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Green flight paths: a catalyst for net-zero aviation by 2050

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Large-scale sustainable aviation fuel (SAF) production and use is essential to achieving net-zero aviation by 2050. In this perspective, we argue that catalysing SAF production from the very low level of 2022 (0.1% of the 2050 required level for net-zero) can be achieved *via* the establishment of "green flight paths" (GFPs) that kick-start SAF implementation through targeted support from key international partner countries. The development of GFPs builds on the Clydebank Declaration from COP26 for green shipping corridors, which is aimed at transforming emissions at sea. Similarly, we define here GFPs as specific aviation routes where financially viable supply chain opportunities for zero-emission air-travel are incentivised. We examine here how GFPs are likely to be spearheaded by countries, such as the UK and the UAE, which are both large international aviation markets that have the political, technical and production capabilities to be world-leaders in pursuing the earlier stages of investment (which are inherently riskier) in developing SAF commercial production capacity for the decarbonization of their aviation sectors. We further discuss how from an energy justice perspective, GFPs are ideal for catalysing SAF adoption and cost reduction in a just way by placing the burden where accountability is required.

Broader context

The aviation sector must rapidly scale up sustainable aviation fuel (SAF) production and use to achieve net-zero emissions by 2050. We propose establishing "green flight paths" (GFPs) between key international aviation markets to catalyse and de-risk the massive investments needed in SAF. GFPs, analogous to green shipping corridors, provide targeted support to kick-start commercially viable SAF supply chains along high-volume routes. The UK and UAE are well-positioned to pioneer GFPs given their status as major aviation hubs, strong decarbonization commitments, and capabilities to lead early investments in SAF production. Focusing initial efforts on busy, long-haul routes like London–Dubai can demonstrate the GFP model for wider adoption. From an energy justice perspective, GFPs rightly place the onus on countries benefiting most from aviation to catalyse the SAF transition. Establishing GFPs requires close collaboration between airports, airlines, fuel suppliers and policymakers to develop enabling infrastructure, regulations and incentives. Coupling GFPs with broader industrial decarbonization plans allows a coordinated approach. With the right ecosystem in place, GFPs can provide SAF producers with critical offtake certainty to unlock investments and achieve the dramatic cost reductions and 1500-fold scale-up in SAF output needed by 2050.

Introduction

Aviation is a foundational element of globalization, and hence, the growth of this industry must be done sustainably. Sustainable growth, however, is easier said than done and requires strong international cooperation especially between key long distance flight paths. In 2019, the global aviation sector accounted for 914 Mt of CO_2 emissions, which represented 2.1% of all anthropogenic CO_2 emissions.[1] When non-CO_2 effects are included, particularly the contrails and the cirrus clouds they induce that have a strong warming effect and account for 57% of aviation's total radiative forcing, aviation was responsible for 3.5% of human-caused climate change in 2018.[2,3] Although the COVID-19 pandemic, which began in early 2020, considerably reduced airline passenger traffic in 2020 and 2021, traffic rebounded to 88% of pre-pandemic levels globally by March 2023. In some international aviation routes, such as between Europe and the United States,

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passenger traffic has even exceeded 2019 levels.[4] As a result, 2022 global CO_2 emissions from aviation reached approximately 80% of 2019 levels, and data for 2023 indicate that passenger numbers are back to pre-pandemic levels.[5] This shows that the move toward decarbonization of aviation[6] achieving net-zero by 2050 will require a portfolio of options,[7] including novel aircraft designs (engines, airframes, *etc.*), operational improvements and new infrastructure, aimed at addressing both CO_2 emissions and non-CO_2 effects.[8] Critically, SAF is seen as playing the key role in decarbonization of the aviation sector, especially towards meeting early emissions reduction targets (*e.g.*, by year 2030).[9] The current aspiration is for 449 billion litres of SAF to be produced in 2050, yet less than 0.1% of this amount, or roughly 300 million litres, was produced in 2022.[10,11] This implies that more than a 1500-fold increase in SAF production is needed in just under 27 years, which translates into roughly 5000–7000 new production facilities, requiring investment of about 1.1–1.45 trillion USD.[12] De-risking investment strategies for this colossal task requires the identification of opportunities to establish guaranteed end users of SAF in optimal geographies, and we propose here that this can be achieved through the establishment of "green flight paths" (GFPs) that we define as specific aviation routes to incentivize the use of 100% SAF for long-haul aviation, and that over time, act as a seed for the broader aviation industry to adopt and scale up SAF. The GFPs concept support a just transition perspective, as countries and regions where the commitment for investments should be first explored are also responsible for emissions from long-haul air travel demand, and who derive economic benefits from their aviation industry as currently reliant on such long-haul flights. For example, the London–Dubai route (LHR-DXB), which is amongst the busiest in the world, is the type of long-haul route that serves as a paradigm for "greening" of the aviation industry by 2050, as discussed in this perspective.

