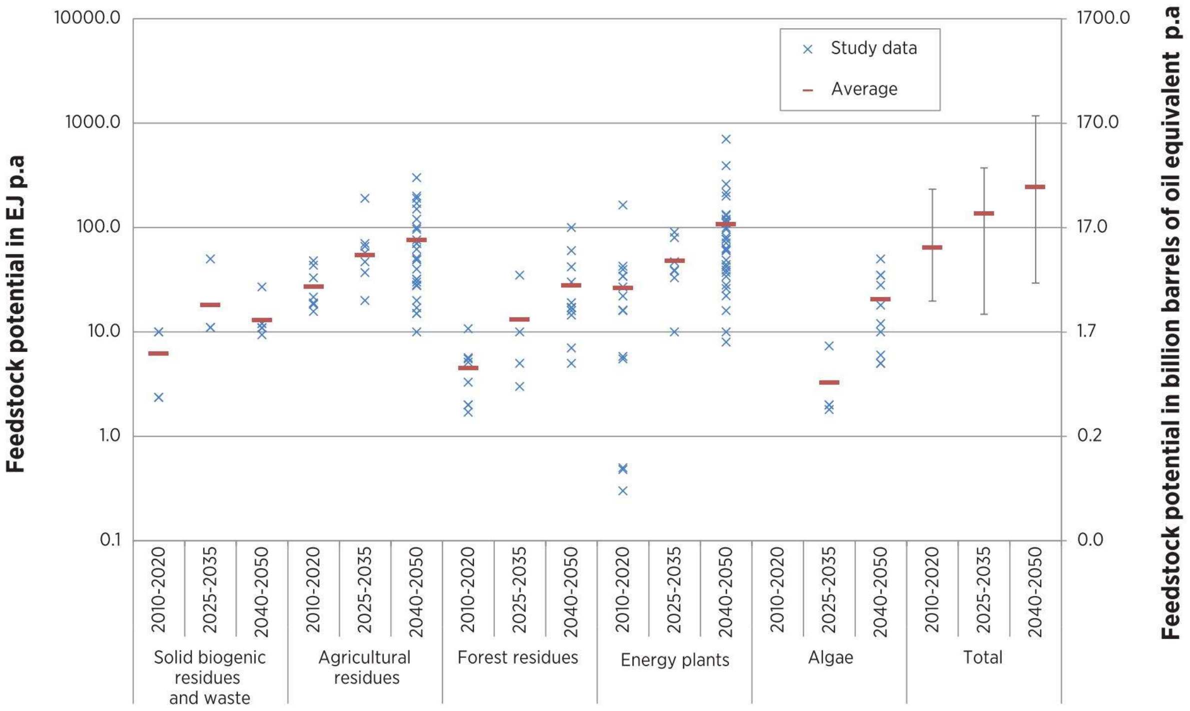

Figure 2 – Summary of estimates of global feedstock potentials for key biomass categories. Source: [41] © IRENA

Another caveat concerns the nature of these estimates. They usually refer to biomass as a primary energy source that must be converted into a usable fuel, which is a secondary energy source. Hence, one must also account for the capacity constraints and efficiency losses associated with collecting and processing that feedstock. As usual with natural resources, cost and technology issues play a major role in the assessment of the quantity of usable energy that can be efficiently obtained from that biomass.

Logistic issues and variable cost considerations

Infrastructure and logistic considerations have a major impact on the delineation of what constitutes a valuable bioenergy resource. For example, the volumes of waste FOG are significant, and FOG is recurrently presented as a privileged feedstock to process SAF. However, a large part of FOG is scattered amongst restaurants, fast-foods or households, requiring costly logistics, a dedicated collection chain, and specific collection policies to unlock that potential [27,51]. Another illustration is lignocellulosic biomass. Because of its very low energy density, that feedstock can hardly be economically transported over long distances, which *de facto* requires sitting the processing plants in the vicinity of production sites, or densification (implying additional costs) for transport over longer distances [27,38,52]. This explains, in part, why logistic considerations have a first-order effect on the variable production costs of most SAF pathways, especially for lignocellulose [53]. In contrast, logistics account for only a tiny portion of the marginal cost of producing conventional jet fuel as the latter remains largely driven by the price of crude oil that includes a substantial share of rent.

Attracting investment

Investment issues at the processing stage also loom large. To meet the industry's stated objectives by 2050 – namely 50% GHG abatement from SAF – around 200 biorefineries must open every year for the next three decades, each one producing 0.22 Mt of fuel, 50% of which are SAF [21]. In contrast, the historical growth recorded between 2002 and 2011 (*i.e.*, during the "golden years" of the first generation of biofuel) involved the opening of 60 new facilities per year. Hence, the envisioned scenario requires a sizable and sustained investment effort into capital-intensive facilities [21]. Another study [54] is even more ambitious and asserts that a fully biofuel-oriented SAF pathway would require 6,000 plants by 2050, more than any other SAF option. Notwithstanding the validity of these projections, the reviewed literature consistently stresses the extent of the collect and processing infrastructure that must be developed to support the large-scale deployment of bio-jet fuel.

Against this background, investment attraction represents a critical issue. However, the profitability of emerging biofuel-SAF projects remains uncertain. Some studies argue that it can be favored by relatively inexpensive feedstock and privileged access to that resource (*e.g.*, through a priority allocation to the conversion of that feedstock into SAF) [21]. Nonetheless, the capital expenditures needed to develop these projects are significant, especially for the plants processing the more sustainable feedstocks [27,55–57]. Furthermore, these projects are subjected to a host of risks, namely the difficult development of existing plants [58], market fluctuations [29,59,60], and uncertain future technological developments and policies [31].

In the short run, considering the higher FRL for fuels produced through the HEFA pathway, waste FOG availability is crucial to meet the forthcoming decarbonization objectives. UCOs in particular are considered to be a still underused resource [51], with a potential four times higher than the current quantities collected [38]. From the bioenergy potential, one must infer the bio-jet fuel potential by considering the selection fraction inherent to the refining process. The IRENA estimates that between 0.12 and 0.42 EJ of SAF could be extracted from UCO potential feedstock [38]: the importance of this potential must not be gauged in light of the 2050 estimates, but rather valued as a readily available SAF pathway for the next few years, pending the large-scale commercialization of other technologies. In the long term, SAF produced from lignocellulosic matter is widely considered a more promising path [29,61]. However, there are considerable variations forged from the expectations of the quantities of SAF emanating from that pathway. The optimistic literature considers it will be capable of yielding 71% of 2030 SAF needs [51], 94% in 2040, or 21.5 EJ (when combined with sugar feedstock) [30], and 77% by 2050 [4]. In contrast, more pessimistic studies only estimate its potential as 1.8% of 2030 jet fuel demand [58].

