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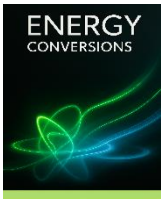

Comparative Assessment of Sustainable Aviation Fuel Pathways: Performance, Sustainability, Certification, and Scale-Up Constraints

Hannah T. Schultz [a,*], Sarah E. Langston[a]

[b] *Sustainable Aviation Institute, ETH Zurich, Switzerland*

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ABSTRACT

Sustainable aviation fuel (SAF) is widely regarded as the most practical near-term route to lower aviation emissions without replacing today's aircraft and airport fuel systems. This review synthesizes the current state of SAF development across biomass-derived and synthetic pathways, with emphasis on feedstock sustainability, conversion performance, lifecycle greenhouse-gas mitigation, production cost, certification status, and deployment readiness. Certified routes such as HEFA, Fischer–Tropsch, and Alcohol-to-Jet are assessed alongside emerging Power-to-Liquid systems that couple renewable hydrogen with CO_2. The comparison shows that no single pathway simultaneously maximizes yield, scalability, cost competitiveness, and climate benefit. Waste-based HEFA is commercially mature but feedstock-limited; FT and ATJ broaden the resource base but require stronger process and capital optimization; PtL offers the deepest long-term decarbonization potential but remains highly dependent on renewable electricity, low-cost hydrogen, and supportive policy. The review concludes that accelerated certification, durable market incentives, and region-specific supply-chain strategies will be essential if SAF is to move from niche deployment to meaningful global scale.

1. Introduction

Aviation remains indispensable to the global economy, yet it is also one of the hardest sectors to decarbonize. Before the pandemic, air transport carried more than 4.5 billion passengers annually and generated roughly USD 3.5 trillion in economic activity. That contribution, however, is accompanied by a substantial climate burden. Civil aviation is responsible for about 2.5% of global CO_2 emissions, while its total warming impact is larger once non-CO_2 effects such as NO_x emissions and contrail-induced cirrus are included. Without meaningful intervention, aviation emissions could rise sharply by mid-century and complicate efforts to hold warming below 2°C. [1]

Alternative propulsion concepts are advancing, but their applicability is uneven across the aviation system. Battery-electric aircraft are constrained by gravimetric energy density, and hydrogen-based propulsion still faces major challenges in storage, airport infrastructure, aircraft integration, and fleet turnover. For long-haul and high-capacity operations, liquid hydrocarbon fuels therefore remain difficult to replace in the near term. Within that context, Sustainable Aviation Fuel (SAF) has emerged as the leading practical option for reducing sectoral emissions while using existing engines, distribution systems, and fueling assets. [2]

The appeal of SAF lies in its drop-in character. When produced within accepted specifications, SAF can be blended with Jet A-1 and introduced into current aviation infrastructure without major hardware modification. Depending on feedstock origin, process route, and system boundaries, reported lifecycle GHG reductions commonly fall in the 50–90% range relative to fossil jet fuel. More recent synthetic routes, particularly Power-to-Liquid (PtL), are attracting attention because they can combine captured CO_2 with green hydrogen to deliver very low, and under some assumptions near-net-zero, carbon intensity.

Despite this promise, market penetration remains extremely limited. SAF accounted for less than 0.1% of global aviation fuel consumption in 2022, reflecting persistent barriers related to production cost, resource availability, certification, and scale-up. HEFA is the most mature route, but its growth is restricted by finite supplies of lipid feedstocks and competition from other biofuel markets. Residue-based FT and advanced ATJ pathways offer a broader resource base, yet they are typically more capital intensive and operationally complex. PtL pathways are conceptually attractive, but they currently depend on expensive renewable electricity, electrolytic hydrogen, and access to concentrated or captured CO_2 streams. [3]

Accordingly, evaluating SAF requires more than a simple comparison of carbon savings. A rigorous assessment must consider pathway efficiency, feedstock sustainability, lifecycle emissions, land and water demands, policy alignment, and certification readiness. Recent regulatory developments—including CORSIA, RED II, and the U.S. Inflation Reduction Act—have begun to strengthen the commercial case for SAF, yet market harmonization and infrastructure build-out remain incomplete. [4]

This review therefore examines SAF as a portfolio of technological options rather than a single solution. It first outlines the literature-review methodology, then compares major feedstocks and conversion pathways, assesses environmental and techno-economic performance, and reviews certification and deployment trends. The paper concludes by identifying the strategic conditions required for SAF to contribute meaningfully to aviation decarbonization. [5]

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* Corresponding author at: Sustainable Aviation Institute, ETH Zurich, Switzerland.