Critical importance of SAF and what needs to be done by 2030

In light of the relatively short time for SAF production to scale up to meet the vital targets stated, it is crucial that attention be given to the enablers of SAF adoption in the near-term, which we refer to as the period between now and 2030, so that sufficient momentum is built to achieve longer-term ambitions. There exists, however, a gap between near-term targets and planned production amounts announced across geographies (Table 1) as well as a significant cost premium for SAF relative Jet A-1 fuel. The cost of SAF production (*i.e.*, production-gate) is currently higher than that of conventional Jet A-1 fuel. According to the International Air Transport Association (IATA), the average price estimate for SAF in 2022 was around USD 2400 per metric tonne, which is approximately two and a half times higher than the price of conventional jet fuel.[13] Further, such SAF options, which have varying amounts of carbon abatement *vis-à-vis* conventional aviation fuel (CAF) emissions baseline, must comply with specific sustainability criteria to be considered as a CORSIA-eligible fuel (CEF).[14] As of November 2023, SAF is priced at around USD 6.69 per gallon in the United States,[15] while Jet A-1 fuel is priced at approximately USD 2–3 per gallon.[16,17] Hence, a scalable, widely adopted SAF will need to achieve a cost that is considerably lower than what is seen today. The cost of SAF production will need to be on par with, or less than, that of Jet A-1 fuel, inclusive of any applicable carbon emissions price or related policy measures. This means that significant efforts are needed to promote SAF adoption so that innovation and scale-up can produce the cost reductions required. As shown in Table 1, 2030 SAF cost targets, where available, are considerably lower than today's costs and so getting on the needed near-term SAF cost trajectory requires a focused effort.

The IEA has stated that in order to achieve net-zero 2050 ambitions, SAF use in aviation must increase to 10% by 2030.[5] Following on this guidance, leading aviation markets have adopted specific 2030 SAF adoption targets as either production targets or blend mandates. The former targets are used in the US, for instance, with the "SAF Grand Challenge" setting a goal of 3 billion gallons (or 11.35 billion litres) of SAF production by 2030.[25] The United Arab Emirates (UAE) is another example, having committed to producing 700 million litres of SAF annually by 2030.[23] For the latter, the EU has adopted SAF blend mandates as a tool to stimulate near-term SAF production,[20] with the April 2023 approval of the ReFuelEU Aviation initiative by the European Commission targeting 6% SAF by 2030, with 1.2% coming from power-to-liquids (PtL) production pathways.[26] Individual countries, such as Japan[21]

Table 1 Current SAF production targets across relevant geographies

	2030 target in line with 2050 net-zero ambitions	Planned production (year)	2030 cost target	Source
World	10%	0.8–1.8% (2027)	0.8–1.2 USD per litre	5, 18 and 19

Country or region	2030 stated targets	Mechanism	2030 cost target	Source
EU	6% total CAF demand	Blend mandate, cap-and-trade (EU ETS)	Not stated	20
Japan	10% CAF demand for international flights (1.7 BL)	Blend mandate	~0.9 USD per litre[a]	21 and 22
UAE	0.7 BL	In development	Not stated	23
UK	10% total CAF demand	Blend mandate	Not stated	24
US	11.35 BL	Subsidies (up to 1.75 USD per L)	Not stated	25

Note: BL = billion litres; CAF = conventional aviation fuels. [a] Original stated target of 100 JPY per litre, converted using historical exchange rate at time of announcement in June 2021.

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and UK,[24] have also implemented SAF mandates of 10% by 2030 for international and all flights, respectively. The UK case amounts to 1.2 million tons of SAF capable of reducing aviation-sector emissions to 35.4 Mt $CO_{2,eq}$ by 2030 and to 19.3 Mt $CO_{2,eq}$ by 2050. In comparison, the UAE commitment translates into around 7% of expected 2030 SAF demand and a cumulative CO_2 reduction of 4.8 Mt CO_2 by that year. In the UAE it is estimated that 7–9 billion USD of investment will be required in SAF production facilities and the supporting value chain to meet this ambition.

