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Future of Sustainable Aviation – opportunities and priorities for UK

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Executive Summary

The UK must urgently find ways to boost productivity. Commercial aviation is a technologically sophisticated industry in which the UK is a global leader, and therefore a prime candidate for productivity-enhancing innovation. This CSEP white paper is the first of two reports that review the state of the aviation sector in the UK, and the opportunities for economic growth brought about by its transition to net zero.

Aviation is an innovative but carbon-intensive industry. Advances in this sector generate social returns that extend well beyond individual companies, especially when they also target carbon emissions. **By investing in aviation decarbonisation, the UK can achieve two goals, economic growth and lower emissions**. The sector's combination of technological complexity, global interdependence and regulatory oversight presents both a significant challenge and an opportunity. Progress in aviation could demonstrate the feasibility of achieving emissions reduction in other hard-to-abate sectors such as shipping, heavy industry and long-distance logistics, as well as serving as a catalyst for stimulating wider economic growth in new industries.

All decarbonisation pathways, however, come with risk. Available options range from proven measures with limited impact to risky solutions that would need further R&D and new infrastructure. Accepting some level of risk is necessary for innovation and productivity growth. The UK should assume a prominent role in aviation decarbonisation to strengthen both its leadership in green technologies and to generate sustainable growth.

This two-part series focuses on the five technology levers that are being considered to reduce the climate impact of aviation and create economic opportunities for the UK:

1. **Sustainable Aviation Fuels** (SAF) are expected to make more of the heavy lifting over the next two decades. However, they are currently too expensive and require a technological and/or business model breakthrough. Investment in R&D is essential to achieve a step-change in cost.
2. **Hydrogen/electric** commercial flight represent a long-term solution that must be built from the ground up. The UK has pioneering companies in the field and has been an early mover in the development of the technology. This will be the subject of the second CSEP report that will explore what is needed to develop zero-emission (ZEV) flight.
3. **Fuel efficiency improvements** will continue to be a significant source of value creation to the UK as draws on a broad industrial base. The UK is strategically positioned to exploit opportunities opened by the next generation of single-aisle aircraft, including both high-bypass engines and high-aspect-ratio wing technologies. Indeed, this study has shown that the highly fuel efficient Ultrafan engine from Rolls Royce could add 141 £billion of Gross Valued-Added (GVA) and 35,000 jobs to the UK economy if successful.
4. Available evidence indicate that **contrails may have a comparable net warming effect to that of aviation's carbon emissions**. Operational improvements could therefore reduce the climate impact of aviation on a much faster timescale. With targeted investment and international engagement, the UK should establish itself as the global leader in contrail management and efficient airspace operations, reinforcing its broader aviation decarbonisation strategy.
5. Carbon removal options such as CCS, CCUS and DAC could theoretically eliminate **residual emissions** in the future, but DAC and CCS are prohibitively expensive, long-term CO_2 storage is unproven, and CCU pathways recycle CO_2 temporarily and therefore cannot be counted as carbon removal for aviation accounting purposes under ETS/CORSIA. There are too few viable CCU use cases that could capture the required residual CO_2 emissions from commercial flight. Carbon management of this type is therefore unrealistic and should not be pursued further for aviation.

Some of those levers are specific to the aviation sector, while others are general-purpose technologies. In general, **aviation's net zero transition must be viewed within the broader decarbonisation landscape**, where private investment is directed to the most cost-effective opportunities with the highest impact potential. Aviation has large abatement costs and long technological development cycles. Immediate priorities should therefore include sustained R&D across all levers to drive down the future cost of decarbonisation, establishing mission-driven support mechanisms to nurture the nascent SAF and GGR industry, and optimisation of operations to reduce unnecessary carbon and non-carbon emissions (e.g., contrails).

Finally, **the UK aviation industry sector offers a strong business case for AI adoption**. Advanced data-driven technologies can accelerate both decarbonisation and productivity gains. By applying AI across the various decarbonisation levers, the UK can showcase tangible examples of how intelligent systems can reduce fuel use, streamline operations and accelerate the path towards net zero, reinforcing the government's ambition to be a global leader in both sustainable aviation and AI innovation.

1. Introduction

This report provides an in-depth analysis of the aviation sector in its journey towards achieving net zero carbon emissions, and the challenges and opportunities this transition brings to the UK economy.

For the purposes of the report, the aviation sector is characterised as civil-commercial aviation – scheduled passenger air travel conducted by airlines operating domestic and international routes. We have excluded business aviation (private jets), military aviation and dedicated air freight services as these present significantly different operational characteristics, emissions profiles and policy contexts that would necessitate separate analyses. The report therefore concentrates on the network of airline carriers, aircraft manufacturers and supporting infrastructure that enable billions of passenger journeys annually in the UK and the rest of the world.

Globally, around 5bn passengers will be carried on 38m flights in 2025. The UK equivalent is around 300m passengers and over 2m flights. Worldwide passenger numbers are growing at around 5% a year,[1] while the UK saw a 7% growth between 2023 and 2024.[2] According to industry estimates, passenger demand could exceed 10bn journeys (counting those with multiple legs as one) by 2050, doubling current levels. The rising demand will fuel a substantial increase in the number of aircraft – the latest 20-year forecasts by Boeing[3] and Airbus[4] predict cumulative sales of over 40,000 new aircraft, roughly equally split between fleet replacement and growth in passenger demand. This trajectory underlines the critical need for immediate and sustained action, not only to reduce current emissions, but to offset the significant additional emissions that will arise from continued growth in the sector. Air travel is very energy intensive – jet fuel can represent over 40% of the take-off weight of the largest aircraft – which makes it a hard-to-abate industry. The civil-commercial aviation segment of aviation accounts for 0.9 gigatons of CO_2 annually, around 2.5% of annual global greenhouse gas emissions. The estimate for the UK[5] was that aviation is responsible for 8% of the total emissions in 2024, with a projection to increase up to around 25% by 2040.

Through a combination of better fuel efficiency and more efficient operations, aviation has seen a significant reduction – well over 50% – in carbon emitted per revenue passenger kilometre (RPK) over the last three decades[6] (Figure 1, red line). While the estimated contribution of aviation emissions to global emissions has grown significantly since the 1970s (blue line, the sharp dip is the result of the Covid-19 pandemic), this needs to be set against the relative growth of the sector compared to the global economy. Note that this data does not include the climate forcing impact of non-carbon emissions, particularly those of contrails. There is increased evidence that contrails have a large net warming effect, discussed later in this report.

Given its substantial and growing carbon emissions, exacerbated by projected increases in passenger travel, civil-commercial aviation is therefore under increasing scrutiny. Industry and government bodies have developed net zero roadmaps, outlining the critical strategies and technologies necessary for the industry to effectively reduce emissions by 2050.

These roadmaps, and others by independent organisations, typically feature the same decarbonisation levers, albeit applying different assumptions about their effectiveness and scalability (see Box 1). In general, there is broad alignment across all roadmaps on the core decarbonisation levers, and the forecast is that sustainable aviation fuels (SAF) will play the leading role in emissions reduction over the next two decades. This needs to be supplemented by advances in aircraft technology and operational improvements aiming at much higher fuel efficiency to (partially) to mitigate the higher cost of SAF, with any residual emissions addressed through carbon dioxide removal strategies. For longer time horizons, most roadmaps consider the gradual introduction of alternative energy sources, notably hydrogen or electric propulsion.

Figure 2 shows aggregated data from the latest net zero roadmaps proposed by the International Air Transport Association (IATA), ICAO, the EU (Destination 2050), the Air Transport Action Group (ATAG), the International Council for Clean Transportation (ICCT) and the US government.

We have used the IATA Net Zero 2050 roadmaps[7] as a reference point, given their prominence within the sector. However, it should be noted that these roadmaps reflect an industry perspective and carry certain biases, most notably, an ambition to continue growing passenger numbers and the omission of measures such as taxation of conventional aviation fuel, which could negatively impact airline margins.[8]

The report examines and compares the governmental policy environments and industry responses within three key geographic blocks, the UK, EU and US. We explore the various policy and industry strategies and levers, and their potential effectiveness in fostering scalable, economically viable and sustainable solutions. We then explore the implications for the UK aviation sector and make recommendations for future avenues for policy and industry intervention.

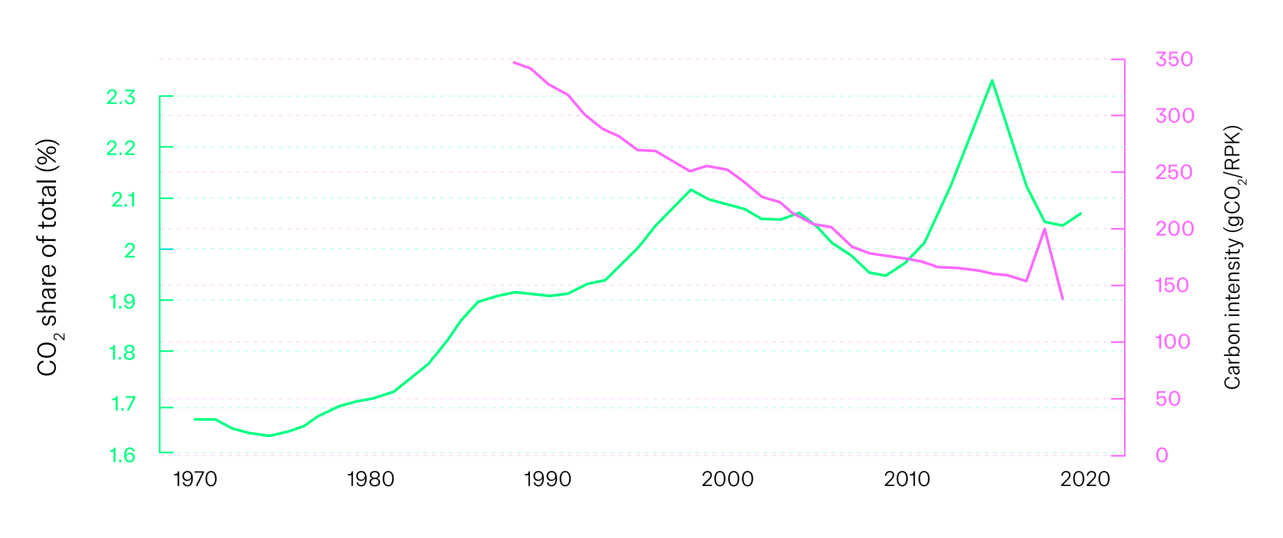

Figure 1. Left axis: Proportion of total amount of CO_2 emissions coming from the aviation sector. Right axis: carbon intensity of the global aircraft fleet (grams of CO_2 emitted per passenger kilometre).

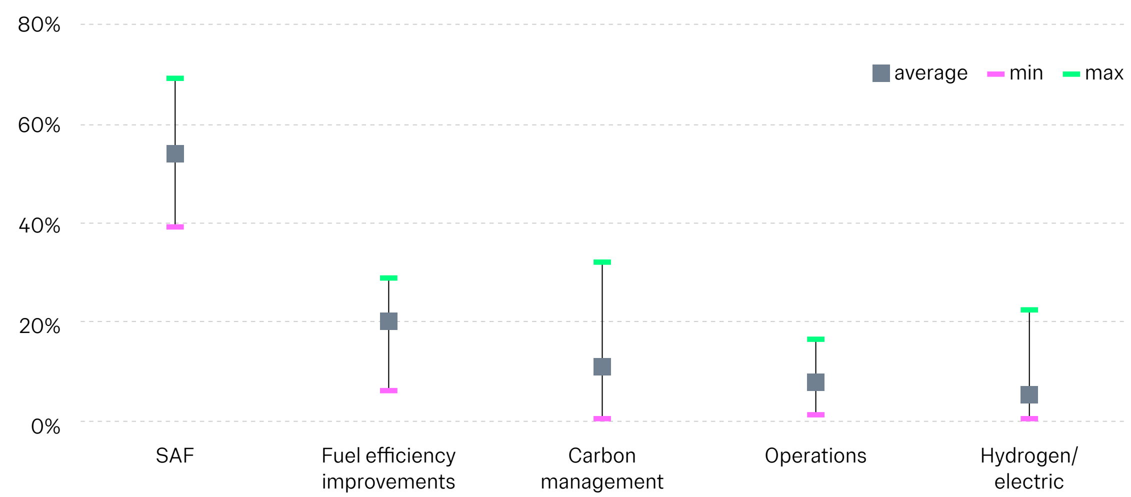

Figure 2. Emissions reduction potential by transition measures/decarbonisation levers in 2050, comparing across roadmaps from IATA, ICAO, ICCT, ATAG, EU Destination 2050, and US ACAP.

[1] https://www.iata.org/en/iata-repository/pressroom/fact-sheets/industry-statistics/
[2] https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/latest-quarterly-statistics/
[3] Boeing Commercial Market Outlook, https://www.boeing.com/commercial/market/commercial-market-outlook (2025)
[4] Airbus Global Market Forecast https://www.airbus.com/en/products-services/commercial-aircraft/global-market-forecast (2025)
[5] UK Climate Change Committee, "The Seventh Carbon Budget", https://www.theccc.org.uk/publication/the-seventh-carbon-budget (2025)
[6] Bergero, C. et al. Pathways to net zero emissions from aviation. Nat Sustain 6, 404–414 https://doi.org/10.1038/s41893-022-01046-9 (2023)

[7] ATA, Net Zero CO_2 Emissions Roadmap - https://www.iata.org/en/programs/sustainability/roadmaps (2024)
[8] Collins, Ocampo, and Thomhave, Greenwashing the skies: How the Private Jet Lobby Uses 'Sustainable Aviation Fuels' as a Marketing Ploy - https://ips-dc.org/wp-content/uploads/2023/04/Report-Greenwashing-the-Skies.pdf (2024)

Box 1. Key decarbonisation levers identified in decarbonisation roadmaps

Exploration of the various decarbonisation levers, as identified in the roadmaps, is central to this report, with each lever's potential contribution towards meeting the industry's Net Zero targets being evaluated. The main levers under consideration include:

- **Sustainable Aviation Fuels (SAF):** Forecasted to account for more than half the industry's emissions reduction by 2050. SAF technologies include Hydro-processed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (AtJ), Fischer-Tropsch (FT) and Power-to-Liquid (PtL).
- **Carbon Management, including carbon capture, utilisation and storage (CCUS) and carbon dioxide removal technologies:** This lever is anticipated to absorb all the residual emissions that cannot be eliminated through efficiency improvements or sustainable fuels. Market-based mechanisms such as carbon pricing and emissions trading schemes (e.g., UK Emission Trading Scheme, ETS, and Carbon Offsetting and Reduction Scheme for International Aviation, CORSIA) are being developed to support the deployment of high-quality carbon removals.
- **Aircraft technologies for increased fuel efficiency:** Due to large cost differential with SAF, innovations in aircraft design, aerodynamics, materials and propulsion technologies are critical to reduce the energy intensity of air transport. The goal is for new aircraft that are 30% more fuel efficient than current ones to be developed in the next 15 years. *This report only offers a high-level view of the policy environment and industry response to this lever. More in-depth exploration of the technological advancements in this area is explored in a separate CSEP report.*
- **Operational Improvements:** These include strategies such as improved air traffic management, optimised flight trajectories, ground operations efficiency and better fleet utilisation, and are expected to contribute less than 10% towards emissions reductions targets. However, this dramatically changes when introducing the climate effects of non-CO_2 emissions (mainly condensation trails or contrails, and nitrogen oxides or NOx). Although barely mentioned in most roadmaps, contrails have an overall positive radiative forcing and their effect on global warming is comparable to that of carbon dioxide.

Box 2: Air travel's carbon footprint. Why 100% SAF is not sufficient.

The carbon footprint of air travel can be decomposed as the product of three factors, as

$$CO_2 = \frac{CO_2}{MJ} \times \frac{MJ}{RPK} \times RPK$$

The first factor is the carbon intensity of the fuel, i.e. how much new carbon is emitted to the atmosphere to produce a unit of energy. The second term is the energy intensity (or fuel efficiency) of the aircraft, namely how many units of energy are needed to move one passenger over one kilometre. The final term measures the volume of passenger traffic and is obtained as the product of all the passengers and the distance they travel (RPK=Revenue Passenger Kilometre, since only paying passengers are accounted for). The carbon footprint of aviation can be reduced by lowering either of those three metrics and all practical solutions need the combined effect of two or more of them.

The carbon intensity is roughly constant for fossil fuels but is reduced when the fuel recycles some or all their carbon, for example by using sustainable aviation fuels (SAF). Note however that in the UK, aviation fuel is certified as sustainable when it delivers over 70% reduction of greenhouse gas emissions over its lifecycle compared to conventional jet fuel. Current SAF pathways alone therefore will not achieve net zero emissions, and they need to be supplemented by other carbon management strategies. Also, the cost of SAF is much higher than conventional fuel and scaling-up adds pressure on increasing fuel efficiency (or demand reduction).

2 Objectives

Our primary objective is to recommend practical strategies and mechanisms that the UK government and industry can use to help the aviation sector meet its Net Zero 2050 emissions targets, while also promoting economic growth and strengthening the UK's position as a global leader in sustainable aviation.

The report aims to support the UK in ensuring its aviation sector can pursue Net Zero goals whilst remaining competitive and resilient. The sector's long-term viability is crucial, not only to preserve its economic contribution to the UK, but also to maintain the UK's international connectivity and strategic positioning within global aviation markets. Protecting and nurturing UK industry through supportive policies will help secure jobs, drive innovation and stimulate sustainable economic growth. The strategic recommendations outlined in this report are designed to help guide the UK government in creating a supportive, coherent and ambitious policy environment for the UK aviation industry.

The report recognises the civil aviation sector's unique structure and position (outlined in Section 3) as a potential catalyst for broader decarbonisation efforts across the UK economy. Because aviation is both complex and a major source of emissions, successfully decarbonising the sector could provide a blueprint that demonstrates the UK's sustainability capabilities. This would strengthen domestic confidence in transitioning other high-emission sectors and enhance the UK's international reputation for climate leadership and sustainable innovation.

In examining the effectiveness of different decarbonisation levers identified above, the report highlights areas which could benefit most from targeted government support and/or private investment. By providing clarity on the proportional impact of each lever, UK policy makers can better prioritise their investments and initiatives, ensuring resources are directed where they can achieve the greatest emissions reductions and economic returns, as well as providing the industry signals on where to direct its efforts.

This report explores how policies and initiatives towards net zero aviation can generate broader economic benefits across related industries and the UK economy more widely. By investing in new technologies, such as advanced sustainable aviation fuel (SAF), zero-carbon aircraft and carbon capture and storage infrastructure, the UK can stimulate new industrial ecosystems, supply chains and skilled employment opportunities extending beyond aviation itself. These investments could strengthen UK's position as a hub of technological innovation, fostering growth in related fields such as renewable energy, chemical manufacturing and advanced engineering.