Should aviation be granted priority access to biofuels?

One of the major obstacles to producing bio-jet fuel, both in the short and long terms, is not so much the availability of potential feedstock, but rather its allocation to the aviation sector. Indeed, several other sectors also consider bioenergy to be an easier path to net zero than alternative rupture technologies or demand management.

As an illustration, we can look at the use of UCOs for jet fuel production, which is jeopardized by the pre-existence of a well-established market for biodiesel produced from UCOs for road transport, already using 90% of the collected said feedstock [29,62]. A fierce rivalry is expected between aviation and road transport to attract bioenergy [38,63], which could result in aviation being delivered as little as 9% of available biofuels by 2050, while road transport would receive the majority as a result of their lower cost for biomass use [64]. The aviation industry nonetheless believes that, as a “hard-to-decarbonize” sector, it should be granted some degree of priority access to biofuels and, as such, can expect to secure 20 EJ/year of bio feedstock [4]. That perspective would mean 10 to 30% of the available sustainable biomass on the planet being reserved for aviation [20,65].

This figure triggers a critical policy debate over the efficiency of such a preferential resource allocation, since biofuels’ marginal GHG emissions mitigations are extremely low, especially compared to biomass-derived heat and electricity [66]. Fairness and ethical considerations are not absent from these discussions, as air transport is predominantly used by the wealthiest people on the planet [67]. Other less wealth-skewed sectors may also claim a degree of priority over bio feedstock, such as the shipping industry, which is also “hard to decarbonize” or at least “hard to electrify” [68].

The sectorial competition can be slightly nuanced since biofuel pathways produce several hydrocarbons, only a portion of which can be used for jet fuel [37,65]. For instance, even when it is optimized for jet fuel, the HEFA process produces approximately the same quantities of jet fuel and road fuel: the Clean Skies for Tomorrow coalition of the WEF holds that a fully jet-fuel-oriented advanced biofuel production (*i.e.*, excluding the first generation) providing 490 Mt of SAF in 2030 would also yield 190 Mt of road fuel [51].

When combining the different constraints, biofuel availability appears smaller than the bioenergy potential estimates would suggest. Figure 3 displays the result of the study by Staples *et al.* [21], with different scenarios for primary energy resources (S1–S3), on feedstock market availability (A1–A3), and on allocation to SAF (F1–F3, with F3 meaning no allocation to aviation). Among those, the F1 scenario, implying a maximum allocation of biofuel to the aviation sector, seems particularly unlikely, and F2, which consists of an allocation proportional to final energy demand, seems more probable [21]. In this regard, even though the ICAO has recently lowered jet fuel demand estimates to around 15–20 EJ [69], only a few estimates from Figure 3 reach the threshold, all of which have rather optimistic hypotheses on price or on bioenergy resources.

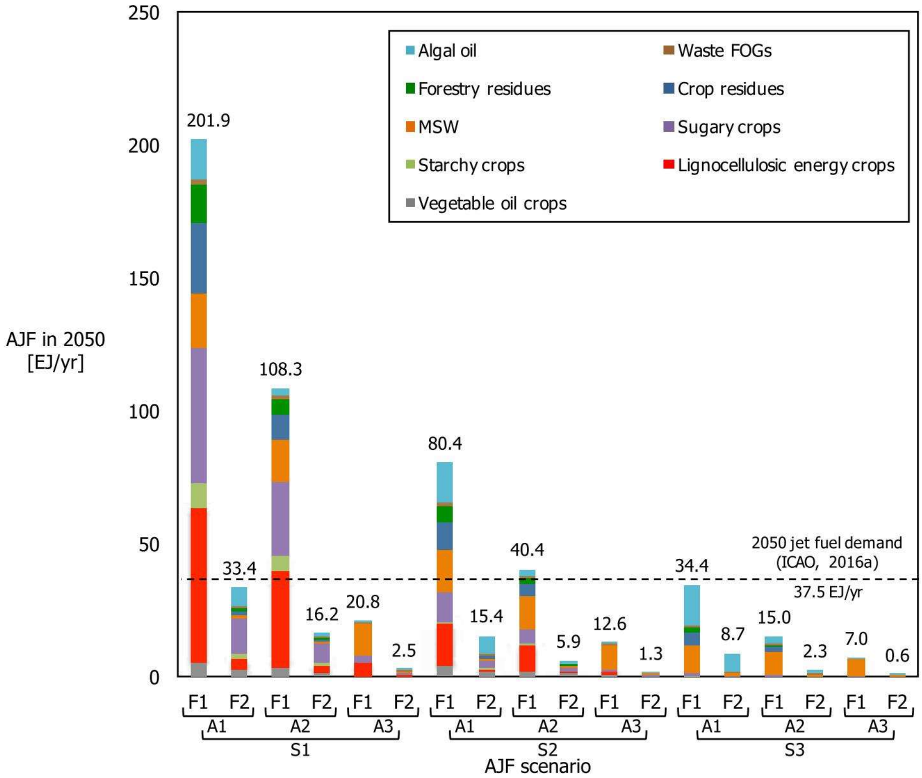

Figure 3 – AJF scenario results, compared to projected 2050 jet fuel demand (ICAO, 2016). Source: [21]

3.1.2. Carbon dioxide

As a result of the limited projected biofuel supply, the aviation industry has shifted its focus toward power-to-liquid (PtL) to fill the gap between SAF demand and biofuel availability [4,63,65,70]. E-fuel processes require carbon dioxide (or monoxide), an abundant resource in absolute terms. Most of the reviewed literature, and notably documents issued by the aviation industry, actually consider it to be a virtually unlimited resource, as opposed to biomass’s limited feedstock [4,51,63,71]. As an illustration, in the long term, European demand is not expected to exceed 500 Mt/year for all uses [72]. Hence, the question is not so much on the availability of the feedstock as it is the source choice. Industrial sources (including biomass processing plants) can provide exhaust gases containing 35 to 100% of CO_2, but in the general atmosphere, the average concentration is 0.04% [37]. Higher concentrations make it easier to collect CO_2, notably by reducing the electricity required. This, in turn, improves the carbon footprint of the end product, depending on the carbon intensity of the electricity mix.

