UNIVERSITY OF CAMBRIDGE

Aviation Impact Accelerator

THE 2030 SUSTAINABLE AVIATION GOALS

Five years to chart a new future for aviation

September 2024

TERRA CARTA
FOR THE HARMONY OF NATURE, PEOPLE AND PLANET
CONCORDIAE NATURAE, HOMINUM ET PLANETAE

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Contents

Executive Summary

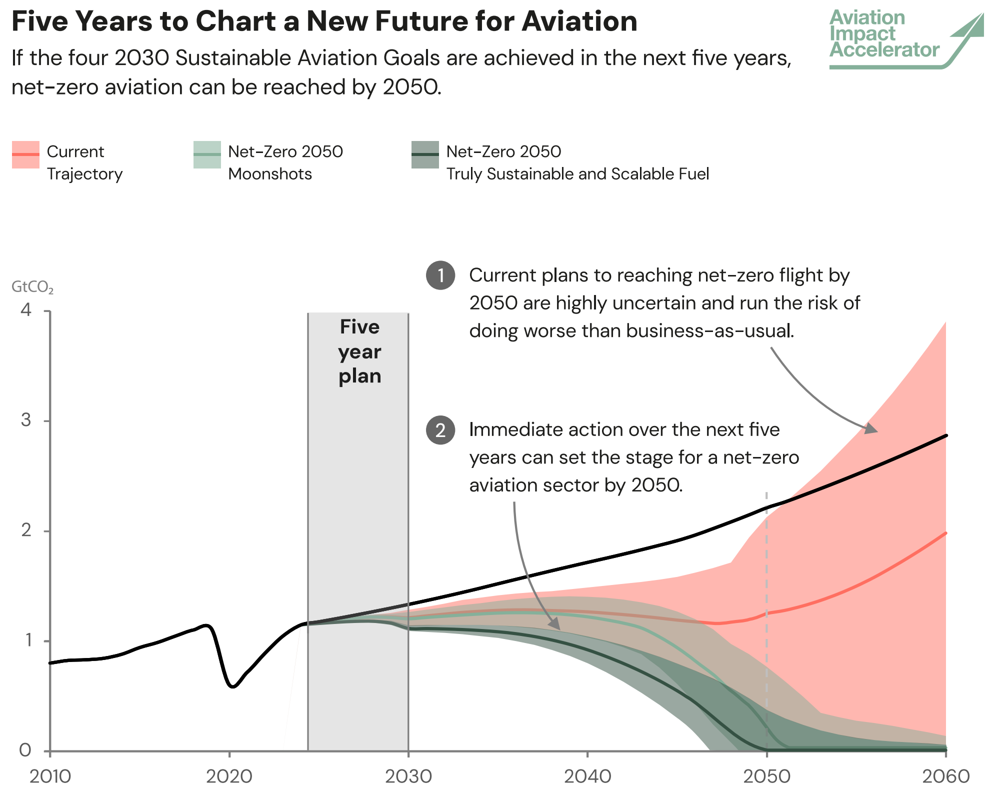
The aviation sector is at a pivotal moment in its history. Currently, only about 10% of the global population flies[1], a figure expected to grow as incomes rise. Yet, aviation already accounts for around 2.5% of global CO_2 emissions, and when non-CO_2 effects are included, its contribution to climate warming increases to approximately 4%. Despite ambitious pledges from governments and industry to achieve a net-zero aviation sector by 2050, the sector remains dangerously off track. Without swift and decisive action, we risk missing the opportunity to reach net-zero emissions by 2050 and delaying the crucial technological and business transformations needed.

While global leaders have endorsed a vision of net-zero carbon emissions for the aviation sector, current efforts fall short in scope and speed. In some cases, proposed solutions could exacerbate the crisis, such as relying too heavily on biomass for jet fuel without managing its environmental impact. It is also crucial to address aviation's broader climate effects, including the formation of persistent contrails. The stakes have never been higher: urgent action is needed to shift the sector onto a sustainable path.

This report outlines an ambitious five-year plan to chart that course. It establishes four pivotal 2030 Sustainable Aviation Goals, each targeting key leverage points with the sector. If these goals are not implemented immediately and achieved by 2030, the opportunity for transformation will slip away, leaving the world to face the escalating climate impacts of a rapidly growing aviation sector, which is projected to at least double by 2050.

Five Years to Chart a New Future for Aviation

If the four 2030 Sustainable Aviation Goals are achieved in the next five years, net-zero aviation can be reached by 2050.



2030

Ambitious Five-Year Plan to Set the Future of Aviation

The five-year plan involves immediately implementing four Sustainable Aviation Goals which provide a plan for delivering net zero aviation by 2050. These goals originated during the inaugural meeting of the Transatlantic Sustainable Aviation Partnership held at MIT in April 2023, with representatives from the UK, US, and EU. They were further discussed at a roundtable hosted by the Sustainable Markets Initiative in the presence of King Charles III, and previewed at the opening of COP28.

Two goals (Goals 2 and 3) can be achieved with minimal new technology but require robust and clear market signals and swift policy action. The other two goals (Goals 1 and 4) demand immediate efforts to push the boundaries of technology, creating new opportunities from 2030. The four goals are:

2030 GOAL 1
Operation Blue Skies

In 2025, governments and industry should create several Airspace-Scale Living Labs to enable, by 2030, the start of deployment of a global contrail avoidance system. These labs must have the capability to test, learn, and pivot approaches while operating within a realistic airspace environment.

2030 GOAL 2
Systems Efficiency

In 2025, leading governments should set out a clear commitment to the market about their intention to drive systems-wide efficiency improvements. In tandem, governments and industry should work together to develop strategies so that, by 2030, a new wave of policies can be implemented to unlock these systemic efficiency gains.

2030 GOAL 3
Truly Sustainable and Scalable Fuel

In 2025, governments should reform Sustainable Aviation Fuel (SAF) policy development to adopt a cross-sector approach, enabling rapid scalability within global biomass limitations. By 2030, governments and industry should implement a demonstration and deployment strategy that enables SAF production to move beyond purely biomass-based methods, incorporating more carbon-efficient synthetic production techniques.

2030 GOAL 4
Moonshots

In 2025, launch several high-reward experimental demonstration programmes to enable the focus on, and scale-up of, the most viable transformative technologies by 2030. These programmes must generate the necessary experience to assess the technology's scalability and develop the expertise required for deployment.

Priority Actions

Two priorities stand out. First, **Goal 1: Operation Blue Skies** offers a low-cost, high-impact solution with significant potential to reduce aviation's climate footprint while also providing the opportunity to reduce cloudiness in areas where air traffic is high, as seen during the COVID-19 pandemic when flights were grounded — an outcome likely to be popular with the public. Successfully implementing contrail avoidance could reduce the climate impact of aviation by roughly 40%.

Second, **Goal 4: Moonshots** represents a once-in-a-generation opportunity for nations to lead in developing new, transformative industries. By investing now in frontier technologies—such as cryogenic hydrogen or methane fuels, hydrogen-electric propulsion, and synthetic biology—governments can unlock opportunities within the aviation sector and across a range of adjacent sectors, much like electric vehicles have reshaped the automotive sector.

Growing awareness and commitment to action are encouraging. Still, it is essential to match those professed concerns with decisive interventions over the next five years to create a credible path to net-zero aviation by 2050.

Introduction

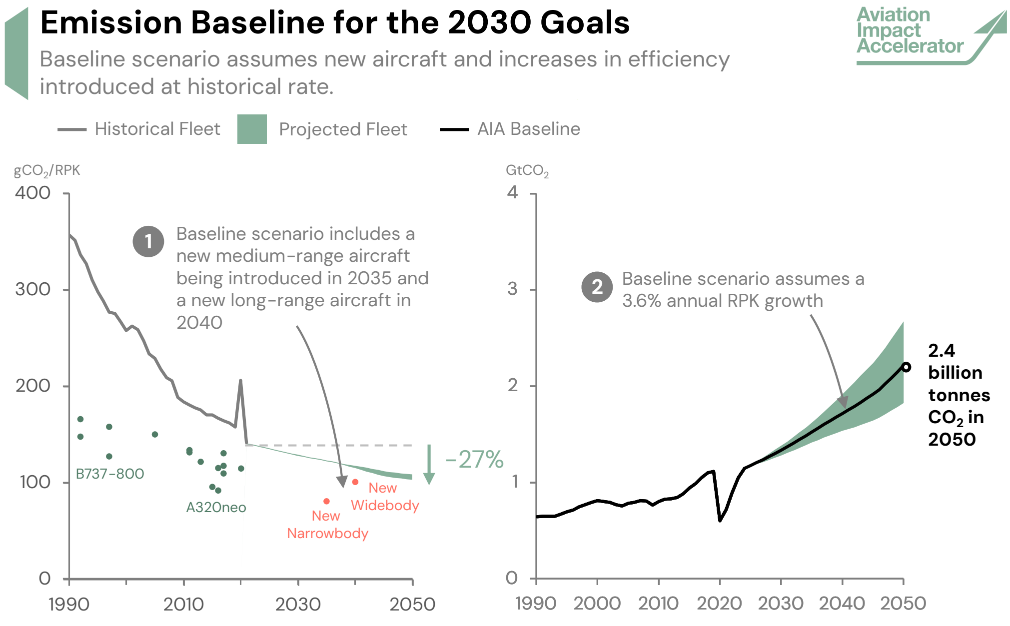
The aviation sector is at a critical crossroads: it has the potential to drive systemic change, or it could fall behind in the race to achieve net-zero emissions. Building on insights from the Aviation Impact Accelerator's model this report identifies the most impactful leverage points within the aviation system. These are key areas where targeted interventions can trigger substantial, transformative shifts. The four Sustainable Aviation Goals outlined here are designed to focus on these leverage points, aiming to significantly raise the sector's ambitions and laying a strong foundation for reaching net-zero emissions by 2050.

These goals were first conceived during the inaugural meeting of the Transatlantic Sustainable Aviation Partnership at MIT in April 2023, hosted jointly by the University of Cambridge and MIT, with participation from the UK, US, and EU governments. They were further discussed at a roundtable event organised by the Sustainable Markets Initiative, attended by King Charles III at the Whittle Laboratory in Cambridge, and previewed at COP28. The goals have been deliberately crafted to exceed current industry and governmental targets, with the intention of driving actions that will substantially raise ambition. Each scenario has been rigorously analysed using the Aviation Impact Accelerator model to ensure that it is grounded in robust, evidence-based analysis.

Achieving these goals by 2030 will require bold leadership and coordinated ambition from governments and businesses. This moment is reminiscent of the late 2000s in the automotive industry when the debate over the future dominance of biofuels versus battery-electric vehicles reached its peak. Similarly, the future of aviation remains uncertain—whether the dominant solutions will be Sustainable Aviation Fuels (SAF) or whether transformative technologies such as cryogenic hydrogen or methane fuels, hydrogen-electric propulsion, or synthetic biology will ultimately supplant them. The 2030 Goals are designed to accelerate this decision-making process, enabling more focused and rapid progress post 2030.

The report concludes by presenting several scenarios that demonstrate how achieving the 2030 Goals can enable the aviation sector to reach net-zero emissions by 2050. It should be noted that all scenarios are based on a business-as-usual baseline, which is detailed in the *Emission Baseline* section.

Introduction: Emission Baseline



Assumptions: Revenue-Passenger-Kilometre (RPK) growth projection of 2.9%-4.2% sourced from ICAO.

The baseline scenario for all analysis in this report is shown above. It assumes that the retirement age of aircraft remains consistent (at 25-30 years) and that the latest generation of aircraft (such as the A320neo, B737 MAX, A350, B777X, etc.) continues to enter the fleet at the historical rate. The scenario also assumes the introduction of a new medium-range aircraft in 2035 and a new long-range aircraft in 2040, each with a single-generation improvement in efficiency (10-15% higher efficiency than the current generation). It is further assumed that these aircraft will penetrate the fleet at historic rates. Demand forecasts project annual growth rates for passenger kilometres (RPK) in a range between 2.9% and 4.2%. This report sets the annual growth rate of aviation's RPK (Revenue Passenger Kilometers) at 3.6% from 2024 to 2060. While decarbonisation measures are expected to impact ticket prices, which may in turn influence demand growth, the extent of this effect remains uncertain. For the purposes of this report, future demand growth has been assumed to remain constant throughout.

GOAL 1

Operation Blue Skies

In 2025, governments and industry should create several Airspace-Scale Living Labs to enable a global contrail avoidance system to start to be deployed by 2030. These labs must have the capability to test, learn, and pivot while operating within a realistic airspace environment.

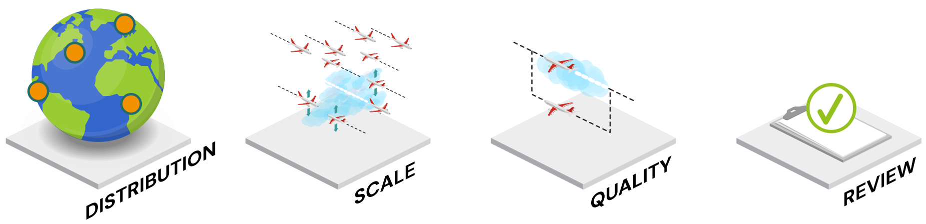
Aviation's climate impact is not just limited to CO_2: aviation's non-CO_2 climate warming impacts include emissions such as nitrogen oxides, stratospheric water vapour and particulate matter, and the formation of persistent contrails. Of these, persistent contrails have the most significant climate effect. The precise size of their climate impact relative to CO_2 depends on the metric used for comparison, but generally, the impact of contrails and aviation's CO_2 emissions are of similar magnitude, although the uncertainty in the size of the climate impact of contrail is much greater than for CO_2.

Persistent contrails can be avoided by adjusting an aircraft's altitude in regions where contrails form, known as ice-supersaturated regions (ISSRs). These regions are pancake-shaped—wide but shallow—making altitude changes effective in preventing contrail formation. However, predicting the location of ISSRs is uncertain, and altitude changes can increase fuel consumption by a few percent.

Goal 1: Operation Blue Skies

Eliminating the climate impact of contrails is a systems problem. Accelerating action requires several Airspace-Scale Living Labs to learn-by-doing.

1. **Distribution**: Several Labs (3-4) are required, strategically selected to represent diverse climate conditions, varying degrees of airspace congestion, and different regulatory landscapes.
2. **Scale**: Each Lab must be at a scale that accurately replicates the real-world complexities of networks, air traffic control, and aircraft proximity.



3. **Quality**: Each Lab must be conducted in a way which ensures statistical significance, independent verification, and includes control aircraft.
4. **Review**: A transparent review process must be set up for the Labs ranging from data sharing, peer review publications and oversight by independent non-governmental organisation.

The main challenge in implementing an effective contrail avoidance system lies in the numerous uncertainties, from the underlying science to the variety of potential implementation methods. The ideal way to address these uncertainties is through a learn-by-doing approach in a realistic, field-based environment. To facilitate this, several Airspace-Scale Living Labs must be established by the end of 2025. These Labs must be designed for iteration—capable of testing, learning, and pivoting as experience is gained.

In developing these Labs, it is crucial to draw on experiences from fields where public confidence is paramount, such as medical trials and epidemiology. Each Lab should be designed to represent the real nature of the challenge in a particular region of the world i.e., to capture the full range of weather and flight traffic conditions that are likely to be encountered. The Labs should also be conducted at a scale that accurately replicates real-world complexities while ensuring statistical quality and following a transparent review process.

The objective of the Labs is to develop the experience and strategic planning necessary to start the deployment of a global contrail avoidance system by 2030.

Outcome

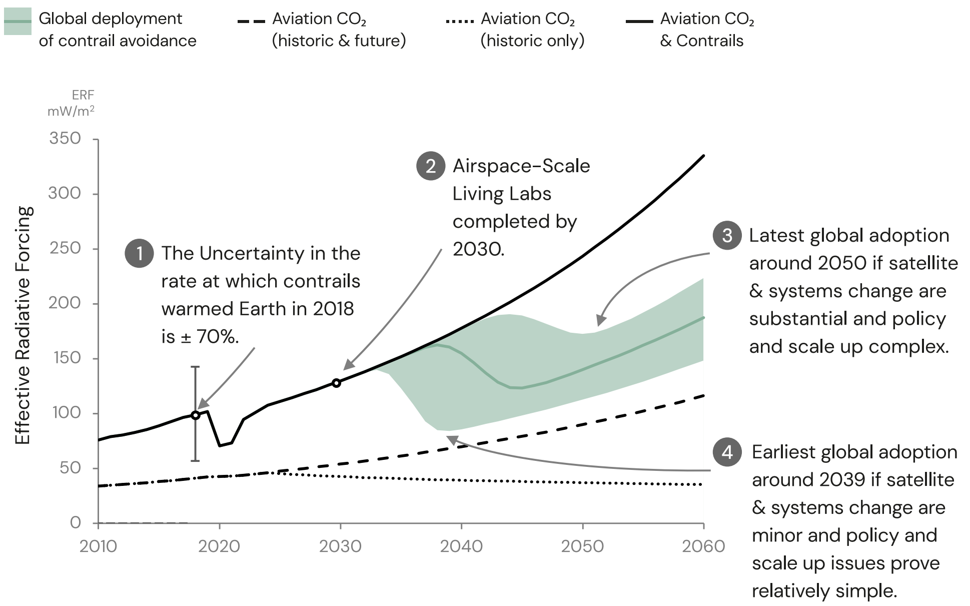
The figure below shows the rate at which the Earth is warmed ("Effective Radiative Forcing", ERF) due to aviation, allowing the comparison of different warming effects including non-CO_2 effects. The black dashed line shows the warming rate due to aviation CO_2 released since 1940, including projections of future aviation CO_2. The solid black line shows the warming effect caused by the combined effect of aviation's CO_2 emissions and persistent contrail formation. The green region shows the impact on warming of deploying a global contrail avoidance system starting in 2030, after the completion of the Airspace-Scale Living Labs. For interest, an extra line, the black dotted line, has been added, showing just the warming impact of aviation CO_2 currently in the atmosphere.