Additionally, by comparing the policy environments and industry responses across the EU, the USA and the UK, the report provides insights into effective policy instruments and industry engagement strategies. This can help to inform UK policymakers on how best to structure incentives, funding and regulatory frameworks to encourage private sector investment and accelerate technological advancements within the UK.

3. The net zero challenge in aviation

The capital-intensive nature of aircraft procurement and aviation infrastructure, along with concerns about integration into existing technology systems, make operators risk-averse when adopting unproven technologies without strong regulatory or financial incentives. Air travel is currently growing at a pace that, without significant additional investment, is likely to far outweigh the impact of all the levers available to achieve decarbonisation (Box 1).

Key features of aviation sector:

- **High capital costs, long asset lifecycles, and limited competition slow the pace of innovation and severely limits the potential for transformative breakthroughs.**
- **Airlines and airport operators face steep and rising costs from environmental compliance but operate on thin profit margins.**
- **Sustainable aviation fuel (SAF) is currently 3-4x more expensive than conventional (Jet A) fuel.**
- **Without strong incentives, SAF adoption stalls due to high price differentials.**
- **Long-term regulatory certainty and policy continuity are essential for private investment.**

3.1 Aviation – a hard-to-abate sector

Civil aviation represents one of the most challenging sectors to decarbonise. Unlike ground-based transportation, aviation cannot simply switch to electric alternatives due to the energy density requirements of flight. Jet fuel remains the most efficient energy carrier in terms of weight and volume, and this dependency creates a significant barrier to rapid decarbonisation.[6]

Compounding this challenge are:

1. The long development times for new aircraft types, which range from 5 to 10 years.
2. The long lead times in the delivery of aircraft (the order backlog for both Airbus and Boeing in 2025 is more than 10 years at current production rates).
3. The long operational lifespans of commercial aircraft, which typically remain in service for 20 to 30 years.[9]

Together, this limits the rate at which new, more efficient or alternative fuel compatible aircraft can be introduced into service. As a result, even if breakthrough technologies become available, it will take several decades for them to fully penetrate the global fleet. For example, Airbus is currently targeting 2035-2040 for entry into service of a more efficient, SAF-ready, next generation of single aisle aircraft.[10]

Aircraft development has a strong and successful culture of safety, built on historical experience and strong regulatory bodies. The certification process heavily relies on testing and physical demonstrators. This burden of proof however results in high development costs and slows down the introduction of new technologies. An example of this is a general system-wide resistance to the latest digital tools which replace experimental tests in certification in order to fast-track development and reduce costs.

Another issue is the aviation sector's historically low profit margins (airline industry net profit margin was 3.4% in 2024[11]), which significantly challenge how best to fund decarbonisation efforts.[12] Airlines already face high operating costs and the additional expense of scaling up SAF or carbon dioxide removal (CDR) solutions risks further eroding financial sustainability. 'Who pays' for decarbonisation measures is an unresolved question. As noted in one study, a small percentage of heavy-emitting companies (e.g., air travel, utilities, cement, etc.) comprise the majority of emissions but generate profits of less than \$100 / tCO_2 of emissions.[13] This raises questions about how to pass on costs to consumers, governments and corporate customers or share the burden with other sectors.

[9]EASA (European Union Aviation Safety Agency) - https://www.easa.europa.eu/en/light/topics/sustainability-end-life-phase-aircraft, Airbus Operating Life - https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life
[10] Airbus CEO Guillaume Faury Reveals Plans for New-Generation Narrowbody - https://aviationweek.com/shownews/paris-air-show/airbus-ceo-guillaume-faury-reveals-plans-new-generation-narrowbody (2023)
[11] Airline Profitability to Strengthen Slightly in 2025 Despite Headwinds - https://www.iata.org/en/pressroom/2025-releases/2025-06-02-01/ (2025)
[12]Can the global airline industry continue its climb? - https://www.mckinsey.com/industries/travel/our-insights/can-the-global-airline-industry-continue-its-climb (2025)
[13] Bridging the Ambition Gap: A framework for scaling corporate funds for carbon removal and wider climate action - https://carbongap.org/wp-content/uploads/2022/11/Ambition_Gap_Report_Nov22.pdf (2022)

3.2 Future growth in air travel and impact on CO_2

Projections show that, under a business-as-usual scenario, civil aviation could generate up to 21.2 gigatons of cumulative CO_2 emissions between 2021 and 2050. Without substantial intervention, annual emissions could double, from around 0.9 gigatons of CO_2 today to 1.8 gigatons by 2050. This growth means that a significant portion of the sector's decarbonisation efforts will be required simply to maintain emissions at current levels. Even with improvements in aircraft efficiency and operations, these gains are incremental and insufficient on their own to match the anticipated surge in demand. Any ambition to reach net zero will therefore demand an even steeper emissions reduction curve.

Consequently, achieving net zero in aviation is not a matter of applying existing solutions more vigorously. It requires accelerated innovation, high levels of investment and comprehensive policy frameworks to enable the scale-up of SAF and carbon capture technology in the short to medium term, and the development of long-term solutions built solely around renewable energy sources. It also necessitates international coordination to manage growth responsibly, while aligning the sector with global climate goals.

3.3 Decarbonisation requires multiple simultaneous interventions

The trade association for the world's airlines, IATA, has proposed a roadmap[7] to close the projected gap of around 20 gigatons of cumulative CO_2 emissions by 2050 if no mitigation actions are taken. The roadmap illustrates the complex and interdependent mix of technological innovation, operational reform and market-based mechanisms required to decarbonise aviation (Figure 3).

The sector's reliance on fossil-based jet fuel is deeply embedded in the IATA roadmap, which places a strong emphasis on SAF, projecting that this will contribute the majority (65%) of total emissions reductions (Figure 4). The proposed actions first envisage a transition to drop-in SAF (i.e. SAF that can be directly used on existing aircraft and infrastructure), supported by carbon-trading and management (including carbon pricing frameworks and carbon market-based mechanisms such as CORSIA), with a longer-term objective to incorporate zero-emissions aircraft (such as hydrogen and electric) into aviation. For the plan to succeed, it is therefore assumed that SAF can scale quickly, carbon trading can be made effective and equitable and emerging technologies will mature in time to complement fuel-based solutions by 2040 and beyond.

Figure 3. IATA Net Zero 2050 Policy Roadmap.
From: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/policy-net-zero-roadmap.pdf

[14] How realistic is the Sustainable Aviation net zero goal? - https://www.mha.co.uk/insights/how-realistic-is-the-sustainable-aviation-net-zero-goal (2025)
[15] Bardon and Massol, Decarbonizing aviation with sustainable aviation fuels: Myths and realities of the roadmaps to net zero by 2050. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2024.115279115279 (2025)

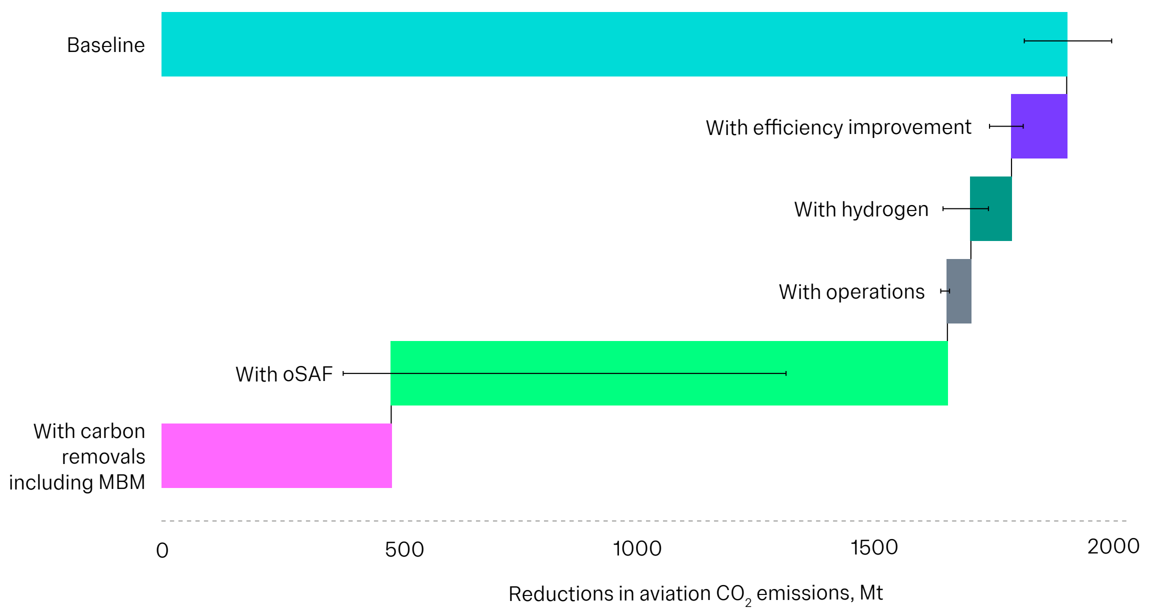

Figure 4. Reduction in aviation CO_2 emissions in 2050 achieved through the different levers of action[7]. The solid-coloured bar indicates the central case, and the black lines indicate maximum and minimum reductions based on the scenarios modelled – the blue bar (baseline) represents projected emissions by 2050

The net zero roadmaps prepared by the aviation industry provide a structured approach for decarbonising the sector but have also attracted criticism.[14,15] One of the principal concerns is the over-reliance on technologies and fuel systems that are not yet mature, scalable and/or not yet proven economic viability. We review these technologies in the next section.

Sustainable Aviation Fuel (SAF)

For at least the next two decades, the net zero ambitions of the aviation sector fundamentally rely on the successful deployment of SAF. IATA's roadmap assumes SAF will contribute 65% of total emissions reductions by 2050. SAF is seen as the most viable near- to mid-term option due to its compatibility with current aircraft and infrastructure. Figure 5 summarises the main SAF technologies – scaling them to reach commercial maturity requires substantial investment, robust supply chains, policy support and access to low-cost energy (i.e., renewable electricity)[16], especially future SAF technologies such as Alcohol-to-Jet (AtJ) and Power-to-Liquid (PtL).

While SAF offers a promising drop-in replacement that can be used in existing aircraft with minimal modifications, its current production levels are very low compared to the scale of global jet fuel demand. Even optimistic forecasts project SAF to account for no more than 10% of total aviation fuel by 2030.[17,18] Note also that current production pathways do not fully eliminate CO_2 emissions and a 10% SAF blend would result in a 6-7% emission reduction. On the positive side, 100% SAF has shown promising results in reducing non-CO_2 climate effects.

Many SAF pathways, particularly advanced options, such as Alcohol-to-Jet (AtJ) and Power-to-Liquid (PtL), are still in early development stages.[19] Commercial production volumes remain limited and the estimated cost of SAF is currently 2-7 times higher than traditional jet fuel, depending on the technology used (see Figure 6). Even accounting for additional cost reductions from future R&D breakthroughs and economies of scale, this is a significant cost differential that may preclude widespread adoption unless sustained price support mechanisms are introduced (i.e., a tax on fossil fuels).

[14] How realistic is the Sustainable Aviation net zero goal? - https://www.mha.co.uk/insights/how-realistic-is-the-sustainable-aviation-net-zero-goal (2025)
[15] Bardon and Massol, Decarbonizing aviation with sustainable aviation fuels: Myths and realities of the roadmaps to net zero by 2050. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2024.115279115279 (2025)
[16] Sustainable Aviation Fuel Ready for lift off? - https://assets.kpmg.com/content/dam/kpmgsites/uk/pdf/2022/11/sustainable-aviation-fuel.pdf.coredownload.inline.pdf
[17] Energy Institute - https://knowledge.energyinst.org/new-energy-world/article?id=127284
[18] World Economic Forum, Financing Sustainable Aviation Fuels: Case Studies and Implications for Investment (in collaboration with Kearney) - https://reports.weforum.org/docs/WEF_Financing_Sustainable_Aviation_Fuels_2025.pdf (2025)
[19] Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net Zero Aviation, McKinsey & Company Insight Report - https://www.mckinsey.com/~/media/mckinsey/industries/travel%20transport%20and%20logistics/our%20insights/scaling%20sustainable%20aviation%20fuel%20today%20for%20clean%20skies%20tomorrow/clean-skies-for-tomorrow.pdf (2020)

Decreasing Maturity		Conversion Technology	Description
	Biofuels	Hydroprocessed Esters and Fatty Acids (HEFA)	• Hydrotreating lipids (fats, oils) to remove oxygen and convert them into hydrocarbons that meet jet fuel specifications • **Most commercially mature and widely used SAF pathway**
	Biofuels	Alcohol-to-Jet (AtJ)	• Converts alcohols (e.g., ethanol, isobutanol) into hydrocarbons via dehydration, oligomerisation and hydrotreatment • **Still in early commercial stages, but with growing adoption**
	Biofuels / Synthetic	Fischer-Tropsch (FT)	• Process can produce both biofuels (from biomass - transformed into hydrocarbons via gasification and catalytic synthesis) and synthetic fuels (from CO_2 and hydrogen – synthesising hydrocarbons from syngas) • **Highly versatile but requires large-scale operations & significant investment**
	Synthetic	Power-to-Liquid/ E-Fuels (PtL)	• Uses renewable electricity to produce hydrogen (via electrolysis) & combines it with captured CO_2 to synthesise hydrocarbons via FT or other methods • **Promising long-term pathway with near-total lifecycle GHG reductions, however, still in early stages of development and not commercially viable yet**

Figure 5. High Level Overview of Main SAF Conversion Technologies[20,21]

Beyond cost and supply constraints, the scaling of SAF is also limited by regulatory certification processes and technical restrictions on fuel composition and aircraft compatibility. While recent test flights using 100% SAF demonstrate technical feasibility[22], full commercial use of unblended SAF is not yet permitted under current ASTM standards. Each new production pathway must undergo a rigorous and time-consuming certification which can take several years. Moreover, using 100% SAF across the global fleet, currently comprising more than 25,000 commercial aircraft, would still require modifications to aircraft and fuelling systems.[23] Hence, blended drop-in SAF is the only viable near-term solution (Box 3).

Finally, feedstock availability, especially for HEFA SAF, is constrained, raising concerns about long-term sustainability and land-use impacts.[8] One recent report looking at the use of biofuels in European aviation has concluded that whilst the costs of waste-based SAFs are relatively low to begin with, they will rise significantly once market penetration reaches around 15%, due to limited feedstock.[24] The EU has ruled out using SAF produced from food and feed crops that have a high risk of causing indirect land use change under its ReFuelEU Aviation Regulation. Were SAF to compete with crops, it is estimated that to meet all the demand from European aviation this way, by 2050 up to 70m hectares of arable land, an area about the size of France, Netherlands, Belgium and Switzerland combined, would be needed.[25] Whilst other countries (e.g., US or Brazil) may have greater capacity to meet this demand, it may not be an efficient use of land, with possibly limited overall environmental advantages and likely unacceptable increase in global food prices.[25]

[20] https://www.bp.com/en/global/air-bp/news-and-views/views/how_all_sustainable_aviation_fuel_SAF_feedstocks_and_production_technologies_can_play_a_role_in_decarbonising_aviation.html (2023)
[21] https://skynrg.com/sustainable-aviation-fuel/technology-basics/
[22] Flight 100 – Our role in enabling the first transatlantic sustainable fuel flight - https://www.caa.co.uk/newsroom/blogs/flight-100-our-role-in-enabling-the-first-transatlantic-sustainable-fuel-flight
[23] Sustainable aviation fuels are not all the same and regular commercial use of 100% SAF is more complex. https://www.greenairnews.com/?p=2460#:~:text=Sustainable%20aviation%20fuels%20are%20not%20all%20the,fuel%2C%20therefore%20unblended%20with%20conventional%20jet%20fuel.
[24] Fathom Independent Thinking, Europe's flightpath to economic competitiveness - https://www.fathom-consulting.com/climate-economics/europes-flightpath-to-economic-competitiveness/
[25] https://www.iba.aero/resources/articles/sustainable-aviation-fuel-how-sustainable-is-it-really/

Box 3: SAF Certification and Standardisation

The successful deployment of Sustainable Aviation Fuels (SAF) at scale depends not only on cost, feedstock availability, and infrastructure, but also on rigorous certification and standardisation processes to ensure fuel safety, performance, and compatibility with existing aircraft.

1. Global Fuel Standards
SAF must meet strict technical specifications equivalent to conventional fossil-based jet fuels (Jet A/Jet A-1). The main global standards include:

- ASTM D1655: Conventional jet fuel standard.
- ASTM D7566: Specifies requirements for SAF blend stocks derived from synthetic hydrocarbons.
- DEF STAN 91-091 (UK MOD) and AFQRJOS (Europe): Aligned closely with ASTM D1655, they serve as the basis for civil aviation fuel certification.

To be certified, SAF pathways must undergo a multi-stage qualification process defined in ASTM D4054, which includes laboratory, rig, and full-engine testing. This process is time-intensive (3 to 5 years) and can cost €1 to 5m.