E-mail addresses: s.langston@cam.ac.u (Hannah T. Schultz)

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Nomenclature

Abbreviation	
SAF	Sustainable Aviation Fuel
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
HEFA	Hydroprocessed Esters and Fatty Acids
FT	Fischer-Tropsch
ATJ	Alcohol-to-Jet
PtL	Power-to-Liquid
ASTM	American Society for Testing and Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation

Symbol	
η	Efficiency
Q	Energy content
C_e	Emission factor

2. Methodology

The review was designed to capture both the technical depth and the policy relevance of the rapidly expanding SAF literature. Rather than relying on a purely narrative survey, the study combined structured database screening with targeted expert judgement so that mature pathways, emerging routes, and deployment-oriented analyses could be assessed within a common comparative framework.

Source identification was conducted using Scopus, Web of Science, ScienceDirect, and Google Scholar, supplemented by grey literature from organizations such as ICAO, IEA, DOE, and the European Commission. Search strings combined terms including "Sustainable Aviation Fuel," "biojet fuel," "HEFA," "Fischer–Tropsch jet," "Alcohol-to-Jet," "Power-to-Liquid," "techno-economic assessment," and "lifecycle assessment." The search window covered 2005–2024, with stronger weight assigned to studies published after 2015 in order to reflect the recent acceleration in certification activity and industrial investment. [6]

Documents were retained when they addressed SAF feedstocks, conversion technologies, environmental performance, certification, or deployment economics and when they reported quantitative indicators such as yield, carbon intensity, production cost, or blending limits. Studies focused exclusively on upstream agriculture, generic biomass processing, or non-aviation fuel applications were excluded unless they provided transferable insights directly relevant to SAF. [7]

Table 1. Summary of database screening and source selection for the SAF review.

Database/Source	Articles Identified	Articles Included
Scopus	48	28
Web of Science	42	24
ScienceDirect	55	35
Google Scholar	61	31
IEA Reports	10	8
ICAO Reports	8	6

In total, 138 primary references were reviewed in full text, comprising 86 journal papers, 34 technical reports, and 18 policy or regulatory documents. These were complemented by 20 secondary references used for contextual interpretation. Each source was classified by topic area—feedstock, pathway, LCA, TEA, policy, or certification—and the extracted quantitative information was cross-checked across sources before synthesis into comparative tables and figures.

The figures presented in this manuscript were rebuilt as comparative schematics from the numerical ranges and pathway relationships reported across the reviewed literature. They are intended to visualize cross-pathway contrasts rather than reproduce any single source figure. [8]

Table 2. Inclusion logic applied during source screening and synthesis.

Criteria	Included Studies (n=138)	Excluded if
Technical focus on SAF	Yes	Focused only on upstream agriculture
Quantitative performance data	Yes	Lacked specific data on SAF yields or emissions
Relevance to policy or deployment	Yes	Covered non-aviation fuels only
Transparency of LCA/TEA methods	Yes	No methods or unclear LCA boundaries
SAF feedstock or conversion scope	Yes	Focused solely on fossil or unrelated processes

3. Results

3.1. Overview of SAF pathways and current deployment status

SAF should be understood as a family of low-carbon jet-fuel options rather than a single fuel product. Its pathway portfolio spans biogenic routes based on lipids, sugars, residues, and municipal wastes, as well as synthetic routes that combine renewable hydrogen with carbon from industrial or atmospheric sources. By 2024, seven pathways had achieved ASTM D7566 approval for blending with Jet A-1, while several additional concepts remained at pilot or demonstration stage. [9]

Among the certified routes, HEFA remains the most commercially established. Using feedstocks such as used cooking oil, tallow, and related lipid streams, HEFA accounts for the dominant share of present SAF output—more than 80% of the roughly 450 million liters produced in 2023. Its industrial advantage arises from high conversion yield and comparatively simple process integration, although those strengths are offset by limited waste-lipid availability and competition from renewable diesel and biodiesel markets. [10]

Fischer–Tropsch (FT) synthesis broadens the feedstock base by accommodating lignocellulosic residues, agricultural wastes, and municipal solid waste. Its appeal lies in feedstock flexibility and strong fuel quality, but commercial expansion has been slower than for HEFA because FT facilities require capital-intensive gasification, syngas conditioning, and catalytic upgrading.