The figure illustrates that the climate impact of contrails and CO_2 emissions are of similar magnitude. However, it is important to note that the climate impact of contrails carries a high degree of uncertainty, as indicated by the error bar in the figure shown for 2018's contrails. While only one in 20 kilometres flown produces a persistent contrail, which lasts less than a day, about half of the CO_2 emitted remains in the atmosphere for around 30 years, with a fraction persisting for a millennium. The climate impacts of the two are comparable because, although contrails are short-lived, their effective radiative forcing is several orders of magnitude greater than that of CO_2 released by the flights that cause them (*Key Fact 1*).

The figure also shows that the effective operational date for a global contrail avoidance system could range from 2039 to 2050, with its effectiveness in avoiding contrails varying between a 50% and 85% success rate. More details on the modelling behind this deployment schedule can be found in *Key Fact 2*. The uncertainty in the timeline and effectiveness stems from the nature of the solution itself—specifically, whether a new constellation of Low Earth Orbit (LEO) satellites will be required and the degree of airspace modernisation

Outcome: Operation Blue Skies

The timeline to deploy contrail avoidance is highly uncertain. To ensure global operation by 2050, Airspace-Scale Living Labs must be completed by 2030.



Assumptions: Historical ERFs from Lee et al. (2021), aviation CO_2 starting 1940, inc. lifecycle fuel emissions (89 g/MJ). Contrail ERF assumed to scale proportional to traffic growth (3.6%/year) & CO_2 ERF decay from Joos et al. (2013). Permission to deviate aircraft for targeting avoidance of all persistent contrails scales from 0% to 85% (barriers, Teoh et al. (2020)) and 95% (no barriers) after scale-up; success rate: 60% (barriers), 90% (no barriers).

and policy development necessary. The only way to reduce this uncertainty is through the establishment and operation of the Airspace-Scale Living Labs.

The global deployment of a contrail avoidance system presents four key implementation challenges (*Key Fact 3*). Focus in these areas is required to accelerate implementation:

1 — **Congestion**: Many regions have congested airspace, limiting opportunities for contrail avoidance.

2 — **Incentives**: Although the cost of contrail avoidance could be very low (*2050 Ticket Cost*), operators need incentives to adopt the necessary behaviours.

3 — **Measuring contrail absence**: There is a practical challenge in accurately determining whether a contrail would have formed without avoidance measures.

4 — **Operational change:** Shifting the behaviour of thousands of individuals and introducing new systems will be difficult.

Finally, delaying action poses significant risks. As shown in *Key Fact 4*, the warming impact from the extra fuel burned for contrail avoidance is minimal, at least 25 times smaller than the smallest possible climate impact of contrails. Furthermore, implementing a global contrail mitigation scheme could deliver substantial benefits. We estimate that a successful scheme could be equivalent to the one-time removal of 5 to 50 billion tonnes of CO_2 from the atmosphere, representing between 2.5% and 24% of the remaining IPCC global carbon budget needed to keep global temperatures within 1.5°C of pre-industrial levels by 2050.

Other Solution
Fuel and Engine Changes

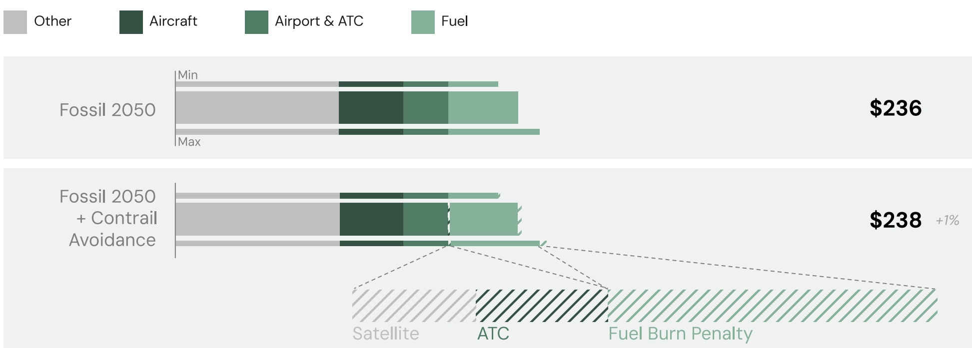
Several approaches to reducing contrail warming have been proposed. Alternative fuels, such as Sustainable Aviation Fuels (SAFs) and hydrogen, could impact contrail formation. SAFs slightly increase engine exhaust water content and reduce soot, though the effect is uncertain, potentially reducing contrail warming by up to 81% or increasing it by up to 18%. Hydrogen would significantly increase exhaust water content and eliminate soot, potentially reducing contrail warming by up to 90% or increasing it by up to 60%. Additionally, engine modifications could potentially reduce particulate production.

Both fuel and engine changes face significant implementation challenges, typically requiring decades to scale up. However, the benefits of changing fuels could be achieved more rapidly by processing jet fuel to reduce its aromatic content.

Operation Blue Skies: 2050 Ticket Cost

Operation Blue Skies: 2050 Ticket Cost

The increase in ticket cost due to fleet wide contrail avoidance is small relative to CO_2 reduction measures such as the introduction of SAF.



1 The cost of implementing contrail avoidance is likely to be very low, as only 1 in 20 to 25 kilometres flown requires an altitude change, with the additional fuel burn per manoeuvre being small.

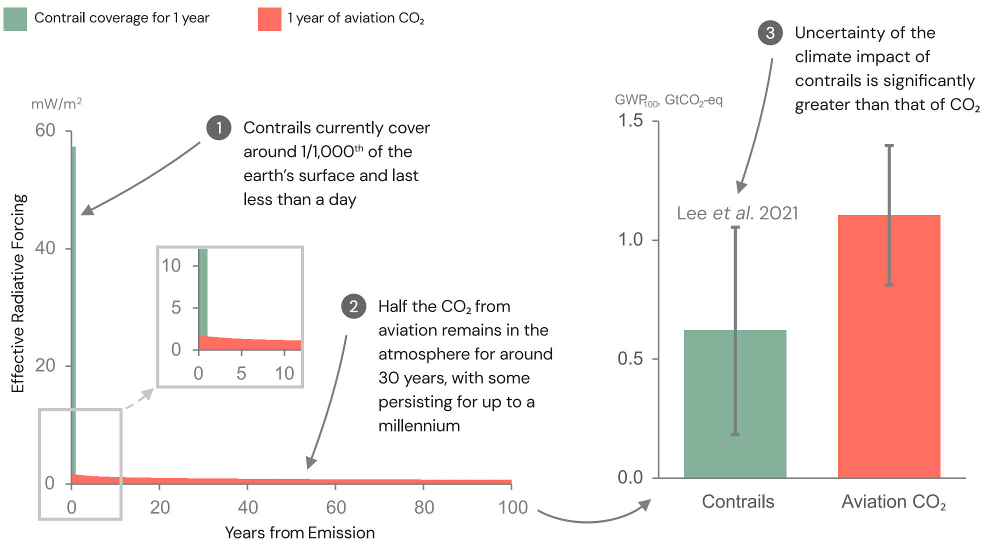
Assumptions: Operator costs are displayed for a global average return flight. Fossil jet fuel excludes carbon taxes. Fleet fuel burn penalty of 0.5-2%. Additional Air Traffic Control (ATC) costs based on additional load due to ISSRs on en route controllers representing 40% of ATC staff. Launch and maintenance of network of Low-Earth Orbit satellites required in worst case estimated at up to $3.6B/year.

Implementing contrail avoidance measures results in a relatively small cost, leading to an estimated ticket price increase of around 1%. This increase is due to the additional fuel needed for altitude adjustments, operating at suboptimal altitudes for portions of the flight, as well as satellite and additional air traffic control (ATC) costs. This rise in cost is the average cost rise over the global fleet: the impact in cost on a flight that has to conduct avoidance manoeuvres is higher, but since only about 1 in every 20 to 25 kilometres flown generates a persistent contrail that requires an altitude change, the impact on average is low.

Operation Blue Skies: Key Fact 1

What is the Relative Climate Impact of Contrails?

When considering the Global Warming Potential (GWP) over 100 years, the climate impact of aviation CO_2 and contrails are of comparable size.



Assumptions: Baseline year: 2018. Contrail ERF: Lee et al. (2021). ERF response to pulse CO_2 emission of CO_2: Joos et al. (2013).

Comparing the relative climate impact of CO_2 and contrails from aviation is not simple. The complexity arises partly from their vastly different lifespans (half of CO_2 remains in the atmosphere for around 30 years, with some persisting for a millennium, while contrails last for several hours) and partly from the variety of metrics available for comparison.

The figure above illustrates the effective radiative forcing of CO_2 and contrails produced by global aviation over a single-year period. Contrails cover approximately one-thousandth of the Earth's surface at any given time but persist for less than a day. In contrast, the CO_2 emitted in a single day increases the global CO_2 concentration by about one millionth, yet some of it remains in the atmosphere for up to a millennium.

A specific time scale must be selected in order to compare the relative climate impact of CO_2 and contrails. When using global warming potential averaged over 100 years, as shown on the right side of the figure above, the climate impacts of CO_2 and contrails can be seen as similar in magnitude. However, it is crucial to recognise that the uncertainty regarding the climate impact of contrails is significantly greater.

Operation Blue Skies: Key Fact 2

How Fast Can we Deploy Contrail Avoidance?

The time required to deploy global contrail avoidance is highly uncertain. This uncertainty will only be reduced by undertaking Airspace-Scale Living Labs.

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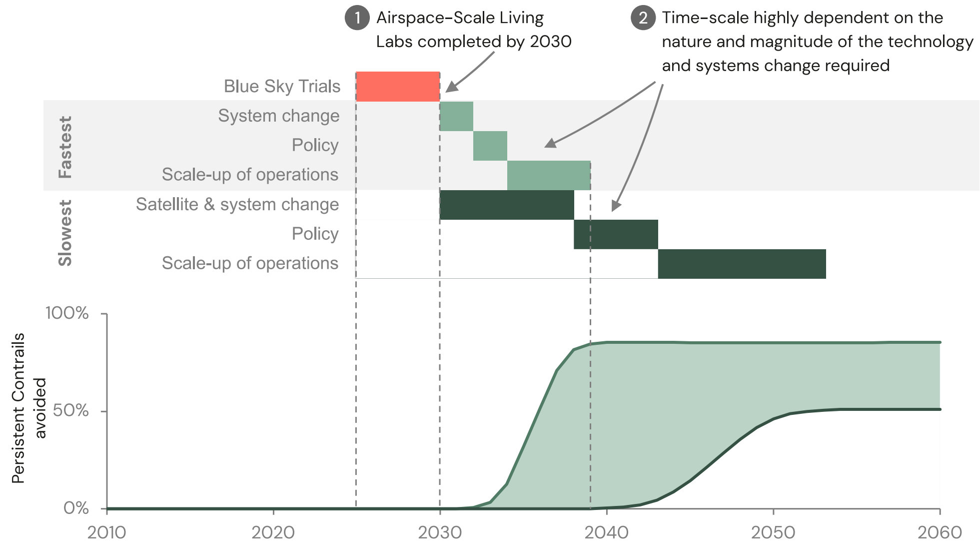

Assumptions: Permission to deviate aircraft for avoidance of contrails scales from 0% pre scale-up to 85% (barriers, Teoh et al. (2020)) and 95% (no barriers) after scale-up. Forecasting success rate: 60% (barriers), 90% (no barriers).

Predicting the timeline for the global implementation of a contrail avoidance system is highly uncertain. This uncertainty stems from the fact that the solution's requirements will not be fully understood until the Airspace-Scale Living Labs are completed. However, an estimate, as illustrated in the figure, can be made by dividing the timeline into three key phases:

1 — The time needed to implement system changes, such as satellite capabilities and flight planning and management.

2 — The time required to develop and enforce effective policies.

3 — The time to scale up operations.

The uncertainty in both the timeline and effectiveness is influenced by factors such as whether a new constellation of Low-Earth Orbit (LEO) satellites will be necessary, and the extent of airspace modernisation and policy development required.

Our modelling highlights significant uncertainty in both the timeline and the effectiveness of contrail avoidance. In the best-case scenario, a global contrail avoidance system that achieves 85% success could be operational by 2039. In the worst-case scenario, such a system might achieve 50% success and not be operational until 2050. Despite this uncertainty, contrail avoidance would still have a considerable positive impact, even in the worst-case scenario. This uncertainty underscores the urgent need to establish the Airspace-Scale Living Labs.

Operation Blue Skies: Key Fact 3

What are the Challenges for Implementation?

There are four areas where focus is required to accelerate implementation: congestion, incentives, measuring contrail absence & operational changes.

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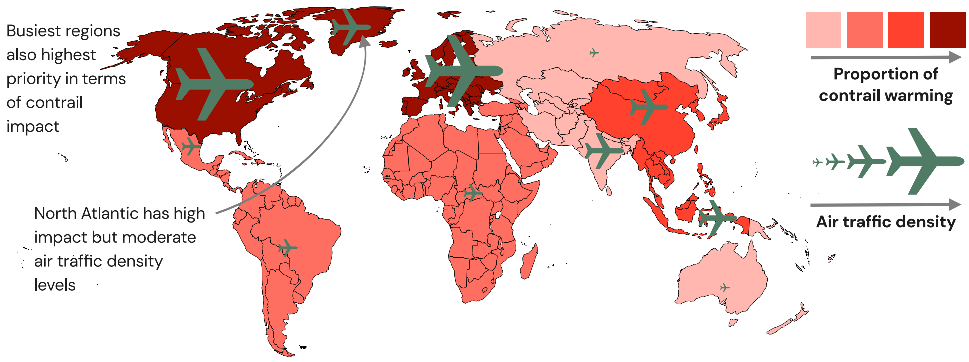
1. **Congested Skies**: Permission for avoidance could be limited in busy airspace. This could be alleviated by increased air traffic control capacity.

2. **Incentivising Operators**: Although cost increases are modest (approximately 2% increase in ticket cost), they may deter action. This can be mitigated through regional or global incentivisation schemes.



3. **Measuring the Absence of Contrails**: It is difficult to determine whether a contrail would have formed if no avoidance had been taken. This could be alleviated by penalising the formation of contrails.

4. **Operational Changes**: Contrail mitigation necessitates altering the behaviour of thousands of individuals and the systems they use. This will require both new systems and comprehensive retraining.

Assumptions: Air traffic density proportions: Teoh et al. (2024). Regional contrail warming proportions: Teoh et al. (2024).

Implementing a global contrail avoidance scheme faces several significant challenges. It is crucial to address these challenges immediately and in parallel with the implementation of the Airspace-Scale Living Labs. The figure below outlines four key areas of focus.

First, many regions where contrail avoidance is most necessary also have the most congested airspaces in the world (e.g., Europe and America). A critical challenge in these areas is the need for increasing air traffic control capacity, and to understand how this can be effectively scaled-up.

Second, while the cost of implementing contrail avoidance is low, it is not negligible. Appropriate incentives must be developed to drive the correct actions. For instance, simply adding the climate impact of contrails to that of CO_2 is not advisable, as the vastly different levels of uncertainty in their warming impact and the radically different timescale behaviour of the two effects are likely to lead to perverse airline behaviour.