2. Drop-in SAF and Blending Limits
Drop-in SAF refers to fuels that can be used directly in existing aircraft and infrastructure without modifications. However, ASTM currently limits most SAF types to a maximum blend ratio of 10–50%, depending on the production pathway (see Table 1).[26]

Table 1 Types of Sustainable Aviation Fuels

Production pathway	Feedstocks	Max SAF share (%)
Biomass Gasification + Fischer-Tropsch (Gas+FT)	Energy crops, lignocellulosic biomass, solid waste	50
Hydroprocessed Esters and Fatty Acids (HEFA)	Vegetable and animal fat	50
Direct Sugars to Hydrocarbons (DSHC)	Energy crops, lignocellulosic biomass, solid waste	10
Biomass Gasification + FT with Aromatics	Sugar, starch crops, lignocellulosic biomass	50
Alcohol to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	50
Catalytic Hydrothermolysis Jet (CHJ)	Vegetable and animal fat	50
HEFA from algae	Microalgae oils	10
AtJ with Aromatics	Sugar, starch crops, lignocellulosic biomass	50
FOG Co-processing	Fats, oils and greases	5
FT Co-processing	FT biocrude	5
Hydroprocessed Lipids co-processing	Hydroprocessed vegetable oils, animal fats, used cooking oils	10

[26]What are sustainable aviation fuels? https://www.easa.europa.eu/en/domains/environment/eaer/sustainable-aviation-fuels/what-are-sustainable-aviation-fuels

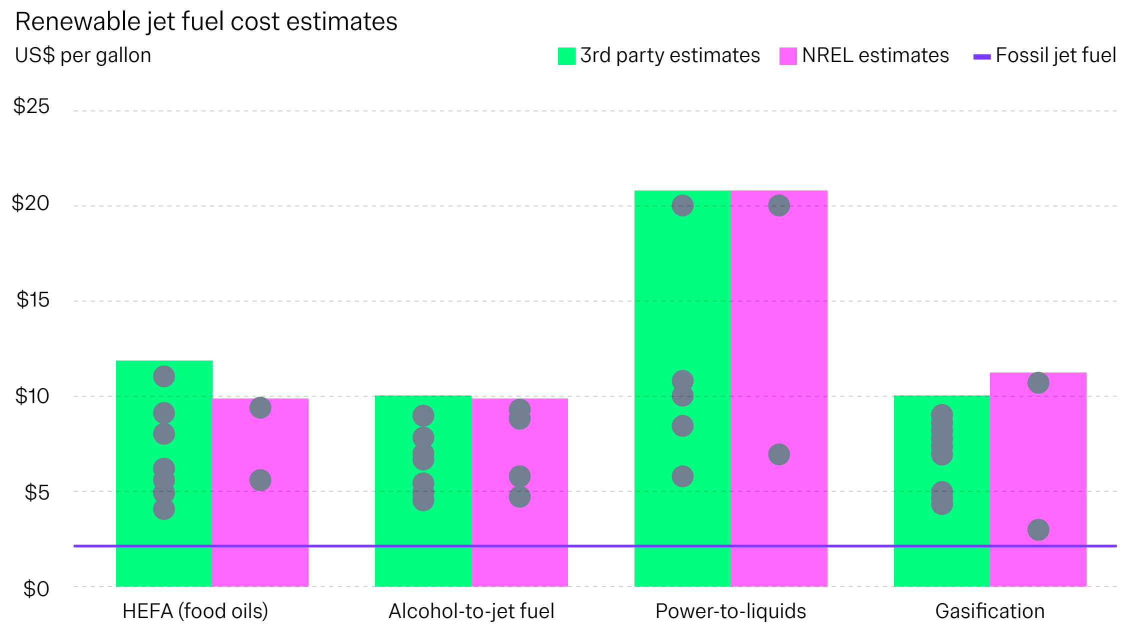

Figure 6. Jet fuel cost estimates for four types of SAF pathways[27]
(Source: "Sustainable Aviation Fuel", DoE, JPMAM, 2024)

Market-Based Mechanisms (MBM) and carbon removals
Table 2 provides concise definitions of the various methods and provides an overview of common CO_2 removal methods and their technology readiness.[28]

Aviation's residual emissions (i.e., emissions that cannot be abated by SAF or efficiency improvements) must be addressed primarily through greenhouse gas removal (GGR) technologies such as Direct Air Capture with Storage (DACCS) and Bioenergy with CCS (BECCS), supported by marked-based mechanisms like emission trading schemes and ICAO's CORSIA scheme (see Box 4). Those provide suitable policy frameworks for high quality carbon removals. Under the IATA roadmap, offsets and carbon removals are expected to deliver 19% of the necessary carbon emission reductions by 2050.

Carbon markets are a key component of MBMs i.e., instruments that leverage economic incentives to drive emissions reductions or removals. These markets operate either as compliance-based schemes (e.g., UK ETS, EU ETS), which are governed by legal obligations, or voluntary carbon markets (VCMs), where credits are purchased by companies to meet internal net zero or sustainability goals. While these systems differ in governance and oversight, both aim to channel finance into climate action and are increasingly expected to prioritise high-quality carbon removals. However, the terms offsets, avoided emissions, and removals are often used interchangeably despite representing fundamentally different approaches:[29]

- **Avoided emissions** (e.g., renewable energy replacing fossil fuels) prevent future emissions but do not remove CO_2 from the atmosphere.
- **Offsets** typically refer to the use of either avoided emissions or removals to compensate for emissions elsewhere.
- **Removals** involve the physical extraction of CO_2 from the atmosphere and its durable storage. This is either through nature-based (e.g., afforestation) or engineering-based (e.g., DACCS, BECCS) solutions, making them a necessary instrument for sectors like aviation where permanent compensation is required.

This distinction is becoming increasingly relevant, particularly in regulated frameworks (like the UK ETS) and VCMs where buyers are prioritising durable removals. Leading institutions including Microsoft, Stripe, and the Frontier Fund,[30] now focus on removals with more than 100 years permanence, reflecting a shift toward high-integrity climate strategies.

[27]Cembalest, M. 15th Annual Energy Paper, J.P. Morgan (2025)
[28]Smith et al: The State of Carbon Dioxide Removal 2024 - 2nd Edition https://doi.org/10.17605/OSF.IO/W3B4Z (2024)
[29]Carbon removal, reduction and avoidance credits explained - https://www.carbon-direct.com/insights/how-do-carbon-credits-actually-work-removal-reduction-and-avoidance-credits-explained
[30]An advanced market commitment to accelerate carbon removal - https://frontierclimate.com/

Box 4. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

CORSIA, overseen by the International Civil Aviation Organisation (ICAO), is a voluntary global offsetting scheme requiring airlines to compensate for emissions exceeding a set baseline (currently 85% of 2019 emissions) by either purchasing carbon credits or using SAF. Full participation in CORSIA will become mandatory from 2027. Its effectiveness will strongly depend on the quality and monitoring of carbon offsetting criteria, the development of carbon management and the enforcement challenges. Environmental groups* have however highlighted that CORSIA allows continued growth in aviation emissions under the guise of offsetting, rather than compelling structural changes within the industry.

*Aviation climate scheme failing to take off - https://futuresupplychains.org/aviation-climate-scheme-failing-to-take-off/

Box 5: What makes a high-quality carbon removal system?

To ensure the integrity of carbon removals, several criteria have emerged as essential:[31]

- Monitoring, Reporting, Verification (MRV): Accurate tracking and third-party validation are required to prove that removals occurred.
- Permanence: Carbon must be stored durably – 100-1000 years is the standard expected in aviation offsets.
- Additionality: Removals must occur because of the carbon finance, not business-as-usual activities.
- Leakage Prevention: Projects must avoid shifting emissions to other locations or sectors.
- Co-Benefits and Safeguards: Projects should deliver environmental and social benefits while avoiding harm.
- Registry Integrity: Projects must be transparently recorded and non-double-counted in recognised registries (e.g., Puro.earth, Verra).

[31] What makes high-quality carbon credits? - https://offsetguide.org/what-makes-high-quality-carbon-credits/

Removals can broadly be divided into nature-based and engineered approaches. While nature-based solutions such as afforestation, wetland restoration, and soil carbon sequestration offer lower-cost options, they often suffer from limited durability (e.g., vulnerability to wildfire, land-use change) and high uncertainty in monitoring, reporting and verification (MRV). Engineered removals, such as DACCS and BECCS, offer greater permanence and MRV robustness but are significantly more expensive. Effective long-term decarbonisation depends heavily on the development and deployment of GGR technologies, but these are still in a nascent stage.[32] They are currently expensive, highly energy-intensive, and not yet deployable at the scale required to deliver the projected 19% emissions reduction.[33,34]

Despite these concerns, one recent study estimated that geological storage of 5-6 gigatonnes (Gt) of CO_2 per year globally is a realistic target by 2050 (this does not include CDR methods that do not rely on geological storage, which could increase this amount further).[35] This would be a plausible benchmark for long-term carbon storage. The technical potential for CO_2 storage is much higher, up to 16 $GtCO_2$ per year, but most of this capacity is in the United States. For context, global aviation currently emits around 1 $GtCO_2$ annually.[36] A key constraint is the scale-up of the storage industry itself. CO_2 injection rates are limited by the physical characteristics of storage sites, such as hydrodynamic pressure buildup in geological formations, which restricts how much can be safely stored each year.[37] It is also important to note that the projected storage capacity will also be in demand from other hard-to-abate sectors such as cement, steel and hydrogen production. Carbon capture and utilisation (CCU) pathways offer additional options but fall well short of the scale needed. Finally, CCU pathways recycle CO_2 temporarily and therefore cannot be counted as carbon removal for aviation accounting purposes under ETS/ CORSIA.

To ensure that carbon dioxide removal (CDR) methods deliver genuine climate benefits, several key conditions must be met:

1. Low-cost capture: while this is improving, the cost of capture remains high, despite research into new solvents and processes.[38,39]
2. Abundant carbon-free energy: CO_2 capture currently requires between 1.8–4 GJ per tonne, though some pilot projects report reductions as low as 0.8 GJ/t.[40]
3. Low-cost and reliable transport and pipeline infrastructure to move captured CO_2 to suitable storage sites.[41]
4. Available, safe, low-cost geological storage:[42] as well as geological constraints, timelines for permits for CO_2 wells are a further constraint – in the USA, Class VI carbon storage wells typically require 6-8 years to permit.[43,44]
5. Robust monitoring, reporting and verification (MRV): To ensure the integrity of CO_2 removals and compliance with carbon market frameworks, transparent and standardised MRV systems are essential.
6. Permanence obligations: for aviation sector offsets, which require durable removal, storage must be verifiable for 100+ years to ensure the permanence of CO_2 sequestration.

[32] Global CCS Institute - https://www.globalccsinstitute.com/resources/insights/carbon-capture-and-storage-challenges-enablers-and-opportunities-for-deployment/
[33] A closer look at CCS: Problems and potential - https://zerocarbon-analytics.org/archives/energy/a-closer-look-at-ccs-problems-and-potential (2024)
[34] Grazia Leonzio, Nilay Shah, Recent advancements and challenges in carbon capture, utilisation and storage, Current Opinion in Green and Sustainable Chemistry, Volume 46 - https://www.sciencedirect.com/science/article/pii/S2452223624000166 (2024)
[33] A closer look at CCS: Problems and potential - https://zerocarbon-analytics.org/archives/energy/a-closer-look-at-ccs-problems-and-potential (2024)
[34] Grazia Leonzio, Nilay Shah, Recent advancements and challenges in carbon capture, utilisation and storage, Current Opinion in Green and Sustainable Chemistry, Volume 46 - https://www.sciencedirect.com/science/article/pii/S2452223624000166 (2024)
[35] Y. Zhang, C. Jackson, & S. Krevor, The feasibility of reaching gigatonne scale CO_2 storage by mid-century. Nat Commun 15, 6913 - https://doi.org/10.1038/s41467-024-51226-8 (2024)
[36] https://concito.dk/en/udgivelser/e-fuels-or-storage-how-to-make-the-most-of-clean-electricity-and-captured-co2
[37] https://www.explocrowd.com/explocrowd-blog/2023/9/26/co2-storage-potential-getting-the-numbers-right
[38] Katrin Sievert, Laura Cameron, Angela Carter, Why the Cost of Carbon Capture and Storage Remains Persistently High - https://www.iisd.org/system/files/2023-09/bottom-line-why-carbon-capture-storage-cost-remains-high.pdf (2023)
[39] Is carbon capture too expensive? - https://www.iea.org/commentaries/is-carbon-capture-too-expensive (2021)
[40] Li et al., A feasible energy-saving analysis of a new system for CO 2 cryogenic capture, Int. J. Low-Carbon Technol –doi:10.1093/ijlct/ctt065 (2016)
[41] Technology Readiness and Costs of CCS - https://www.globalccsinstitute.com/wp-content/uploads/2022/03/CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf (2021)
[42] Gidden, M. J. et al. A prudent planetary limit for geologic carbon storage. Nature 645, 124–132 (2025).
[43] Moore EJ, Karplus VJ, Morgan MG. Expert elicitation of the timing and uncertainty to establish a geologic sequestration well for CO_2 in the United States - https://pmc.ncbi.nlm.nih.gov/articles/PMC10769833/ (2023)
[44] Carbon Capture, Utilization, and Storage: Class VI Wells and US State Primacy - https://www.mayerbrown.com/en/insights/publications/2022/06/carbon-capture-utilization-and-storage-class-vi-wells-and-us-state-primacy (2022)

Table 2. Definitions of common CDR methods:[43]

CDR Method	Definition
Afforestation / Reforestation	Conversion to forest of land that was previously not forest, or was previously deforested
Forest management	Stewardship and use of existing forests. To count as CDR, forest management practices must enhance the long-term average carbon stock in the forest system
Soil carbon sequestration in croplands and grasslands	Land management changes in croplands and grasslands that increase the soil organic carbon content
Peatland and coastal wetland restoration	Assisted recovery of inland ecosystems that are permanently or seasonally flooded or saturated by water (such as peatlands) and of coastal ecosystems (such as tidal marshes, mangroves and seagrass meadows). To count as CDR, this recovery must lead to a durable increase in the carbon content of these systems
Durable wood products	Wood products which meet a given threshold of durability, typically used in construction. These can include sawn wood, wood panels and composite beams, but exclude less durable products such as paper
Biochar	Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Used mostly as a soil amendment
Bioenergy with carbon capture and storage (BECCS)	Process by which biogenic carbon dioxide (CO_2) is captured from a bioenergy facility, with subsequent geological storage
Bio-Oil Storage	Oil made by biomass conversion and placed into geological storage
Direct air capture and carbon storage (DACCS)	Chemical process by which carbon dioxide (CO_2) is captured from the ambient air, with subsequent geological storage
Direct ocean carbon capture and storage (DOCCS)	Chemical process by which carbon dioxide (CO_2) is captured directly from seawater, with subsequent geological storage. To count as CDR, this capture must lead to increased ocean CO_2 uptake
Enhanced Rock Weathering	Increasing the natural rate of removal of carbon dioxide (CO_2) from the atmosphere by applying crushed rocks, rich in calcium and magnesium, to soil or beaches
Mineral Products	Production of solid carbonate materials for use in products such as aggregates, asphalt, cement and concrete, using CO_2 captured from the atmosphere
Ocean Alkalinity Enhancement	Spreading of alkaline materials on the ocean surface to increase the alkalinity of the water and thus increase ocean CO_2 uptake
Ocean Fertilisation	Enhancement of nutrient supply to the near-surface ocean with the aim of sequestering additional CO_2 from the atmosphere stimulated through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably

[43]Carbon Dioxide Removal Methods - https://netzeroclimate.org/research/carbon-dioxide-removal/

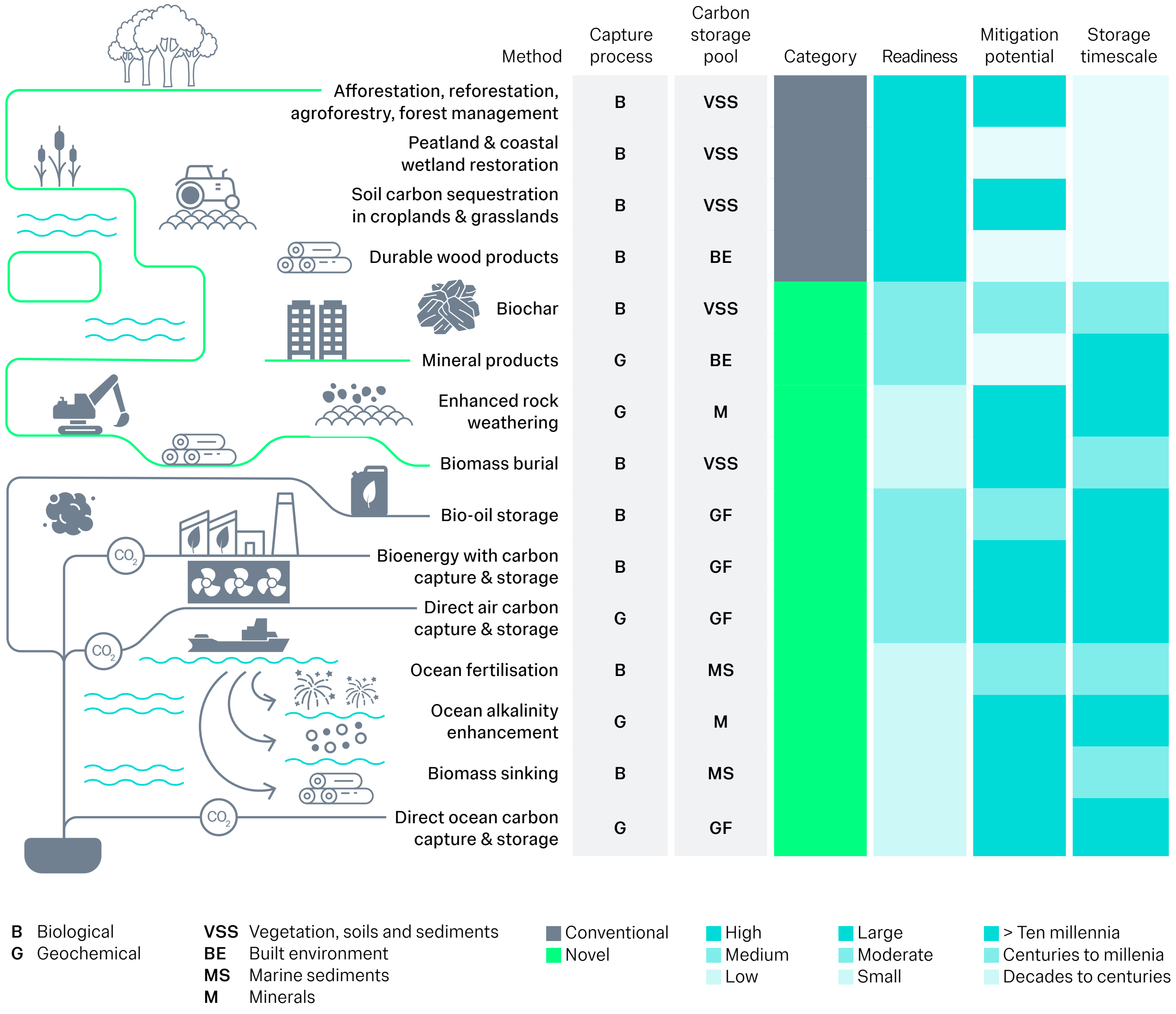

Figure 7. Summary of Carbon Dioxide Removal methods, noting their respective capture process and carbon storage pool, categorisation as 'Conventional' or 'Novel' (i.e., well established vs early stages of technology development), their current readiness to scale (based on technology readiness levels), their maximum mitigation potential (Large: >9 $GtCO_2$/year; Moderate: 3-9 $GtCO_2$/year; Small: <3 $GtCO_2$/year), and characteristic storage timescale

Aircraft technology and efficiency improvements
As seen in Figure 1, the aviation industry has achieved a sustained improvement of fuel efficiency throughout its history. New aircraft need to bring at least 15% fuel efficiency improvements to justify their costly development. The pressure to achieve net zero means that that next generation aircraft would need an even larger additional fuel efficiency (on the order of 25%, in other words about two generations of technology) for them to have the desired impact. This has been assumed in the IATA roadmap, where new aircraft are expected to contribute approximately 13% to aviation's decarbonisation by 2050. This assumes new models are delivered from around 2035, with partial fleet replacement by 2050. IATA also identifies future potential in hydrogen-powered and electric-hybrid aircraft, although their near- to mid-term impact is expected to be limited and primarily confined to short-haul and regional operations.

Hydrogen and electric propulsion, while receiving increasing interest and investment, are unlikely to play a significant role in the decarbonisation of commercial aviation before 2050. Battery-powered aircraft are constrained by energy storage limitations, restricting their range and making them more viable for urban air mobility applications such as air taxis in the foreseeable future.