In the short term, from a European standpoint, the best CO_2 sources in terms of GHG benefits are chemical plants, paper mills, coal and natural gas power plants, and steel and iron industries [72]. Several studies also consider hydrogen plants, which emit quasi-pure CO_2 [72,73], which experts argue is counterproductive since PtL is roughly the opposite of hydrogen production through steam reforming [73].

Nevertheless, PSCC from industrial fossil sources is not sustainable in the medium and long term. First, with the growing decarbonization and the shift to low-carbon electricity generation, CO_2 supply from these sources is expected to shrink in the coming years [63,72]. In addition, it is likely that capturing carbon from industries disincentivizes more ambitious decarbonization efforts because of the additional revenues yielded by e-fuel production [37,74]. For example, in the case of pulp mills, e-fuel production would theoretically make these mills carbon neutral without sustainable forest management [75]. This phenomenon could dilute emissions responsibilities between the emitting industry and the aviation sector, if both claim to be carbon neutral when the process as a whole remains carbon intensive. In this respect, there exists a risk of counting the GHG benefits twice, through both industrial regulations (*e.g.*, EU ETS) and energy regulations (*e.g.*, RED II) [37,71]. Lastly, the ICCT also suggests that if double-counting is prevented, the emitting industry would need to "achieve emission reductions elsewhere, for example through carbon capture and storage (CCS)" [71]: on the contrary, it is crucial to ensure that e-fuel production is not used by industries as an excuse to choose offsetting over reducing their direct CO_2 emissions, following an "avoid, reduce, compensate" strategy.

The current development of bioenergy may provide alternative concentrated CO_2 sources, originating from fermentation, biogas combustion, and other renewable processes [19,72,76]. As mentioned in section 3.1.1, these facilities are expected to grow exponentially in the coming decades for the objectives to be met, making biomass processing and CO_2 capture coupling all the more interesting. Several policy briefs have emphasized the benefits of coupling methanization and methanation/gasification, for instance, as a way to upcycle carbon byproducts [73,77].

Direct air capture (DAC) is considered by many as a long-term solution, especially in the industry [4,51,63,65]. Supply is not the issue here, given the scale difference between the amount of carbon dioxide in the atmosphere and the required amounts for aviation. DAC poses significant difficulties regarding technological readiness, cost, and energy requirements (cf. 3.2.2).

3.1.3. Hydrogen

Hydrogen, or dihydrogen H_2 to be precise, is required for both hydrogen propulsion technologies, and some categories of SAF. PtL and some biofuels use hydrogen in the F-T or methanol pathways, combined with carbon dioxide or monoxide. Consequently, the industry estimates that, depending on renewable energy availability, aviation hydrogen demand would be around 95 and 160 Mt (11–19 EJ), corresponding to 10 to 30% of global hydrogen demand by 2050 [65].

Currently, 96% of the hydrogen produced worldwide originates directly from fossil fuels (natural gas or coal gasification, oil refining by-product), and out of the 4% produced in electrolyzers, only around a third can be regarded as renewable, corresponding to the renewable share in the global electricity market [78]. Thus, due to its high carbon footprint, most of the hydrogen produced today is unfit for SAF. E-SAF production will call for a substantial scaling up of hydrogen production through water electrolysis, since a plant producing 100 kt/year of e-fuel (4.3 TJ) needs an electrolysis capacity of 600 MW_e, while most existing plants range in the hundreds of kW_e [19]. Hydrogen production uses water as feedstock, with consumption ranging between around 1.3–2.6 L of water per liter of power-to-jet fuel produced [79]: around 60 billion liters of water could be required for electrolysis by 2050 per year, which corresponds to 5% of current daily water consumption in the US alone [80]. This pales in comparison to biofuel water consumption [37], so water for hydrogen must rather be considered from a geographical standpoint in the environmental assessment of PtL plants, in terms of local water depletion [79].

One key issue is ensuring a continuous supply of green H_2, which will be difficult since most renewable energies are intermittent [16]. Aside from the electricity supply itself (cf. 3.2.3), the continuous supply of carbon-free hydrogen requires the large-scale deployment of either non-intermittent low-carbon generation (i.e., geothermal or nuclear), electricity storage (i.e., batteries), or oversized electrolyzers coupled with H_2 storage equipment to compensate for the intermittency [81]. An alternative approach is to organize a flexible production of H_2 so that hydrogen is produced when solar and wind generation is available. By nature, that approach requires building H_2 inventories to cope with possibly asynchronous supply/demand patterns. A possible limitation is the electricity grid's capacity, which can become overloaded [24].

Similar to those for biomass, transportation and logistical issues also apply to hydrogen; however, they come with higher hazards due to hydrogen's flammability. Pio *et al.* [81] have designed a specific plant model where the electrolyzers are fully coupled with SAF production, which is the most cost-effective model [38]. Nonetheless, the aforementioned hydrogen capacity for an SAF production plant implies very large electrolyzers, which might make infrastructure proximity more difficult. The delivery of hydrogen can then be conducted using pipelines or freight. With a global total length of only 4,500 km, hydrogen pipelines are still under development [78] and face technological barriers, but they are considered to be a promising option [82]. Furthermore, a burgeoning literature advocates for an infrastructure push regarding the installation of H_2 pipelines [83]. Otherwise, transport by freight (mostly road) is rendered difficult by the low density of hydrogen (even compressed or liquefied), and the explosion risks associated with highly compressed hydrogen, or the energy (25% loss) and temperature (below −253°C) required to liquefy it [11,18].

Similar logistic considerations also hold for carbon dioxide, which also has a low density and requires compression for transport when that gas is captured from concentrated sources, though not for DAC [72]. Hence, these logistic issues curse the two essential inputs needed to manufacture e-fuels. As the transportation of these gases is costly, energy-intensive, environmentally impacting, and hazardous, the most effective option is to locate e-fuel production plants close to carbon sources and/or water sources.