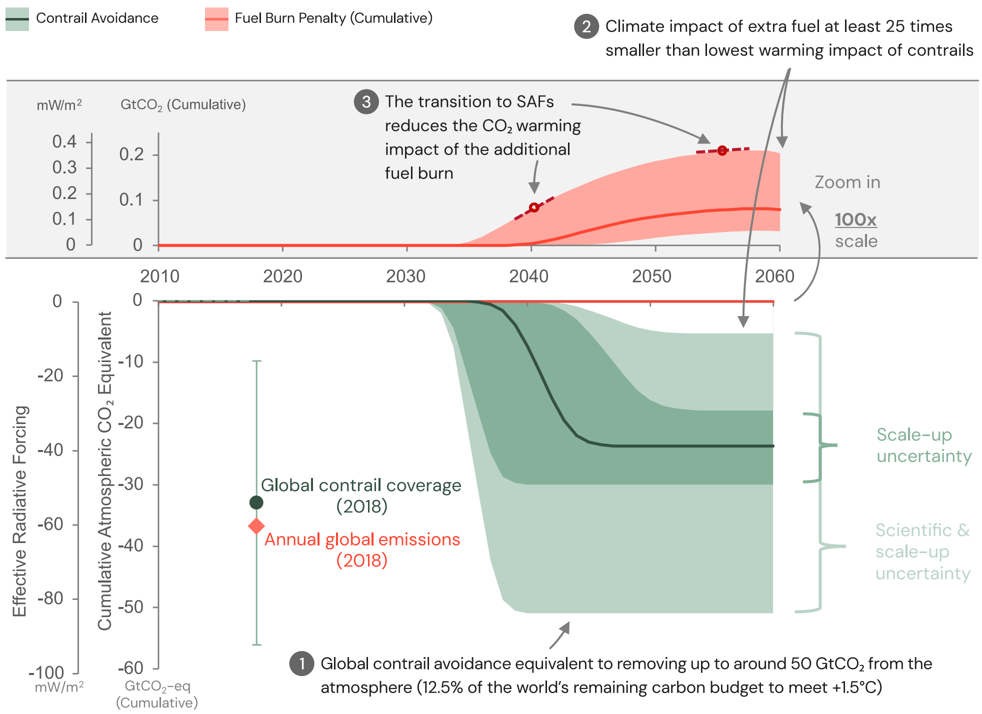
Third, a significant challenge is the 'absence of contrail' problem. Once the global contrail avoidance system is operational, few contrails should be formed, making it difficult to determine whether a contrail would have formed without intervention. This issue could be addressed by penalising or disincentivising the formation of contrails rather than rewarding their elimination.

Finally, implementation will necessitate developing new software, such as flight planning tools, and training thousands of personnel across the sector. This will be a complex process, and the speed of the transition will depend on the enthusiasm and cooperation of individuals throughout the industry.

Operation Blue Skies: Key Fact 4

What are the Risks of Delaying Action?

The highest warming impact of extra fuel burn is 25 times smaller than the lowest warming impact of contrails.



N.B. Scenario with no demand growth to remove uncertainty of contrail scaling with demand

Assumptions: Scenario shown with demand fixed at 2024 levels. Contrail ERF and scientific uncertainty from Lee et al (2021), contrails assumed to scale with km flown (fixed at 2024). Scale-up uncertainty: mid-case warming from Lee et al. (2021) with scale-up with and without barriers. Total uncertainty: uncertainty from Lee et al. (2021) with scale-up with and without barriers. Fuel burn penalty based on perfect avoidance from Dray et al. (2022), with penalty adjusted due to false positives and negatives.

Eliminating contrails through contrail avoidance is comparable to a one-time removal of CO_2 from the atmosphere. The lower section of the figure shows that the contrail avoidance scheme described in Key Fact 2 is equivalent to removing between 5 and 50 billion tonnes of CO_2 from the atmosphere. However, implementing contrail avoidance results in a slight increase in fuel consumption due to aircraft adjusting their altitude. This is magnified 100 times in the upper section of the figure, showing that the additional fuel burn would add between 0.05 and 0.2 Gt (billion tonnes) of CO_2 to the atmosphere. Notably, this value plateaus by the late 2050s due to the decarbonisation of aviation. This demonstrates that the highest warming impact of the extra fuel burn is 25 times smaller than the lowest warming impact of contrails.

Given that the IPCC's remaining global carbon budget for a 50% chance of limiting the temperature rise to 1.5°C is 200 Gt (billion tonnes) of CO_2, successful contrail avoidance could, at its upper limit of 50 Gt, have an effect equivalent to altering the carbon budget by up to 25%.

Considering the substantial climate impact of contrails and the fact that the warming effect of additional fuel burn is 25 times smaller than the lowest warming impact of contrails, the risk of delaying action is significant.

It should be noted that the figure shows a scenario with no future demand growth of aviation to help with clarity: both contrails and fuel burn penalty would grow with demand, but there is an additional layer of uncertainty – in both – as to the precise impact of demand growth; however it does not change the conclusion as to the relative impact of the fuel burn penalty versus the reduction in contrail warming.

GOAL 2

Systems Efficiency

In 2025, leading governments should set out a clear commitment to the market about their intention to drive systems-wide efficiency improvements. In tandem, governments and industry should work together to develop strategies so that, by 2030, a new wave of policies can be implemented to unlock these systemic efficiency gains.

Reducing fuel burn in aviation can be achieved through conventional measures such as new aircraft and engine technologies and improved operational efficiency. Based on a range of sources[2,3], the Aviation Impact Accelerator model predicts that these conventional measures can lead to up to a 22% reduction in fuel burn by 2050.

However, several bold efficiency measures exist which are currently hard to access because they involve systems-wide change. If implemented, these measures could reduce fuel burn by up to 50% by 2050.

Goal 2: Systems Efficiency

System-wide efficiency improvements have the potential to double the expected fuel burn reductions by 2050.

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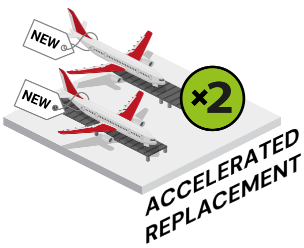


1

Bold Measure 1
Halving fleet age by building aircraft more quickly can reduce fuel burn by 11–14%.

2

Bold Measure 2
Designing aircraft which fly 15% slower would reduce fuel burn by 5–7%.

3

Bold Measure 3
Ensuring that more aircraft are flown close to their design range can lower fuel burn by 4–7%.

These measures include:

1 — **Accelerated Replacement**: Increasing aircraft production to halve the fleet age.

2 — **Fly Slower**: Reducing flight speed by around 15%, increasing transatlantic flight times by about 50 minutes.

3 — **Match Range**: Ensuring more aircraft operate close to their design range by introducing new aircraft types and optimising purchasing and operating practices.

These bold measures are frequently overlooked because they require broad changes to the whole aviation sector, which are beyond the control of airlines. Therefore, policies must be implemented to drive the necessary system wide sector change needed to achieve a 50% reduction in fuel burn by 2050, returning aviation to 2019 emissions levels.

Governments and industry must collaborate to develop strategies that will enable the implementation of a new wave of policies to unlock these bold efficiency gains. Additionally, leading governments should immediately send clear market signals about their commitment to drive system-wide efficiency improvements.

An example of how bolder efficiency measures can be incentivised is the Corporate Average Fuel Economy (CAFE) standards the US introduced for its automotive sector, which have reduced fuel burn by about 25% since 1975[4]. Similar standards – many more ambitious - have been introduced in other locations such as the EU, Japan and China. To achieve similar results in aviation, governments could adopt a number of measures including: introducing Green Mandates for annual fuel burn reduction targets for the aviation industry; provide loan guarantees incentivising the purchase of more fuel-efficient aircraft; shifting accounting or taxation approaches to support accelerated turnover; mandates or incentives for aircraft scrappage; and more.

Outcome

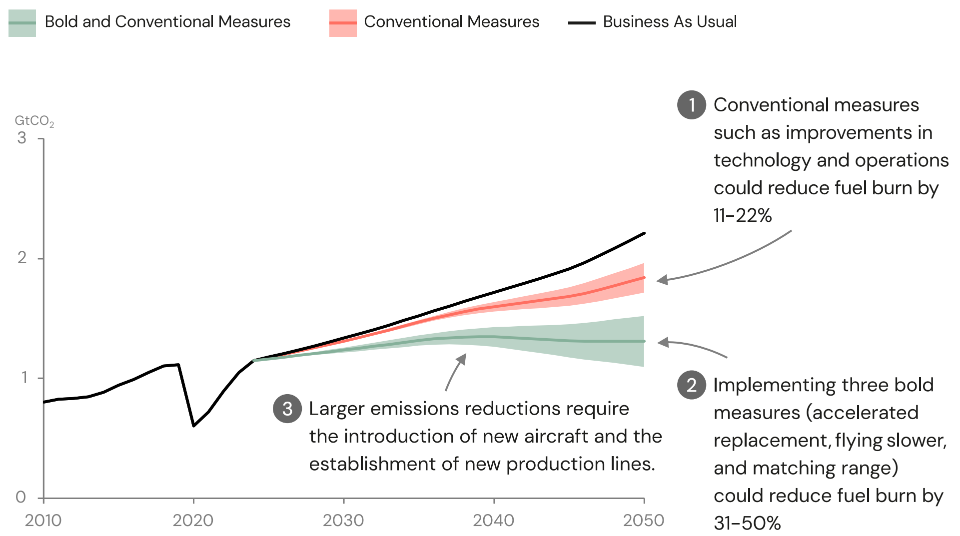
The black line in the Outcome Figure below shows a business-as-usual scenario. This includes the introduction of a new generation of medium-range aircraft in 2035 and a new generation of the long-range aircraft in 2040, both featuring standard generational efficiency improvements. More details on the business-as-usual scenario are given in the *Emission Baseline* section.

The conventional measures, shown as the red region in the figure below, are projected to achieve an 11% to 22% reduction in emissions by 2050. The majority of this reduction comes from the introduction of 'leap technologies', which double the typical generational efficiency improvements to the aircraft launched in 2035 and 2040. Additional emissions reductions come from better air traffic control, decarbonising aircraft operations at airports, and increasing aircraft occupancy rates. A detailed breakdown of the conventional efficiency measured can be found in *Key Fact 1*.

The addition of the bold measures to the conventional ones, shown as the green region in the figure below, is projected to achieve a cumulative 31% to 50% reduction in emissions by 2050. A detailed breakdown of the bold efficiency measured can also be found in *Key Fact 1.*

Outcome: Systems Efficiency

If policies are enacted to drive systems efficiency measures by 2030, emissions reductions of 31% to 50% can be achieved by 2050.



Assumptions: Conventional measures are based on ICAO (2022) and predictions for the efficiencies of next generation aircrafts. Analysis on fleet age is based on global fleet data (Oliver Wyman (2020), JADC (2024), Emerald (2016), Boeing (2024), Airbus (2024). Analysis on flight speed is based on work conducted at MIT (Yutko (2014) & Lovegren (2011)). Analysis on aircraft use by mission range is based on ICCT (2020).

The first bold measure involves accelerated fleet replacement, aiming to halve the aircraft retirement age from 30 to 15 years by 2050. This change alone could reduce fuel burn by 11% to 14%. Achieving this would require a notable increase in aircraft production over the next 30 years. Over this period, Airbus and Boeing are planning to double production, and either a further increase in their output by 50% or a third manufacturer joining the market would meet this need. While this might seem daunting given current aircraft delivery challenges, this increase in production can be strategically planned over 30 years. More details can be found in *Key Fact 2*.

The second bold measure is to reduce flight speed by around 15% and design aircraft for these lower speeds [5]. This could reduce fuel burn by 5% to 7%. One drawback of reducing speed is the potential negative impact on airline productivity and passenger acceptance, especially for longer flights. However, for a transatlantic flight, the flight time would only increase by about 50 minutes, which could be offset by reduced airport waiting times.

The third bold measure is to better match aircraft design and operating ranges, ensuring more aircraft fly close to their design range. This could reduce fuel burn by 4% to 7% and can be achieved in three ways:

1 — Incentivising airlines to prioritise matching design and operating range in their aircraft purchases and operations.

2 — Introducing two new aircraft types, in addition to existing medium and long-range ones, with ranges of 2,000 km and 8,000 km into the market (the recent Airbus A321XLR, with an operating range of 8,700 km, is already ideal for one of these).

3 — Dividing flights over 10,000 km into two segments where feasible[5], thus lowering the design range of the aircraft for each leg. More details can be found on better matching aircraft design and operating ranges in *Key Fact 3*.

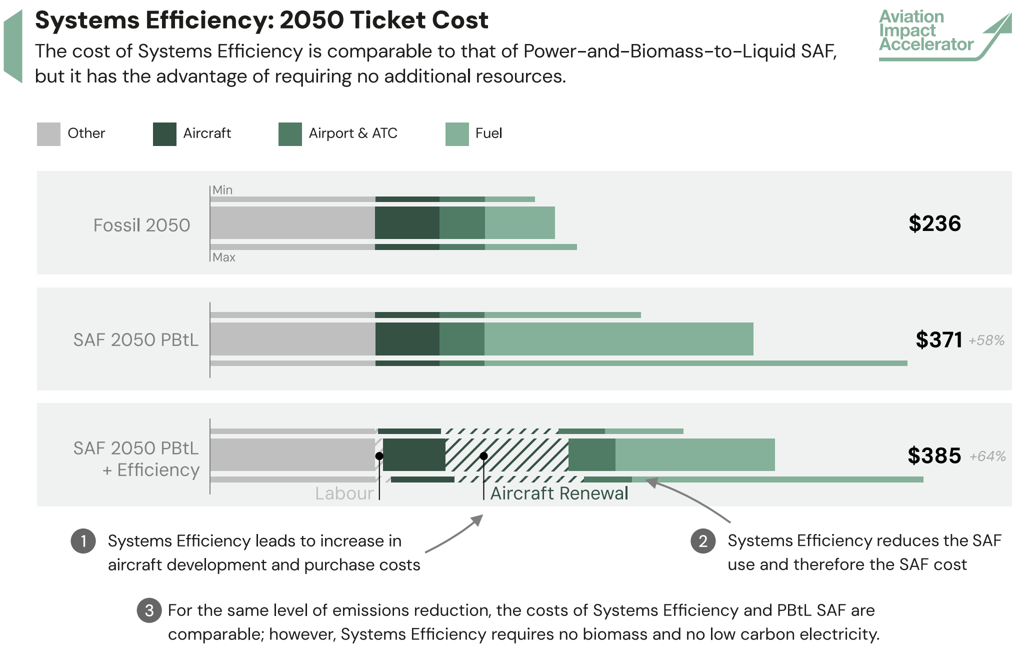
For a fixed emissions reduction, the cost of implementing system efficiency improvements (*2050 Ticket Cost*) is comparable to the cost of purchasing sustainable aviation fuel (SAF) produced using Power-and-Biomass-to-Liquid (PBtL). System efficiency improvements reduce the volume of SAF required, thereby lowering the demand for biomass and renewable electricity. Consequently, prioritising systems efficiency is a cost-effective way to reduce global resource consumption.

Other Solution
Demand Management

Reducing aviation's environmental impact can also be achieved by managing demand, such as encouraging people to decrease travel or switch to alternative modes of transport. For instance, France has banned flights on routes with a rail alternative under 2.5 hours, cutting emissions by up to 95% per passenger kilometre, where a direct train is available. However, only about 7% of aviation fuel burn is regional, and only a small fraction can be replaced by rail.

Only about 10% of the world's population have ever flown1, but with the rising size of the middle classes in Asia, Africa, and South America, air travel is expected to double by 2050. This growth makes significant emission reductions through demand management challenging. Restricting emerging markets' access to air travel would be strongly resisted as these countries seek the same opportunities industrialised nations have long enjoyed. In industrialised countries, significant restrictions would need to focus on frequent fliers to gain public acceptance.

Systems Efficiency: 2050 Ticket Cost



Assumptions: Costs are displayed for a global average return flight. The fossil ticket does not include a carbon price and assumes that all non-fuel costs only change with inflation. Fossil jet fuel 0.70$/L. Typical 2050 SAF route assumed as Power-and-Biomass-to-Liquid (PBtL) at $1.60-$4.20/L. The cost of efficiency measures includes: increased staff costs due to longer flights (fly slower & multi-hop); increased aircraft capital & finance costs for faster renewal; increased aircraft costs due to lower aircraft utilisation (using range-matched aircraft, slower speeds & multi-hop); increased aircraft R&D due to additional aircraft design ranges, slower speed aircraft design and technology improvement; and increased airport costs due to multi-hops.