Using hydrogen as energy carrier is feasible but faces significant hurdles:

- Hydrogen contains more energy per kilogram than jet fuel but far less per unit of volume, requiring new aircraft configurations (e.g., blended wing body) with larger internal volume. Retrofitting existing configurations to accommodate cryogenic tanks would substantially reduce available passenger or luggage space.[46,47]

- Green hydrogen is expensive, and currently in very limited supply, raising questions about aviation's ability to secure sufficient quantities without abundant cheap renewable electricity.

- Certification pathways for hydrogen aircraft are still underdeveloped, with regulators needing to define entirely new safety and performance standards.[48]

- The lack of refuelling infrastructure at airports, requiring large-scale investment and new safety protocols. and lack of aircraft themselves.

As a result, technologies are expected to be confined to short-haul operations, with a regional focus and requiring limited capital investment, in the short-to-medium term.[49,50,51]

Operational improvements, including contrail reduction
Operational Improvements, such as better air traffic management, optimised flight paths and electrified airport operations (e.g., electric ground vehicles), make up the remaining 3% contribution to aviation decarbonisation in IATA's roadmap. While modest in overall impact, these measures are considered cost-effective and relatively quickly deployable. An area of increasing interest is the reduction of contrails in the upper atmosphere. It is argued that there has been a focus on CO_2 emissions at the expense of non-CO_2 impacts[52], and IATA has called for research on contrail formation and its potential climate impacts.[53] Non-CO_2 emissions have significant radiative forcing on the planet – they can trap heat in the atmosphere by forming thin clouds, contributing to global warming even though they do not release additional CO_2. Some 50% of aviation's contribution to warming is believed to come from contrails.[54,55] Although our understanding of all the relevant physical processes is still developing and there is therefore substantial uncertainty on the warming contribution, contrail management presents an opportunity for policy and industry.[56] Consequently, contrail avoidance, obtained via route optimisation and atmospheric condition monitoring, is emerging as an area for immediate emissions impact with minimal infrastructure change. Similarly, high-altitude emissions tracking and upper atmosphere research could inform new regulatory and operational strategies that go beyond just looking at carbon emissions.[57]

A transition to SAF would also have an impact on contrail formation. Sustainable aviation fuel, even the drop-in type, has a different chemical content from conventional fuels, which reduces soot particles, and therefore the size and characteristics of the aircraft contrails. A recent study has estimated that contrails may be responsible for over 40% of the warming effects of aviation by 2050 on current trends and are the single biggest contributor overall from the aviation sector.[58] Recent flight tests[59] with 100% SAF have shown a reduction of over 50% in ice particles and provide some initial evidence that SAF may reduce contrail formation compared to conventional fuel. As only a relatively small number of flights generate persistent contrails, strategic deployment of SAF on the routes most likely to produce warming contrails could increase the overall climate benefit for a given amount of SAF.[60,61]

[46] Soleymani et al., Hydrogen propulsion systems for aircraft, a review on recent advances and ongoing challenges - doi.org/10.1016/j.ijhydene.2024.10.131 (2024)
[47] Adler and Martins, Hydrogen-powered aircraft: fundamentals, key technologies and environmental impact - doi.org/10.1016/j.paerosci.2023.100922 (2023)
[48] https://www.politico.eu/article/5-problems-facing-hydrogen-powered-airplanes/
[49] Airbus tells EU hydrogen won't be widely used in planes before 2050 - https://www.reuters.com/business/aerospace-defense/airbus-tells-eu-hydrogen-wont-be-widely-used-planes-before-2050-2021-06-10/
[50] https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf
[51] https://www.hydrogeninsight.com/transport/leading-hydrogen-jet-engine-developer-rolls-royce-says-h2-powered-planes-wont-happen-for-20-years/2-1-1562402
[52] https://www.aerosociety.com/media/20657/contrails-and-contrail-management-briefing-paper.pdf
[53] ATA Calls For More Research On Contrails As EU Pushes For Tighter Regulation - https://simpleflying.com/iata-contrail-research-eu-regulation/ (2024)
[54] Contrail control – what are we waiting for? - https://www.aerosociety.com/news/contrail-control-what-are-we-waiting-for/
[55] Beyond carbon dioxide: Aviation needs a multi-pronged strategy to address contrails and reduce climate impacts - https://www.catf.us/2025/03/beyond-carbon-dioxide-aviation-needs-multi-pronged-strategy-address-contrails-reduce-climate-impacts/ (2025)
[56] Understanding Contrail Management: Opportunities, Challenges, and Insights - https://rmi.org/insight/understanding-contrail-management-opportunities-challenges-and-insights/ (2024)
[57] Contrail avoidance: aviation's climate opportunity of the decade - https://www.transportenvironment.org/uploads/files/Contrails-Briefing-2.pdf (2024)
[49] https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf
[50] https://www.hydrogeninsight.com/transport/leading-hydrogen-jet-engine-developer-rolls-royce-says-h2-powered-planes-wont-happen-for-20-years/2-1-1562402
[58] ICCT, Aviation Vision 2050: The potential for climate-neutral growth https://theicct.org/publication/aviation-vision-2050-sept25 (2025)
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[60] Woeldgen, E. et al. Sustainable Aviation Fuel Deployment Strategies in Europe. *Environ. Sci. Technol.* https://doi.org/10.1021/acs.est.5c02364 (2025)
[61] IATA, The non-CO_2 climate co-benefit of SAF and other fuels with low aromatic and sulfur content, https://www.iata.org/globalassets/iata/publications/sustainability/saf-non-co2-benefits.pdf (2025)

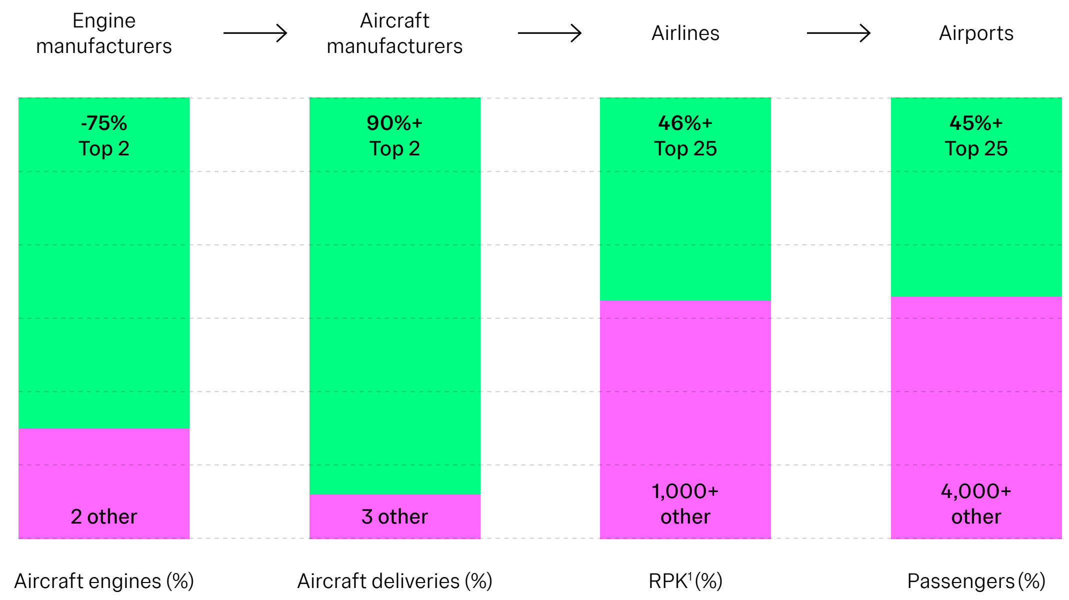


Figure 8. Market shares in aviation.
From: https://www.shell.com/business-customers/shell-low-carbon-solutions/_jcr_content/root/main/section_489901290_co_48639111/promo_526075953_copy_1898310424/links/item0.stream/1667916358181/e4f516f8d0b02333f1459e60dc4ff7fd1650f51c/decarbonising-aviation-industry-report.pdf

3.4 Potential of aviation for driving decarbonisation and economic growth

The structural characteristics of the global aviation sector present opportunities for it to stimulate decarbonisation, technological advancement and productivity growth. The degree of industrial concentration (see Figure 8) means that influencing a relatively small group of key decision-makers – aircraft and engine manufacturers, major airlines and airport authorities, can potentially drive substantial change across the entire sector.[62]

The supply-side: aircraft manufacturing and airlines
Aviation is relatively concentrated on the supply-side. Aircraft manufacturing is largely dominated by two major OEMs, Boeing and Airbus, who together produce the vast majority of commercial aircraft globally. This duopoly exerts a strong influence over the pace and direction of technological innovation in aviation. This also has a big impact on the R&D policy in their home markets. Boeing and Airbus are among the largest exporters from the USA and the EU respectively and are broadly supported by the policymakers in each region. Tier 1 suppliers, such as Rolls Royce and GKN in the UK, are also influential but need to ensure they remain the partners of choice when new aircraft (or aircraft derivatives) are launched by the OEMs.

Similarly, while there are hundreds of airline operators worldwide, the number of major carriers within each national or regional market is relatively small. This concentration extends to infrastructure as well. Most passenger flows are managed through a limited number of large international airports, often operating as regional or national hubs.

The demand-side: passenger travel needs
On the demand-side, consumer choices for long-distance travel are very limited. For journeys beyond several hundred kilometres, especially international or intercontinental, flying is often the only practical option. This is a form of inelastic demand and given that airlines operate with very thin margins[63] this encourages airlines to pass on the cost of decarbonisation to passengers (e.g. through a carbon tax or a SAF levy, as implemented by Singapore Airlines in 2026). While higher prices would have some impact on passenger demand, the lack of other viable travel substitutes means the aviation sector could potentially fund its net zero transition. This needs concerted agreement between jurisdictions, as most air travel is across borders. Emissions trading schemes (ETS) already exists for flights within the UK and the EU, and the EU ETS requires that the revenue is invested towards decarbonisation efforts. Private companies can also play a key role as they incorporate their business travel footprint

[62] Deloitte. Decarbonising Aviation: Cleared for take-off. https://www.deloitte.com/global/en/Industries/energy/perspectives/decarbonizing-aviation.html (2024)
[63] IATA reported in 2024 a return of investment around 3% below the cost of capital across the sector. IATA, Airline Profitability Outlook, June 2024, https://www.iata.org/en/pressroom/2024-releases/2024-06-03-01/

into their emissions reduction targets.[64] Finally, policies such as progressive taxation are needed to ensure that air travel does not become an even more exclusive activity for the world's wealthiest.

The implications for economic policy are significant. As aviation involves high capital costs and long asset lifecycles, any decarbonisation technologies that are adopted, whether in new propulsion systems, fuels or airport infrastructure, become embedded in the sector for decades. These choices influence future operations, emissions and investment pathways long after the initial adoption. This positions aviation as a strong candidate for industrial strategy, particularly in areas where the UK already has strong research and manufacturing capabilities, such as engineering, next generation sustainable fuels and carbon capture technologies.

[64]https://worldenergy.net/resource/insets-versus-offsets/

4. Policy environment – EU, USA, UK

The EU, USA and UK have ambitious strategies for sustainable aviation, yet their policy approaches differ in terms of technology focus, implementation mechanisms and investment priorities. The UK approach is largely built around the same core decarbonisation levers discussed above. It places the greatest emphasis on SAF (like IATA) and carbon capture and management, although it highlights the role of advancements in aircraft technology more prominently. The EU's sustainable aviation policy is characterised by robust regulatory mandates, ambitious future SAF technology targets and research funding for emerging technologies like hybrid-electric/hydrogen aviation. The US approach relies heavily on financial incentives, rapidly scalable and proven SAF pathways and market-driven growth supported by targeted subsidies and tax credits.

4.1 EU policy approaches to sustainable aviation

The EU's strategy, embodied in initiatives like the European Green Deal and Fit for 55 package, heavily relies on regulatory frameworks and mandates.[65,66] Central to the strategy is the ReFuelEU Aviation initiative, which mandates specific SAF blending targets, aiming for at least 6% SAF by 2030 and up to 70% by 2050, with substantial sub-targets for synthetic fuels like PtL (up to 10% by 2040).[67] These mandates demonstrate the EU's regulatory-driven approach, which aims to create market certainty and drive investment (see figure 9).

The EU also utilises an Emissions Trading System (EU ETS), effectively pricing carbon emissions to incentivise airlines towards cleaner operations and utilising the funds to subsidise and further SAF development through auction revenues. Since 2025, the EU ETS also includes monitoring, reporting, and verifying (MRV) of non-CO_2 emissions.

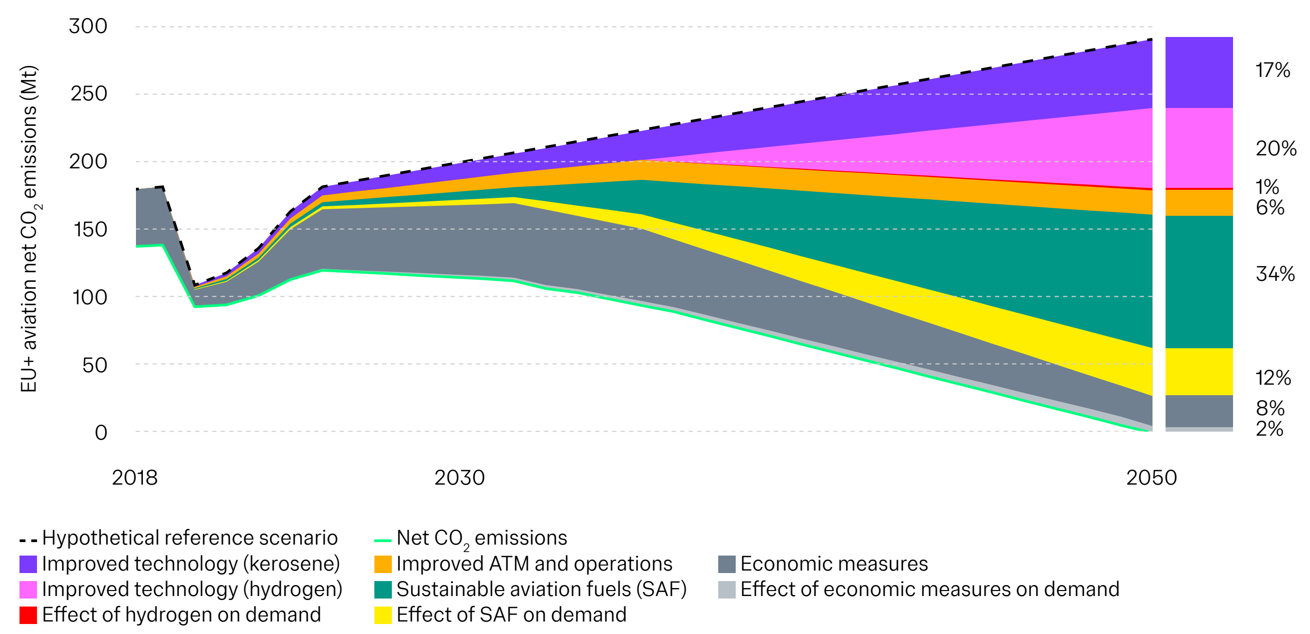


Figure 9, Decarbonisation Roadmap for European Aviation developed by Destination 2050.
(Source: https://www.destination2050.eu/wp-content/uploads/2021/03/Destination2050_Report.pdf)

[65]The European Green Deal - https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (2019)
[66]Fit for 55 Package - https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733513/EPRS_BRI(2022)733513_EN.pdf (2021)
[67]ReFuelEU Aviation Initiative - https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/refuel-eu-aviation-handbook.pdf

Sustainable aviation fuel
While these measures have been effective in accelerating SAF investment and deployment in Europe,[68] the high PtL blending mandates and steep non-compliance penalties, up to 40 times the current EU ETS allowance price, have been criticised for potentially diverting clean electricity (needed to convert captured carbon into E-fuels) away from sectors where it could deliver greater climate benefits, such as power generation, industry or heating.[69]

In addition, it has been argued that simply storing captured CO_2 underground may be a more cost-effective and technically viable option than converting it into E-fuels.[73] These trade-offs raise important questions about the most efficient allocation of clean energy and carbon removal resources, and whether aggressive SAF targets might delay broader decarbonisation progress in the short to medium term. Indeed, a recent independent review of GGR[70] has recommended to move from a SAF mandate to a Net zero Aviation mandate, in which the specific technology pathway (SAF or permanent GGR) is determined by market forces.

Aircraft technology and efficiency
The EU is also investing in hydrogen infrastructure and research (hydrogen being a key component of the PtL SAF production process). This is happening via initiatives like the Clean Industrial Deal's €1bn Hydrogen Bank for financing the establishment of a full hydrogen value chain in Europe[71] and the Clean Aviation Joint Undertaking (part of Horizon Europe), which has dedicated approximately €4.1bn to developing zero-emission aircraft (hybrid-electric/hydrogen) and other related technologies.[72] It has been recently argued[23] that the EU should make zero emission flight (ZEF) even more of a strategic priority, highlighting it as the most promising pathway for deep decarbonisation of aviation in the long term. A further recommendation is to prioritise ZEF for routes up to 2,000 kilometres, which include most existing flights, whilst using SAF for longer routes, if indeed ZEF is constrained by technology and/or infrastructure limitations by 2050. Further exploration of the aircraft technologies will be done in the second report in this series.

4.2 US policy approaches to sustainable aviation

The US aviation decarbonisation roadmap is heavily reliant on SAF, which is expected to account for up to 66% of emissions reductions by 2050 (Figure 10). This incentives-driven approach aims to stimulate private investment and rapid market growth, positioning the US as a dominant player in the global SAF production market. There have been some changes to the approach to emphasise energy independence and rural economic development, rather than climate change, under the administration, but the general direction remains in place (see Box 6).

Sustainable aviation fuel
The US approach primarily centres around financial incentives rather than stringent regulatory mandates. Under the Inflation Reduction Act (IRA) and other initiatives, such as the SAF Grand Challenge, substantial tax credits (up to $1.75 per gallon of SAF under Section 45Z, although now reduced to $1.00 under the new Trump administration) and subsidies are provided to encourage the rapid scale-up of SAF production, with the US government setting a SAF production target of 3bn gallons by 2030 and 35bn gallons by 2050.[73]

The US policy heavily favours commercially mature SAF pathways, particularly HEFA (Hydro-processed Esters and Fatty Acids), due to ample feedstock availability and the proven scalability of the technology in the near-term.[74] Compared to the EU and UK, the US has placed fewer sustainability restrictions on feedstock types that can be used in production (e.g., inclusion of food crops), allowing more flexibility in production methods. However, US policy also recognises the importance of investing in future SAF technologies (i.e., AtJ, FT and PtL) to lay the groundwork for when these technologies become more proven and scalable.