Globally, this ambition for 10% SAF share in meeting aviation fuel demand is expected to require at least 30 million tons of SAF by 2030, equal to 300 new production facilities with an investment of 250 billion USD by 2030;[27,28] more than 40 new facilities per year are needed from now until 2030. SAF production will require commitments to both conventional fuel infrastructure and support for emerging technologies. Beyond this near-term imperative for refining capacity, the production of green hydrogen needs to be scaled-up, both for direct use as fuel and as a feedstock for SAF. IATA estimates that by 2030, SAF production and blending capacity needs to reach 24 Mt per year.[29]

The SAF challenge for the aviation sector is vast, both for the near term (*i.e.*, 2030) and long-term (*i.e.*, 2050). Many strategies have been put in place to address this challenge, including the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a market-based measure for allowing the industry to compensate its emissions while the technology, operations and infrastructure continue to develop. The degree to which such options are effective tools is, nonetheless, hotly debated,[30] and reflect the urgency to address CO_2 and non-CO_2 climate effects from aviation using practical solutions.

The establishment and incentivisation of financially viable supply chain opportunities for zero-emission air-travel are also essential for SAF adoption.[31] Although decarbonising aviation is challenging, some routes have economic advantages as they are close to SAF supply hubs and have favourable operational scale and hence are highly suited for accelerated action.[32]

Herein, we advocate to borrow a page from the maritime sector and the concept of "green corridors"[33] in the aviation sector to accelerate SAF uptake by establishing clean/low-carbon aviation "green flight paths" (GFPs) between key markets, where the adoption of SAF is intrinsic to decarbonization aspirations. In the maritime sector, public–private partnerships across the entire value chain are aiming to accelerate low-carbon fuel adoption in the this industry by focusing on, and supporting, green corridors.[34] This has been supported on the international level *via* the Clydebank Declaration, a non-binding declaration of intent launched at COP26 in November 2021.[33] The primary aim of the declaration is to put the maritime sector on track to achieve net-zero by 2050. Since the launch of the declaration, 44 green corridor initiatives have emerged globally (with 21 initiatives by 2022 and 23 new initiatives in 2023) with the intent of achieving 5% zero-emissions shipping fuels supplied by 20 ports across three continents by 2030.[35,36] In particular, the Clydebank Declaration strives to bring together international partners to develop key technologies, identify optimal geographies (shipping lanes), and therefore, somewhat analogous to the GFPs concept proposed here. Challenges that have arisen in moving these shipping initiatives rapidly ahead include defining a fuel pathway, prioritizing corridors, involving key stakeholders early in the process, mobilizing customer demand and planning and coordinating public and private sector collaboration.[37] Here, we examine how developing GFPs will proactively address scalability of SAF production, in line with the ambition for maritime green corridors. This said, we recognize that shipping green corridors are aimed at accelerating the decarbonization of the shipping industry through deployment of zero-emission fuels, vessels, and infrastructure while SAF, which is fundamental to GFPs, leverages drop-in fuels that will require comparably less infrastructure change. The key points of comparison for GFPs are: (1) the need for public–private partnerships between airports, airlines, regulators and fuel suppliers to collaborate on enabling infrastructure and incentives; (2) establishing favourable economics, regulations, and logistics along specific flight paths to accelerate adoption of clean technologies; (3) using green flight paths between major hubs to demonstrate sustainability concepts that can later expand to wider networks; and (4) leveraging predictable, high-volume flight paths where there is existing interest in sustainability. For aviation, these are likely to be major long-haul routes. Hence, ships fuelled on, for example, ammonia in one country can follow a green shipping corridor and be assured of ammonia fuel availability at ports within the corridor. We propose a green flight path (GFP) to obtain the same security for aviation when using SAF. Recently, a 100% SAF flight took place from London Heathrow to JFK New York where the main message was "If you make it, we will fly it".[38]

GFPs will benefit from an ecosystem of fit for purpose regulatory measures, financial incentives, and safety regulations, forging joint ventures and demand aggregation structures similar to those for shipping.[39] Green shipping corridors have stimulated participation from all value chain actors needed to scale zero-emission shipping, including fuel producers, shipowners and operators, cargo owners, and regulatory authorities.[36] In particular they provide offtake certainty to fuel suppliers, supporting essential investments in zero-emission fuel production and bunkering infrastructure that are instrumental for final investment decision (FID). Importantly, coupling plans for GFPs with the growing agenda for decarbonization of industrial clusters[40,41] offers the opportunity to tackle many of these challenges in a coordinated, holistic fashion.

Unlike other transport sectors,[42] continued demand for liquid hydrocarbon fuels entails that some SAF production capacity will remain in place beyond 2050. This is a result of current technology adoption trajectories and the typical operation lifetime of commercial aircraft. SAF production technologies today, thus, aim for the production of molecules or blends of chemicals that perform as closely as possible to existing conventional aviation fuel (CAF).[43] This matching of fuel characteristics to CAF is required as strict performance and safety requirements must be met. That is, before being authorised for use, SAF candidates must qualify under international standards

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(namely ASTM D4054), which evaluate fuel specification properties, fit for purpose (FFP) properties, as well as performance under controlled, bench-scale rig and engine testing. Only then will successful SAF candidates be added to ASTM D7566 (the standard specifying synthetic hydrocarbon fuels eligible for use as SAF) and allowed to be used as drop-in fuels compatible with ASTM D1655 (or equivalent standards, such as DEFSTAN 91-91 in the UK).