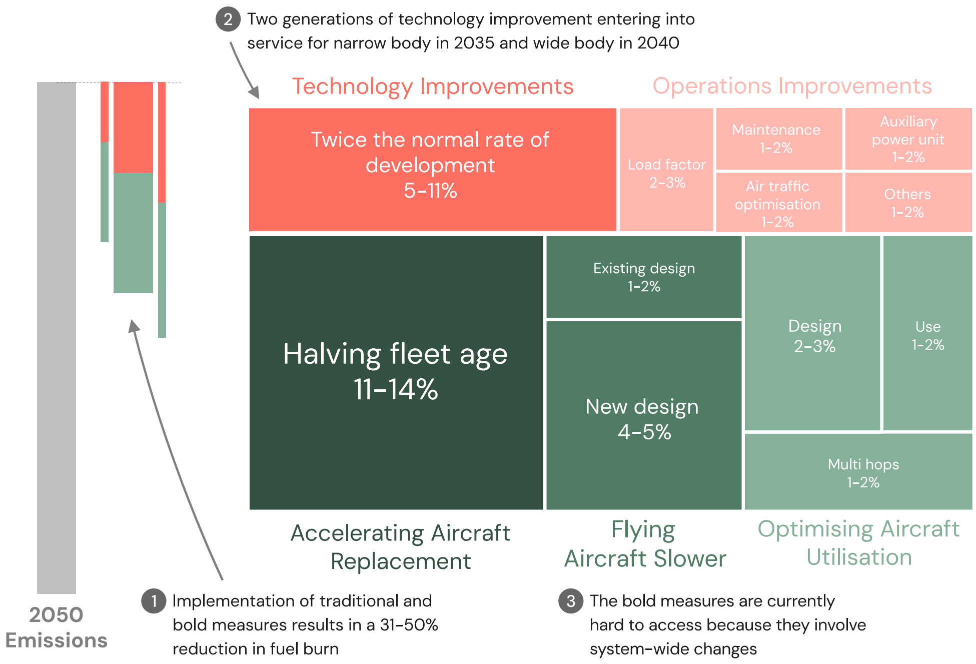
Implementing system efficiency improvements is comparable in cost to purchasing a typical 2050 sustainable aviation fuel (SAF) produced via a power-and-biomass-to-liquid (PBtL) route. These costs arise from developing, manufacturing, and financing of new aircraft. The figure details the average global cost of a return flight in 2050, fuelled by fossil jet fuel (with no carbon taxes); fuelled entirely with a typical 2050 SAF (PBtL); or fuelled entirely with a 2050 SAF and with the efficiency measures proposed implemented. It should be noted that these are the costs to the airlines and the price passed through to consumers may differ from this.

As shown in the bottom two bars of the figure, the expenses are similar, whether investing in system efficiency or opting for a truly sustainable SAF like PBtL. However, improving system efficiency reduces the amount of SAF needed, which in turn lowers the demand for biomass and renewable electricity. Therefore, prioritising system efficiency is a cost-effective strategy for minimising global resource consumption. It should be noted that, like for the uptake of SAFs, policies would likely be required to ensure all operators improved systems efficiency, as the efficiencies of the system come with a net cost under fossil jet fuel prices, since the fuel-saving does not outweigh the additional costs. As for SAF at 2050 uptake, these additional costs would also be mostly or entirely passed onto consumers (or subsidised in some way by the state) as very little could be adsorbed in airline profit margins.

Systems Efficiency: Key Fact 1

How can Fuel Burn be Halved by 2050?

Bold strategies like accelerating aircraft replacement, flying aircraft slower, and optimising aircraft utilisation can significantly reduce fuel burn.



Assumptions: Other operations include decreasing aircraft weight (e.g. lighter seats) and use of automated operations and fuel management systems at airports (source: ICAO (2022)). Analysis on fleet age is based on global fleet data (Oliver Wyman 2020). Analysis on flight speed is based on work conducted at MIT (Yutko (2014), Lovegren (2011)). Analysis on range is based on data reported by ICCT (2020).

System efficiency improvements are divided into two categories: conventional measures proposed by various organisations and bold measures yet to be widely considered. When combined, these measures have the potential to reduce fuel burn by up to 50% by 2050.

Conventional measures aim for an 11% to 22% reduction in fuel burn, with half of the benefits from technology improvements and the other half from operational enhancements. Technology improvements involve implementing leap-generation technologies in medium-range aircraft by 2035 and long-range aircraft by 2040, achieving efficiency gains normally expected over two generations of development. Operational efficiencies include improved air traffic control, decarbonisation of ground equipment, and increased aircraft occupancy rates.

Bold measures could achieve a 20% to 28% reduction in fuel burn and are divided into three categories:

1 — Accelerating aircraft replacement to halve the fleet age.

2 — Flying aircraft slower, where one third of the benefit comes from flying existing aircraft slightly slower to match their optimal design speed, and the other two thirds are due to designing new aircraft to fly around 15% slower than current aircraft.

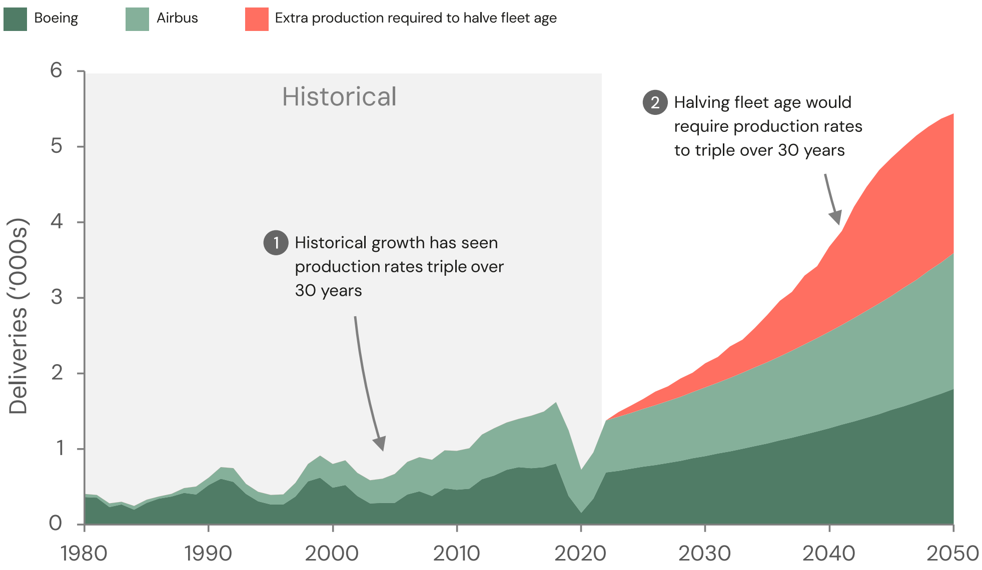
3 — Optimising aircraft utilisation is split into three effects, the first two optimising operations and purchase of aircraft to ensure that more aircraft fly at close to their design range. The final effect involves reducing the range aircraft fly, by splitting flights over 10,000 km into two hops. It is important to recognise that theoretically this effect could be much larger but is in practice limited by the current location and capacity of airports.

Systems Efficiency: Key Fact 2

Why Halve the Age of the Fleet by 2050?

Halving the fleet age would introduce new technology into the fleet more quickly, reducing fuel burn by 11-14%.

Aviation Impact Accelerator



3 To halve the fleet age, either current manufacturers would need to increase production by 50% by 2050, or a third manufacturer would have to enter the market

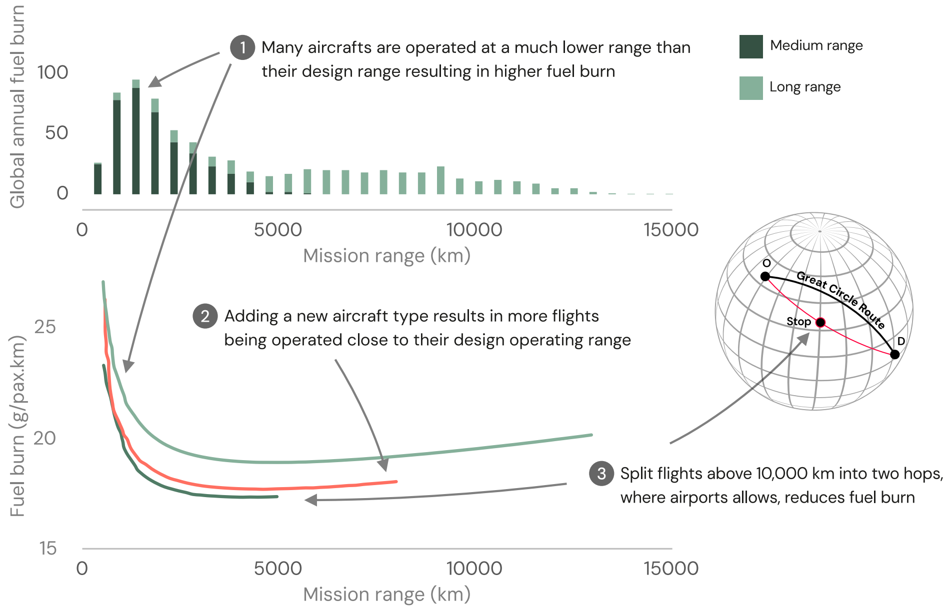
Assumptions: Historical build rates and fleet composition are adopted from Emerald (2016), JADC (2024) World Market Forecast, and IATA (2024) Global Outlook for Air Transport. Total projected deliveries are based on the global commercial market forecasts published by Boeing (2024) and Airbus (2024).

To meet market demand, Airbus and Boeing plan to double aircraft production by 2050. Halving the fleet age would require an additional 50% increase in production. This could be achieved by boosting manufacturing rates at Airbus and Boeing or introducing a third manufacturer into the market. The total number of aircraft deliveries required over the next 25 years to halve fleet age is roughly one-tenth of the aircraft delivered in five years during World War II. While today's aircraft are more complex, this historical precedent demonstrates that the required production rates are easily achievable in a state of crisis.

Systems Efficiency: Key Fact 3

Why Operate Aircraft at Close to Optimal Range?

Designing and operating aircraft so that more aircraft operate at closer to their design operating range can reduce fuel burn by 4-7%.



Assumptions: Analysis on aircraft design and multi-hop is based on Yutko (2014). Analysis on range is based on data reported by ICCT (2020).

Flying aircraft closer to their design range reduces fuel burn because aircraft are structurally optimised to carry their maximum fuel load. The figure shows that long-range aircraft are often flown on short or medium-range routes. Policies should incentivise the operation and purchase of aircraft that are utilised near their design range. Additional benefits can be achieved by developing two new aircraft with design ranges tailored to current fleet needs. The first aircraft would have a short range of around 2,000 km, offering limited fuel burn reduction per aircraft but significant overall savings due to the high volume of flights in this range. The second aircraft would have a range of about 8,000 km, providing greater fuel burn savings per aircraft, albeit for fewer flights. Finally, splitting flights over 10,000 km into two hops would allow the use of aircraft with lower design ranges, thus reducing overall fuel burn.

The measures described in this section involve varying levels of cost and complexity. However, due to the system-wide challenges of implementing these measures, they will only be exploited with supportive policies.

GOAL 3

Truly Sustainable and Scalable Fuel

In 2025, governments should reform Sustainable Aviation Fuel (SAF) policy development to adopt a cross-sector approach, enabling rapid scalability within global biomass limitations. By 2030, governments and industry should implement a demonstration and deployment strategy that enables SAF production to move beyond purely biomass-based methods, incorporating more carbon-efficient synthetic production techniques.

Globally, progress is being made in deploying Sustainable Aviation Fuels (SAFs) - synthetic kerosene fuels produced from renewable resources in production pathways that seek to cut the overall carbon footprint. Various bodies have set targets for their rollout. The UN's International Civil Aviation Organisation aims for a 5% reduction in the carbon intensity of aviation fuels by 2030, while the European Union mandates a 6% SAF uptake by 2030.

One key resource for the production of such fuels is biomass – which provides the carbon critical for the development of the fuel. However multiple sectors draw on and are planning to draw on this resource, and producing it has implications for land use which is already highly pressured. There are real limitations to the scale of biomass that can be safely deployed across the economy and constraints on the sources.

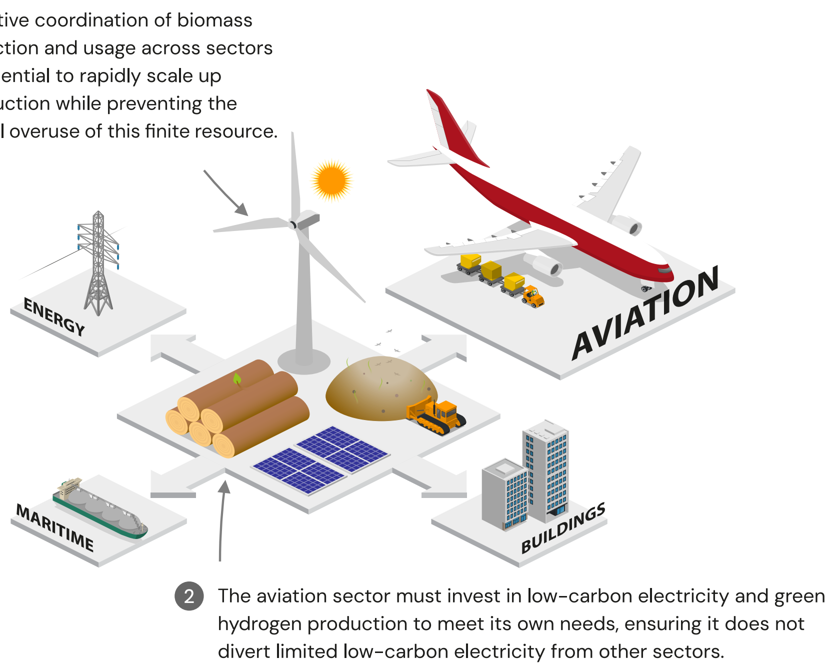
Currently, SAF policies focus on reducing life cycle emissions within aviation and overlook the impact this biomass demand may have on emissions in other sectors. If left unaddressed, SAF production could lead to biomass consumption patterns that create significant emissions increases in other sectors, ultimately negating the benefits achieved within aviation. In turn, this would undermine the policy basis driving the rollout of SAFs and threaten the prospects for effectively scaling up. To rapidly scale SAF production within global biomass limits, aviation must take part in a cross-sector perspective, ensuring that biomass demand is understood and total emissions are minimised across all sectors.

Shifting to looking at SAFs through a cross-sector perspective offers the aviation industry an opportunity to demonstrate global leadership by developing a framework that encourages cross-sector coordination and best practices to minimise total cross-sector emissions. To achieve this, governments must immediately reform their Sustainable Aviation Fuel (SAF) policies to introduce a cross-sector approach, providing the industry with the certainty needed to invest. By 2030, governments and industry should implement a demonstration and deployment strategy that advances SAF production beyond biomass-based methods, incorporating more carbon-efficient synthetic production techniques. Additionally, policies must ensure that the aviation sector invests in low-carbon electricity and green hydrogen production to meet its own needs, preventing the diversion of limited low-carbon electricity and green hydrogen from other sectors.

Goal 3: Truly Sustainable and Scalable Fuel

Sustainable Aviation Fuel (SAF) policies to adopt a cross-sector approach, enabling rapid scalability within global biomass limitations.

Aviation Impact Accelerator



Outcome

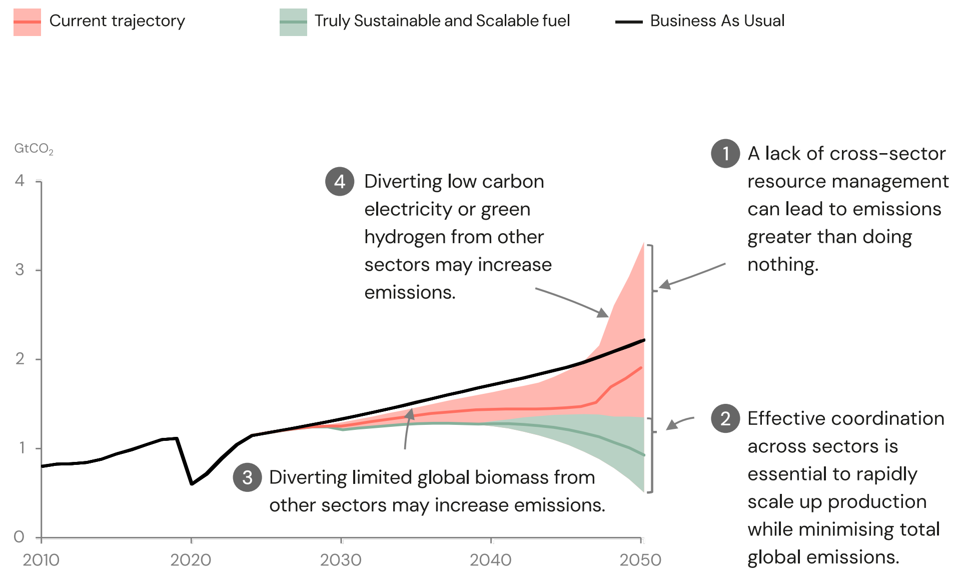
The figure below illustrates a scenario where 80% of global jet fuel is replaced with SAF by 2050. The red region represents the increase in total global emissions resulting from this scenario, including both emissions within aviation and those triggered in other sectors. Uncertainty is high, and in the worst cases, the emissions from other sectors could offset or even exceed the savings made in aviation. This uncertainty is based on modelling a wide range of scenarios, considering the transition of other sectors and the scale-up of biomass collection and low-carbon electricity.