Overall, a stage-gate policy approach is in use, effectively supporting technologies in phases based on their level of readiness. In the short term (to 2030), policies focus on incentivising proven, commercially available SAF options to quickly scale production. At the same time, support is also directed towards less mature, more innovative SAF technologies that could offer greater sustainability and scalability in the long run (towards 2050), once they become viable. This approach allows near-term progress while preparing for more impactful decarbonisation later.

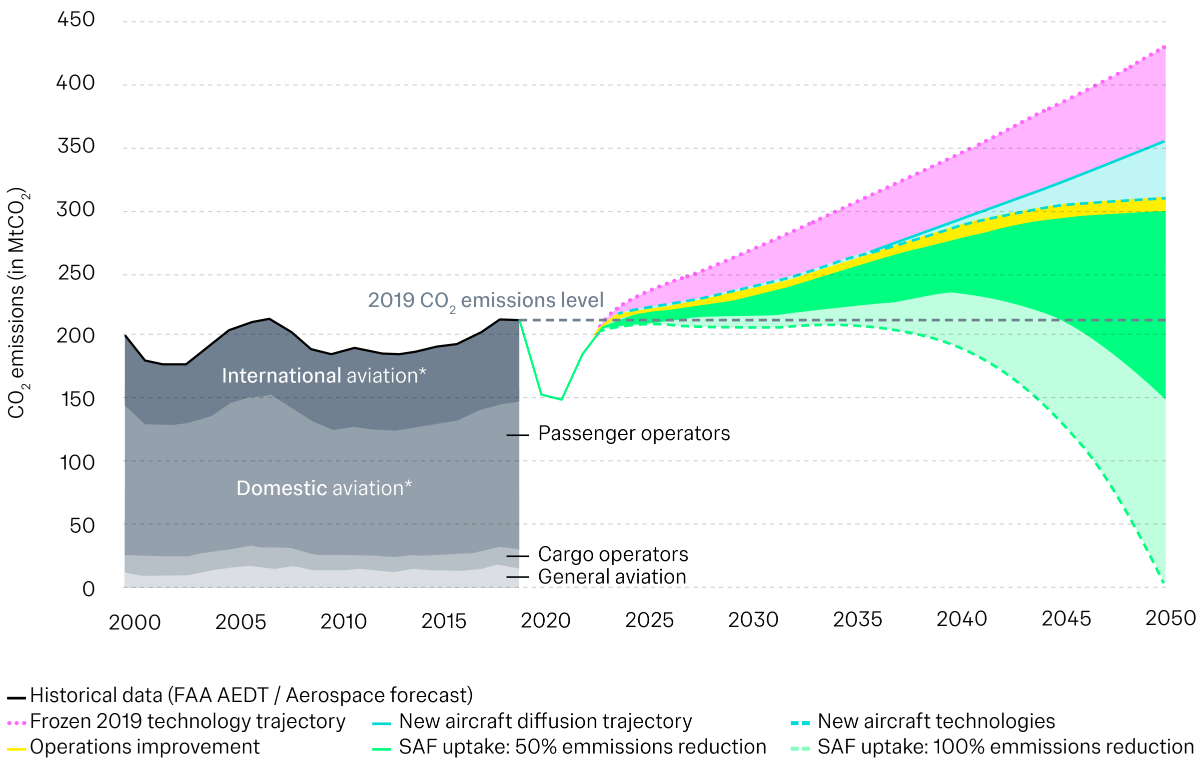
[68] https://future-bridge.eu/subsidized-sustainable-aviation-fuel-europes-eu6-l-market-boost-explained/
[69] https://concito.dk/en/udgivelser/e-fuels-or-storage-how-to-make-the-most-of-clean-electricity-and-captured-co2
[70] Whitehead A. Independent Review of Greenhouse Gas Removals https://assets.publishing.service.gov.uk/media/68f8d27a0794bb80118bb764/independent-review-of-ggr.pdf (2025)
[71] The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation - https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0085 (2025)
[72] Clean Aviation Joint Undertaking - https://www.clean-aviation.eu/
[73] SAF Grand Challenge Roadmap - https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf (2022)
[74] NREL, Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway - https://docs.nrel.gov/docs/fy24osti/87803.pdf (2024)

Box 6. Trump administration changes to SAF policy

Under the current Trump Administration, previous SAF policy has been tweaked to reflect a stance that is rooted in energy independence and rural economic development, rather than climate-first principles. The Administration has extended the Section 45Z clean fuel production tax credit through 2027 as part of the 'One Big Beautiful Bill' (OBBB)[75], with a provision for optional review periods to add extensions based on several criteria. There has also been an adjustment to the credit values of the 45Z tax credit, changing from $1.75 per gallon to $1 per gallon, reflecting political pressure to tighten spending while still preserving meaningful incentives. Furthermore, the Bill imposes a 20% reduction on the credit value if SAF is produced using imported feedstocks. This aims to boost the use of US-sourced corn, soy, tallow and other agricultural and waste-based inputs. Backers argue this framework supports domestic jobs and agriculture while positioning the US as a global leader in next generation fuel production. In a supportive move for the SAF industry, the administration also approved a $1.67bn federal loan to expand a major SAF production facility in Montana, which is expected to scale production to 315m gallons per year.[76] These actions have been praised by industry coalitions such as Americans for Clean Aviation Fuels, which see SAF as a market opportunity that aligns with America First energy policies.[77]

At the same time, the administration has subtly shifted the branding around SAF, with the Department of Energy and related agencies now referring to it as 'Synthetic Aviation Fuel', a move interpreted by some as an attempt to distance the technology from climate-focused rhetoric without materially changing eligibility criteria or policy scope.[78] Despite these early, seemingly supportive moves, the broader sustainability community still remains wary. Industry groups like IATA and several major US airlines have expressed concern that Trump's wider scepticism towards climate policy, including efforts to roll back elements of the Inflation Reduction Act (IRA), could weaken the long-term policy certainty that SAF developers rely on for financing and investment decisions.[79]

[75] One Big Beautiful Bill Act - https://www.congress.gov/bill/119th-congress/house-bill/1/text (2025)
[76] Trump administration approves sustainable aviation fuel refinery loan - https://www.reuters.com/sustainability/trump-administration-approves-sustainable-aviation-fuel-refinery-loan-2025-02-11/ (2025)
[77] https://www.americansforcleanaviationfuels.com/acaf-thanks-president-trump-and-congressional-republicans-for-including-clean-aviation-fuels-in-obbb (2025)
[78] Sustainable aviation fuel becomes 'synthetic' under Trump administration - https://advancedbiofuelsusa.info/sustainable-aviation-fuel-becomes-synthetic-under-trump-administration (2025)
[79] Aviation sector officials warn of Trump effect on green jet fuels - https://www.reuters.com/sustainability/aviation-sector-officials-warn-trump-effect-green-jet-fuels-2024-11-26/ (2024)



*Note: Domestic aviation from U.S. and foreign carriers. International aviation from U.S. carriers.

Figure 10. Estimates of US domestic and international aviation CO_2 emissions
(Source: https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf)

Carbon capture and management
Focusing more on incentives than regulatory driven policies, the US is leveraging its carbon capture potential through schemes like the 45Q tax credit to encourage investment in Carbon Capture, Utilisation, and Storage (CCUS) technologies. Investments have also been made in Direct Air Capture (DAC) innovation hubs, with the South Texas DAC Hub and Project Cypress in Louisiana receiving $1.2bn to explore commercialisation of the technology.[80] This approach aligns with the US's broader industrial decarbonisation strategies, supporting significant investments in CCS projects. The US does not have a federal level carbon trading scheme like the UK or EU ETS, but some state level schemes do exist (with California's cap-and-trade programme being the most established[81]). However, aviation is not specifically included in these schemes, with the focus currently more on stationary sources of carbon emissions like power plants and industrial facilities.[82]

4.3 UK sustainable aviation policy direction

The UK government has opted for a strategy that combines regulatory pressure (i.e., SAF mandates and the UK emissions trading scheme), with early-stage grant funding, avoiding large-scale incentives or subsidies on alternative fuels. Investment is focused instead on future technologies such as next generation SAF (AtJ, FT & PtL SAF), and carbon capture, utilisation and storage (CCUS).

This approach may limit the pace of near-term emissions reductions, which will be mostly driven by fleet replacement, but could position the UK to lead in emerging technologies that may define the long-term future of net zero aviation.

The current UK approach reflects both structural constraints, such as feedstock availability, and a strategic choice to try and leverage national strengths in aerospace and engineering. However, this model carries inherent risks. Speculative technologies may not deliver in time and, without sufficient market incentives, private investment in SAF and CCUS may stall.

[80]https://www.energy.gov/oced/DACHubs
[81]https://www.c2es.org/content/california-cap-and-trade/
[82]US State Carbon Pricing Policies - https://www.c2es.org/document/us-state-carbon-pricing-policies/

Sustainable Aviation's roadmap
The UK aviation industry, via the organisation Sustainable Aviation, has published its own decarbonisation roadmap (Figure 11). Whilst largely built around the same decarbonisation levers discussed above, this goes further by breaking down the levers in greater detail. It places most of the emphasis on SAF (like IATA), projecting it to deliver around 39% of emissions reductions by 2050, whilst also advocating for increased government support to scale domestic production and associated SAF infrastructure.

Compared to the Jet Zero Strategy (discussed below), the Sustainable Aviation roadmap places less emphasis on market-based measures (UK ETS and CORSIA), assigning them a smaller proportion of overall the emissions reduction. It highlights the role of advancements on aircraft technology more prominently, both through incremental improvements to current fleets and investment in future zero-emission aircraft (30%) and gives more space to carbon capture and removals as a long-term solution (13%).

Overall, while aligned in direction, the industry roadmap is more granular, forward-leaning on technology, and policy-driven in its calls for government intervention to enable aircraft innovation and SAF deployment at greater scale.[83]

Jet Zero Strategy
The UK government's approach to decarbonising aviation is articulated primarily through the Jet Zero Strategy, launched in 2022. This outlines a roadmap for achieving net zero aviation by 2050.[84] The strategy places a strong emphasis on a mix of regulatory tools, public funding programmes and policy support mechanisms intended to leverage private sector investment and technological innovation. It also makes clear that there are no government plans to limit the number of flights or the capacity of airports, removing demand management as a possible decarbonisation lever.[85] The baseline assumption is a growth in air passenger numbers for the UK of around 25%. This is a much lower rate of growth than in the global IATA projections and reflects the maturity of the air travel sector in the UK. Figure 12 shows the high-ambition scenario adopted as decarbonisation roadmap in the UK Jet Zero strategy. By 2050, 17% of the carbon reductions with respect to the business-as-usual strategy are expected to come from SAF, which are defined by government as fuels derived from sustainable feedstock that produce at least 40% GHG reduction over the entire lifecycle.[86] An additional 15% of the reduction will come from fuel efficiency improvements, which includes both fleet replacement and operational improvements in air traffic control and airport operations. It also opens the way for zero-carbon aircraft for short routes, which are expected to account for 4% of the overall reductions.

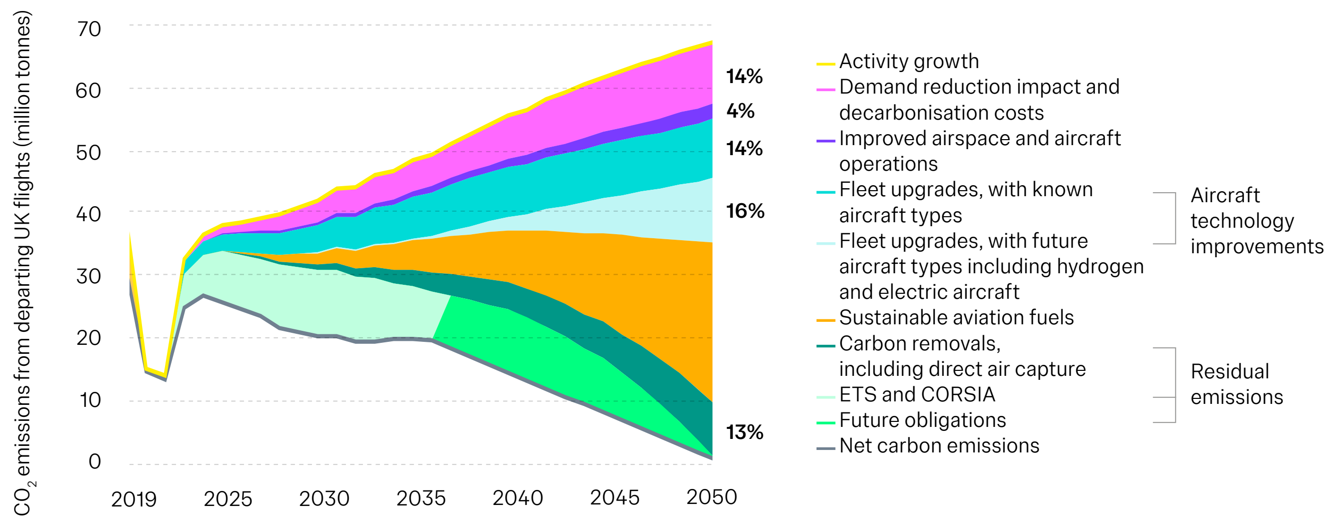


Figure 11. Sustainable Aviation's Decarbonisation Roadmap 2050
(Source: https://www.sustainableaviation.co.uk/wp-content/uploads/2024/05/Sustainable-Aviation-One-Year-On-Policy-Progress-Report.pdf)

[83]Sustainable Aviation, Net Zero Carbon Road-Map One Year On: Progress Report - https://www.sustainableaviation.co.uk/wp-content/uploads/2024/05/Sustainable-Aviation-One-Year-On-Policy-Progress-Report.pdf (2024)
[84]Jet Zero Strategy: Delivering net zero aviation by 2050 - https://assets.publishing.service.gov.uk/media/62e931d48fa8f5033896888a/jet-zero-strategy.pdf (2022)
[85]Jet Zero Consultation: Summary of responses and government response, 2022, https://www.gov.uk/government/consultations/achieving-net-zero-aviation-by-2050
[86]Department for Transport, "RTFO and SAF Mandate Technical Guidance", Jan 2025, https://www.gov.uk/government/publications/rtfo-and-saf-mandate-technical-information

More than half of the anticipated emissions reductions in the Jet Zero Strategy come from actions that occur outside the aviation sector itself. Approximately 27% is expected from market-based mechanisms (MBM) such as the UK ETS and CORSIA, and a further 37% from carbon removals and abatement in other sectors, including power, land use, and GGR technologies.[87] These reductions are not achieved by lowering direct aircraft emissions, but rather by financing mitigation activities elsewhere.

The Jet Zero Strategy envisions the use of multiple MBMs to support aviation's decarbonisation. These include compliance markets, such as the UK ETS and CORSIA, as well as voluntary carbon markets (VCMs). Each operates under distinct rules. The UK ETS is a cap-and-trade system covering domestic UK flights and requires aircraft operators to surrender UK Allowances (UKAs) equal to their emissions.

Importantly, the UK ETS does not currently permit the use of offsets or removals to meet compliance obligations; only UKAs can be used. However, the UK government is actively reviewing options to integrate GGRs into the ETS.[88] This marks a potential shift toward greater flexibility for hard-to-abate sectors like aviation while reinforcing the demand for permanent removals.

In contrast, CORSIA applies to international aviation emissions and does allow the use of offsets from approved carbon credit programmes. ICAO approved the inclusion of engineered GGRs (e.g. DACCS, BECCS) that meet criteria for permanence, additionality, and robust monitoring, reporting and verification (MRV).[89]

Outside these compliance schemes, VCMs offer another route for aviation actors to purchase carbon removal credits, often with longer-term durability, to meet their own corporate net zero pledges. Although these removals are not required for regulatory compliance, they are increasingly seen as a mark of climate leadership, especially as buyers shift away from traditional avoidance offsets and toward high-integrity removals.

This patchwork of overlapping mechanisms, some regulating emissions directly, others enabling compensation through external actions, reflects the complexity of market-based strategies for decarbonising aviation. The strategy also acknowledges that non-CO_2 climate impacts (e.g., contrails and NOx emissions) may substantially contribute to aviation's warming potential and calls for further research to develop appropriate mitigation approaches.

Whilst the UK government and IATA roadmaps broadly align in terms of the key decarbonisation levers, there are important differences. IATA places significantly greater weight on SAF, projecting it to deliver around 65% of the total emissions reduction by 2050. In contrast, while SAF plays an important role in the UK Jet Zero Strategy (17%), there is far greater reliance on market-based mechanisms (UK ETS and CORSIA) and on carbon removal technology/abatement as a means of addressing emissions (64%).

Sustainable aviation fuel

Sustainable aviation fuel forms an important component of the UK's aviation decarbonisation strategy (17%), with the UK government setting a SAF mandate starting in 2025 of 2% of total UK jet fuel demand, increasing linearly to 10% in 2030 and then to 22% in 2040.[90]

However, SAF production in the UK faces structural limitations. The UK has a relatively constrained supply of feedstock and has ruled out the use of SAF produced from food, feed or energy crops (e.g., vegetable oils, maize) on sustainability grounds.[91] This decision reduces flexibility and places greater pressure on the development of second and third-generation SAF pathways, such as Alcohol-to-Jet (AtJ), Fischer-Tropsch (FT) and Power-to-Liquid (PtL) technologies. These advanced pathways, however, are not yet scaled, remain expensive and would likely require strong policy guarantees and price support to become viable.