This focus on the drop-in characteristics of SAF extends beyond compatibility with existing aircraft engines and can provide advantages on the supply-chain configuration[44] and technology platform selection[45] of SAF. Hence, the roadmap for SAF technology selection, which we align here with the recently published IATA SAF roadmap,[46] is based on the expansion of Hydro-Processed Esters and Fatty Acids (HEFA)-based SAF production capacity and investment in Fischer–Tropsch (FT)-based and Alcohol-to-Jet (AtJ)-based SAF between now and 2030. However, the dependence of these pathways on biogenic feedstocks, some of which are burdened with other climate and socio-economic impacts or which are limited to only certain geographies (Table 2), makes their applicability limited both spatially and temporally.

Expanding on the evaluation of SAF technologies typically discussed when comparing SAF candidates,[51,52] additional consideration is required concerning the extent to which a given SAF is scalable across geographies and promotes the broader adoption of "green technologies". The latter concern is predicated on the notion that SAF production and use is most likely to succeed when the technologies on which it depends are intrinsic to decarbonization imperatives across a multitude of sectors. In other words, SAF technologies can be synergistic with other related green technologies of importance, such as carbon removal (*e.g.*, direct-air carbon capture or DAC), zero-carbon power and the overall PtL technology value chain. Further, concerns about the use of food-related feedstocks are generally addressed by the promotion of PtL technology due to its non-biomass origin and potential to support renewable energy deployment. In the latter case, the use of flue gas and industrial point-source emissions as a sources of gaseous feedstock leads to so-called recycled carbon fuels (RCFs) or renewable fuels of non-biological origin (RFNBO). It is important to note that deploying PtL at scale results in large increases in electricity demand. Estimates, considering only current technologies, indicate the need for 1.1 TW h of electricity in the manufacturing of 30 kt of SAF per year, with another 20 kt of other liquid fuels being co-produced.[53] Hence, significant investments are needed for bringing large pilots and demonstration-scale projects to commercial scale as fast as possible.

Scaling SAF in key technology markets *via* GFPs

With these considerations in mind, the SAF roadmap toward 2030 necessitates technologies that are currently at near-commercial scale, being already demonstrated in industrial contexts, in conjunction with the utilization of existing infrastructure for refining, distribution, and storage of jet fuel. Moreover, it depends upon the availability of infrastructure for generating renewable or clean energy. In comparison to approaches like HEFA and AtJ, the PtL pathway has garnered considerable attention due to its geographical flexibility. Similar to HEFA, PtL presents minimal technological risk when combined with FT, as current ASTM certification standards require up to 50% blend volumes.[54] Furthermore, retrofitting existing refinery facilities carries limited risk, particularly for Fischer–Tropsch synthesized paraffinic kerosene (FT-SPK), given the technology's century-long history. However, FT-SPK is costlier than HEFA, by a factor of 2 to 3.[55–57] Finally, FT-SPK is more feedstock-agnostic than HEFA, as it can utilize renewable carbon from diverse sources, such as municipal solid waste (MSW), water-treatment sludge, agricultural residues, cellulosic biomass, or carbon directly sourced from the atmosphere through DAC. Nonetheless, both ATJ and methanol synthesis towards SPK production are the leading, near-term SAF candidates for serving as bridge technologies until infrastructure for PtL from low-carbon hydrogen matures. Based on this assessment, SAF prioritization should aim for countries and regions where SAF production can be certifiably and rapidly scaled-up by leveraging existing production capacity for CAF and where support for near-commercial SAF technologies can rely on wider initiatives for clean fuels adoption in industrial contexts. This approach has been leveraged for shipping in the development of supportive clean fuel measures, including capacity building, technical cooperation and R&D.[58]

In order to scale SAF production in the near-term, lead markets for scale-up are needed. Such markets should ideally have a strong need for SAF in their aviation sectors and be committed to achieving net-zero by 2050, aided by government policy support. Hence, in various national contexts, SAF as a decarbonized fuel technology is situationally required in flight routes, as proposed in our GFPs, where direct electrification or hydrogen use are not expected to be technically feasible (Fig. 1). Such routes are characterized by distances greater than 3500 km to 4000 km (*i.e.*, long-haul), which are routes typically served by high passenger count airframes powered by turbofan engines.[12,59] The energy and power requirements of such aircraft flying these routes vastly exceed the energy density afforded by battery and hydrogen storage systems.[60] As shown in Fig. 1, this conclusion is expected to hold even in the long term (2050 and beyond) as electric and hydrogen technologies mature. Countries with large demand for long-haul flights, with multiple wide-body airframes operating such segments daily, should lead an aggressive expansion of SAF production in the near-term. Although hydrogen may be able to be adopted for short- and medium-haul flights (which are typically defined as flight lengths of 500–1500 km and 1500–4000 km, respectively) by 2050, the routes where SAF is the only feasible option are some of the most commercially important ones, as identified for the GFPs.