The green region represents the case where Goal 3 has been effectively implemented, minimising emissions in other sectors. This scenario demonstrates that, if managed properly, emissions reductions of 50% to 70% are achievable by 2050.

Up until the early 2040s, the difference between the red and green regions will be primarily due to insufficient global biomass, with aviation taking priority over other sectors. After the 2040s, as more Power-to-Liquid fuels are employed, the difference also results from limited low-carbon electricity and green hydrogen production, with aviation taking priority over other sectors.

Outcome: Truly Sustainable and Scalable Fuel

If policy shifted from aviation-centric to cross-sector perspective, then emission reductions of 50%-70% can be achieved by 2050.



Assumptions: Model targets 5% GHG reductions globally through SAF in 2030 rising to 80% in 2050, with biomass and carbon resources limited by availability and growth. When sufficient resource available, SAF routes selected on economic basis, based on AIA SAF cost model. Electricity use is not additional in worst cases; additionality obeyed in best cases. In this figure, non-additional electricity & biomass use above sustainable limits is penalised based on emissions avoided if those resources had been used to decarbonise electricity grids by displacing any remaining natural gas power generation (420 g/kWh). Bio-electricity efficiency: 40%.

A major challenge in sustainably scaling up SAF production is the significant biomass requirement. Aviation's ability to outbid other sectors for biomass, given its small cost fraction in *ticket prices*, exacerbates this issue. By 2050, biomass costs are expected to account for only around 10% of the average ticket price if biofuels are used. Without regulation, SAF production could monopolise limited biomass resources, diverting them from other sectors and increasing their emissions.

Key Fact 1 shows that the maximum available global biomass, estimated by a range of international studies, is between 50 EJ and 160 EJ, considering only waste and currently collected biomass, with no land-use changes. While it's impossible to estimate this sustainable limit with precision, it will likely evolve as our scientific understanding of global land use improves and agricultural advances are made. However, it is clear that there is a practical upper limit, and as easier-to-collect biomass is depleted, the harder-to-collect biomass will prove uneconomical and environmentally damaging. Today, the easiest biogenic feedstock available to produce SAF is waste biogenic fats, oils and greases, such as tallow and used cooking oil, typically converted in HEFA processes. However, the supply of these waste feedstocks is very limited and could only supply a small fraction (<5%) of 2050's jet fuel demand. In many cases, demand for these feedstocks competes with other non-energy sectors such as cosmetics and pet food, and displacement of these feedstocks from these use cases would result in additional net virgin oils and fats production, usually eliminating the aviation sector emission benefit.

Key Fact 2 shows that the total global biomass required to decarbonise all sectors, including aviation, by 2050 is estimated to be between 80 EJ and 190 EJ. The lower estimates assume that all sectors, except for the hardest-to-decarbonise industries such as plastics, wood products, pulp, and paper, have ceased using biomass and that aviation fuel is produced using the most carbon-efficient method, Power-and-Biomass-to-Liquid (PBtL). The higher estimates assume that in addition to using biomass in the hardest-to-decarbonise industries, biomass is used to decarbonise heavy vehicles, around 15% of global electricity production, and about 15% of final building energy use, with aviation fuel produced through the less carbon-efficient Biomass-to-Liquid (BtL) method. It should be noted that even this higher estimate represents an extremely aggressive strategy for removing biomass from other sectors and will be extremely hard to achieve by 2050.

Comparing the global biomass requirement of 80 EJ to 190 EJ with the global biomass limit of 50 EJ to 160 EJ, it is clear that staying within the biomass limit will require all sectors that can transition away from biomass to do so, while those that cannot must then prioritise the most carbon-efficient methods of production.

Key Fact 3 shows that using Power-and-Biomass-to-Liquid (PBtL) is an effective way to lower the resource requirements of SAF in terms of both biomass and electricity use. It demonstrates that biomass usage is less than half of that required by Biomass-to-Liquid (BtL) and that low-carbon electricity consumption is less than half of what is needed for pure Power-to-Liquid fuels using Direct Air Capture (DAC).

While reducing the overall amount of low-carbon electricity used in fuel production is important, the more critical issue is that this electricity must be additional—specifically generated for the aviation sector. The required amount of low-carbon electricity is significant, with Power-and-Biomass-to-Liquid (PBtL) expected to consume 9-16% of the world's planned low-carbon grid by 2050, and Power-to-Liquid (PtL) requiring 23-41%. Ensuring that this power supply is additional is crucial, as displacing electricity from other sectors would result in continued reliance on fossil-based energy elsewhere, ultimately negating the emissions savings made in aviation.

Finally, it is important to note several other ways to minimise emissions. These are explained in more detail in *Key Fact 4*. These include:

1 — **Resource-Efficient Production**: Choose methods of fuel production like Power-and-Biomass-to-Liquid (PBtL) that make efficient use of biomass.

2 — **Integration of Carbon Removals**: Incorporate carbon capture into bio-based SAF production to offset emissions.

3 — **Strategic Co-Location with Other Sectors**: Combine SAF production with other sectors to collectively reduce emissions.

Other Solution

Offsetting Jet Fuel with Carbon Dioxide Removals (CDR)

Producing synthetic SAF is complex due to the processes needed to create long-chain hydrocarbons. This raises the question of whether it might be better to store carbon from biomass or CO_2 extracted directly from the air (using Direct Air Capture, DAC) underground while continuing to use fossil jet fuel. This method could be net zero or even carbon negative and could be significantly cheaper, costing around 50% to 75% of a Biomass-to-Liquid SAF.

However, this approach faces several challenges. Offsetting fossil emissions with carbon removals requires transparent auditing to ensure credibility and prevent double counting. Additionally, the continued use of fossil jet fuel might be used to justify ongoing crude oil extraction. In the long term, as other sectors phase out crude oil, aviation could become isolated as one of the last users, facing major public acceptance issues and potentially rapidly rising costs.

It is, therefore, recommended that further work be conducted on the public acceptance, economic, technical, and policy challenges of offsetting jet fuel through carbon dioxide removals (CDR).

Other Solution

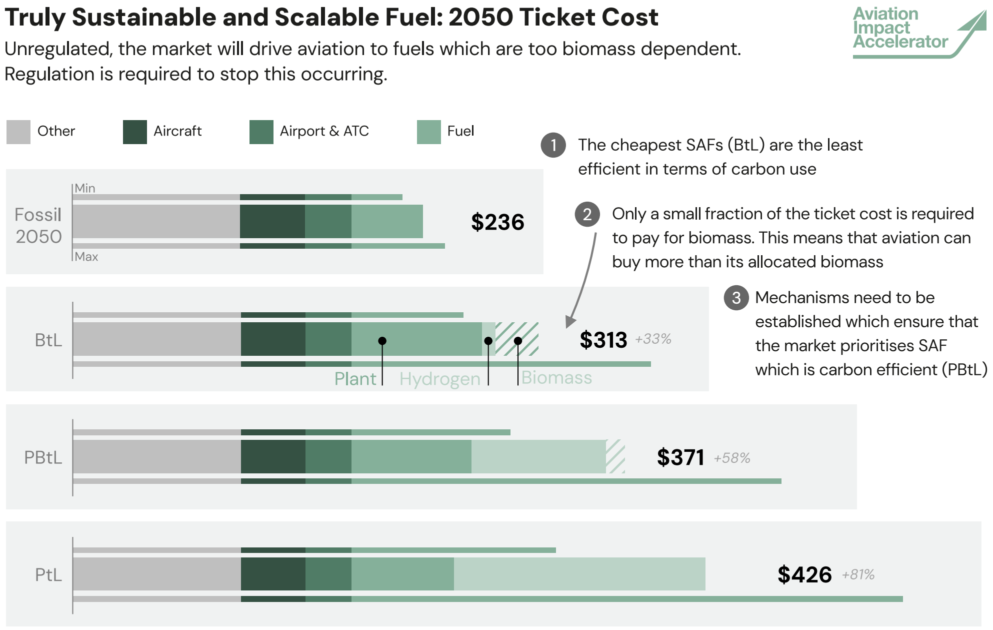
Low Carbon Aviation Fuel

Emissions from current jet fuel can be reduced by approximately 17% through Low Carbon Aviation Fuel (LCAF), which lowers emissions associated with extracting and refining crude oil. As jet fuel represents approximately 5% of crude oil product, the impact of reducing upstream emissions driven by the use of LCAF could be around 20 times larger than the savings of the aviation sector.

Truly Sustainable and Scalable Fuel: 2050 Ticket Cost

Truly Sustainable and Scalable Fuel: 2050 Ticket Cost

Unregulated, the market will drive aviation to fuels which are too biomass dependent. Regulation is required to stop this occurring.



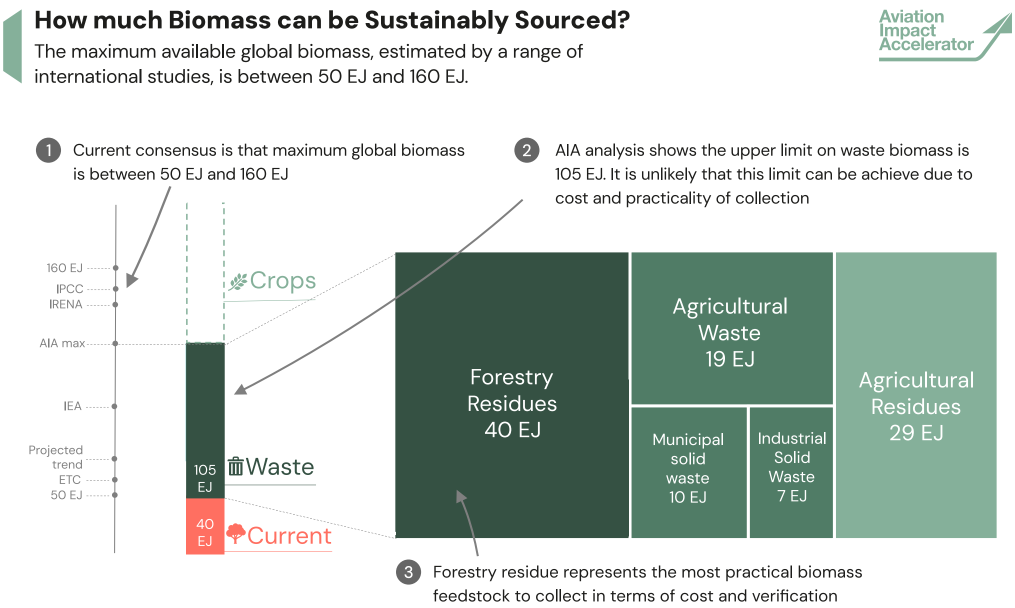
Assumptions: Costs shown are for a global average return ticket. The fossil ticket does not include a carbon price and assumes that all non-fuel costs only change with inflation. Fossil jet fuel cost $0.70/L. Efficiency of 2050 aircraft. Data for SAF costs extracted from AIA Fuels Model: Biomass-to-Liquid (BtL): $1.20-$2.90/L; Power-and-Biomass-to-Liquid (PBtL): $1.60-$4.20/L; and Power-to-Liquid (PtL): $2.10-$5.40/L.

The primary challenge in achieving Truly Sustainable Fuel is that the least expensive Sustainable Aviation Fuels (SAFs) often make the least efficient use of carbon, making them less likely to be truly sustainable. The figure above illustrates the projected costs of various SAF types in 2050, which range from a 33% to a 78% increase in average ticket costs, depending on the production method. This cost increase is more pronounced for long-haul flights than short-haul flights due to the differing proportions of fuel costs in the overall ticket price. The sidebars in the figure highlight the uncertainties in these ticket costs.

The figure also breaks down the components of ticket costs, revealing that the portion spent on biomass is relatively small compared to other sectors that could utilise biomass to decarbonise. This price insensitivity could lead to a situation where aviation diverts biomass from other sectors simply because it can afford to pay more. Compounding this issue, one of the cheapest fuel production methods, biomass-to-liquid, is also the least carbon-efficient. Without regulation, the market is likely to favour this low-cost option, leading to excessive biomass consumption and outbidding other sectors for resources.

Without mechanisms to manage this situation, there is a risk that the wrong type of SAF production facilities will be built, resulting in significant increases in emissions in other sectors.

Truly Sustainable and Scalable Fuel: Key Fact 1



Assumptions: Biomass projections sourced from: ETC (2021). IEA (2023). IRENA (2022). IPCC (2011). Feedstock breakdown derived from: FAOSTAT (2023). World Bank (2022). Biogenic portions only of Municipal & Industrial Solid Wastes.

The left-hand bar in the figure illustrates that the estimated maximum sustainable global biomass available in 2050, based on various international studies (ETC, IEA, IRENA, IPCC), ranges from 50 EJ to 160 EJ. While these studies predominantly focus on waste biomass, IEA, IRENA, and IPCC also include some crop-based sources. It's important to note that different studies make varying assumptions regarding how much biomass can be practically and sustainably collected.

To prevent biomass production from competing with food resources and resulting in significant up-front land use change emissions, it is essential to prioritise waste as the primary source of biomass. However, the cost of production, along with the challenges of collection and verification, varies significantly between different types of waste. The Aviation Impact Accelerator (AIA) conducted a study on the maximum potential of global waste biomass and its sources, as shown in the figure. The analysis estimates the maximum waste biomass that could be achieved with perfect collection, indicating that the upper limit of waste biomass is 105 EJ. The right-hand side of the figure breaks down the various sources of waste biomass, with uncollected waste, particularly forestry residues, emerging as the most practical and cost-effective source.

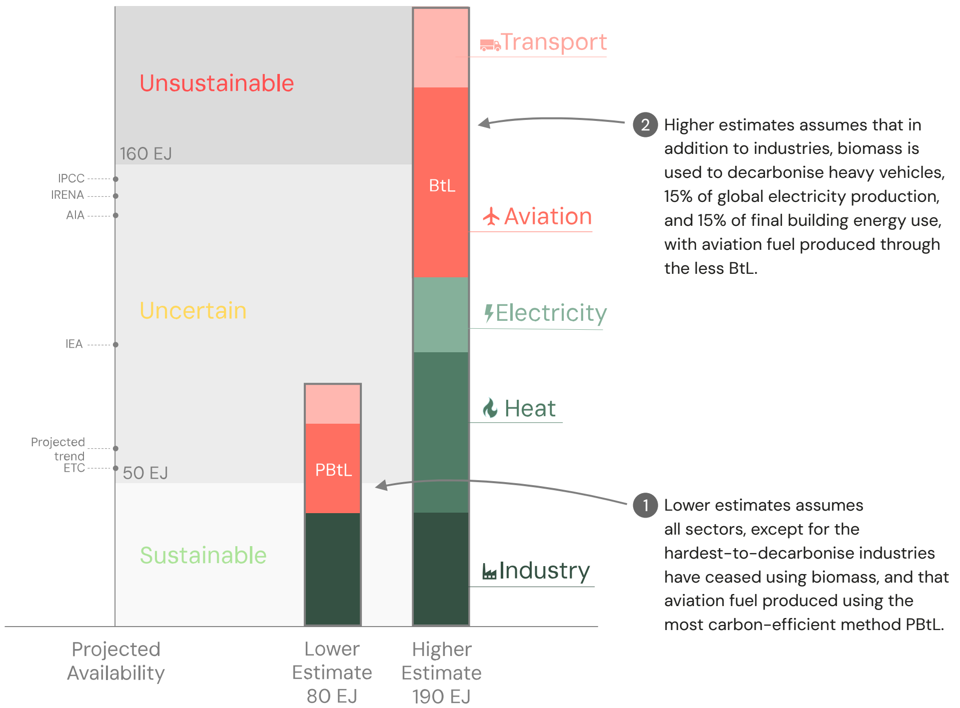
It should be noted that this analysis is subject to several uncertainties. Factors such as significant global land-use changes, major dietary shifts, or unexpected advancements in genetically engineered crops could potentially increase the available biomass. Conversely, practical challenges in biomass collection, efficiencies reducing some wastes or negative impacts on biodiversity could reduce it.

The key takeaway is that whether the maximum available biomass is closer to 50EJ or to 160 EJ depends on whether the reader believes in the ability to economically scale the efficient collection of the many different forms of waste worldwide.

Truly Sustainable and Scalable Fuel: Key Fact 2

How much Biomass do all Sectors Require?

The total global biomass required to decarbonise all sectors, including aviation, by 2050 is estimated to be between 80 EJ and 190 EJ.



Assumptions: Biomass projections sourced from: ETC (2021). IEA (2023). IRENA (2022). IPCC (2011). The biomass allocation to transport (shipping, heavy & off-road vehicles) is the co-products of SAF production. Biomass projections exceeding ~160 EJ require significant land use changes, which are assumed to be unsustainable without other major shifts e.g. food production. AIA model used for 2050 biomass requirements for SAF & co-products. Lower estimate based on ETC (2021), higher estimate based on IRENA (2022) (non-transport effects).