Even so, FT remains strategically important because it can couple SAF production with waste-management systems and exploit resources that are geographically more abundant than waste lipids. [11]

Alcohol-to-Jet (ATJ) pathways convert ethanol or isobutanol—derived from sugar, starch, or lignocellulosic feedstocks—into jet-range hydrocarbons through dehydration, oligomerization, and hydrogenation. Pre-commercial projects have demonstrated that ATJ can reach roughly 60–65% yield, with reported GHG reductions around 50–70%, but the route remains cost-sensitive because of its multistep upgrading sequence and competition for alcohol feedstocks in other markets. [12]

Power-to-Liquid (PtL), or e-kerosene, follows a different logic: renewable electricity is used to generate hydrogen, which is then reacted with CO_2 through Fischer–Tropsch or methanol-based synthesis. Although commercial deployment is still nascent, PtL is widely regarded as the most scalable long-term route because it is not fundamentally constrained by biomass availability and can deliver very deep GHG reductions when paired with low-carbon electricity and captured CO_2. [13]

A wider innovation pipeline also exists beyond the most cited commercial routes, including catalytic hydrothermolysis, upgraded pyrolysis oils, and integrated biorefinery concepts intended to improve carbon efficiency, reduce hydrogen demand, or expand the usable feedstock base.

Figure 1 reorganizes these pathways by certification year and current market maturity, illustrating how industrial deployment remains concentrated in a small subset of the approved technology portfolio.

Fig 1. Certification chronology and present market maturity of major SAF pathways.

3.2. Fuel yield and process efficiency profiles

Yield and efficiency are central to SAF pathway comparison because they determine feedstock demand, plant sizing, and ultimately the cost of delivered fuel. In this review, pathway performance is interpreted in terms of fuel yield, overall conversion efficiency, hydrogen intensity, and the extent of process integration required to approach competitive operation. [14]

HEFA consistently exhibits the strongest fuel yield among the approved routes, commonly reaching 80–90 wt% of feedstock input. This reflects the structural similarity between triglyceride-derived feedstocks and jet-range hydrocarbons, which allows hydrodeoxygenation and isomerization to proceed with limited carbon loss. [15]

Commercial HEFA facilities typically report thermal efficiencies near 70–80%, with hydrogen production representing the dominant external energy demand. The pathway is therefore efficient at the plant level, but not necessarily scalable at the system level because suitable lipid feedstocks are finite.

FT pathways generally achieve lower fuel yield—often about 35–45 wt% of dry feedstock—but offer greater flexibility in feedstock choice. Standalone facilities may operate near 40–50% overall efficiency, whereas integrated plants that recover heat or export coproduct power can exceed 60%. [16]

ATJ routes typically convert alcohol intermediates to jet fuel at approximately 60–65% yield. Their performance benefits from existing fermentation infrastructure, yet the multistep upgrading sequence increases hydrogen demand and process losses relative to HEFA. [17]

From a systems perspective, the long-term attractiveness of ATJ depends on shifting from food-derived alcohols toward lignocellulosic intermediates, thereby improving both sustainability and the resilience of the feedstock base. [18]

PtL performance is more naturally expressed on an energy basis than on a feedstock mass basis. Current plants generally convert electricity to liquid hydrocarbons at around 35–45% efficiency, which is lower than biomass-derived routes but potentially compatible with very low lifecycle emissions.

Accordingly, PtL is less a near-term efficiency leader than a long-term decarbonization platform whose competitiveness will depend on cheap renewable power, improved electrolyzers, and access to low-carbon CO_2. [19]

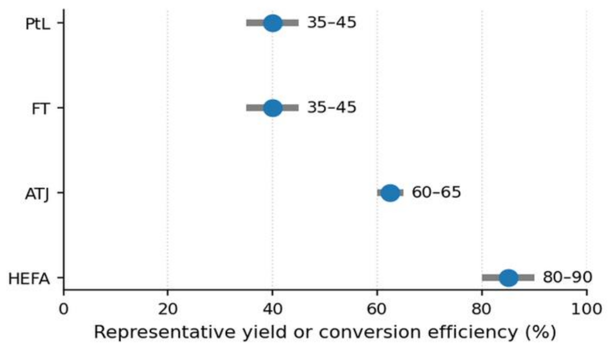

Fig 2. Indicative fuel-yield and conversion-efficiency ranges across representative SAF routes.

3.3. Lifecycle GHG emissions and climate benefits

Because all jet fuels emit CO_2 at combustion, the climate value of SAF is determined mainly by upstream emissions. Lifecycle assessment therefore remains the appropriate basis for comparison, capturing feedstock sourcing, cultivation or collection, processing energy, transport, and land-use effects rather than focusing only on tailpipe performance. [20]

Waste-based HEFA pathways—especially those using used cooking oil or animal fats—deliver some of the strongest lifecycle results among today's commercial options. Published studies and GREET-based assessments frequently report 75–90% well-to-wake GHG reduction relative to fossil jet fuel. [21]

These strong reductions arise because waste lipids avoid most cultivation emissions and can displace disposal routes that would otherwise create additional climate impacts.