With consideration of SAF beyond 2030, continued R&D support is essential as technology options are still being

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Table 2 Overview of SAF production technology pathways

SAF technology pathway			SAF market readiness			
Processing technology	Renewable and waste feedstocks	L_{CEF}[47] g CO_2e per MJ	ASTM approval status	TRL[48]	FRL[a]	Main producers and technology developers
Fischer–Tropsch (FT)	Flue gases; syngas; gasified biomass and gasified MSW; CO_2 and low-carbon hydrogen mixes	−22.5 to 20.8[f]	Yes, A1[b]	5–8	7	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Hydro-processed esters and fatty acids (HEFA)	Bio-oils, animal fats oils and greases (FOGs), recycled and waste cooking oils (WCOs)	−1.3 to 99.1	Yes, A2[b]	9	9	AltAir Fuels, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
Synthesized iso-paraffins (SIP)	Biomass-derived sugars	43.6–52.6	Yes, A3[b]	5–8	7	Amyris, TotalEnergies
FT with aromatics	Same as FT	−22.5 to 20.8[f]	Yes, A4[b]	6–7	7	Sasol
ATJ	Bio-ethanol; iso-butanol	−14.3 to 100.6; −10.7 to 77.9	Yes, A5[b]	7–8	7	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
	Mixed alcohols	—[g]	Yes, A8[b]	6–7	7	Swedish Biofuels
Catalytic hydrothermolysis (CHJ)	Biomass; organic waste (*e.g.*, OF-MSW, wood and pulp waste); other waste (*e.g.*, tyres, MSW)	—[g]	Yes, A6[b]	6	7	Applied Research Associates
Hydrocracking with HEFA (HC-HEFA)	Microalgae oils	—[g]	Yes, A7[b]	5–6	7	IHI Corporation, NEDO
MTJ	Synthetic methanol (*e.g.*, from low-carbon hydrogen and captured CO_2)	—[g]	No	6	5	ExxonMobil, Honeywell UOP
Pyrolysis	Same as CHJ	—[g]	No	4–6	5	Alder Fuels, Topsoe
Co-processing with CAF	Animal fats oils and greases (FOGs), FT-derived biocrude	16.7–67.7[f]	Yes, A1[c]	9[d]	7	Air bp, Phillips 66, TotalEnergies, OMV, Eni
Power to liquids (PtL)[e]	CO_2 and low-carbon hydrogen mixes with or without FT	—[g]	Partial[h]	3–5	5	Air Company, Infinium

[a] CAAFI fuel readiness level.[49] [b] D7566 Annex code. [c] D1655 Annex code. [d] Refers to CAF refining infrastructure. [e] e-Fuels can refer to power-to liquid (PtL), power-to-X (PtX), power-to-gas (PtG) and synthetic fuels. PtL is used in this work since liquids are the focus. [f] Biogenic fraction only. [g] Not yet defined in ref. 47, to be calculated using ref. 50. [h] PtL using syngas and FT complies with ASTM D7566 A1 Annex, while alternative PtL solutions without FT use are not yet certified.