In addition, the UK still expects to rely on SAF imports by 2050, even if domestic production of the 8.4Mt of SAF forecasted by then was met (around 65% of total 2050 SAF needs).[92] A previous commitment in the UK government's Jet Zero Strategy was for five SAF plants to be under construction by 2025, to produce over 300,000 tonnes of SAF a year.[93] Currently, only one of these plants is in operation (the Phillips 66 Humberside facility), two plants are still under construction (LanzaJet's AtJ plant in Port Talbot and Velocys's Fisher-Tropsch Altalto plan in Immingham), while the future of the NorthPoint SAF facility at Stanlow Refinery in Cheshire is in question

[87] https://www.climatechangenews.com/2024/08/23/london-airport-expansion-spotlights-danger-of-false-hope-jet-zero-strategy/
[88] Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme: Main Response - https://assets.publishing.service.gov.uk/media/689cda8487bf475940723f5b/uk-ets-ggrs-main-response.pdf
[89] ICAO approves CCS, carbon removal credits for use under CORSIA global aviation offset scheme - https://carbon-pulse.com/454422/
[90] UK government SAF mandate - https://www.gov.uk/government/collections/sustainable-aviation-fuel-saf-mandate
[91] The SAF Mandate: an essential guide - https://www.gov.uk/government/publications/about-the-saf-mandate/the-saf-mandate-an-essential-guide (2024)
[92] Sustainable Aviation, Net Zero Carbon Road-map Summary Report - https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO2RoadMap_Brochure_v4.pdf
[93] https://www.gov.uk/government/news/lift-off-for-projects-fuelling-jet-liners-with-bin-liners

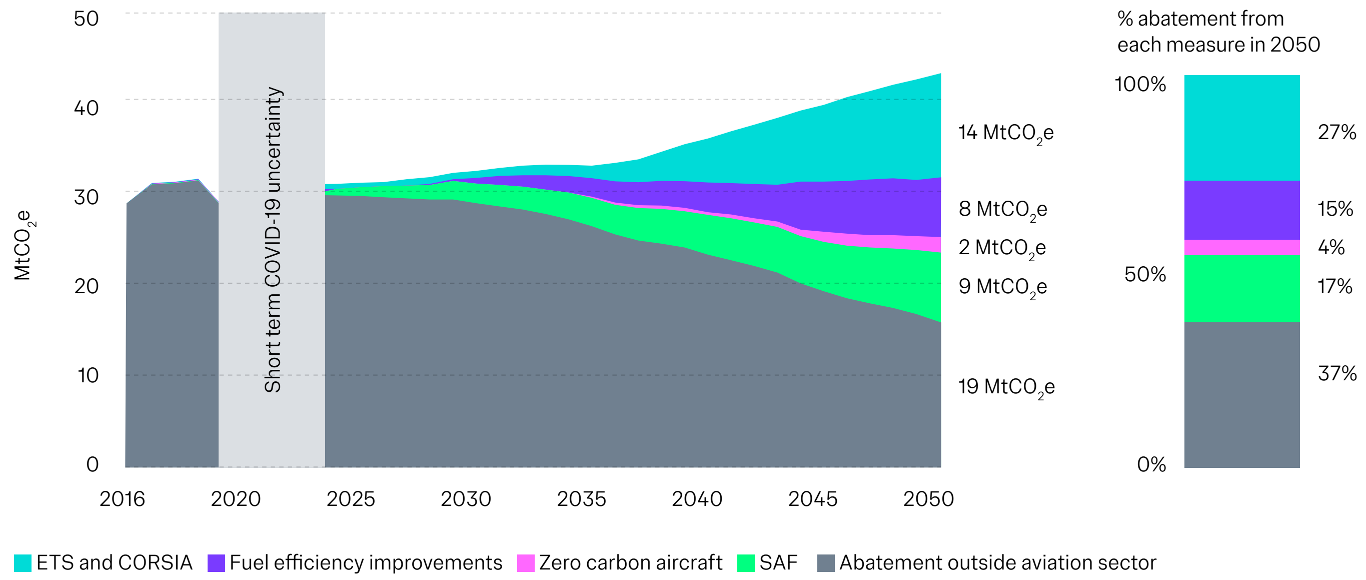


Figure 12. UK Government's Jet Zero Strategy Decarbonisation Roadmap 2050
(Source: https://assets.publishing.service.gov.uk/media/62e931d48fa8f5033896888a/jet-zero-strategy.pdf)

with the project developer, Fulcrum BioEnergy, filing for bankruptcy in 2024.[94] Alfanar's Lighthouse Green Fuels sustainable aviation fuel (SAF) plant in Teeside is still at the planning stage.

Recognising these barriers, the UK government has committed over £200m to the Advanced Fuels Fund (AFF),[95] which aims to accelerate the commercialisation of early-stage SAF projects. However, this level of funding remains relatively modest compared to the scale of investment seen in the US via IRA tax credits and other funding initiatives. The UK's PtL SAF mandate trajectory is also cautious, with a target of 3.5% of total aviation fuel coming from PtL SAF by 2040, compared to a 10% target in the EU.[96] This lower mandate likely reflects both technological uncertainty and an unwillingness or inability to provide the long-term financial support required to sustain and scale next generation SAF production.

The UK government's SAF policy has faced criticism, notably:

- The current SAF mandate, targeting 10% of jet fuel by 2030 and rising to 22% by 2040, is insufficiently ambitious, especially given the projected growth in air travel.[97] According to Carbon Brief, the climate benefits of reaching this mandate could be entirely outweighed by rising aviation demand, meaning no net reduction in sector-wide emissions. Using government data, they estimate that UK aviation emissions in 2025 would be 36.0 $MtCO_2e$, falling to 35.7 $MtCO_2e$ by 2040, a drop of just 0.8%.[102] This would mean that the SAF mandate merely prevents an increase in emissions resulting from higher jet fuel use in 2040, rather than leading to any meaningful reduction.
- There is a failure to provide the financial mechanisms necessary to support large-scale SAF investment and deployment, e.g., tools like price guarantees, contracts for difference, or long-term subsidies.[98]

In response, the UK government is considering new legislation through the Sustainable Aviation Fuel Bill, which aims to establish a Revenue Certainty Mechanism (RCM) to create more favourable conditions for SAF investment and production.[99] Whilst this has been generally welcomed by the aviation industry,[100,101] the consultation period highlighted the lack of differentiation between SAF types and a lack of focus on supporting e-Fuels.[102]

[94] UK's NorthPoint SAF facility uncertain as project developer files for bankruptcy – https://www.fastmarkets.com/insights/uks-northpoint-saf-facility-uncertain-as-project-developer-files-for-bankruptcy (2024)
[95] Advanced Fuels Fund (AFF) - https://www.gov.uk/government/publications/advanced-fuels-fund-competition-winners/advanced-fuels-fund-aff-competition-winners, https://www.ricardo.com/en/news-and-insights/campaigns/aff
[96] The SAF Mandate: an essential guide - https://www.gov.uk/government/publications/about-the-saf-mandate/the-saf-mandate-an-essential-guide (2024)
[97] Analysis: Benefits of UK 'sustainable aviation fuel' will be wiped out by rising demand - https://www.carbonbrief.org/analysis-benefits-of-uk-sustainable-aviation-fuel-will-be-wiped-out-by-rising-demand/
[98] https://www.sustainableaviation.co.uk/news/urgent-government-action-needed-to-meet-10-sustainable-aviation-fuel-by-2030-target/ (2022)
[99] Sustainable Aviation Fuel Bill 2024-25 - https://researchbriefings.files.parliament.uk/documents/CBP-10279/CBP-10279.pdf
[100] https://www.britishchambers.org.uk/news/2025/07/bcc-welcomes-government-saf-funding/
[101] https://centreforaviation.com/news/airlines-uk-ceo-welcomes-saf-production-and-rcm-legislation-to-parliament-1317552
[102] SAF bill: Future-proofing the UK's e-SAF production - https://www.transportenvironment.org/uploads/files/SAF-bill_-Future-proofing-the-UKs-e-SAF-production_Updated.pdf (2025)

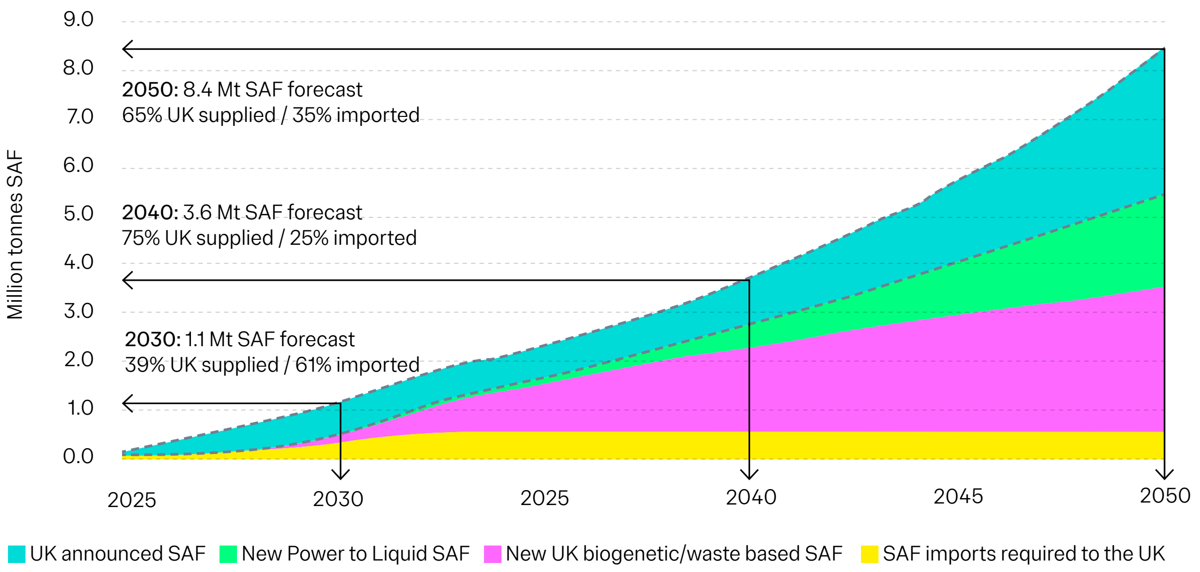


Figure 13. Sustainable Aviation (SA) forecast SAF supply for the UK.
(Source: https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO2RoadMap_Brochure_v4.pdf)

E-Fuels offer the greatest long-term potential for decarbonisation of the existing fleet, yet much lower energy prices would be necessary to ensure their viability in the UK as renewable electricity is the dominant cost component in the production of green hydrogen, the essential feedstock for e-Fuels.[103] Electricity accounts for up to 70–80% of the total cost of producing hydrogen through electrolysis,[104] meaning that even small differences in electricity prices translate into large cost penalties for e-Fuels. The UK currently faces industrial electricity prices that are significantly above those in competitor regions – almost four times higher than the USA and around 40% higher than large EU countries.[105] Consequently, without substantial reductions in electricity costs, or new policies to close the competitiveness gap, the UK will be uncompetitive in the development and scale-up of e-Fuels compared to countries with much lower energy costs. While expecting local production of SAF to meet the total need of the UK aviation sector is probably impractical even in the long term, energy security concerns demand of a strong domestic industry across the SAF supply chain.

Carbon capture and management

Carbon capture plays two distinct roles in climate mitigation strategies. The first is Carbon Capture and Storage (CCS), which prevents CO_2 emissions from entering the atmosphere at source (e.g., power plants, industrial facilities). The second is GGR, which includes methods such as DACCS and BECCS that actively remove CO_2 from the atmosphere.

While CCS is not strictly speaking a carbon removal technology, it is a crucial enabler of GGRs: both DACCS and BECCS require safe, permanent storage of captured CO_2. Infrastructure for CCS – including pipelines, compression systems, and geological storage – is therefore a shared backbone between mitigation and removal pathways. In the context of sustainable aviation, this makes CCS highly relevant: it underpins removals used to offset residual emissions, supports the possible use of biogenic CO_2 in SAF, and offers broader system-wide decarbonisation benefits through shared infrastructure.

Technologies for CCS and GGR are emerging as high priority areas, with government and private sector partnerships exploring opportunities for UK-based deployment. While GGR technologies such as DACCS and BECCS remain relatively expensive and nascent, CCS is a more mature technology with several large-scale facilities already in operation globally.[106] Nevertheless, both require further scale-up and policy support. In practice, a portfolio approach to GGR is likely, with a mix of nature-based and engineered removals deployed at varying cost and permanence levels and a trend toward longer-term, durable solutions as markets and standards mature. While permanent and durable GGR technologies are expensive and still early-stage, they are

[103] Dawkins, Ash, Suvendiran, Cost reduction pathways of green hydrogen production in Scotland – Climate Exchange http://dx.doi.org/10.7488/era/2100 (2022)
[104] Splitting the Difference: Reducing the cost of electrolytic hydrogen to accelerate deployment - https://www.renewableuk.com/media/gjkhpx2n/splitting-the-difference-hydrogen-co-report.pdf (2025)
[105] Why are the UK's industrial electricity prices so high? - https://www.ft.com/content/f3bcd4a4-0a5f-4fc1-ad8a-cf2530e6001a (2025)
[106] Global Status of CCS 2025 - https://www.globalccsinstitute.com/global-status-of-ccs/

increasingly viewed by many (including Airbus and other major airlines) as a significant option for offsetting residual emissions from long-haul aviation.[107,108]

The UK's geological storage potential in the North Sea (reportedly up to 70bn tonnes of potential CO_2 storage, one of the largest in Europe[109]) and existing infrastructure and carbon management expertise potentially provide a favourable context for investment.[110] The UK aims to be a first mover in carbon capture, committing £21.7bn over the next 25 years to support the establishment of two Carbon Capture, Utilisation & Storage (CCUS) clusters by the mid-2020s (East Coast Cluster in Teesside and HyNet in North West of England and North Wales) and a further two by 2030 (Acorn, North-East Scotland and Viking in the Humber).[111] The overall aim is to capture 20-30Mt CO_2 per year by 2030. Currently, UK planned capacity is between 2.5-10.5 $MtCO_2$ per year.[115]

Despite the potential of carbon capture, there is caution around decarbonisation roadmaps being too reliant on the technology, due to its early-stage nature.[112,113] Scientists have also noted that it is important to weigh up the risks and benefits of emphasising the use of carbon capture too heavily. Policymakers face a dilemma in designing incentives to scale-up sustainable carbon removal, while ensuring these measures do not reduce the motivation for emissions reductions through conventional mitigation pathways.[119]

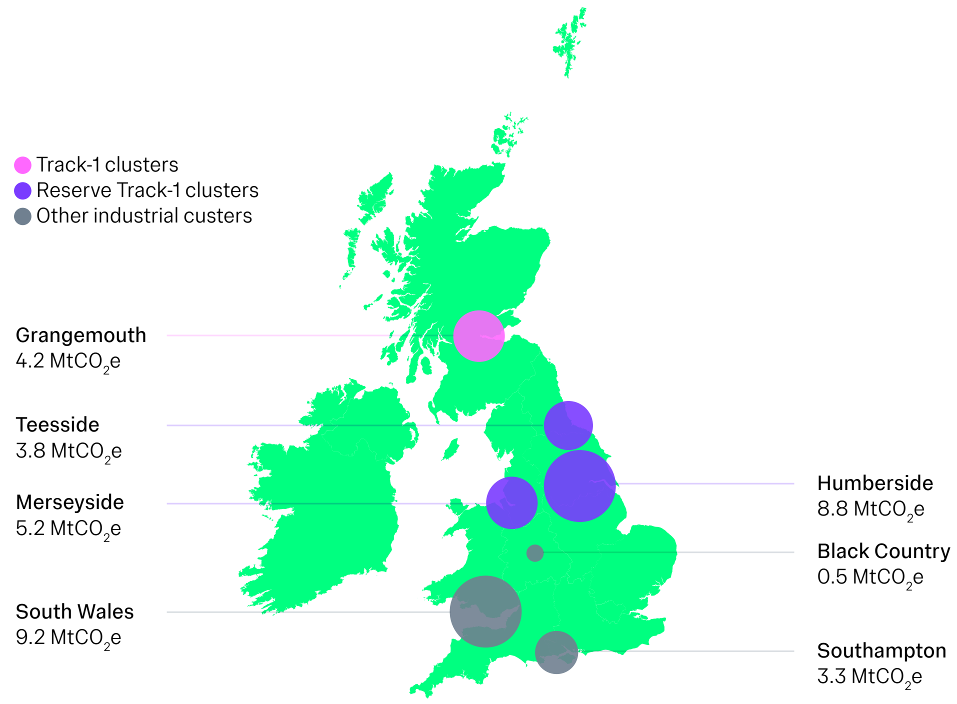


Figure 14. Map of major UK industrial cluster emissions from large point sources
(Source: https://assets.publishing.service.gov.uk/media/64a29b7d06179b00131ae94e/ccus-investment-roadmap.pdf)

[107] https://www.airbus.com/en/sustainability/our-approach-to-sustainability/decarbonisation
[108] https://carbonengineering.com/news-updates/net-zero-aviation/
[109] Sustainable Aviation, Net Zero Carbon Road-map Summary Report - https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO2RoadMap_Brochure_v4.pdf
[110] CCUS Net Zero Investment Roadmap: Capturing carbon and a global opportunity - https://assets.publishing.service.gov.uk/media/64a29b7d06179b00131ae94e/ccus-investment-roadmap.pdf (2023)
[111] https://www.gov.uk/government/collections/uk-carbon-capture-usage-and-storage-ccus (2025)
[112] EU climate policy is dangerously reliant on untested carbon-capture technology - https://www.nature.com/articles/d41586-024-00391-3 (2024)
[113] EU unveils controversial climate target: what scientists think - https://www.nature.com/articles/d41586-024-00361-9 (2024 [114] Evaluation of the UK Emissions Trading Scheme - https://assets.publishing.service.gov.uk/media/657c4d9595bf65001071908c/evaluation-of-uk-ets-phase-1-report.pdf (2023)
[115] Dept for Energy Security & Net Zero, UK Government: Greenhouse Gas Removals Business Model summary www.gov.uk/government/publications/greenhouse-gas-removals-ggr-business-model (2025)
[116] Polluter pays? A large share of Europe's aviation emissions remain unpriced - https://www.transportenvironment.org/uploads/files/EU-ETS-REPORT-2025_2025-04-25-143049_jjhw.pdf (2025)
[117] Polluter pays? A large share of Europe's aviation emissions remain unpriced - https://www.transportenvironment.org/uploads/files/EU-ETS-REPORT-2025_2025-04-25-143049_jjhw.pdf (2025)
[118] UK ETS: Warning that low carbon pricing undermines future success - https://www.edie.net/uk-ets-warning-that-low-carbon-pricing-undermines-future-success/ (2025)
[119] The UK Emissions Trading Scheme: Leaking Value - https://ieefa.org/sites/default/files/2025-03/IEEFA_Carbon%20Pricing%20Briefing%20Note_16504.pdf (2025)

Carbon management – Emissions Trading Schemes (ETS)
Emission trading schemes provide a policy architecture for pricing emissions and supporting the development of engineered GGR. The UK Emissions Trading Scheme (replacing the EU ETS post-Brexit) covers domestic flights and flights to the European Economic Area but excludes emissions from long-haul international flights. The scheme complements the global CORSIA scheme, in which the UK participates, with international flights not covered by the UK ETS. The UK ETS introduces a gradually tightening cap on emissions (phasing out the aviation industry's free allowances by 2026) and supports decarbonisation through market-based pricing signals.

The UK has committed to passing legislation so that the integration of GGRs into UK ETS is operational before 2030. A revenue support mechanism is being introduced with a 15-year price guarantee for GGR credits provided through Contracts for Difference (CfD) between the UK government and a GGR developer. The British Standards Institute is also developing the framework for quantification of both DACCS and BECCS removals.

Several criticisms have been levelled at the UK ETS:[116]

- The limited scope of coverage (i.e., excludes long-haul flights, the primary driver of emissions).
- The overreliance on free allowances (although these are being phased out).
- The lack of incentives for SAF.
- The possibility of UK airlines losing out to competitors that are not subject to the same regulatory pressures on carbon reduction.