The picture changes markedly for HEFA produced from virgin vegetable oils. Once indirect land-use change is considered, feedstocks such as palm or soybean oil may provide only modest savings or even perform worse than fossil jet fuel in some cases. [22]

This sensitivity explains why sustainability certification under schemes such as RSB and CORSIA places strong emphasis on traceable sourcing and land-use integrity. [23]

FT fuels derived from municipal solid waste, forestry residues, or agricultural by-products generally fall within a 70–85% GHG-reduction range. Their performance improves further when low-carbon heat and electricity are used or when carbon capture is integrated into the process. [24]

An additional strength of FT is that it can valorize waste streams that might otherwise decompose, emit methane, or be openly burned, thereby improving its comparative carbon performance beyond the refinery boundary.

ATJ exhibits wider variability, with reported GHG reductions typically spanning 40–70% depending on feedstock and regional energy conditions. Sugarcane-based ethanol can perform relatively well in low-carbon electricity systems, whereas corn-based ethanol often carries a heavier upstream emissions burden. [25]

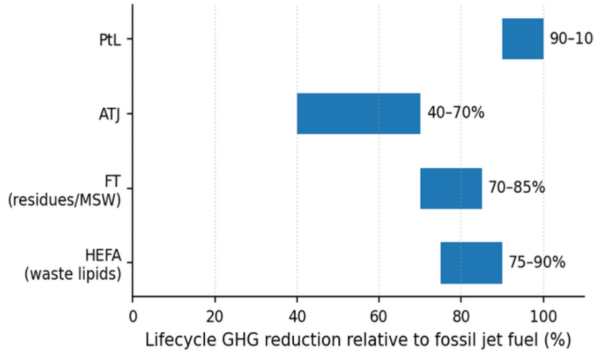

Fig 3. Reported lifecycle GHG-reduction ranges relative to conventional jet fuel.

Advanced ATJ pathways based on lignocellulosic alcohols could narrow that gap substantially and may eventually approach or exceed 80% reduction, although commercial deployment remains limited. [26]

PtL offers the highest theoretical decarbonization potential. When hydrogen is produced by renewable electrolysis and CO_2 is supplied from atmospheric or other low-carbon sources, reported lifecycle reductions commonly reach 90–100% relative to fossil jet fuel.

That result, however, is highly contingent on electricity carbon intensity. PtL produced with carbon-intensive grid power can lose most of its climate advantage and, under unfavorable conditions, even exceed the lifecycle burden of conventional jet fuel. [27]

The literature therefore shows PtL to be an electricity-sensitive pathway whose performance can range from net-negative values to strongly positive emissions depending on the source of power, as summarized in Figure 3 and revisited in Figure 7. [28]

3.4 Economic viability and cost structure

The main barrier to rapid SAF adoption is not technical feasibility alone but delivered cost. Compared with recent fossil jet-fuel prices of roughly USD 0.60–0.90 L^{-1}, SAF commonly falls in the USD 1.10–3.00+ L^{-1} range, depending on pathway, plant scale, feedstock price, and local energy conditions. [29]

HEFA: comparatively affordable, but feedstock constrained

HEFA is presently the most cost-competitive SAF route, often reported around USD 1.00–1.20 L^{-1} when waste oils or tallow are available. Its economic advantage comes from high yield and a relatively mature process configuration.

That advantage is fragile, however, because feedstock cost can account for 60–70% of total HEFA production cost according to NREL assessments. Where domestic waste lipids are scarce, reliance on imported or virgin oils can quickly erode both price competitiveness and environmental benefit. [30]

Fischer–Tropsch: capital intensive with slower returns

FT routes generally fall near USD 1.50–2.00 L^{-1}, with capital recovery playing a much larger role than in HEFA because of gasification, air separation, syngas cleanup, and synthesis requirements. [31]

Their economics improve when plants are integrated with waste-management systems, biomass-processing infrastructure, or coproduct valorization. Access to carbon credits or CCS-linked incentives can also materially improve project viability. [32]

Alcohol-to-Jet: moderate capital, elevated operating burden

ATJ is often reported between USD 1.30 and 1.80 L^{-1}. Although capital intensity can be lower than FT—especially where ethanol production is already established—the overall route remains expensive because of catalytic upgrading, hydrogen demand, and purification stages.

Regional context matters strongly: sugarcane ethanol may provide both cost and emissions advantages in Brazil, whereas corn ethanol introduces greater cost volatility and higher indirect emissions exposure in other markets. [33]

Power-to-Liquid: highest current cost, strongest long-term upside

PtL remains the most expensive pathway, with published estimates commonly in the USD 2.50–4.00+ L^{-1} range. A large share of that cost is linked to green hydrogen, which can contribute roughly 50–70% of the total depending on electricity price and electrolyzer performance. [34]

Capital requirements are also substantial because PtL plants combine electrolysis, CO_2 supply, synthesis, and upgrading units. Nevertheless, the pathway retains long-term strategic value because falling renewable-power costs and policy support could materially narrow the gap by 2040 in favorable markets.