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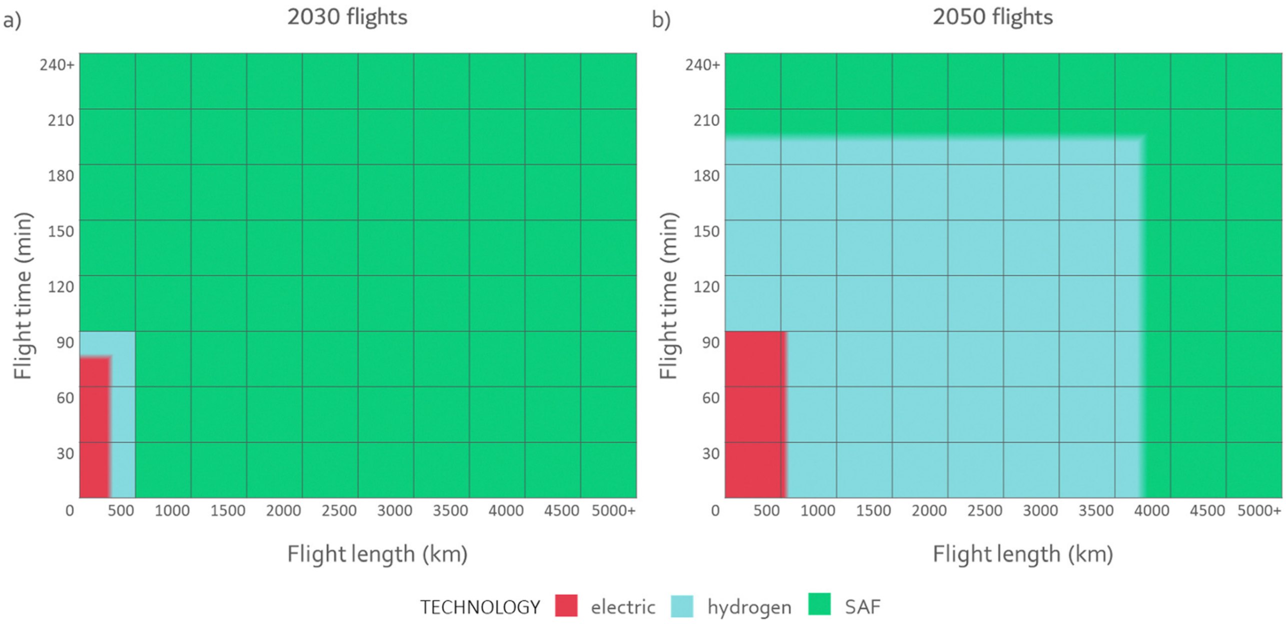

Fig. 1 Long-term relevance of SAF in commercial flights. Expected share commercial airline routes amenable to electrification (red), hydrogen fuel (fuel cell and turbine combustion) (blue) and SAF (green) by 2030 (a) and 2050 (b). SAF is the only feasible technology option in both time horizons for long-haul flights (>4000 km), which are optimal for establishing "green flight paths". Data from ref. 12 and 59.

explored at lab scale, but they may become the foundation for a future PtL-based SAF ecosystem, inclusive of carbon removal technologies, clean energy production and fuel synthesis. A portfolio of technologies must therefore be aligned towards compatibility with a PtL-based SAF landscape. This includes the coupling of HEFA biogenic feedstocks with PtL processing, the evolution of ATJ and MTJ production systems towards green hydrogen and DAC CO_2 use, and the exploration of carbon negative SAF production.

Financial support to overcome the SAF price premium is also key and our proposed GFPs will hard-wire such support into the aviation industry logistic chain. For example, for 2023, London Heathrow allocated 460 GBP per tonne of SAF,[61] which corresponds to about 30% of the previously discussed SAF premium, not inclusive of any further support measures. Airports linked through GFPs should pursue such initiatives, which creates both an opportunity and a challenge. The opportunity is for airports to show leadership in the decarbonization of aviation fuel supply while the challenge lies in the means by which such incentives will be financed. The Heathrow incentive scheme is funded by an increased NO_x emission charge on aircraft landing at the airport and so other airports may leverage this as precedent for a similar scheme. We note, however, that while such support from airports is helpful to mitigate the cost of SAF to airlines, increased fuel costs will nonetheless be present and passengers may need to shoulder these costs through increased airline ticket prices.

This, however, is not necessarily an obstacle. According to the World Economic Forum, the most viable near-term SAF option, HEFA, carries about a 300% fuel cost increase relative to CAF, resulting in a business-to-business (B2B) green premium of perhaps 45–60%.[62] HEFA, however, carries an average

Table 3 Top countries in CO_2 emissions and RPKs for all departure flights and international departures only

All departure flights						International departures only				
Rank	Departure country	CO_2 emissions (Mt)	% global emissions	RPK (billions)	% global RPKs	Departure country	CO_2 emissions (Mt)	% global emissions	RPK (billions)	% global RPKs
1	US	179	23	1890	22	US	61.9	7.9	668	7.7
2	China	103	13	1167	13	China	34.5	4.4	397	4.6
3	**UK**	**31.8**	**4.1**	**365**	**4.2**	**UK**	**30.3**	**3.9**	**353**	**4.1**
4	Japan	25.9	3.3	274	3.1	**UAE**	**21.5**	**2.7**	**243**	**2.8**
5	Germany	23.1	2.9	253	2.9	Germany	21.4	2.7	243	2.8
6	**UAE**	**21.5**	**2.7**	**243**	**2.8**	Spain	16.7	2.1	217	2.5
7	India	21.2	2.7	248	2.9	Japan	16.0	2.0	187	2.1
8	France	20.6	2.6	237	2.7	France	15.9	2.0	183	2.1
9	Spain	19.8	2.5	249	2.9	Australia	12.5	1.6	145	1.7
10	Australia	19.5	2.5	217	2.5	Canada	11.9	1.5	141	1.6