The figure presents two scenarios for the total biomass required across all sectors. The first scenario, a lower estimate, assumes that all sectors—except for the industries hardest to decarbonise without biomass use, such as plastics, wood products, pulp, and paper—have stopped using biomass and that aviation fuel is produced using the most carbon-efficient method, Power-and-Biomass-to-Liquid (PBtL). In this scenario, the total biomass requirement is 80 EJ.

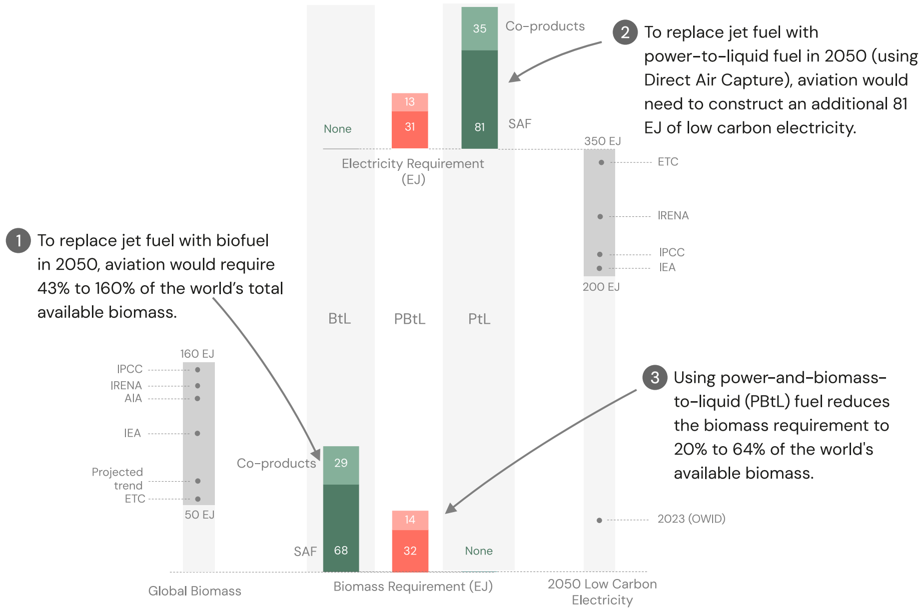
The second scenario, a higher estimate, assumes that, in addition to supplying biomass to the hardest-to-decarbonise industries, biomass is also used for decarbonising heavy vehicles, around 15% of 2050 global electricity production, and approximately 15% of final energy use in buildings. In this case, aviation fuel is produced through the less carbon-efficient Biomass-to-Liquid (BtL) method, bringing the total biomass requirement to 190 EJ. It should be noted that the fuel for heavy vehicles comes from by-products of Sustainable Aviation Fuel (SAF) production, which must be utilised. This higher estimate still represents an extremely ambitious strategy to phase out biomass use in other sectors by 2050.

The key takeaway is that in a net zero carbon 2050 world, global biomass demand totals 80 EJ to 190 EJ, depending on how aggressive one believes other sectors will and can be in adopting non-biomass solutions and the priority given to or taken by aviation, over other sectors, in terms of biomass allocation.

Truly Sustainable and Scalable Fuel: Key Fact 3

How can Resource Requirements of SAF be Reduced?

Carbon-efficient fuel production methods, like Power-and-Biomass-to-Liquid (PBtL), lower both biomass and electricity demands.



Assumptions: Biomass projections sourced from: ETC (2021), IEA (2023), IPCC (2011), IRENA (2022). Current and planned low carbon electricity sourced from ETC (2021), IEA (2020), IRENA (2023), Our World in Data (2024). 100% SAF uptake in 2050 of 25 EJ. SAF resource requirements extracted from the AIA Fuels Model, average SAF/co-product split of 70/30.

Reducing resource requirements for SAF production requires a focus on carbon and electricity efficiency, with carbon efficiency being especially critical due to the finite availability of biomass. The figure above illustrates the biomass and low-carbon electricity needed to replace global jet fuel by 2050 using three different fuel production methods. Biomass-to-Liquid (BtL) is carbon-inefficient, consuming a significant portion of global biomass, with much of the biogenic carbon lost to the atmosphere rather than synthesised into fuel. In contrast, Power-to-Liquid (PtL) using Direct Air Capture (DAC) is electricity-inefficient, requiring a large amount of dedicated low-carbon electricity above that planned for all other demands. Additionally, DAC has yet to be demonstrated at scale, adding uncertainty to this method of fuel production.

A more resource-efficient option is Power-and-Biomass-to-Liquid (PBtL), which is both more carbon-efficient and electricity-efficient. This option requires less biomass and electricity and doesn't require scaling up direct air capture technologies.

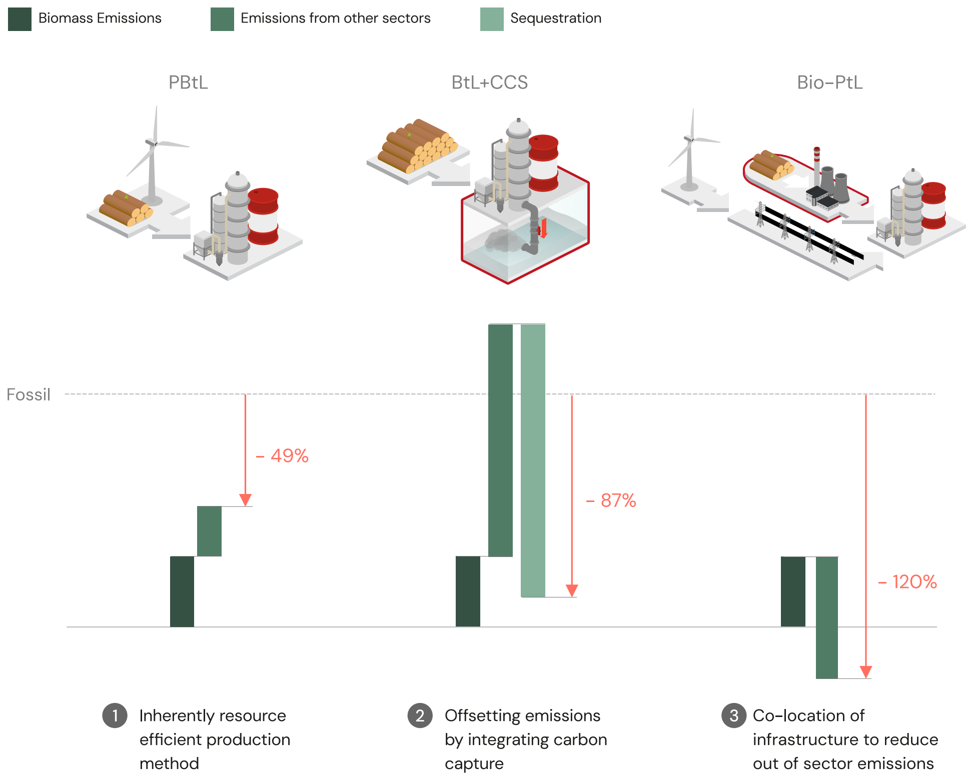
The key takeaway is that not all SAF production methods are equally efficient in their resource use. Current regulations, such as ICAO's CORSIA, only partially address these differences. Given the global limit on biomass, it is essential to implement mechanisms that prioritise SAF production methods that maximise carbon efficiency.

Truly Sustainable and Scalable Fuel: Key Fact 4

What makes a Fuel Truly Sustainable?

There are multiple ways to achieve Truly Sustainable Fuel, with the best approach varying based on regional conditions around the world.

Aviation Impact Accelerator



Assumptions: The Truly Sustainable SAF production routes highlighted here are as follows: Power-and-Biomass-to-Liquid (PBtL), Biomass-to-Liquid with Carbon Capture & Storage (BtL + CCS) and Biogenic Carbon Dioxide Power-to-Liquid (Bio-PtL). Fossil jet fuel baseline: 89 gCO2/MJ. 100% SAF uptake in 2050 of 25 EJ. Low carbon electricity obeys additionality. Aviation biomass use above 30 EJ is penalised based on emissions avoided if those resources had been used to decarbonise electricity grids by displacing any remaining natural gas power generation (420 g/kWh). Bio-electricity efficiency: 40%. Carbon Capture and Sequestration efficiency: 90%.

There are multiple ways that fuel can be made truly sustainable, and the choice will depend on the local environment in which the plant is located. However, three principal strategies can be employed:

1 — **Resource-Efficient Production:** Power-and-Biomass-to-Liquid maximises carbon efficiency by converting all biomass carbon with green hydrogen, minimising emissions in other sectors even when global biomass is limited.

2 — **Integration of Carbon Removals:** Although less efficient directly, Biomass-to-Liquid fuels can achieve negative emissions by incorporating carbon capture and storage, effectively offsetting induced emissions in other sectors.

3 — **Strategic Co-Location with Other Sectors:** Co-locating a Power-and-Biomass-to-Liquid plant with a coal power station allows for the displacement of coal with biomass and the capture of carbon dioxide for SAF production, thereby reducing emissions in both sectors. The biogenic CO_2 could be upgraded to SAF with hydrogen produced during periods of intermittent renewables on the grid, or alternatively the CO_2 feedstock could be transported to another remote, off-grid location with cheap renewables.

To quickly scale up SAF production, it may initially be necessary to permit the construction of plants that are not yet truly sustainable. However, it is crucial to establish plans that ensure these plants become truly sustainable by the early 2040s. Without such plans, there is a risk that plants will be built that cannot be converted to true sustainability in the future.

GOAL 4

Moonshots

In 2025, launch several high-reward experimental demonstration programmes to enable the focus on, and scale-up of, the most viable transformative technologies by 2030. These programmes must generate the necessary experience to assess the technology's scalability and develop the expertise required for deployment.

The primary pathway to decarbonising aviation currently focuses on producing Sustainable Aviation Fuels (SAF). However, the substantial resource requirements and complexity of fuel production present significant challenges and risks in realising this approach.

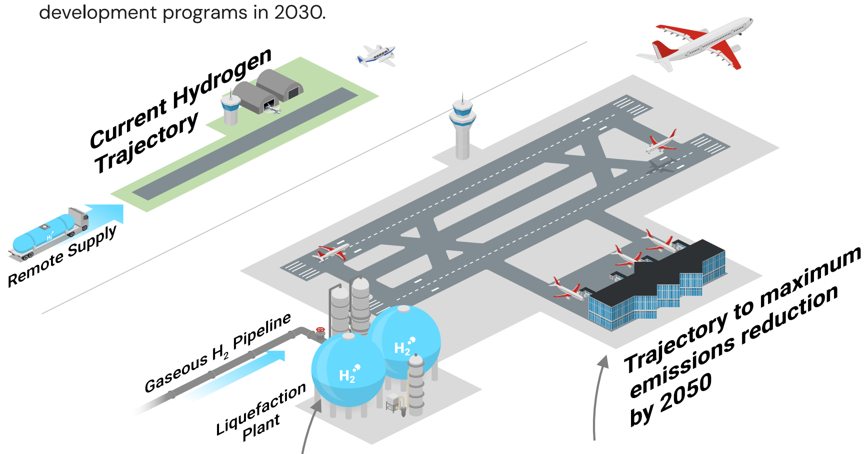
Relying solely on SAF could be avoided through the adoption of transformative technologies. In the automotive sector, for example, the shift to battery electric vehicles reduced both the planned and potential dependence on biofuels. Similar transformative technologies for aviation could include cryogenic hydrogen or methane fuels, hydrogen-electric propulsion, or synthetic biology to dramatically lower the energy demands of fuel production. Each of these technologies offers the potential to reduce aviation's resource requirements and simplify fuel production compared to SAFs. By investing now in frontier technologies, governments have a once-in-a-generation opportunity to lead in transforming aviation, much like electric vehicles have reshaped the automotive industry.

Goal 4: Moonshots

By 2025, launch several high-reward demonstration programmes to enable scale-up of the most viable transformative technologies starting in 2030.

Aviation Impact Accelerator

1 Hydrogen demonstrator 1
Initial concept and technology development complete ready to launch aircraft and engine development programs in 2030.



2 Hydrogen demonstrator 2
Transition plan and feasibility studies complete for transitioning hub airports to hydrogen by 2030.

3 Hydrogen demonstrator 3
Transition plan and demonstration programmes complete by 2030 for hydrogen liquefaction plants with an output a hundredfold greater than today's plants.

However, for such an effort to achieve significant climate benefits by 2050, demonstration programmes must be launched immediately. These programmes should be designed to give real insight into the viability of new technologies by 2030, allowing the focus on and scale-up of the most viable transformative technologies shortly after. They must generate the experience needed to assess the scalability of these technologies and develop the expertise required for their deployment.

Several transformwative technology demonstrators are discussed, but this chapter specifically focuses on cryogenic hydrogen and its potential contribution to emissions reduction by 2050. The AIA model indicates that targeting long-range flights first is critical for minimizing emissions by 2050. Long-range flights account for nearly half of the aviation sector's emissions yet involve replacing only around 5,000 aircraft and converting approximately 50 of the world's largest hub airports. Additionally, even with cryogenic tanks, the low weight of hydrogen, makes it an ideal fuel for long-range flights.

Three hydrogen demonstrator programmes are required:

1 — The initial concept and technology development necessary to assess the potential of a long-range aircraft and engine development programme.

2 — Conducting feasibility studies for transitioning hub airports to hydrogen.

3 — Implementing technology feasibility and demonstration programmes for hydrogen liquefaction plants with outputs a hundredfold greater than today's plants.

Delivering the three hydrogen demonstrator projects by 2030 will be extremely challenging, requiring focused effort from either an international coalition or a large country. However, the cost of these demonstrators is relatively small compared to other actions, such as scaling up SAF production.

The central point is that without launching and completing several focused demonstrator programmes by 2030, the aviation sector will be locked into relying on SAF for most of the emissions reductions in 2050 – exposing the sector to increased risks should there be challenges in delivering of SAF production.

Other transformative technologies will require different demonstrators, but the central principle remains the same: if these demonstrations prove successful by 2030, a significant reduction in emissions can be achieved by 2050. Conversely, a delay in demonstrations risks missing the opportunity to reach net-zero emissions by 2050 and delaying the crucial technological and business transformations needed.

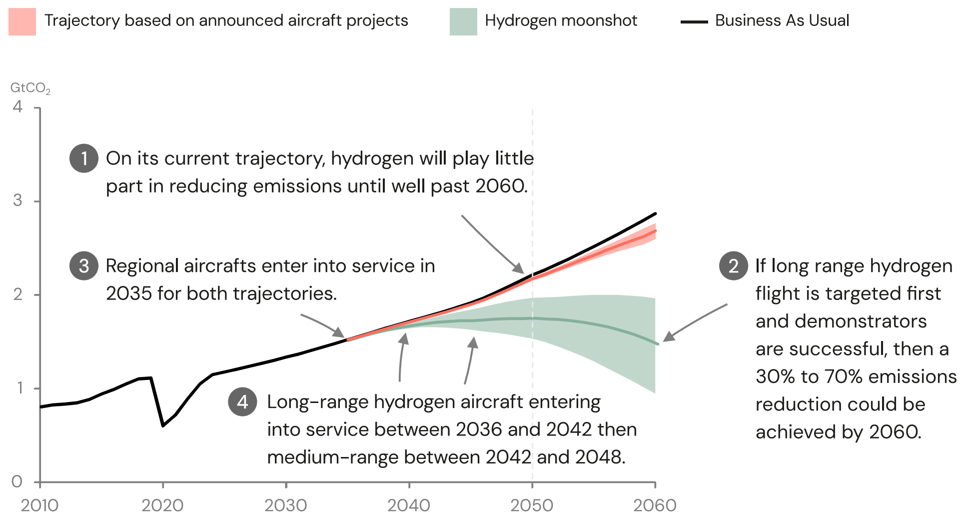
Outcome

The red region in the figure illustrates the projected trajectory of hydrogen aviation, based on currently announced aircraft projects. Despite substantial progress in this field, hydrogen aviation is expected to contribute only 5% to 9% of emission reductions by 2050. In this scenario, hydrogen's impact on aviation emissions would remain minimal until after 2060. This is mainly because the announced hydrogen-powered aircraft are for regional use, accounting for only a small share of global aviation fuel consumption. Additionally, it is important to note that no major aircraft manufacturer is currently considering hydrogen technology for the next generation of medium-range aircraft expected in the late 2030s.

The green region in the figure illustrates the projected trajectory for the case where the hydrogen moonshot demonstrators are successful, and a large-scale programme is launched in 2030. In this scenario, hydrogen aircraft will reduce emissions by 15% to 30% in 2050 and 30% to 70% in 2060.

Outcome: Moonshots

Successful demonstration of the hydrogen demonstrator by 2030 would allow a 15% to 30% emission reduction by 2050.