3.2. Infrastructure and other technology considerations

3.2.1. Aircraft readiness

One of the critical characteristics of SAF is their presupposed drop-in capability. Unlike liquid hydrogen or electric propulsion, SAF should not require breakthrough technology and can be used on existing aircrafts. However, compared with conventional jet fuel, SAF have very low aromatic content [74,84], impacting chemical and physical properties such as compatibility with fuel tank materials, lean blow-off limit, thermal stability or ignition, and relight [85]. This feature explains the maximum blending rate of 50% for the seven ASTM-approved SAF processes mentioned in 2.2 [43]. Therefore, drop-in has not been reached yet for unblended or “neat” SAF. In addition to the already mentioned feedstock concerns, the ability to attain the target incorporation rates for 2050 thus critically rests on the minor nature of the modifications needed to use neat synthetic fuel [18].

We observe that achieving complete drop-in is an overlooked and underestimated task for at least two reasons.

Firstly, using neat synthetic fuel has major non-CO_2-related GHG benefits. On top of carbon dioxide savings, several studies have determined that, notably due to their low level of aromatics, SAF tend to reduce contrail cirrus thickness, optical density, and persistence [37,86,87], by cutting particle number emissions by up to 97% [85,88]. Quite logically, blending SAF with fossil fuel or incorporating synthetic aromatics weakens those benefits [89]. In fact, evidence suggests that “it is more effective to use SAF in high concentration for flights with contrail forming conditions than distribute the available SAF over all aircrafts and flights evenly” [84]. It is important indeed to note that contrail cirrus persists only in particular atmospheric conditions: only around 5% of worldwide jet fuel is burned in such conditions [37]. As a result, neat SAF capability is instrumental in making the most of SAF use.

Secondly, the diversity of SAF pathways raises questions of interoperability. While the need for fuel tank seal adaptations to 100% SAF on legacy aircrafts is discussed in most of the technical literature [18,85,89–92], our research failed to identify studies reviewing multi-pathway blending and the effects of successively using different types of SAF on the same aircraft. This issue appears to be neglected, which is odd, considering the high safety standards of aviation [91,92], and the important composition differences between SAF from different pathways [93]. The interoperability of SAF seems extremely important for its development, since airports will likely not have access to the same types of SAF, compelling aircrafts to acquire fuel flexibility, which is not in the sector's habits. Other linked questions remain unanswered, notably the need for separate airport storage for different types of SAF, blended or neat.

3.2.2. Technological readiness

Many different production pathways struggle to achieve FRL 9 for a variety of reasons. Table 2 illustrates the diversity of critical elements in the pursuit of technological development for each pathway (which have not significantly evolved since 2016).

Jet fuel production pathway	**Technology Readiness Level (today)**	**Critical element (e.g., determining bandwidth bottom)**
PtL	5 – 8	CO2 extraction from air (TRL 6)
Fischer-Tropsch (low-temp)	6	Reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5	high-temperature electrolysis (SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	5	SOEC, ASTM approval, final conversion
BtL	5 – 9	Gasifying feedstock other than wood
Fischer-Tropsch pathway	5 – 9	
Methanol pathway	5 – 8	ASTM approval, final conversion
HEFA	4 – 9	Feedstock
Used cooking oil	9	quantity, logistics
Palm, rape seed	9	sustainability, quantity
Algae	4 – 5	reactor, extraction
HTL	4 – 6	Feedstock
Wastes/residues	6	quantity, structure
Algae	4	reactor, extraction, conversion
AtJ (sugar, starch)	5 – 9	Feedstock quantity
SIP (sugar)	7 – 9	Feedstock quantity

Table 2 – TRL levels in 2016 of production pathways to SAF. Source: [79]

Jet fuel production pathway	**Technology**	**Critical element (e.g., determining**

	Readiness Level (today)	bandwidth bottom)
PtL	5 – 8	CO_2 extraction from air (TRL 6)
Fischer-Tropsch (low-temp)	6	Reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5	high-temperature electrolysis (SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	5	SOEC, ASTM approval, final conversion
BtL	5 – 9	Gasifying feedstock other than wood
Fischer-Tropsch pathway	5 – 9	
Methanol pathway	5 – 8	ASTM approval, final conversion
HEFA	4 – 9	Feedstock
Used cooking oil	9	quantity, logistics
Palm, rape seed	9	sustainability, quantity
Algae	4 – 5	reactor, extraction
HTL	4 – 6	Feedstock
Wastes/residues	6	quantity, structure
Algae	4	reactor, extraction, conversion
AtJ (sugar, starch)	5 – 9	Feedstock quantity
SIP (sugar)	7 – 9	Feedstock quantity

Many biofuel pathways face difficulties regarding feedstock in terms of quantity or collectability (cf. 3.1.1) and processing. For instance, algae biofuels face challenges both in growing process calibration and in processing which must eliminate all of the unwanted hazardous compounds in algae oil [94].

Regarding PtL, that option is ill-fated by the low TRL of carbon capture technologies. So far, only a handful of demonstration plants have been developed, and the scaling up of PtL is reputed to be difficult due to the enormous quantities of CO_2 required to start full-scale e-fuel production [19]. An aggravating factor concerns the certification of these fuels. Many e-fuels are not certified by the ASTM [11,79], and still require extensive research to reach drop-in capability in combustion and turbine [16].

One of the distinctive features of SAF processes (i.e., compared to fossil fuel) is their energy-intensive nature as the quantity of output (in MJ) is typically lower than the amount of energy consumed when operating the process. The ratios of the former by the latter are as follows: fossil fuels such as gasoline or diesel obtain a ratio of 5, first-generation biofuels can reach up to 1.6 [22], and most SAF pathways score between 0.3 and 0.8 [11]. Improving energy efficiency is paramount to scaling up SAF production and improving business models. Indeed, for now, biofuel production remains the least beneficial of all biomass uses because of the high energy losses [95].

Biofuels implying gasification and F-T synthesis (lignocellulose-derived) have a particularly high energy consumption, up to five times that of their first-generation counterparts, such as rapeseed or sunflower [22]. PtL energy efficiencies vary depending on the carbon capture method, from 11 and 49% for existing technologies, and could reach up to 63% by 2050 with upcoming high-temperature electrolysis technologies [18,19]. PSCC from fossil sources such as cement or coal industries is technologically mature and has medium energy efficiency (between 0.6 and 0.8) [46] but is subject to the drawbacks mentioned in section 3.1.2. This is why improvements must be made to DAC efficiencies if it is to be pursued, as it is one of the most energy-consuming processes, with energy efficiencies as low as 0.2 [96], since it requires heat to run the chemical processes and electricity to manage the airflow and compress the end product [97]. These efficiencies do not include jet fuel selectivity, namely the percentage of jet fuel in the final product: in practice, the study by Pio *et al.* [81] emphasized practical yields including selectivity around 10 to 15% for the PtL obtained from PSCC. Overall, CO_2 capture is not a consensual solution because of these yields and the underlying problem of CO_2: its absence of energy content [92].