There are also concerns around the low pricing of carbon, which does not represent the real costs to society of the emissions produced and disincentivises polluters from reducing their emissions.[117] The price of carbon within the UK Scheme has decreased since 2023 and currently remains lower than EU ETS carbon prices.[118] These low carbon costs also lead to lower tax revenues for the UK government, reducing the ability to fund climate change mitigation and support efforts to decarbonise the economy.[119] The UK ETS scheme has recently been extended to 2030, with continuing consultations for an extension past this period to a post 2030 Phase II.[120] Multiple other consultations are also taking place around how best to build upon the scheme (four consultations alone on the second Free Allocation window), with worries that the continuous flow of new policy will undermine the effectiveness of the scheme and lead to greater uncertainty for industry.[121]

Advanced aircraft technologies
The Aerospace Technology Institute (ATI) programme supports R&D in ultra-efficient aircraft, zero-emission propulsion systems and hybrid-electric and hydrogen-powered designs.[122] It has been allocated an additional £975m by the government for the financial years 2025/2026 to 2029/2030, reinforcing the UK's strategic focus on potentially high-impact innovations that align with the UK's advanced aerospace engineering capabilities. This corresponds with the priorities outlined in the recently launched UK Modern Industrial Strategy (2025), which identifies aerospace as a critical advanced manufacturing sector capable of driving long-term productivity growth.[123] The strategy stresses the need to maintain and grow the UK's competitive edge in high-value R&D, particularly in jet engines, wings, and digitalisation for large commercial aircraft, to ensure the sector is well-positioned to meet future demand for the next generation of aircraft.[130]

Complementing this, the Advanced Manufacturing Sector Plan – published alongside the Industrial Strategy – calls for the UK to become a global innovation hub in net zero aerospace. It emphasizes clean propulsion as a path to greater resilience, supply chain growth, and skilled job creation.[124] The plan announced an extension to the ATI programme, committing £2.3bn to 2035 to accelerate development of technologies that boost growth, competitiveness, and productivity in next generation, low-emission aircraft.[131]

[120]Extending the UK ETS cap beyond 2030 - https://www.gov.uk/government/consultations/extending-the-uk-emissions-trading-scheme-cap-beyond-2030/extending-the-uk-ets-cap-beyond-2030-english-consultation-document-html-version
[121] UK ETS Consultation Overload - https://www.cfp.energy/en/insights/uk-ets-authority-adds-two-more-consultations-to-a-growing-list-for-stakeholder-input
[122]Aerospace Technology Institute, Destination zero: the technology journey to 2050 - https://www.ati.org.uk/wp-content/uploads/2022/04/ATI-Tech-Strategy-2022-Destination-Zero.pdf (2022), https://www.ati.org.uk/news/government-announces-ati-programme-funding-up-to-2030/
[123]UK's Modern Industrial Strategy - https://assets.publishing.service.gov.uk/media/68595e56db8e139f95652dc6/industrial_strategy_policy_paper.pdf
[124]UK's Modern Industrial Strategy: Advanced Manufacturing Sector Plan - https://assets.publishing.service.gov.uk/media/6858622776eec44bf9d71dcf/industrial_strategy_advanced_manufacturing_sector_plan.pdf
[125]UK Hydrogen Strategy - https://assets.publishing.service.gov.uk/media/64c7e8bad8b1a70011b05e38/UK-Hydrogen-Strategy_web.pdf (2021)
[126]https://zeroavia.com/zeroavia-to-build-manufacturing-hub-in-scotland/ (2025)
[127] Aviation industry bets on hydrogen to decarbonise - https://sciencebusiness.net/news/hydrogen/aviation-industry-bets-hydrogen-decarbonise (2024)
[129]CAA, Airspace Modernisation Strategy 2023–2040, https://www.caa.co.uk/our-work/publications/documents/content/cap1711 (2024)
[130]Jet Zero Strategy: Delivering net zero aviation by 2050 - https://assets.publishing.service.gov.uk/media/62e931d48fa8f5033896888a/jet-zero-strategy.pdf, pg 55-58 (2022)
[131] ETS Allowances for SAF - https://climate.ec.europa.eu/document/download/9a82627a-8a5c-4419-93de-e5ed2d6248eb_en?filename=policy_ets_allowances_for_saf_en.pdf&prefLang=hu (2023)

Through the *Future of Flight* action plan, the ATI programme has also supported the development of safe, sustainable advanced air mobility solutions, such as drones and electric vertical take-off and landing (eVTOL) aircraft. This includes building the necessary regulation, infrastructure, and technologies to enable their routine use.[131]

Further backing for zero-emission aviation comes from the UK Hydrogen Strategy, which highlights the long-term potential for hydrogen-powered aircraft.[125] There is support for R&D and demonstration projects that explore hydrogen's role in aviation, for example the ATI's £18.5m contribution to ZeroAvia's development of HTPEM fuel cells.[126] However, zero emission flying at scale remains a longer-term prospect.[127] In February 2025, Airbus announced a delay to its ZEROe hydrogen-aircraft programme, citing concerns around slow progress in hydrogen technology and infrastructure. Rolls Royce has stated that hydrogen will not play a role in decarbonising aviation within the next 15-20 years.[128]

The most recent UK Strategic Defence Review has opened new opportunities for developing dual-use aerospace technologies with both civilian and military applications. Realising this potential will require closer coordination across government funding bodies to identify and nurture strategic technologies. The example of JetZero in the USA offers a relevant model. JetZero is developing a 250-passenger blended wing body aircraft that promises 50% fuel savings. This can also be adapted to a tanker version for the US Air Force, which has contributed over $200m to the development programme.

Operations, including contrail mitigation
The UK supports improvements in air traffic management and airport ground operations, though these are generally seen as incremental contributions rather than transformative levers. The UK air traffic operator, NATS, is a key constituent in CAA's Airspace Modernisation Strategy[129] and is restructuring the use of the UK-managed air space to enable more flight efficient flight profiles.

There are potentially significant environmental gains by introducing contrail mitigation (see above). While there is still some uncertainty in estimates of their impact, evidence increasingly suggests that contrail avoidance is by far the cheapest strategy to reduce adverse climate effect of aviation. The UK Jet Zero Strategy has already acknowledged the critical role of the non-CO_2 climate impacts of aviation.[130] Contrail avoidance is an area in which the UK is building considerable expertise and where the country should take a leadership role in establishing operational standards.

4.4 Strategic differences and similarities in sustainable aviation policies – UK, EU and US

Key aspects of the three regional approaches are summarised in Table 3. All three view SAF as an important lever driving decarbonisation in their roadmaps but differ in their approaches to developing and supporting the industry. The UK and EU are similar in relying on regulatory SAF mandates, compared to the US reliance on tax credits, but they differ in their subsidy approach. Although both the UK and EU employ emissions trading schemes (ETS), only the EU currently leverages its ETS revenue to directly subsidise price differences between SAF and traditional jet fuel.[131]

The UK and EU both share a strong strategic focus on long-term innovations like hydrogen-powered and electric aircraft, advanced PtL SAF and carbon capture technologies compared to the USA, which is more focused on near-term, scalable and proven technologies.

This shared emphasis on long-term innovation could provide the UK with opportunities to align more closely with EU efforts, especially in advancing carbon capture and PtL SAF technologies.

Until recently, the EU has benefited from a degree of stability and consensus on climate policies due to regulatory alignment across member states. However, there are signs that this is being challenged across Europe, where parts of the population are questioning environmental, climate and clean energy policies.[132,133] The UK, while largely supportive of net zero goals across the political spectrum, also faces policy uncertainty and budgetary constraints. This may negatively affect policy continuity over a longer time scale.

In the US, aviation sustainability efforts enjoy some bipartisan backing and early actions from the Trump Administration have been more supportive than previously anticipated, especially for domestically produced SAF. However, these policies are more vulnerable to political swings, with the Trump Administration's climate scepticism creating ongoing uncertainty around future policy decisions. **This uncertainty could enable the UK to take an international lead in certain areas such as carbon management and zero-emission air travel.**

[132]Europe's Swing to the Right Threatens Global Climate Policy - https://insideclimatenews.org/news/07062024/eu-parliamentary-election-global-climate-policy/ (2024)
[133]Polling the Politics of Net Zero: What Can Politicians Learn From EU and UK Views on Climate Policy? - https://institute.global/insights/climate-and-energy/polling-politics-of-net-zero-what-can-politicians-learn-from-eu-and-uk-views (2024)

Table 3, Key features of UK, EU, and USA sustainable aviation policy approaches

Feature	UK	EU	USA
SAF policy type	Mandate + Seed Funding	Mandate + ETS Revenue	Tax Credits (45Z)
SAF target (2030)	10%	6%	3bn gallons (est. ~10%)
Support for PtL	Moderate	High	Medium
Carbon market	UK ETS	EU ETS	None (Federal); some states
Infrastructure investment	CCUS, ATI, Hydrogen Hubs	Hydrogen Bank, Clean Aviation	CCS Hubs, SAF Loans

5. Strategic opportunities and challenges for the UK Aviation Sector

5.1 The sustainable aviation fuels ecosystem

The UK's SAF strategy faces clear structural challenges. Domestic feedstock availability is constrained, with the government ruling out food, feed and energy crops for sustainability reasons. This reduces flexibility and increases reliance on advanced pathways – Alcohol-to-Jet, Fischer–Tropsch and Power-to-Liquid (PtL) – which remain costly and immature.

Of the five production plants envisaged under the Jet Zero Strategy for 2025, only Phillips 66's HEFA facility in Humberside is operational. Investment flows remain insufficient, and the UK will need to import SAF (or rely on book and claim, see below) to meet projected its own mandates.

The UK's very high industrial electricity prices also undermine the competitiveness of e-fuels, given that electricity accounts for 70–80% of the cost of producing green hydrogen for PtL fuels. Unless addressed, they risk deterring investment in one of the most scalable long-term SAF pathways.

It is also critical to consider SAF as part of a wider 'sustainable fuel' environment – including maritime and heavy-duty road transport – and that supporting SAF, within the context of a greater sustainable fuel industry, would benefit a wider array of sectors than just aviation.

The UK has several areas of strength to build on:

- World-class aerospace and chemical process research capacity, the SAF mandate, funding schemes and proposed Revenue Certainty Mechanism (RCM) provide credible signals to investors. Given the constraints for cost-effective SAF production in the UK, the emphasis should be on R&D that reduces costs and on developing strategic expertise across the fuels supply chain, both to generate new export opportunities in engineering and electrolysers, and to improve the UK's energy security.
- The UK can also draw lessons from the EU's regulatory approach, which couples SAF mandates with emissions trading revenues to subsidise deployment. Coupling the UK's North Sea carbon infrastructure potential with energy-intensive innovation zones could enable early PtL demonstration at scale, while integration with CCUS clusters would create industrial synergies.
- The development of a credible SAF certificate market architecture, linked with UK ETS reforms and high-integrity carbon standards, could also draw in corporate demand and unlock additional private capital (see box).

Box 7. The Book & Claim model

World Energy's Book & Claim model, which separates the environmental benefits of SAF from the physical fuel itself, allows companies to purchase and claim reduced carbon emissions even if they do not physically receive the fuel itself. A digital registry tracks the SAF's environmental attributes, enabling the company to 'book' these attributes by purchasing them and then 'claim' the reduction toward its sustainability goals without needing direct access to the physical SAF. This system bridges supply and demand gaps, scales SAF adoption and helps decarbonise aviation, as well as other hard-to-abate sectors.

Source: World Energy - https://worldenergy.net/our-approach/book-claim/

5.2 Carbon capture and management

The UK benefits from a relatively strong starting position in carbon management:

- The country has significant geological storage potential in the North Sea – up to 70bn tonnes of CO – making it one of the largest storage resources in Europe, along with Norway.
- Government has committed over £21.7bn over 25 years to support two CCUS clusters (in the northeast and northwest of England), with operations to start by 2028 and two more planned by 2030. The ambition is to position the UK as a potential leader in carbon storage technology and services.
- The UK has a strong research base, with the British Standards Institute developing MRV (monitoring, reporting and verification) frameworks for DACCS and BECCS,[134] and pilot projects exploring energy and cost reduction in capture technologies
- Early policy moves, such as the planned integration of Greenhouse Gas Removals into the UK ETS before 2030,[135] supported by 15-year revenue contracts for CDR via Contracts for Difference (CfD), provide a foundation for a credible domestic carbon removal market

Nevertheless, several risks and weaknesses must be addressed. Carbon capture and DAC remain expensive and energy intensive, with current costs far above the levels needed for large-scale deployment. Scaling up storage capacity is subject to regulatory and permitting bottlenecks (with US experience suggesting 6-8 years for approval). The UK ETS itself has faced criticism for low carbon prices, limited coverage and policy volatility, undermining investment signals. Without reform, its ability to drive aviation decarbonisation and support durable CDR integration is limited.

The UK is well-placed to shape international standards on CDR integrity and accounting, ensuring credibility in offset markets and avoiding double counting. DESNEZ's recently released GGR business models could help to develop a sustainable market. This would involve engineered GGRs funded by polluting industries to compensate for their residual emissions via their inclusion in the UK ETS, and GGR credits verified in accordance with the UK government's GGR Standard (currently in development).[136] Such a model is structured similarly to the CfDs model used to scale up renewable electricity in the UK by providing long term revenue certainty. In the GGR context, the CfD-like structure guarantees a fixed price per tonne of verified and durably stored CO_2, offering predictable returns that de-risk early investment in nascent technologies such as DACCS, BECCS, and biochar. This could unlock greater private investment in support of early deployment of carbon removal technologies and position the UK as a leader in this area.

Carbon management offers important opportunities for the UK to lead. The combination of extensive geological storage capacity established oil and gas supply chains and world-class research institutions creates the potential for the UK to become an international hub for high-integrity CDR services.

[134]https://knowledge.bsigroup.com/products/direct-air-carbon-capture-and-storage-daccs-quantification-of-greenhouse-gas-ghg-emissions-and-removals-specification (2025)
[135]https://www.gov.uk/government/consultations/integrating-greenhouse-gas-removals-in-the-uk-emissions-trading-scheme
[136]https://assets.publishing.service.gov.uk/media/68ad77c2969253904d1557ff/greenhouse-gas-removal-business-model-summary-august-2025.pdf

5.3 Advanced aircraft technologies

The UK possesses significant strengths in this area. Its aerospace sector is globally competitive, with established leadership in aerostructures, jet engines and advanced systems for large commercial aircraft. The Aerospace Technology Institute (ATI) programme has been allocated £2.3bn to 2035. This long-term funding commitment reflects a deliberate strategy to invest in UK based high-value R&D, particularly in ultra-efficient aircraft and zero-emission propulsion systems. The UK Modern Industrial Strategy (2025) and the Advanced Manufacturing Sector Plan both highlight aerospace as a core growth sector, reinforcing government prioritisation. Complementary programmes, such as the Future of Flight, are also advancing regulatory frameworks and infrastructure for drones, eVTOLs, and advanced air mobility.

There are, however, significant structural challenges to aerospace technology innovation. Aircraft development timelines (5-10 years for design, 20-30 years in service) mean that even breakthrough technologies will take decades to diffuse through fleets. Capital costs are high, and operators are risk-averse when adopting unproven aircraft. Although there is strong UK investment in hydrogen and electric propulsion R&D, these technologies face fundamental barriers. Hydrogen requires radical airframe redesign and new airport refuelling infrastructure, while electric propulsion is currently viable only for small, short-range aircraft. Airbus's delay to its ZEROe hydrogen programme and Rolls-Royce's statements downplaying hydrogen's near-term role both highlight the lack of social and regulatory pressure for zero-emission air travel.

Despite the inherent challenges, the UK has opportunities to lead. Its R&D base in propulsion, systems and aerostructures means it can position itself at the forefront of component development for the next generation of single-aisle aircraft expected to dominate global fleets. Rolls-Royce and its supply chain can take advantage of the shift towards SAF by developing the engines of the future, capable of handling different fuel SAF types and fit for the next generation of aircraft.

A renewed emphasis on technology demonstrators, combining digital design, materials innovation and low-emission propulsion, could enable the UK to capture a larger share of the aerospace market. There is also scope for the UK to pioneer both the basic technologies and the regulatory reform and certification pathways for hydrogen and hybrid-electric aircraft, working closely with the airworthiness certification authorities.

Box 8. Rolls Royce Ultrafan Engine – An opportunity for Technical leadership, growth and jobs creation in the UK

As part of this study, an estimate was made of the Gross Value-Added (GVA) and jobs creation impacts to the UK economy from the scale up and commercialisation of the Rolls Royce Ultrafan aeroengine for single-aisle aircraft, which if successful would be the World's most energy efficient aeroengine judging from the engines initial test results. The GVA, jobs model and analysis can be found in the Appendix of this report. The model estimates that the Rolls Royce Ultrafan engine production could add £3.9 Billion/yr (PV) to the UK economy and £141 Billion (PV) from the annual GVA created over 40 years, whilst also adding 35,000 jobs to the economy. This estimate is comparable with Rolls Royce's own claims of £120 Billion and 40,000 jobs.

5.4 Operations including contrails and weather management

NATS (the UK's air traffic control service provider) has an established reputation for delivering high levels of operational efficiency and safety, with the UK actively participating in airspace modernisation programmes aligned with the Single European Sky ATM Research (SESAR) initiative.[137] The UK also has leading academic and research capacity on non-CO_2 climate impacts, including contrails. This positions the UK well to integrate contrail mitigation strategies into operational practice and international standards.

Contrail research has not yet resulted in operational protocols, and requires additional investment in atmospheric monitoring, predictive modelling and data-sharing across airlines and air traffic management systems. The UK has opportunities to lead globally by being the first to integrate contrail management into mainstream aviation operations. Targeted route adjustments to avoid atmospheric conditions that generate high radiative forcing contrails could deliver disproportionate climate benefits at minimal cost. Combining this with selective use of any available SAF on high-risk routes could amplify the impact.

The UK can lead in developing digital airspace management tools and protocols that optimise efficiency, reduce delays, and enhance resilience. However, airspace modernisation has faced delays,[138] with funding and delivery risks jeopardising timely implementation. Without accelerated progress, potential fuel and emissions savings could be lost.

[137] Joining up Europe's air traffic jigsaw - https://www.nats.aero/static/sesar/
[138] CAA, Airspace Modernisation - Progress Report, https://www.caa.co.uk/publication/download/25755 (2024)

6. Recommendations

We believe that the UK can leverage its established position in aerospace innovation to become a hub for net zero aviation technologies, generating skilled jobs, driving R&D and supporting domestic supply chains. By aligning the interests of government, industry and consumers through targeted regulation and investment, aviation can not only decarbonise but also catalyse broader industrial and economic transformation. This will depend on how effectively the UK can de-risk innovation, coordinate and target the most impactful levers and build investor and public confidence in the long-term pathway to Net Zero aviation.

We highlight the following areas for attention by government and the aerospace / aviation sector:

Development of holistic strategy for emissions reduction in aviation
A mission-driven approach is needed for net zero aviation, with SAF and GGR as the technology vectors. Cost reductions and technology upscaling through R&D and pilot plants should be the main focus, with the development of supply chains (e.g., electrolyzers) and technological expertise (e.g., catalyst design) as the near-term objectives.