RPK: revenue passenger kilometres; bold: suggested GFP pair-countries (UK and UAE). Source.[65]

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premium of just 3–12% per plane ticket. By 2050, the increase in ticket prices over 2019 reference values could amount to an even lower 2–6%, depending on the SAF uptake and pathway scenario assessed. Hence, the use of SAF mandates, such as those imposed by the ReFuelEU Aviation initiative in the European countries subject to it, can be an effective tool to stimulate SAF demand. On the production side, infrastructure policy support is a complimentary tool for the integration of multiple production and demand centres for decarbonisation solutions *via* industrial clusters and hydrogen valleys, creating synergistic opportunities. From an energy justice perspective, GFPs are ideal for catalysing SAF adoption and cost reduction by placing the financial burden where accountability is required – mostly developed countries where long-haul aviation is a priority and the vast majority of passengers contributing to aviation emissions depart and land.[63] That is, focusing on infrastructure investments and the pursuit of first-of-a-kind (FOAK) commercial projects in such countries acts as an effective de-risking mechanism for developing countries who may, in the longer-term, need rely on SAF for their aviation industries as well. Leveraging potential offtakers of SAF as co-investors *via* equity financing, in contrast to traditional debt financing or venture capital investments, can also help create financing capacity for FOAK projects. In turn, cost transmission of such investments can be allocated, selectively and proportionately, to passengers in developed economies, and even segmented based on class of service. Singapore, for instance, has recently announced the introduction of a SAF levy, chargeable to passengers, to cover the price difference between CAF and SAF to meet its target of 1% SAF by 2026. The levy will be continuously calculated based on the cost spread between CAF and SAF, and issued on a fixed basis depending on class of service and route. Additional costs to passengers may vary, for instance, between three and sixteen Singaporean dollars (2.23 to 11.91 USD) for flights to Bangkok and London, respectively, in economy class.[64]

Given the likely need to increase consumer costs to stimulate SAF deployment, a key policy measure for GFPs to succeed will be information campaigns aimed at demonstrating the positive social and environmental impacts of SAF relative to these costs. Emphasizing the energy justice considerations discussed here is particularly important.

Selection of optimal geographies for GFPs

The top ten countries in terms of CO_2 emissions in 2019 accounted for nearly 60% of worldwide aviation CO_2 emissions, but also for around 60% of revenue passenger kilometres (RPKs) in the same year.[65] While these top emitting countries are ranked similarly in terms of total emissions and RPKs, the flight routes originating from airports in such countries can vary significantly in terms of share of international flights (Table 3). While it is true that a small portion of the global population engages in long-haul travel today and only 2–4% of the population travelled internationally by air in 2018, aviation is growing rapidly with the highest growth in the Global South.

As shown in Table 3, the UK and the UAE exemplify the type of countries that would serve as SAF production lead markets. In terms of aviation emissions in 2019,[65] the UK and UAE emitted 31.8 Mt CO_2 per year and 21.5 Mt CO_2 per year, respectively (or 4.1% and 2.7% of total sectoral CO_2 emissions in that year). In terms of RPKs, they also top global markets, at 4.2% and 2.8% of total RPKs in 2019, respectively. Most of the emissions from these countries are from international flights (over 73% and 99% of total number of flights for the UK and UAE, respectively), while in the US (highest in terms of total CO_2 emissions in 2019) international flights are only 35% of CO_2 emissions. Dubai and London Heathrow airports are also the first and second highest ranked airports in the world in terms of CO_2 emissions from international flights in 2019, responsible for around 16 Mt CO_2 each. These two airports are also the first and second-ranked airports in the world in total international passengers in both 2019 and 2022 (which represent pre- and post-COVID-19 operational years), totalling 66.1 and 58.2 million passengers in 2022, respectively.[66] Lastly, the London–Dubai route (LHR-DXB) not only is among the busiest in the world, but it is also mostly served by large wide-body aircraft (including four-engine A380s) over the long-haul distance of 5500 km, which makes it a prime candidate for a 2030 SAF adoption focus. Moreover, London Heathrow is a world leader in SAF ambition, with a goal of 1.5% SAF blending in 2023 and a target of 11% SAF blending by 2030.[67] An analogue is the recent UK funded green shipping corridor, namely the ''Clean Tyne Shipping Corridor'' between UK and Rotterdam (the most polluting port in EU) with dedicated funds for e-methanol.[68]

Countries such as the UK and UAE are, therefore, prime candidates for the establishment of GFPs as catalyst for large scale SAF production. This strong market presence is supported by other systemic advantages, such as compatible roles in the international trade of jet fuels (the UAE is a top 5 CAF exporting country, while the UK is a top 5 importing country).[69]