3.2.3. Electricity

Aviation electricity demand is projected to grow exponentially in the coming years, due to the high energy requirements of SAF, higher rates of aircraft electrification, and high demand for hydrogen from electrolysis. In this regard, the aviation industry has put forward extremely ambitious figures, starting with IATA which claims that "aviation could require, by 2050, 20% of the world's electricity production" [3]. Table 3 summarizes the different estimates. Despite the spread of these values, the trend shows a marked increase in the aviation industry's electricity needs and hence a higher share in total electricity production. It is worth noting that in 2019, electricity production amounted to 27,044 TWh [98], of which 420 TWh were used for the entire transportation sector [99]. The minimum value of 416 TWh in Dray *et al.* [54] omits that for similar growth levels, at least 3,800 TWh are needed when including PtL or LH_2. Accordingly, regardless of economic growth rates, the consensus emphasizes that aviation will require more than 10 times the electricity consumed today by the transportation sector if, as planned, electricity-derived fuels are used.

Table 3 – Electricity needs in 2050

Study	Electricity demand in 2050	Share of total electricity production 2050	Geographical perimeter
International Air Transport Association [3]	10,000 TWh (36EJ) of additional electricity	20%	World
Institut Montaigne	12,000 TWh (43 EJ) of	21% of the additional	World

(with Airbus and AirFrance) [63]	additional electricity	electricity produced for the transportation sector	
Transport & Environment [74]	660 TWh (only for PtL) (2.4 EJ)	12.5%	Europe
Dray *et al.* [54]	416[a] – 8,372[b] TWh (1.5 – 30 EJ)		World
Becken *et al.* [20]	5,833[c] – 9,444[d] TWh (21 – 34 EJ)	9% of renewable energy production	World
The Shift Project and Supaéro Décarbo [100]	6,389 – 8,571 TWh (23 – 31 EJ)		World
Planès *et al.* [101]	5,414[e] TWh (19.5 EJ)		World
International Council on Clean Transportation [49]	25 EJ		World
Salgas *et al.* [55]	20.3 EJ	8% (based on IEA's NZE scenario)	World

[a] *Low demand (1.7% CAGR 2019-2050) and biofuel only scenario*
[b] *High demand (3.7% CAGR 2019-2050) and biofuel+PtL scenario*
[c] *Prudent scenario*
[d] *Optimistic Renewable Energy scenario*
[e] *Example scenario*

Not only does aviation require large amounts of electricity, but the power system must also support the uninterrupted supply of H_2 as mentioned above. Because of their intermittent nature, dedicated wind or solar generation must be supplemented by dispatchable backup assets or storage capabilities. Both options have their drawbacks. Storage through batteries or hydrogen is less energy efficient and requires oversized batteries or electrolyzers to spread out supply [81]. Dedicated renewable generation can be supplemented by dispatchable low-carbon sources, such as nuclear and geothermal energies, but also with electricity from the grid. The latter poses two major risks, namely grid overload [24], and if the decarbonized electricity share is below 90%, the obtained SAF do not respect the 65% CO_2 abatement requirement of European directive RED II [81].

Access to decarbonized energy is instrumental in developing truly sustainable SAF, whether for e-fuels or biofuels which also require electricity (heat and processing, hybrid fuels). Further decarbonization of the electricity mix significantly improves the GHG balance of biofuels, especially in the case of carbon-intensive electricity mixes such as the ones in the US [23] or China. As for e-fuels, their GHG benefits are simply annulled if the mix is not low carbon: producing e-fuels with the current world electricity mix would increase GHG emissions fourfold compared to fossil kerosene [37].

4. Cost implications

The transition to SAF is hardly cost neutral. Figure 4 reports the literature review results of Dahal *et al.* [11] on the minimum jet fuel selling price (MJSP) estimates. It considers different SAF pathways and non-drop-in alternative fuels such as LNG, liquid methane or LH_2. Unsurprisingly, drop-in fuels are, on average, two to seven times more expensive than fossil jet fuel, although the estimates include diverse extrema. These higher costs stem from the aforementioned challenges linked to feedstock, supply chain, transport, low energy efficiency, decarbonized energy access, technological readiness, and market readiness [11,22,28], resulting in higher operating and capital expenses [27,55]. That said, we observe that the cost implications of the recent increased interest rates have to date never been discussed, which is surprising given the capital-intensive nature of SAF production.

HEFA and ATJ display a wide range of price estimates due to the differences in feedstock, some having lower energy density and/or higher oxygen content, resulting in higher energy consumption [28]. Lignocellulose and microalgae correspond respectively to the maximum values of ATJ and HEFA, the latter multiplying by 10 the cost of the fuel compared to other oils [30] as a result of the lack of large-scale commercial applications of microalgae production [40]. On the other hand, e-fuels are extremely sensitive to energy prices [102]: their production cost is expected to decrease by 2050 as renewable energy becomes cheaper [103]. That said, it is unlikely that the magnitude of these cost declines are sufficient to reach cost parity with fossil Jet A or even HEFA fuel (excluding microalgae) by 2030 [104] or even 2050 [7,103,105]. Furthermore, the recent European energy crisis caused by the war in Ukraine shows that energy-intensive industries can be vulnerable to high energy prices, which impede price visibility [75].