Assumptions: Aircraft development programmes assumed 7-11 years from start of programme to entry into service. Fuel assumed to be green hydrogen with dedicated low-carbon electricity production.

The development and rollout programme for hydrogen aircraft is shown in *Key Fact 1*. It accounts for the time needed to conduct initial concept studies, develop the underlying technologies, complete the aircraft and engine development programmes leading up to the first flight, achieve entry into service, and ramp up production. Two timelines are considered: the slow one, which considers the current time scales in the aerospace industry, and the fast one, which considers historical projects which have been developed in times of strategic urgency. The analysis shows that a long-range hydrogen aircraft can enter into service between 2036 and 2042, followed by medium-range aircraft between 2042 and 2048. A new regional aircraft is also considered to enter the market in 2035.

Targeting long-range aviation first offers several advantages. Flights departing from around 50 of the world's largest hub airports consume approximately half of aviation fuel. Focusing on long-range flights minimises the number of airports that need to transition. The leading airports would begin their transition in the mid-2030s and complete it by 2050. As medium-range aircraft are introduced by the mid-2040s, a number of medium-sized airports will also need to start transitioning five to ten years after the large airports. Initially, these airports are likely to rely on tanked liquid hydrogen before fully transitioning to new infrastructure.

The optimal solution for large hubs involves delivering hydrogen to hub airports via gas pipelines with on-site liquefaction, requiring hydrogen liquefaction plants about one hundred times larger than any existing facilities. For example, London Heathrow Airport (*Key Fact 2*) would need 1.6 GW to power on-site hydrogen liquefaction, equivalent to a large UK power station, which could be supplied by a dedicated electrical grid connection or a hydrogen-power station. The scenario requires significant international coordination for airport transitions and the introduction of hydrogen aircraft into the current network.

As discussed in *Key Fact 3*, hydrogen is ideal for long-range flight. This is because, even when accounting for the weight of the tanks, hydrogen fuel weighs only half as much as jet fuel. Notably, 45% of the take-off weight of the longest-range aircraft is fuel. Another advantage is that hydrogen is stored as cryogenic liquid, and the liquefaction process serves as an energy reserve. This can be harnessed during flight, reducing the overall energy required by about 10% to 15% compared to current aircraft.

Starting with long-range aircraft offers the advantage of maximizing emissions reductions while minimizing global infrastructure changes. However, this approach faces political challenges, as it requires multiple regions to transition simultaneously. An alternative, politically simpler solution is to focus on a single large region, such as the EU, and prioritise medium-haul aircraft first. While our model shows that this approach results in lower emissions reductions and increased infrastructure complexity, it could enable a more politically practical solution.

It should be noted that the ticket cost of hydrogen in 2050 is comparable to introducing biofuel (*2050 Ticket Cost*) but is more affordable than fuels like Power-and-Biomass-to-Liquid.

Other Solution
To Mars and Back

Both SAF and hydrogen have significant disadvantages as aviation fuels. SAF is challenging to produce due to the complexity of manufacturing long-chain hydrocarbons, while hydrogen, though easy to produce, is difficult to implement in aircraft. Methane offers a potential solution. Its renewable production is simpler and less resource-intensive compared to SAFs, as it can be produced directly by anaerobic digestion of biomass or in one step from CO_2 and hydrogen via the Sabatier Process. Methane's higher liquefaction temperature (-162°C) and greater volumetric energy density (58% of kerosene's) compared to hydrogen (-253°C, 23%) simplify its implementation in aircraft.

The simplicity of producing methane is why it is considered for rockets to Mars, where it can be produced for the return journey. The existing gas infrastructure supports its distribution and allows for a gradual transition by mixing fossil and green methane. A potential issue is methane's potency as a greenhouse gas, necessitating minimised leaks during production, transport, and flight, which is a manageable technical challenge.

Other Solution
Hydrogen-Electric Propulsion

Hydrogen-electric propulsion offers the potential for aircraft to have a very low climate impact. The low temperatures in fuel cells mean that nitrogen oxide (NOx) does not form, and water vapour can be condensed out of the exhaust while flying through regions where contrails are formed. Additionally, electric propulsion enables the introduction of novel aircraft configurations, such as blown wings for reduced cruise fuel consumption, short take-off and landing (STOL), and vertical take-off and landing (VTOL).

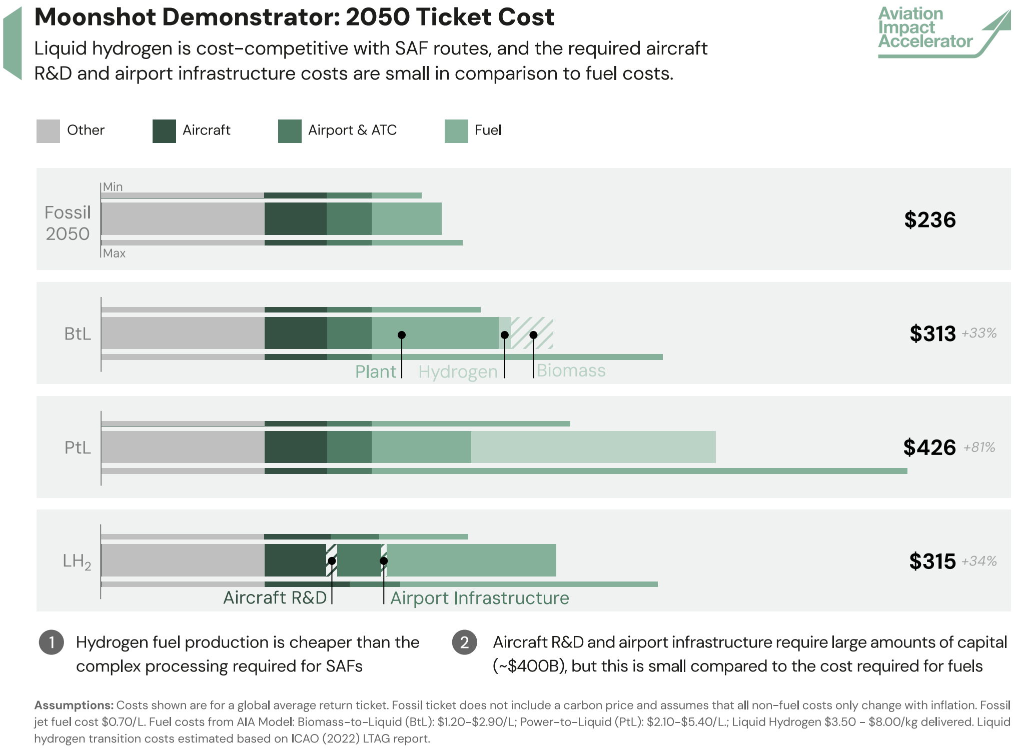
Recent demonstrations, such as Joby and H2Fly's 523-mile flight, highlight the rapid advancements in this technology. The AIA model shows that the range of hydrogen-electric aircraft is expected to increase from less than 1500 km today to over 4000 km by 2035[6]. This would allow hydrogen-electric propulsion to compete with A320 and B737 in the medium-haul market, potentially replacing up to 50% of aviation's fuel burn.

Other Solution
Synthetic Biology

Producing long-chain hydrocarbons using the Fischer-Tropsch process is resource-intensive and involves many conversion steps, resulting in low efficiency and high costs. This process relies on chain-elongation and chain-splitting techniques using thermochemical catalysts at high temperatures and pressures. These non-selective techniques lack the precision of biological enzymes, which can precisely stitch or cut hydrocarbon chains.

Synthetic biology offers a solution by designing organisms that convert common feedstock components, such as lignocellulose, CO_2, water, and energy from sunlight or electrons, directly into kerosene-like molecules in a single step. This approach could dramatically reduce the resources required to manufacture jet fuel.

Moonshot Demonstrator: 2050 Ticket Cost



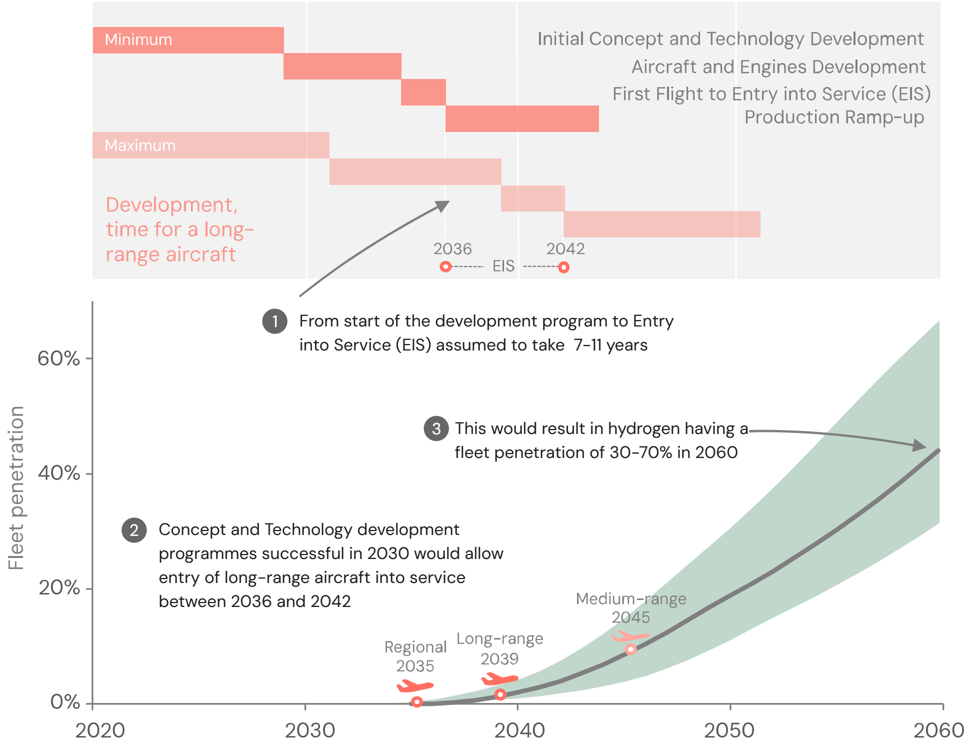
By 2050, the cost of flying on a hydrogen-powered aircraft could be similar to that of an aircraft fuelled by Biomass-to-Liquid (BtL) SAF. Although BtL SAF is about 25% more expensive than hydrogen, the additional costs of aircraft R&D and airport infrastructure for hydrogen, balance the overall ticket cost. In comparison, tickets using more carbon-efficient SAFs like PBtL or PtL are expected to be 20-30% more expensive than hydrogen. Notably, the costs of aircraft R&D and infrastructure changes for hydrogen are relatively small compared to the capital costs of SAF production.

The key takeaway is that in the long term, hydrogen-powered flights could remain cost-competitive with cheaper SAFs, even when considering the expenses for aircraft development and infrastructure adjustments.

Moonshot Demonstrator: Key Fact 1

What is Hydrogen's Potential Contribution?

If hydrogen moonshot demonstrators are successful by 2030, hydrogen could achieve 10% to 30% fleet penetration by 2050.



Assumptions: Data extracted from the Aviation Impact Accelerator Fleet Rollout Model. Scenario shown assumes an even market share between the first mover and the rest of market. Ramp up for aircraft production based on Global Aircraft Registration. Aircraft development times based on Airbus A350, A380, Boeing 787, Lockheed A-12, de Havilland Comet and Brewer (1991).

The development timeline for a clean-sheet hydrogen aircraft, from the start of the programme to Entry into Service (EIS), is estimated to range from 7 to 11 years. The longer estimate of 11 years reflects the timeframe for the traditional aerospace industry working with urgency. We have estimated this as 2 years longer than the typical 6 to 9 years required for clean-sheet aircraft designs that incorporate a substantial number of new technologies, such as the Airbus A350, A380, and Boeing 787. It's important to note that clean-sheet engine designs, such as the Trent 1000, Trent XWB, and the UltraFan demonstrator, typically take only 5 to 6 years and therefore do not represent the limiting factor in the overall development timeline.

The quicker estimate of 7 years is based on the timeframe achievable if a world-class team were assembled and operated with a sense of urgency outside the conventional aerospace industry culture. This estimate draws on historical cases where development timelines were significantly compressed during periods of strategic urgency. For example, after the downing of the U-2 spy plane over the Soviet Union in 1960, Lockheed developed the A-12—a groundbreaking aircraft that became the first to sustain speeds over Mach 3 and employ operational stealth technology—in just 6 years. Similarly, the de Havilland Comet, the world's first jet airliner, which introduced the first pressurized cabin, swept wings, and integral wing fuel tanks in a civil aircraft, was developed in only 6.5 years, driven by a wartime culture of urgency. These examples, such as the A-12 and the Comet, represent transformational technological shifts comparable to the challenge of developing a long-range hydrogen aircraft today.

Prior to the aircraft and engine development phase, an initial concept development and a technology development phase is required. This phase is less well defined, but 2020 is considered the starting point in this analysis because it marked the launch of hydrogen technology programs by Airbus and Rolls-Royce, and the UK's FlyZero project, which focused on initial concept studies. With concentrated effort, this phase could potentially be completed by 2029, or at the latest, 2031. Notably, in previous transformative technological shifts, this phase continued in parallel with the aircraft and engine development process.

Once the aircraft and engine development phase are complete and the aircraft has entered into service, the final phase measures the time required to ramp up aircraft production. Historical data from the Global Aircraft Registration Database indicates that it takes, on average, 7 years for a new aircraft model to reach full production capacity (100% of deliveries). It is therefore assumed that at best a hydrogen aircraft would take the same 7 years and at worst it would take 9 years. In the figure above, it is also assumed that there is 8 years delay from the first lead manufacturer entering a hydrogen aircraft into service and the remainder of the aircraft manufacturers having hydrogen aircraft ready to enter into service.

The key takeaway is that if a world-class team were assembled and operated outside the conventional aerospace industry culture, the Entry Into Service (EIS) of a long-range hydrogen aircraft could be achieved by 2036, with hydrogen fleet penetration reaching 70% by 2060. In contrast, if the traditional aerospace industry worked with urgency, the EIS for a long-range hydrogen aircraft would likely occur by 2042, with fleet penetration at 30% by 2060.

It should also be noted that in both scenarios, a medium-range hydrogen aircraft is expected to enter service six years after the long-range model, while a regional fuel cell aircraft is projected to enter service in 2035.

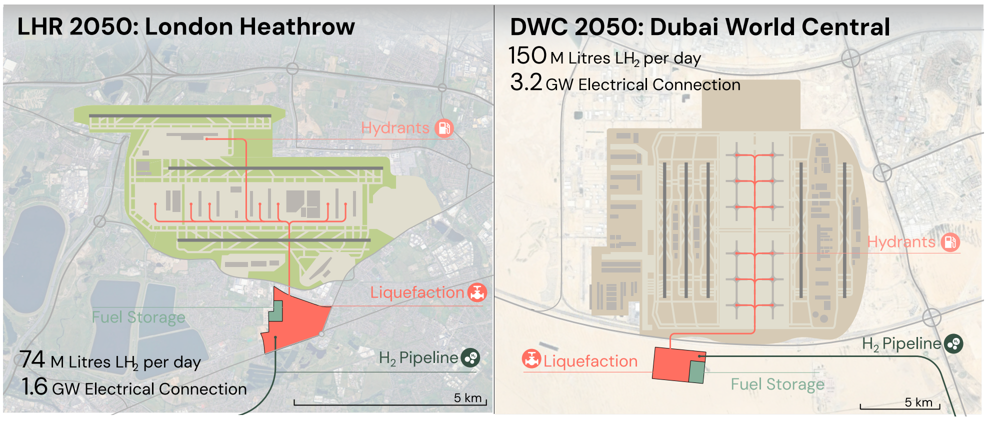
Moonshot Demonstrator: Key Fact 2

Aviation Impact Accelerator

Why Transition Hub Airports to Hydrogen?

Transitioning just 50 of the world's largest hub airports to hydrogen could meet 50% of global aviation fuel demand.

1 Dubai (DXB) and London (LHR) are the world's largest consumers of jet-fuel today.



2 Heathrow would need 1.6 GW to power onsite hydrogen liquefaction for all its fuel—equivalent to the output of a large UK power station. This could be supplied via a dedicated electrical grid connection or a hydrogen-powered station.

3 The optimum solution is hydrogen delivered via gas pipelines. On-site liquefaction plants about one hundred times larger than any existing facilities.

Assumptions: Scenarios depicted are for a 100% hydrogen transition. Data taken from Heathrow Expansion Consultation (2019) and Dar Dubai South Project (2024).

The success of scaling up long-range hydrogen aircraft first depends on converting approximately 50 of the world's largest hub airports to hydrogen, as these airports fuel around 50% of global jet fuel consumption. Assessing the feasibility of transitioning a significant number of these hubs to hydrogen is crucial for enabling long-haul hydrogen flights.