On the policy side, SAF upscaling would benefit from long-term price guarantees and the development of a credible SAF certificate and Book & Claim system to unlock private capital. Developing SAF will also generate spillover benefits across multiple sectors. The underlying technologies used for SAF production can also be applied to decarbonise other sectors such as road transport, shipping and heavy industry. Moreover, the same chemical processes and intermediates support the production of renewable lubricants and specialty chemicals, strengthening the UK's wider low-carbon manufacturing base and creating cross-sector industrial synergies.

There are two main roadblocks that will continue to limit the development of the SAF industry and where the UK government will need to show global leadership. Firstly, the absence of a global taxation on fossil fuels for aviation needs to be resolved to reduce the cost differential with SAF. Secondly, the high electricity prices in the UK will need to come back to their historical trend to stop being a deterrent in the investment on carbon capture and SAF plants at scale.

The UK should maintain a core strategy on high-risk but high-reward aviation technologies
The UK and EU are currently investing more in future-focused aviation technologies than in maturing SAF production, given the challenges to scale HEFA pathways and the high cost of alternatives. This aligns with the UK's strengths in aerospace R&D, but it exposes the decarbonisation pathway to short-term uncertainty resulting from technological and infrastructure readiness. The UK should:

- Continue support and invest in the development of zero-carbon aviation technologies.
- Lead on SAF-compatible aircraft and engine design, coordinating and supporting OEMs and Tier 1 suppliers.
- Support dual-use R&D (civil and defence) to accelerate breakthrough technologies.

There will be a very large market for engines that offer more than 15% fuel-burn reduction for future single-aisle aircraft. Rolls-Royce could secure a unique position with its UltraFan technology, which offers a credible, competitive solution capable of achieving this target.[139] Supporting policies, such as strategic R&D partnerships, export finance and industrial strategy, could be decisive in the development of a successful UK manufacturing base for single-aisle engines. Success would create thousands of high-value jobs across the UK aerospace supply chain and deliver very significant economic value over the coming decades, thus perfectly aligning with the UK's Net Zero and industrial strategy objectives while showcasing the role of advanced engineering in driving green growth.

Rising demand threatens to undermine carbon reductions
Forecasted growth in passenger numbers may more than outweigh the emissions reductions under the current trend. Without demand-side measures or stronger mitigation levers, overall emissions will continue to rise. The UK needs to consider its approach to this and how it can lead international agreements to address demand management, e.g. via carbon pricing and taxing. The UK should:

- Raise UK ETS carbon prices to reflect real social costs and drive decarbonisation.
- Integrate GGRs into the UK ETS with robust monitoring, reporting and verification (MRV) standards by 2030.

[139] Boeing held early talks with Rolls-Royce over engine for 737 Max successor - https://www.ft.com/content/2fdca020-797a-490e-adf0-929f703ab661 (2025)

- Scale carbon capture infrastructure by streamlining permitting and increasing storage incentives.
- Coordinate investment in DAC/BECCS pilots with a clear support strategy.

Regulatory stability and industrial strategy must be strengthened
UK's industrial decarbonisation framework and regulatory environment have been criticised as fragmented and vulnerable to political shifts.[140,141] Long-term asset investment requires policy predictability and therefore the UK will need to look at ways to de-risk private investment and attract global manufacturers and innovators to the UK. Several cross-cutting measures should be put in place:

- Link aviation strategy with energy and industrial policy (e.g. green hydrogen, renewable power).
- Improve policy certainty by minimising consultation churn and providing stable long-term roadmaps.
- Lead on strengthening international partnerships (EU, ICAO, USA) on SAF standards and emissions monitoring.

Contrail mitigation and non-CO_2 effects offer a leadership opportunity
The UK is seen as a global leader in research on contrail management and upper-atmosphere effects. These non-CO_2 impacts represent a significant portion of aviation's climate footprint but remain unregulated. While the environmental impact of contrail avoidance will be large, the economic cost will be very limited. Contrail avoidance will need new skills in the air traffic control workforce, but its impact on job creation is only marginal. Nevertheless, contrail mitigation represents an opportunity for UK to lead international efforts to standardise and integrate them into emissions accounting. This requires:

- Fast-track airspace modernisation and support for NATS-led efficiency improvements.
- Investment in contrail avoidance technology including atmospheric prediction tools.
- Incentivisation of SAF deployment on high-contrail routes for maximum climate benefit.

Aviation can be a pioneer industry to demonstrate AI leadership and the green transition
Given the structural characteristics of the UK aviation sector outlined earlier in this report – high technological sophistication, strong industrial concentration and significant public visibility – aviation could serve as a prototype industry for the UK's broader green and digital transition ambitions. The sector offers a uniquely visible platform to demonstrate how productivity-enhancing innovation can deliver both economic and environmental benefits. Artificial intelligence (AI) provides a transformative opportunity to accelerate aviation's decarbonisation pathway while aligning with the UK government's ambition to become a global leader in AI development and deployment. State-of-the-art AI could be deployed to improve productivity and reduce emissions across multiple levers, showcasing tangible uses of the technology, for example:

- Optimising air traffic management.
- Better contrail and weather management.
- Enhancing airport and ground operations.
- Improving flight path efficiency.

By positioning aviation as a pilot sector for AI-driven decarbonisation, the UK government could demonstrate real leadership in two key strategic areas simultaneously, sustainable industrial transformation and AI innovation. This would not only help to reinforce public confidence that the transition to net zero can be achieved through technological excellence, but that it will also lead to improved productivity in the UK economy.

[140] Healing a fragmented state: How Labour's plan for 2030 power decarbonisation can be delivered - https://assets.nationbuilder.com/stonehaven/pages/523/attachments/original/1721374708/24_07_19__ProjectTempo_-_Healing_A_Fragmented_State.pdf?1721374708
[141] Making UK Industrial Strategy Work: A Hard-Headed Approach Guided by Green Industry - https://institute.global/insights/economic-prosperity/making-uk-industrial-strategy-work-a-hard-headed-approach-guided-by-green-industry (2025)

7. Closing remarks

The UK needs to define its comparative advantage in global aviation transition. Government should consider which technologies / capabilities the country is best positioned to take a lead in and focus investment and support in those areas where necessary.

As we have discussed in this report, the strengths are on high-end aerospace engineering, development of future zero-carbon technologies, carbon management technology and infrastructure, certification reform and/or operational innovation (e.g. airspace modernisation, contrail avoidance). Future ambitions to build large scale SAF production or carbon capture will need first to overcome the lack of feedstock availability and high energy prices.

Finally, the government must also be more proactive in educating the public on the role of sustainable aviation in achieving net zero, including the likely costs, behavioural implications and possible trade-offs involved.

Appendix

An estimation of the GVA and jobs creation impacts to the UK economy from the scale up and commercialisation of the Rolls Royce Ultrafan aeroengine for single-aisle aircraft.

1. Background

It has been forecast that 44,000 new commercial airliners will be required between 2024 and 2044, of which 72% of these will be twin-engined, single-aisle jets such as the Airbus A320, and A220 families and the Boeing 737[1]. Such aircraft demand would create a single-aisle engine demand of 64,500 new engines over the next 20 years. Such a demand would translate to a growth from around 2000 to 3200 engines per year for single-aisle engines. The 1200 per year of additional annual engine supply opens the door for a new supplier and especially one with an engine design like the Rolls Royce Ultrafan that is estimated to be 10% more fuel efficient that the most fuel- efficient single-aisle engines currently available on the market[2], the CFM LEAP and PW1000G engines. Given the significant growth opportunity and the clear competitive advantage of Ultrafan, Rolls Royce has a perfect opportunity to exploit the scale-up and commercialisation of its new engine design and target the slated replacements of the A320neo and 737Max families that are planned to enter service in 2035+. This paper estimates the Gross Value Added (GVA) and jobs creation to the UK economy of the production of this new technology and supply of associated service contracts.

2. Calculation of GVA/year

In this study, GVA/year is calculated using the Income Method.

GVA/year = EBITDA + Wages & Salaries + Depreciation

Estimates of the ranges of each of these variables that contribute to GVA will also be used to assess the sensitivity of GVA outcomes to each of these variables.

Assumptions used to calculate the required value and ranges of EBITDA, Wages & Salaries and Depreciation are outlined in sections 2.1 to 2.3 below.

2.1 The determination of EBITDA

In the context of this study EBITDA can be calculated as follows.

EBITDA = (Engine Sales + Parts & Services Sales) x EBITDA margin (%)

2.1.1 Engine Sales

Engine Sales = Total Annual Engine Demand x Market Share x Engine Price

a) **Total Annual Demand** for single-aisle aircraft engines is assumed to be 3140 per year with a possible range of 3000-3400 based upon estimates of single-aircraft growth over the next 20 year[1].

b) **Market share** for the Rolls Royce Ultrafan is assumed to be 30% with a range from 5% to 59%. 5% represents the market share for Rolls Royce RB211 engines on the Boeing 767[3], and 59% was the market share for the RB211 on the Boeing 757[4], Rolls Royce achieved a 33% market share on wide-body large jets in 2023[5]. In this study a normal distribution is applied and a conservative mean value of 30% is used with a standard deviation of 10% to provide a 5% to 59% spread to reflect past historical performance ranges. 30% as a mean seems reasonable as the single aisle jet engine field already has two well established players in the field, CFM and ,Pratt and Whitney, who will compete to access the growth in the future single aisle jet engine market.

c) **Engine Price** for the Ultrafan is assumed to be priced at the current level of the CFM LEAP engine (14 M$ US)[6] or at a price premium (18 M$ US) due to its improved fuel efficiency, noting that other engines such as the older CFM56 engine is priced new at 10 M$ US[7]. A normal distribution of price has therefore been assumed with a conservative mean value of 14 M$ US and a standard deviation of 1.32 M$ US to reflect the 10-18 M$ US range. Engine prices have increased over time, and a recent study by Sirius Aviation Capital[32] indicates that from 2000-2021 engine prices have seen a CAGR of 3%, and over the past 4 years this has grown to 6.8%. In this study a baseline of 3% is adopted and range from 0 to 6.8% is analysed to assess sensitivities to GVA outcomes.

2.1.2 Parts & Services Sales

Parts & Services Sales = Number of engines in operation

x Service charge per Engine Flight Hour (EFH)

x Hours of flight per Year

a) **Number of Engines in operation** will accumulate over time as more engines are sold. In this study a 5-year ramp up in engine production is assumed, then a plateau is achieved that can supply the single aisle aircraft engine market demand. The production plateau will hold for 10 years and then a ramp down is assumed. Before the ramp down begins it is assumed that an upgraded version of the engine will become available, and it will ramp up to replace the first generation of Ultrafan and that engine demand continues at the same level as the previous 20-year period. Such as scenario is highly likely based upon history where we know that the Rolls Royce RB211 family was produced for 33 years[22], in 2025 Rolls Royce celebrated the 30th anniversary of the Trent family of engines[23], and the CFM56 engine family has been in production for 50 years[24]. In this study a 40- year period is studied to determine the net present value of the annual GVA values.

Engine lifetimes are around 20 years and will require servicing and new parts over this period. Single aisle aircraft engines typically undergo 3 major overhauls in their lifetimes with the first occurring after 7-8 years, then the second after a further 5 years, followed by a final third overhaul 3 years later. CFM56 engine lifetimes have been reported at 35,000 engine flight cycles and a use rate of 4-6 cycles per day, this translates to a lifetime of 16-24 years [26]. An engine lifetime of 20 years is used in this study.

Over the 40-year period the number of engines operating in any one year is tracked as new engines enter service and older engines are retired.

b) **Flight hours and Service Charge per Engine Flight Hour** ranges and means are estimated using several data points. A 2002 study for CFM56 engines indicated a $/EFH a range of 111-155 $/EFH with an average of 123 $/EFH[27]. Applying an annual inflation rate (PPI) of 2.84% (average CAGR 1989-2025)[28], these figures equate to a mean of 240 $/EFH. Another reference[29] suggests that MRO costs can equal or exceed the initial purchase price of the engine suggesting a EFH figure of around 480 $/EFH. Lifetime engine maintenance costs for single aisle jet engines have been reported to lie in the range of $4-15 Million depending on engine type and scope, indicating an EFH range for 1800 hrs per year of flight[27] of 148-555 $/EFH. In this study a mean of 177 £/EFH with a range of 111-361 £/EFH are used applying an exchange rate of 0.75 £ to the dollar. Annual parts and service charges will increase over time and a historical annual inflation rate (CPI) of 2.84% (2000-2026 data)[30] is used in this study with a range of 1-4% to assess sensitivities to GVA outcomes.

2.1.3 EBITDA Margin

EBITDA Margins in the range of 15-25% have been assumed. These figures are based 2024 EBITDA margin results generated by the aeroengine divisions of Rolls Royce Holdings[8], Pratt & Whitney[9], GE Aerospace[10], and Safran[11]. Their EBITDA margins were 16.6%, 8.1%, 23.1%, and 18-19% respectively. The low value at Pratt & Whitney was due to production challenges and did not reflect normal operations. For this study EBITDA ratios in the 15-25% range with a mean of 20% have been adopted.

2.2 The determination of Wages & Salaries

a) **Annual salaries** at Rolls Royce, Derby have been reported to be in the £30k/yr - £64/year range depending on role, with an average around £44k/yr[12,13,14]. For this study a normal distribution is assumed for the workforce annual salary using a mean of £44/yr and a standard deviation of £4k/yr.

b) The **number of employees** required to build the 1000 engines per year assuming a 30% market share needs to be determined. This has been estimated using benchmarks from other sites making smaller aeroengines like the single-aisle type engines. Rolls Royce's Dahlewitz division making the Pearl engines for business and commuter jets employees 2400 employees[15] and made 251 engines/yr in 2024[8] suggesting 10 employee-years are required per engine. For CFM, GE employs 9000 people at Evendale[16], Ohio, USA and Safran employs 5000 people at Villaroche[17], France to collectively produce 1407 CFM LEAP engines in 2024, again suggesting a ratio of 10 employee-years/engine.

c) The **additional number of supply chain jobs** required to build engines. According to the literature[18-21] the ratios of aeroengine assembly jobs to supply chain jobs can vary between 1:0.77 to 1:2.2, with the OECD indicating that the ratio of manufacturing jobs to indirect local community jobs can reach as high as 1:4. In this study a range of 1:0.8 to 1:4 has been assumed.

d) The total number of jobs will also be impacted by market share ultimately and a Monte Carlo analysis has been used to determine the mean number of jobs and the potential ranges for study. The Monte Carlo analysis suggests a mean of 35,000 jobs with a range from 18,000 – 50,000.

2.3 The determination of depreciation

Depreciation numbers for the aeroengine companies is usually reported together with amortisation, however on the odd occasion in annual reports a depreciation figure is reported. Based upon these rare findings a range for depreciation between £150 million and £550 million has been applied in the GVA analysis.

3. Determination of Net Present Value (NPV) of Annual GVA figures

Annual GVA numbers have been calculated over a 40-year time-period using the assumptions outlined above. The annual GVA numbers has been discounted using a social time preference rate of 3.5% (real) which is commonly used to discount future Gross Value Added (GVA) impacts to present values as defined in HM Treasury's Green Book[31]. The GVA discounted model has subsequently been used to determine sensitivities to the possible range of values that can impact GVA such as market share, engine price, workforce size and salaries, inflation rates, EBITDA margin, depreciation, parts and services charges etc.

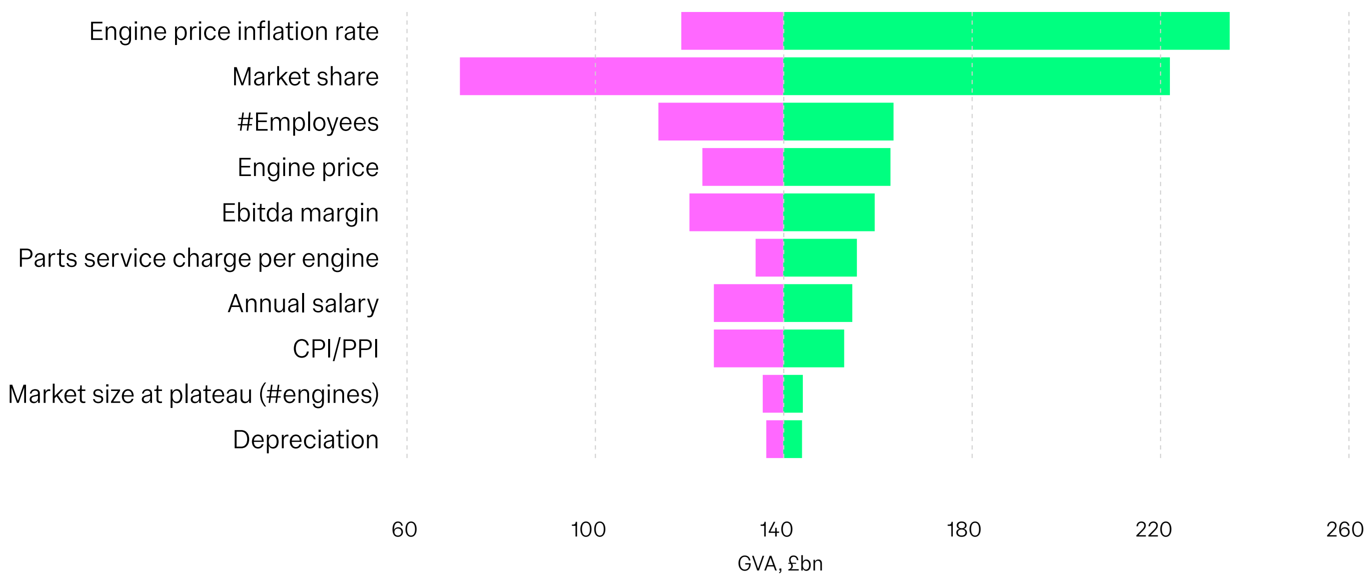
4. Results and Conclusions

A GVA DCF model was built and run based upon the inputs described above. The model estimates that the Rolls Royce Ultrafan engine production could add £3.9 Billion/yr (PV) to the UK economy and £141 Billion (PV) from the annual GVA created over 40 years, whilst also adding 35,000 jobs to the economy. This estimate is comparable with Rolls Royce's own claims of £120 Billion and 40,000 jobs[25].

A sensitivity analysis shows that GVA is most impacted by assumptions around engine price inflation rate, market share, and job creation, and this is illustrated in the Tornado diagram below.

The sensitivity results teach us the importance of engine design and performance in achieving a high value-in-use benefit to airline customers through variables such as energy and cost efficiency, as well as reliability. These sources of competitive advantage will confer a higher market share and hence revenue and profitability as well as creating employment which are the key drivers of GVA. In addition, a continued investment in innovation in Ultrafan over its lifetime will enable lifetime extensions to the product, and this ensures a longer lasting creation of GVA growth in the economy over time.

Tornado diagram of sensitivities Rolls Royce Ultrafan GVA



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