As mentioned previously, a further benefit of GFPs is synergy with related cross-sectoral efforts, particularly the development of industrial clusters and of hydrogen oases,[70] which will be essential to producing SAF in significant quantities. Current industrial decarbonization efforts in the UK already place an important role on SAF and other e-fuels production as an outcome of programs aimed at bringing near-commercial technologies to market. For instance, five commercial SAF plants are expected to be under construction by 2025 in the UK, supported by a dedicated 165 million GBP (or almost 210 million USD) fund in line with the UK ''Jet Zero'' strategy announced in July 2022.[71] This dedicated ''Advanced Fuels Fund'' is being implemented in sequential allocation windows, with the initial window focusing on FOAK commercial and demonstration-scale projects within the UK. Further, it has a specific allocation of 22 million GBP (or around 28 million USD) for SAF technologies using point-source carbon capture or DAC as the main carbon source.

Among the projects selected for funding during the first window, four are employing FT (with PtL) and one is based on

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ATJ. Notably, one of the funding recipients in this first window (granted 11 million GBP or around 14 million USD) is the "Lighthouse Green Fuels" project,[72] which is based at the Teesside Industrial Cluster. This project, expected to be operational by 2028, leverages FT for SAF production, and is expected to produce 86.6 kt per year of SAF at full capacity. This link between strong governmental SAF production support and the involvement of industrial clusters (such as Teesside) as a tool for decarbonization is key for reaching the SAF 2030 target.

The GFP paradigm, including investments in R&D, advancements in aircraft technology, and the promotion of SAF production in key geographic locations, offers a common playbook for reducing the carbon footprint of the aviation sector. Given the growing importance of the aviation sector in both UK and UAE,[23,73,74] the adoption of GFPs, particularly when linked to low-carbon industrial cluster initiatives, creates an opportunity for these countries to align their decarbonization efforts and further coordinate cross-sectoral decarbonizing activities.

The establishment of a primary GFP route, such as that of the UK and UAE, provides a model for other countries and regions with similar contexts to follow. Such countries and regions include Singapore (connecting with European markets), East Asia (Japan and Korea, connecting with US and Canada-bound flights, in particular towards the Atlantic), and Australia. Taking a lesson from the Clydebank Declaration in the context of shipping, establishing the paradigm of GFPs *via* lead countries could encourage the establishment of an international accord aimed at establishing more GFPs, with countries like Singapore, Japan, Korea, the US, Canada and Australia, all dependent on long-haul aviation, likely to be supportive. Signatories could then collectively and proactively address potential barriers to SAF adoption, including defining a common SAF adoption pathway, prioritizing particular corridors, involving key supply chain stakeholders early in the SAF adoption process, mobilizing customer demand, and in general coordinating public and private sector collaboration. Further, increased global cooperation will promote long-term aviation decarbonization technologies where R&D investment in key green technologies such as DAC and low or zero-carbon hydrogen, is essential. Such broad cooperation on GFPs would further open the opportunity for alignment across a broader number of complementary decarbonization initiatives, such as low-carbon industrial clusters, where stimulation of customer demand, public–private coordination and national policy initiatives to scale and reduce the cost of priority clean technologies are already underway.

Conclusion

In this perspective, we have argued that a GFP strategy for key long-haul routes, such as the Dubai and London Heathrow, can catalyse the demonstration and deployment of SAF technologies in lead aviation markets, which is essential to global efforts to decarbonize aviation by 2050. The GFP paradigm builds on the concept of green shipping corridors that is paving the way for net-zero shipping. A similar framework for prioritizing long-haul flight segments is becoming increasingly urgent for catalyzing the production and use of SAF technologies. The UAE and UK are both highly dependent on long-haul flights and hence are afforded a compelling opportunity for leadership in the establishment of GFPs to support the demonstration and deployment of SAF. We have also considered how the synergistic establishment of GFPs and low-carbon industrial clusters can catalyse commercial adoption of SAF technologies. Finally, establishing GFPs, such as those proposed here, and related SAF production, can not only catalyse decarbonization of the aviation sector, but also lead to international cooperation for the development of SAF, and related clean technologies, required to achieve net-zero by 2050 on a global scale. Lastly and from an energy justice perspective, countries prioritizing long-haul aviation development, such as the UAE and UK, have an ideal opportunity to leverage GFPs to help solve the aviation emissions challenge rather than simply contribute to it.

Author contributions

All authors: conceptualization; formal analysis and writing.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this perspective.

Conflicts of interest

The authors declare no competing interests.

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6 Although the term "decarbonisation" is used in this paper given it wide use in the sustainability discourse, the authors recognize that the term "de-fossilisation" may be more appropriate given the potential ongoing need for carbon in our energy systems, as argued in this Perspective.

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