Figure 4 breaks the cost ranges into indicative CAPEX, OPEX, and feedstock-related components, highlighting the very different economic signatures of HEFA, FT, ATJ, and PtL.

Fig 4. Indicative production-cost composition by pathway (CAPEX, OPEX, and feedstock-related burden).

3.5 Feedstock sustainability and resource availability

Feedstock supply ultimately determines whether SAF can move from marginal deployment to structural relevance. The central challenge is not only obtaining carbon-rich inputs, but doing so in ways that remain sustainable, traceable, and logistically reliable at scale. [35]

Lipid feedstocks: attractive in carbon terms, limited in volume

Waste oils and animal fats perform well from a lifecycle perspective because they carry little or no cultivation burden and often avoid disposal-related emissions. These characteristics explain why such feedstocks dominate the current HEFA market. [36]

Their limitation is scale: the sustainable global supply of waste lipids is widely estimated to cover only about 2–3% of present jet-fuel demand. Competition with road-fuel markets further tightens availability and increases price volatility. [37]

Virgin vegetable oils are more abundant, but their sustainability credentials are much weaker when linked to deforestation, peatland conversion, or biodiversity loss. Accordingly, their role in SAF remains heavily dependent on stringent certification and supply-chain verification.

Lignocellulosic biomass: broad potential, difficult logistics

Agricultural residues, forestry by-products, and dedicated energy crops offer one of the largest long-term resource pools for SAF. IEA estimates suggest that sustainable biomass availability could exceed 100 EJ yr^{-1}, theoretically enough to satisfy a substantial fraction of aviation demand by 2050. [38]

The difficulty lies in mobilization: these resources are diffuse, seasonal, low in bulk density, and often require extensive preprocessing, storage, and transport before they become refinery-ready. [39]

Sugars and starches: transitional rather than ultimate solutions

First-generation sugar and starch feedstocks underpin much of today's ethanol industry and therefore support early ATJ deployment. They benefit from mature agricultural and fermentation systems, but their long-term role in SAF is constrained by food-system competition and indirect land-use concerns. [40]

Brazilian sugarcane ethanol is often cited as a relatively favorable case because of high crop productivity and bagasse-based process energy, whereas corn ethanol generally carries a less attractive emissions profile and greater land-use sensitivity.

CO_2 and renewable hydrogen: scalable in principle, constrained in practice

PtL depends on two core inputs: a low-carbon carbon source and renewable hydrogen. CO_2 can be supplied from biogenic streams, industrial point sources, or direct air capture, making the carbon input theoretically abundant even if not yet inexpensive. [41]

In practice, hydrogen is the sharper bottleneck. Green H_2 remains expensive and supply-limited, so the scalability of PtL is tightly linked to renewable-electricity expansion, electrolyzer deployment, and supportive infrastructure planning. [42]

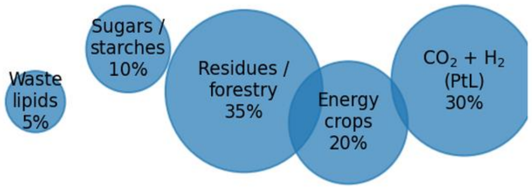

Fig 5. Relative sustainable feedstock potential by major resource class.

3.6 Infrastructure compatibility and certification

Commercial success depends not only on producing SAF, but on qualifying it for use in an extremely safety-sensitive sector. The value proposition of SAF is inseparable from its ability to move through existing engines, storage systems, hydrants, and airport fuel logistics with minimal disruption.

ASTM D7566 as the central certification pathway

ASTM D7566 provides the principal technical route through which synthetic or alternative blending components are approved for aviation use. Once a pathway satisfies the required chemical and performance criteria, the approved blend can enter service under ASTM D1655 alongside conventional jet fuel. [43]

By 2024, seven SAF routes had been approved under D7566, including HEFA-SPK, FT-SPK, FT-SKA, ATJ-SPK, CHJ, SIP, and FT-based PtL. This expanding list signals genuine progress, but it also reveals that certification remains selective and time-consuming. [44]

Approved blend limits generally range from 10% to 50% by volume, depending on pathway composition and fuel properties. These limits are not administrative conveniences; they reflect real material-compatibility and operability requirements, particularly for aromatic content, density, lubricity, and low-temperature performance. [45]

Aromatics are especially important for seal swelling in some legacy components, which is why paraffinic routes such as HEFA and FT-SPK are commonly capped at 50% unless additional aromatic functionality is introduced.