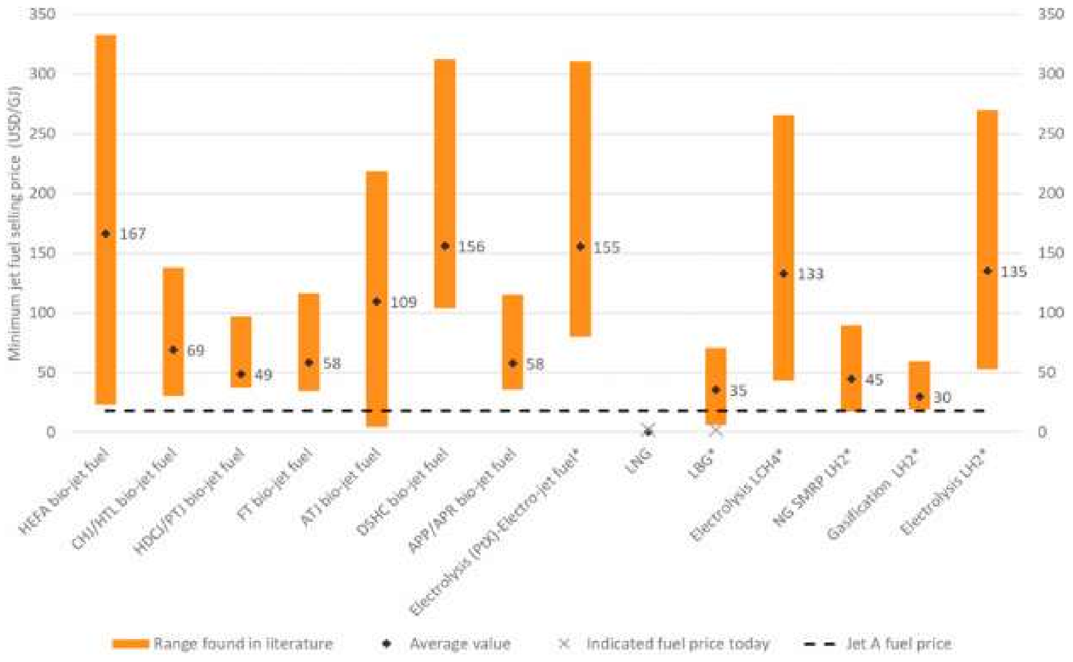

Figure 4 – Minimum jet fuel selling price (MJFSP) or fuel production cost for alternative aviation fuel pathways found in the literature review, presented in \$2019/GJ. Source: [11]
[HEFA = hydrogenated esters and fatty acids, CHJ/HTL = catalytic hydrothermolysis (decarboxylation/hydrotreating)/hydrothermal liquefaction, HDCJ = hydrotreated depolymerized cellulosic jet, DSHC = direct sugar to hydrocarbons, ATJ = alcohol to jet, FT= Fischer-Tropsch, APP/APR = aqueous phase processing/reforming,

SMRP = steam methane reforming process, LNG = liquefied natural gas, LBG = liquefied biogas, LCH4 = liquefied methane gas, LH2 = liquefied hydrogen.]

Consequently, considering both the high SAF prices, and the low crude oil prices [28,106], airlines will have little to no incentives to transition to SAF spontaneously. An aggravating factor that reinforces the prevalence of fossil fuels is the sector's business model. During the past decades, fierce competition among airlines has resulted in lowered airfares, increased passenger and freight transportation volumes, and low profitability [107]. Overall, this discussion questions the sustainability of the aviation contemporary business model, yet the aviation sector as a whole seems reluctant to initiate a dialogue about it. For example, price considerations are typically omitted in the transition narratives issued by airlines. These discourses typically claim that the transition to SAF will be nearly cost neutral thanks to major public investment and policy interventions but never consider the possibility of higher airfares as an adjustment variable in foresight scenarios. Indeed, to the best of our knowledge, the reference decarbonization scenarios issued by the industry [4,65,80] do not account for the interactions between high SAF prices, higher airfares, and the demand for transportation. Most of these studies consider the demand as an exogenously determined parameter. From a methodological perspective, this representation contrasts sharply with the assumptions retained in academic and independent studies [49,54,55,68,107] that typically account for negative price feedback in their scenarios. In other words, the aviation sector deliberately chooses to be blind to SAF-induced airfare increases.

5. Discussion and policy implications

5.1. The credibility of the objectives: Insights from a retrospective analysis

Most of the literature reviewed in this paper is very recent since the sector has had to reassess its trajectory post-COVID-19. Still, options for aviation decarbonization have been considered for more than two decades, and it is opportune to discuss that recent literature by resituating it within that more extended history.

Failed prophecies and missed targets

It should be noted that SAF incorporation targets have already been set in the past without yielding results. IATA has repeatedly revised its target incorporation rates downwards, going from 10% announced in 2008 for 2017 to 2% announced in 2019 for 2025 [108]. Furthermore, several SAF pathways have been certified for some years and are still nowhere near full-scale commercialization and use: Fischer-Tropsch since 2009, HEFA since 2011, ATJ since 2016, etc. [85]. Fischer-Tropsch biofuels, compellingly, are still virtually nonexistent in the jet fuel market, despite the process having been mastered for fossil hydrocarbon resources during WWII, and its application to biomass being considered promising since the late 1990s–early 2000s [109].

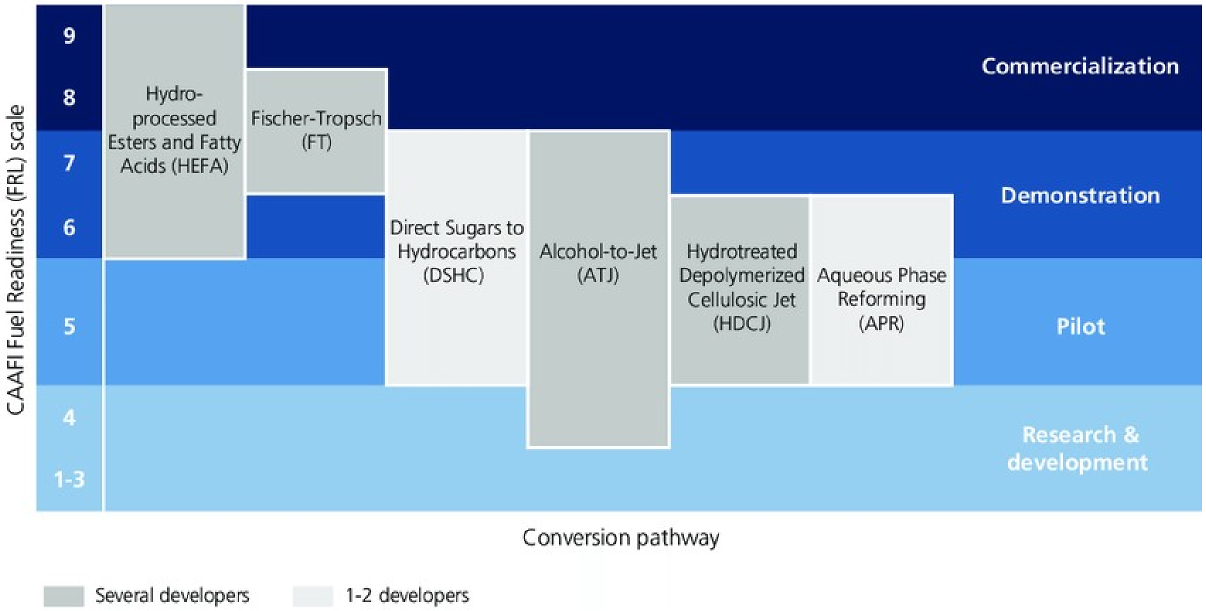

Figure 5 – Fuel readiness levels of SAF conversion technologies in 2017. Source: [110]