Newer pathway variants such as FT-SKA and CHJ aim to address this limitation by producing more suitable hydrocarbon distributions, and recent demonstration flights using neat SAF have intensified the push toward 100% drop-in approval. [46]

Airport and distribution-system integration

One of SAF's strongest practical advantages is that it can be transported and dispensed through much of the existing fuel-supply chain, including pipelines, tanks, hydrant networks, and fueling trucks. That compatibility sharply lowers the infrastructure burden relative to hydrogen or battery-electric alternatives. [47]

The remaining challenge is spatial rather than functional. SAF production is often remote from major airports, so blending terminals, transport corridors, and regional hub strategies are needed to connect supply with demand efficiently. [48]

Table 5. ASTM-certified SAF pathways and currently approved blend limits.

Pathway	Feedstock Type	Max Blend Limit (%)	ASTM Approval Year
HEFA-SPK	Used Cooking Oil, Animal Fats	50	2011
FT-SPK	MSW, Agricultural Residues, Biomass	50	2009
FT-SKA	Same as FT-SPK, but with aromatics	100	2015
ATJ-SPK	Sugars, Starches, Alcohols	50	2016
CHJ	Oils via hydrothermolysis	50	2020
SIP	Sugar fermentation (farnesene)	10	2014
PtL (FT-based)	$CO_2 + H_2$ via FT synthesis	50	2023

3.7 Regional and global production capacity

Global SAF capacity has expanded, but current output remains far below decarbonization needs. Production in 2023 was still below 0.5 billion liters—well under 0.1% of aviation fuel demand—whereas net-zero scenarios imply eventual production on the order of hundreds of billions of liters per year.

Present supply is still dominated by HEFA facilities in North America, Europe, and Asia. Producers such as World Energy, Neste, and Eni account for most commercial volumes, largely using used cooking oil and tallow as feedstock. [49]

ATJ and FT projects have advanced more slowly and remain concentrated in demonstration or early commercial phases. Facilities such as LanzaJet's plant in Georgia and Fulcrum BioEnergy's Nevada project illustrate progress, but they do not yet alter the overall HEFA-dominated market structure. [50]

PtL remains even earlier in the scale-up sequence, with projects in Norway, Germany, and the Gulf region reflecting strong strategic interest but limited current volume. [51]

Figure 6 summarizes the present regional concentration of SAF capacity, which is still strongly weighted toward OECD markets with clearer incentives, stronger offtake signals, and more developed certification ecosystems.

Policy is the main accelerator behind this concentration. ReFuelEU Aviation, California's LCFS, and comparable national roadmaps are converting climate ambition into bankable demand signals and thereby shaping the geography of new investment.

In Asia, Singapore has emerged as a prominent refining and export hub, while Japan, South Korea, and China are expanding national programs that include both bio-based and waste-based SAF routes. [52]

The Middle East is increasingly relevant to the PtL discussion because abundant renewable resources and hydrogen strategies in countries such as the UAE and Saudi Arabia create conditions that may favor synthetic-fuel deployment. [53]

The principal barriers to rapid capacity growth are persistent HEFA feedstock scarcity, the high capital intensity of FT and PtL projects, remaining gaps in blending and certification infrastructure, and the absence of fully harmonized international standards.

Overcoming these constraints will require coordinated financing, long-term procurement structures, and more deliberate regional supply-chain planning. [54]

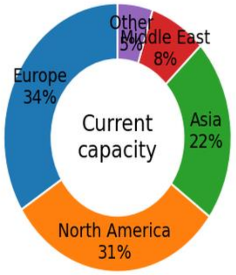

Fig 6. Regional distribution of current SAF production capacity.

3.8 Energy and water footprint

Carbon intensity alone is insufficient to judge SAF sustainability. Energy consumption and water demand can materially alter the desirability of a pathway, particularly in regions where power or freshwater are already constrained. [55]

HEFA generally imposes the lowest process-energy burden because lipid feedstocks are already chemically close to jet-range hydrocarbons. Typical net energy requirements are reported near 10–12 MJ per MJ of fuel when hydrogen is supplied by natural-gas reforming. [56]

FT is more energy intensive because drying, gasification, syngas cleanup, and catalytic synthesis all add demand; total process energy commonly falls in the 18–22 MJ per MJ range unless extensive heat integration is implemented.

Even where heat recovery is available, the complexity of the process makes efficiency optimization a plant-specific exercise rather than an automatic outcome. [57]

ATJ occupies an intermediate position, with literature values commonly around 14–18 MJ per MJ of fuel owing to fermentation, dehydration, and upgrading requirements. [58]

PtL is the most electricity-intensive route. Using current PEM electrolysis, published requirements are often in the 45–55 MJ electricity per MJ fuel range, making the pathway highly sensitive to both electricity price and renewable-power availability. [59]

Water use introduces a second layer of differentiation. HEFA and ATJ can inherit very large agricultural water footprints when the underlying feedstocks are irrigated—for example, soybean oil or sugarcane under water-stressed cultivation systems.

FT routes based on residues generally avoid large agricultural water burdens, but they still consume water for cooling, steam generation, and gas cleaning, with reported totals of roughly 5–15 L per liter of fuel. [60]

PtL has comparatively low direct process-water demand—mainly for electrolysis, often around 9–18 L per liter of fuel—but it can still embody indirect water burdens through the supporting electricity infrastructure. [61]

These differences imply that regional suitability matters. Water-stressed regions may favor PtL or residue-based FT, whereas rainfed agricultural regions may be better positioned to support some biomass-based pathways.

For that reason, future SAF planning should rely on integrated energy–water–carbon assessment rather than carbon metrics alone. [62]

3.9 Land-use impacts and biodiversity risks

Land use remains one of the most contested aspects of bio-based SAF. The concern is not limited to the area directly cultivated for fuel crops; it also includes indirect effects on food systems, ecosystem conversion, and long-term biodiversity loss. [63]

First-generation feedstocks such as soybean, corn, sugarcane, and oil palm tend to impose the largest direct land requirements. Reported values exceed 1 m^2 of cropland per liter of fuel for some of these pathways, while monoculture production systems can amplify ecological pressure through fertilizer, pesticide, and habitat-intensity effects. [64]

Dedicated lignocellulosic energy crops such as switchgrass and miscanthus can improve per-hectare fuel output and reduce some agronomic inputs, but large-scale deployment still competes with other land functions unless carefully sited.

Indirect land-use change (ILUC) further complicates the picture because SAF expansion can displace food or feed production and trigger new agricultural conversion elsewhere. [65]

Where that displacement affects forests, peatlands, or grasslands, the carbon penalty can be severe enough to erase the intended climate benefit of the fuel. Palm-driven deforestation remains the most frequently cited example. [66]

Because ILUC is difficult to estimate precisely, certification systems increasingly rely on traceability, land-type screening, and low-ILUC designations to manage risk rather than claiming perfect quantification. [67]

Biodiversity impacts are similarly pathway dependent. Converting natural ecosystems to energy-crop monocultures fragments habitat, reduces species richness, and can threaten sensitive taxa, as observed in regions affected by palm, soybean, and cane expansion.

Lower-risk strategies include the use of true wastes and residues, agroforestry systems, and carefully managed marginal-land concepts that avoid direct displacement of food production and preserve ecological corridors. [68]

PtL generally has the smallest land footprint among the major pathways because its primary inputs are electricity, water, and carbon rather than large cultivated biomass streams. Comparative studies suggest land demand can be less than 1% of that associated with soybean-derived fuel when renewable electricity is efficiently sourced. [69]

That advantage does not eliminate siting concerns, however: large solar and wind installations still occupy space and must be planned to avoid disruption of desert biodiversity, bird migration routes, or other sensitive landscapes. Figure 7 highlights the related point that PtL sustainability hinges not only on land but also on the carbon intensity of the electricity used. [70]

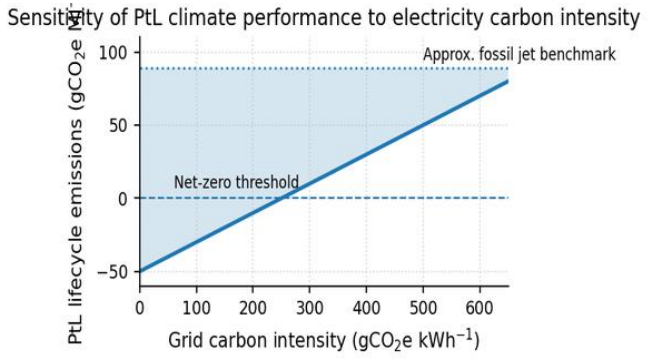

Fig 7. Sensitivity of PtL lifecycle emissions to electricity carbon intensity.

4. Discussion

The comparative analysis presented here shows that SAF is best viewed as a pathway portfolio shaped by trade-offs rather than as a single universal solution. No route simultaneously delivers maximum scalability, minimum cost, highest yield, lowest land and water demand, and deepest carbon reduction. That finding helps explain why SAF deployment has progressed unevenly across regions and why policy design has become as important as process engineering.