A halted technological progress

Some technologies appear to have frozen TRL/FRL. Figure 5 and Table 2

Jet fuel production pathway	**Technology Readiness Level (today)**	**Critical element (e.g., determining bandwidth bottom)**
PtL	5 – 8	CO2 extraction from air (TRL 6)
Fischer-Tropsch (low-temp)	6	Reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5	high-temperature electrolysis (SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	5	SOEC, ASTM approval, final conversion
BtL	5 – 9	Gasifying feedstock other than wood
Fischer-Tropsch pathway	5 – 9	
Methanol pathway	5 – 8	ASTM approval, final conversion
HEFA	4 – 9	Feedstock
Used cooking oil	9	quantity, logistics

Palm, rape seed	9	sustainability, quantity
Algae	4 – 5	reactor, extraction
HTL	4 – 6	Feedstock
Wastes/residues	6	quantity, structure
Algae	4	reactor, extraction, conversion
AtJ (sugar, starch)	5 – 9	Feedstock quantity
SIP (sugar)	7 – 9	Feedstock quantity

date back to 2016-2017, yet the FRL indicators are still relatively the same as in Table 1 and in other recent studies: F-T is still around FRL 5–7, and ATJ revolves around 7–8 but only for sugar and starch while lignocellulose remains at 4–6 [1,10,11,18]. These biofuel processes were expected to be commercialized between 2021 and 2026 [17], yet despite widespread support in several countries, advanced biofuel plants regularly face significant delays in reaching their envisioned capacity [58]. Peters *et al.* [111] even suggest that several sustainable options like jatropha, hydrogen, waste animal fats, and algae are "technology myths," which drew mediatic attention in 2008 following the 2007 IPCC report and then slowly faded away. HEFA has fully reached FRL 9, but demonstrates one of the major flaws of the indicator: this last level can theoretically be achieved with a single commercial plant, even though the volumes remain very limited [17]. Carbon capture from industrial sources seems to be at an impasse, facing the same difficulties since 2014, namely high energy loss, high cost for low revenue, and low technological availability on a large scale (cf. 3.2.2) [73]. However, it is important to stress that electro-jet fuels are a much more recent endeavor than bio-jet fuels, since only 14 academic publications were issued between 2005 and 2019 on the topic, as opposed to 617 for bio-jet fuels [11].

A low-investment trap for low-carbon solutions

Underlying TRL stagnation and low commercialization is the cost issue. As previously mentioned (cf. 4), SAF is not competitive compared to jet fuel in the market, in addition to which capacity-building requires significant investment, around \$1 to \$1.7 trillion in total until 2050 for industry-aligned growth rate projections [4,7,54].

The current organization of the industry looks poorly adapted to channel that investment. Indeed, aircraft manufacturers claim responsibility for certifying SAF, building 100% SAF-compatible airplanes, and political advocacy [7,112]. Many airlines refuse to acknowledge their role in driving SAF production, shifting this responsibility to oil companies and startups [108,113,114]. Said airlines also regret the consumers' reluctance to pay more expensive airfares to fund SAF use [115]. Dodd *et al.* [113] observed "free-riding across sectors," *i.e.*, a phenomenon whereby all actors – biofuel companies, airlines, and policymakers – consistently refuse to take the leadership, and are, at best, only willing to follow others, when their objective is not simply to free-ride. Several companies stand out, however, by their proactivity: this is the case of several large US airlines [113,114], or companies like the AirFrance-KLM group and the International Airlines Group, who secured SAF amounts with energy companies through off-takes [116,117]. Still, while this tends to de-risk SAF investments [59], it will likely not be enough to compensate for the numerous uncertainties linked to projects such as PtL, which discourage first-movers [31]. There is a need for the whole industry – from energy providers to airlines and aircraft manufacturers – to invest directly in SAF production, something which even the most committed airlines are reluctant to do [116]. Considering this, it is possible that SAF resource scarcity will not affect their use as much as the sector's unwillingness to commit financially to creating a supply chain, stemming from a certain lack of accountability of each actor in the industry.

5.2. Lifting barriers to scaling up

Changing the sector's forged perceptions

This paper has put forward the reluctance of the entire aviation industry (*i.e.*, airplane manufacturers, airlines) to invest in SAF, hidden behind the apparent decarbonization ambition. Therefore, policies must aim to overcome this reluctance, which has stalled the rise of SAF incorporation rates for almost two decades. The scope of the transition to net zero requires a much more resolute commitment of the whole aviation market than largely voluntary "long-term aspirational goals," which, arguably, never drive markets [32,108], and/or lead to greenwashing, as is already the case for voluntary carbon offsets [118]. Public investment in research, development, and scaling up, is essential to improve SAF competitiveness [30].

The United States "SAF Grand Challenge Roadmap" [61] follows this path: it aims to invest significantly, notably through the Inflation Reduction Act [119], in scaling up SAF production to reach competitive prices. Other facilitating mechanisms exist, such as the promotion of power purchase agreements for SAF pathways requiring significant amounts of electricity, to ensure stable electricity prices [75]. However, the price gap between fossil and sustainable jet fuel is such that "positive" policies will likely not suffice [120]. Carbon taxes are one effective possibility to increase SAF competitiveness [30] and mitigate traffic growth [107,121]. The other option is to impose blending mandates or, in other words, imperative SAF incorporation rates in the airports inside a given territory: they send a strong demand signal, incentivize the energy providers to invest in lowering the costs of SAF, and give a higher impetus to reach the targets, being one of the most effective policies to achieve technological change [31,122].