4.1 Balancing yield, cost, and decarbonization value

The most immediate tension is between short-term commercial readiness and long-term decarbonization potential. HEFA performs well on yield and near-term deployability, but its feedstock base is intrinsically narrow. PtL sits at the opposite end of the spectrum: it offers strong strategic scalability and exceptional carbon performance under low-carbon electricity, yet it remains expensive and heavily dependent on green-hydrogen expansion. [71]

FT and ATJ occupy the middle ground. They can unlock broader resource bases than HEFA and avoid some of the structural constraints associated with waste lipids, but their economics and operational complexity still limit rapid scale-up. [72]

This trade-off structure implies that carbon policy must do more than reward current volume. Durable support instruments—such as blending mandates, tax incentives, contracts for difference, and low-carbon fuel credits—should be designed to accelerate both mature routes and strategically important emerging pathways.

Certification is another decisive variable. Aviation's strict safety culture fully justifies rigorous fuel qualification, but the pace of ASTM approval can slow commercialization for otherwise promising routes. More coordinated testing between fuel developers, engine manufacturers, and regulators would help reduce this lag without compromising safety. [73]

The push toward 100% drop-in SAF further raises the stakes. Once blend ceilings are removed, the climate relevance of certified pathways could increase sharply, but only if remaining issues related to aromatics, lubricity, and low-temperature behavior are resolved in a robust and standardized way. [74]

A second major lesson is that sustainability cannot be reduced to carbon intensity alone. Water demand, land occupation, biodiversity exposure, and ILUC risk materially affect the legitimacy of SAF strategies, especially where resources are scarce or ecosystems are fragile. [75]

Consequently, the optimal pathway is often region specific. Water-constrained regions may find PtL or residue-based FT more appropriate, while countries with abundant residues or favorable bioethanol systems may prioritize FT or ATJ. The implication is clear: effective SAF roadmaps must be geographically tailored rather than globally uniform.

4.2 Deployment bottlenecks and market structuring

Even after years of momentum, SAF remains a very small fraction of total jet-fuel use. Achieving the penetration levels implied by net-zero scenarios would require extraordinary production growth, which in turn demands synchronized progress in finance, feedstock mobilization, infrastructure, and regulation. [76]

Moving beyond isolated demonstration projects will require industrial clustering. Locating SAF plants near major feedstock pools, renewable-power assets, or airport demand centers can lower transport cost, improve logistics, and create more credible investment cases. Long-term offtake agreements and green procurement frameworks are particularly important for first-of-a-kind projects. [77]

The emerging SAF market must also be internationally inclusive. Countries with weaker capital access, smaller domestic markets, or limited certification capacity should not be excluded from the transition, especially where aviation is essential for connectivity and economic resilience. [78]

Over the longer term, SAF is likely to remain central for long-haul aviation even as electrification or hydrogen advance in shorter-range segments. In that sense, SAF functions both as a bridging option for present fleets and as a durable energy vector for parts of aviation that will remain difficult to electrify.

The coming decade will therefore be decisive. If certification, infrastructure, and investment frameworks mature quickly enough, SAF can move from demonstration status toward structural relevance; if not, aviation risks remaining dependent on fossil jet fuel while other sectors decarbonize more rapidly. [79]

5. Conclusion

Sustainable aviation fuel remains the most credible near- to medium-term decarbonization lever for commercial aviation because it can be introduced through existing aircraft and fuel infrastructure while materially lowering lifecycle emissions under appropriate conditions. This review shows, however, that SAF is not one fuel and not one pathway story. [80]

The main conclusions can be summarized as follows:

First, pathway performance is heterogeneous. HEFA offers the strongest near-term readiness and high yield, but it is fundamentally constrained by feedstock availability; FT and ATJ expand the resource base but require further optimization and policy support; PtL provides the strongest long-term decarbonization logic but remains highly dependent on renewable electricity and low-cost hydrogen.

Second, lifecycle climate benefit is highly pathway- and context-dependent. Waste-based HEFA and residue-based FT generally deliver strong GHG reduction, whereas food-crop-based routes and carbon-intensive electricity can sharply erode the environmental case for SAF. [81]

Third, sustainable scale-up will depend on resource quality as much as on process design. Feedstock traceability, land-use integrity, water demand, and biodiversity protection must be treated as core deployment criteria rather than secondary constraints. [82]

Fourth, economics remain the principal obstacle. Most SAF pathways still face a substantial price premium over fossil jet fuel, which means durable policy frameworks and long-term offtake mechanisms are essential to move projects from pilot scale to bankable commercial deployment. [83]

Finally, certification and infrastructure progress are encouraging but incomplete. Expanding the approved pathway portfolio and advancing toward neat-SAF use will be important for maximizing the sector’s long-term climate contribution.

Overall, SAF should be pursued as a regionally differentiated portfolio strategy backed by coordinated action across fuel producers, airlines, airports, regulators, electricity providers, and financial institutions. [84]

If that coordination is achieved within this decade, SAF can become not merely a transitional supplement to fossil jet fuel, but a cornerstone of aviation’s longer-term decarbonization pathway. [85]

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