The EU has opted for a hybrid approach, with blending mandates through the ReFuelEU proposal [35], higher fossil jet fuel prices through the end of free emissions quotas (EU ETS) for aviation [123], and encouragement for the member states to invest in SAF development (France recently announced a 200 M€ investment for SAF [124]). Blending mandates can include sub-mandates to assist the development of specific technologies further. For example, the EU has included sub-mandates for e-fuels [35], and T&E suggests doing the same for DAC [74]. As an alternative to blending mandates, California implemented a Low Carbon Fuel Standard (LCFS), which compels companies to reduce the carbon intensity of their fuels, thus having the advantage of being technology-neutral [29]. The EU mandates and the LCFS are only imposed upon fuel providers, but the EU is open to broadening its scope to airlines: perhaps this would be a more efficient way to trigger investment on their side as well.

Shifting from purely coercive to "carrot and stick" policies

The European policies have a restrictive nature. They have already been met with significant resistance from the air transport sector, as it typically argues that these policies are not economically efficient, create deadweight loss, divert investment from decarbonization R&D, and do not favor a level playing field [115,125,126]. Carbon taxes are particularly rejected [31] while blending mandates are merely "not IATA's preferred option" [126]. That restrictive approach must thus be supplemented with supply-side investment and incentives to retain the sector's support.

It is also pivotal for restricting authorities, such as the EU, to demonstrate their willingness to instate an international level playing field. Indeed, the EU blending mandates raise the possibility of flight rerouting to non-EU airports (*e.g.,* London, Geneva, Istanbul) if they do not have mandates [32,127]. The other main risk is the so-called "fuel tankering" – *i.e.*, excess tank filling in airports with low fuel prices to avoid fully refueling at the next – which causes excess mass and thus lower fuel efficiency [128]. The ReFuelEU proposal also includes an article against fuel tankering in its airports which dictates that 90% of the fuel used by planes departing from the EU shall be from the departure airport [35]. Lastly, blending mandates must be paired with strict fuel sustainability criteria and incentives to use emerging and more sustainable feedstock, to avoid using cheaper food-based biofuel and other less sustainable feedstocks [29,120,129].

5.3. **Present-day considerations for upcoming issues**

The abovementioned approach holds for the next decade but is insufficient to reach net zero by 2050. Even if the SAF industry manages to be scaled up, the amounts of biomass, hydrogen, and electricity required to reach net zero will call for strong political decisions giving aviation priority access to these resources and jeopardizing other sectors' efforts to decarbonize [20]. Here, fairness and social acceptability motives are likely to come into play: dedicating 20% of the electricity production to a mode of transport that was only used by 11% of the population in 2018, most of which was considered "high income" [67], is unreasonable. Policymakers could choose *laisser-faire*, leaving resource allocation to the market and only imposing blending mandates to increase airlines' willingness to pay. This policy leads to significant uncertainties over the final allocation, which could strongly favor aviation or not at all.

An aviation-skewed resource allocation would be detrimental to decarbonization efficiency, as the carbon abatement benefits of using renewable energy for e-fuels pale in comparison to other uses: the British Climate Change Committee, for instance, recommended they be avoided and priority be given to more effective transitions such as coal power plant replacement, electric vehicle or heat pump powering [130]. More generally, several studies [66,131] have shown that CCU through liquid biofuels is less effective in terms of GHG abatement than other solutions, such as CCS or biomass-derived electricity and heat generation. In light of the unfairness and inefficiency of such a policy, this paper argues that granting aviation priority over the industry-forecasted amounts of critical resources in 2050 is neither sensible nor fundamentally feasible.

A “*laissez-faire*” aviation policy being out of the question, the only option is implementing policies constraining the sector’s growth [32]. In this regard, it is worth noting that the IEA’s *Net Zero by 2050* roadmap is based on low-growth assumptions (around 1.8% p.a. between 2019 and 2050) [132]. Policies will be necessary to complement the demand feedback associated with higher airfares caused by increased SAF use, as these will not be sufficient to decelerate compound annual growth rates by more than 0.5% compared to industry references [49,54,55]. Research on concrete policies has already focused on frequent flyer taxes, domestic and corporate flight reductions, the end of first and business class, and carbon taxes [67,74,100,107,121,122]. Aviation can achieve decarbonization only through a more sustainable air traffic growth associated with reasonable resource utilization.

6. Conclusion

Aviation decarbonization through sustainable aviation fuels faces two main challenges, namely two thresholds to overcome: in the short term, 1% of SAF use, and in the long term, 100% SAF use. The short-term goal relates to the acceleration and scaling up of SAF production, and the long-term one relates to resource limits for SAF production. This paper has reviewed the expected availability of biomass, CO_2, hydrogen, technologies, and electricity, considering issues of feedstock, technological readiness, energy losses, infrastructure, transport, and their consequences on cost, and competition vs. synergy perspectives with other sectors.

Results show that, in addition to an incentivizing policy including significant investment to develop the necessary technologies and scale up feedstock production, more ambitious policies are needed to bridge further the gaps between technologically ready and cheap fossil fuels and SAF. A deregulated or insufficiently regulated market, even with decarbonization aspirations and a degree of SAF uptake, will lead the aviation industry to choose inefficient solutions, ranging from greenwashing and the promotion of technological myths to the use of unsustainable feedstock and energy or a disorganized SAF uptake mitigating benefits such as non-CO_2 effects reduction potential. Furthermore, regulations are necessary to lower market expectations. Otherwise, aviation will either not decarbonize or will capture an excessive amount of resources critically needed to smoothen other sectors' transition.

Further research is certainly needed on the policies that can be implemented to guide the sector's transformation. These measures must account for the sector's specific industrial organization, marked by the prevalence of fierce competition among airlines. Another possible extension concerns the current lack of understanding of how SAF incorporation mandates (or low carbon fuel standards) affect fuel prices – and consequently airfares – as well as the performance of the industry and its capacity to invest in low-carbon solutions. Lastly, the analysis in this paper has pointed out possible resource scarcities. A related issue is thus how low-carbon fuels should be allocated to the competing sectors that can consume them. Further research is necessary to analyze how emerging incorporation mandates will affect the dynamics of resource allocation, and whether additional policy intervention is required.

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