A comprehensive demonstration and feasibility study is crucial to build confidence in transitioning all 50 hub airports to hydrogen. This study would encompass practical refuelling demonstrations, strategic infrastructure planning, and the establishment of safety and standardisation agreements. The objective would be to demonstrate how key hub airports can transition one terminal to hydrogen by 2035, with the majority of terminals converted by 2050.

It is also important that from a network perspective the hub airports which are chosen, maximise fleet penetration rates. This involves prioritising airports that can replace the most long-range flight miles with hydrogen, while also targeting short-range flights from the hub airports where aircraft can tanker fuel for the return journey, thereby minimising the need to convert smaller airports.

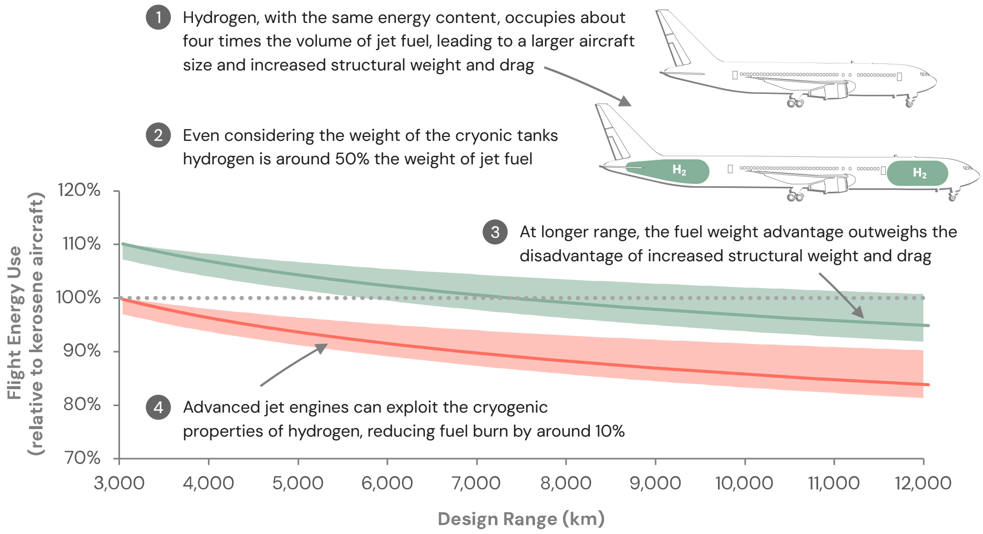
Additionally, a techno-economic feasibility study is necessary to explore how hydrogen liquefaction plants can scale to outputs a hundred times greater than current capacities. At scale, hub airports would likely transport hydrogen via gas pipelines and perform on-site liquefaction. Preliminary analysis suggests that these large-scale liquefaction plants could halve the energy required for the process. For instance, London Heathrow Airport would need around 1.6 GW of power (about 6-8% of UK electricity) to operate its liquefaction plant, which could be supplied through a dedicated grid connection or by constructing an on-site hydrogen combined cycle power station.

Moonshot Demonstrator: Key Fact 3

Why is Hydrogen Ideal for Long-Range Flight?

Aviation Impact Accelerator

Hydrogen's low mass per unit of energy makes it ideal for long-range flight. In addition, advanced hydrogen jet engines can exploit the cryogenic fuel.



Assumptions: Aircraft design using AIA's low order aircraft design model. Cryogenic tank gravimetric efficiency ranging from 55% to 85%. Advanced hydrogen jet engine improves fuel efficiency by 10% compared to conventional jet engines.

The proportion of an aircraft's weight taken up by fuel increases with its range. On long-range flights, fuel can account for 45% of the aircraft's take-off weight. Switching from kerosene to hydrogen, even when factoring in the weight of cryogenic fuel tanks, cuts this fuel weight in half. This weight advantage becomes more pronounced as the aircraft's range increases, giving hydrogen-powered aircraft a growing fuel efficiency edge over kerosene-powered ones on longer flights.

However, liquid hydrogen requires around four times the volume of kerosene. This larger volume, combined with the need to store hydrogen in the fuselage, necessitates a larger aircraft design, leading to higher structural weight and increased drag. As a result, kerosene-powered aircraft are more fuel-efficient on short ranges, while hydrogen aircraft excel at longer ranges. It's important to note that no modern hydrogen jet aircraft has been manufactured yet, so there is significant uncertainty.

Additionally, cryogenic hydrogen enables advanced jet engine designs that can improve fuel efficiency by about 10%. This gain is achieved by harnessing the additional energy stored in the hydrogen fuel during liquefaction and exploiting hydrogen's thermal properties. Overall, the potential energy reduction for long-haul hydrogen-powered flights is estimated to be 10-15% lower than for kerosene-powered aircraft.

Practical delivery of the 2030 Goals

The 2030 Goals are designed to drive substantial and systemic change in the aviation sector. History shows that crafting effective policies and strategies to achieve such a significant shift is incredibly challenging, often leading to imperfect outcomes and requiring multiple iterations. Therefore, it is crucial that decision-makers developing these policies and strategies can access the insights within the model simply and intuitively. This would enable them to experiment quickly and grasp the consequences of their actions.

A policy dashboard was developed for the Transatlantic Sustainable Aviation Workshop at MIT in April 2023 to support this need. This tool proved highly effective, enabling a collaborative team of UK, US, and EU policymakers to explore the complexities of the Aviation Impact Accelerator model and identify the most impactful leverage points within the system.

This section will show three future scenarios using a policy dashboard underpinned by the Aviation Impact Accelerator model. The first scenario shows the sector's current trajectory where the 2030 Goals have not been enacted. The second and third scenarios show cases where different combinations of the 2030 Goals have been enacted, enabling net zero aviation to be achieved by 2050.

As discussed in Goal 3, global biomass is limited, with estimates ranging between 50 EJ and 160 EJ. In these scenarios, we have assumed that the practical upper limit for biomass collection is 100 EJ, with aviation aiming to use a maximum of 30% of this total global biomass. While opinions will vary over whether these assumptions are correct, the authors believe they are reasonable.

It is important to note that many potential future scenarios are possible, but only three are shown here. The ones that have been chosen are simply to illustrate the importance of the 2030 Goals for achieving net zero by 2050 and do not represent the preference of the authors.

Scenario 1
Current Trajectory

In this scenario, ambitious targets and mandates for the scaled-up SAF production have been enacted and achieved. However, the four 2030 Goals have not been implemented. As shown below, this scenario fails to achieve net zero aviation by 2050.

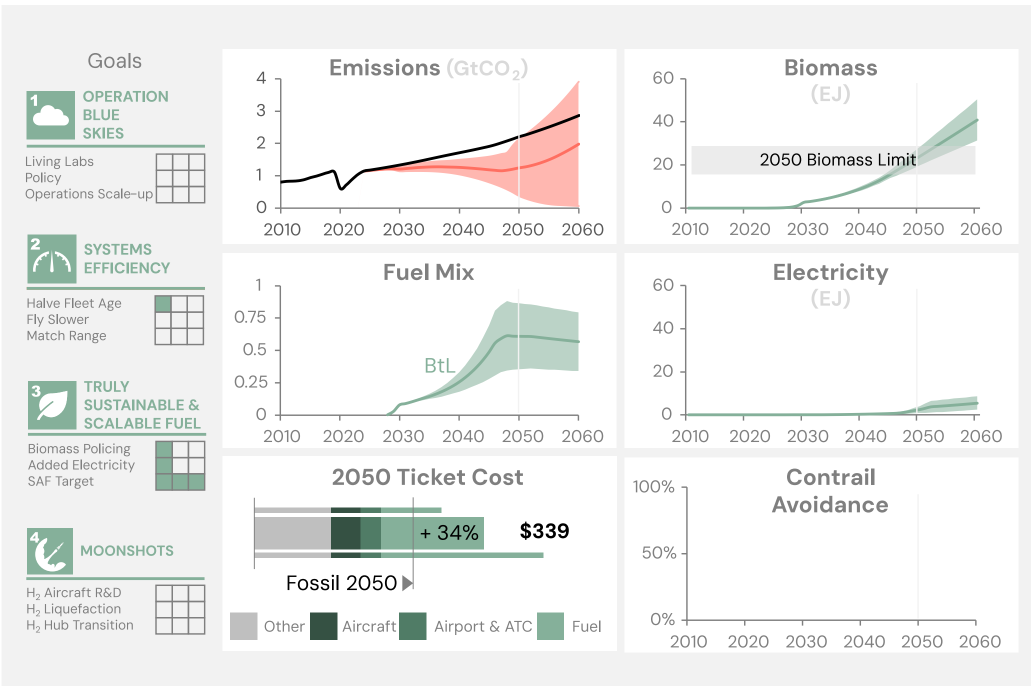
The dashboard indicates the market has scaled up the cheapest form of SAF but has a low level of success in mitigating the cross-sector impact of biomass and low-carbon electricity use. Consequently, aviation consumes more than the desired 30% of this total global biomass. The emissions caused in other sectors mean the uncertainty of the outcome is very high and dependent on the transition path of other sectors. In the worst case, the consequence of the scenario is to raise global emissions.

Additionally, in this scenario aircraft production has increased slightly faster than forecasts from Airbus and Boeing due to the entry of a third manufacturer into the market. This has reduced the retirement age of aircraft by 5 years. Contrail avoidance has been delayed while the focus has been placed on reducing scientific uncertainty.

Scenario 1: Current Trajectory

Ambitious targets for the scale up of SAF production are achieved. The four 2030 Goals are not implemented. Net zero aviation is not achieved by 2050.

Aviation Impact Accelerator



Scenario 2
Net-Zero 2050 — Moonshots

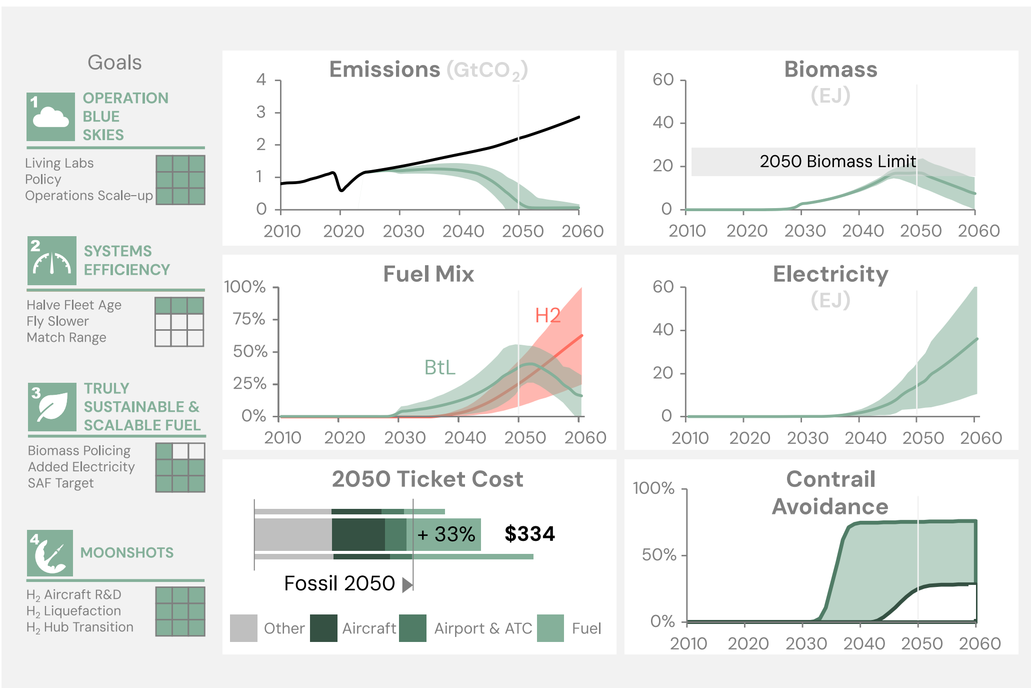
In this scenario, the four 2030 Goals have been implemented, the Hydrogen Technology Demonstrator has proven successful, and the focus has shifted to scaling up long-range hydrogen aviation as quickly as possible. A key advantage of this approach is that, in the long term, it eliminates the need for biomass. Operation Blue Skies has also been successful, with a global contrail avoidance scheme beginning to scale up from 2030. This scenario achieves net-zero aviation by 2050.

To reach net-zero by 2050, the dashboard indicates that additional policies must be implemented. These include increasing aircraft production rates to 50% below current forecasts by 2050, which would halve the average fleet age. This accelerates the introduction of hydrogen-powered aircraft, leading to hydrogen being responsible for a 40% reduction in emissions by 2050. As hydrogen technology is adopted, the aviation sector's reliance on Sustainable Aviation Fuels (SAF) decreases, allowing simpler Biomass-to-Liquid (BtL) plants to meet demand. Consequently, aviation's biomass consumption remains below the target of 30% of global biomass and begins to decline after 2050. Moreover, this scenario eliminates the need for efficiency measures such as flying slower or tailoring aircraft design to specific flight ranges.

Scenario 2: Success of Moonshot Demonstrator

Four 2030 Goals are implemented. Hydrogen Technology Demonstrator is successful, hydrogen aviation is rapidly scaled, and net zero aviation achieved by 2050.

Aviation Impact Accelerator



Scenario 3

Net-Zero 2050 — Truly Sustainable and Scalable Fuel

In this scenario, the four 2030 Goals are implemented, but the result of the Moonshot Demonstrators is that no transformative technology is viable on the necessary timescales. As a result, the pressure on biomass becomes extremely high and must be managed through bold efficiency measures and strong biomass policies. Operation Blue Skies has been successful, with a global contrail avoidance scheme beginning to scale up from 2030. This scenario achieves net-zero aviation by 2050.

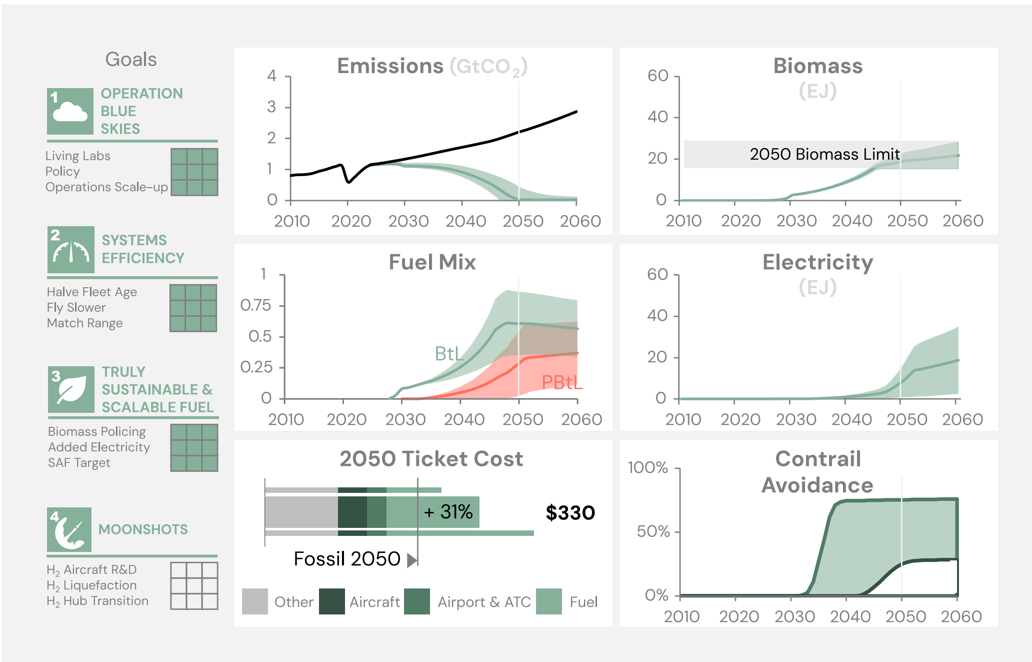
The dashboard indicates that the primary challenge is limiting biomass usage to 30% of global biomass. To achieve this, policies must drive the most aggressive efficiency measures, reducing the demand for SAF by 31% to 50% by 2050. These measures include halving the average fleet age, designing aircraft to fly 15% slower, and ensuring that more aircraft operate closer to their design range. The dashboard also highlights the urgent need to rapidly scale up Power and Biomass to Liquid (PBtL) production starting in the late 2030s, which acts to hold aviation biomass use to the desired level. PBtL plants would need to produce roughly half of the required SAF by 2050.

It is important to note that this scenario heavily relies on successfully scaling up global biomass in an economically and ecologically sustainable manner, leaving the aviation sector vulnerable to external factors beyond its control. In such cases, dashboards powered by models like the Aviation Impact Accelerator are incredibly useful, as they enable the development of policies that are more resilient to known uncertainties and allow for rapid adjustments as new information becomes available.

Scenario 3: Scale-Up of Responsibly Resourced SAF

Four 2030 Goals are implemented. Moonshots are unsuccessful. System efficiency and sustainable and scalable fuels are successful. Net zero aviation is achieved by 2050

Aviation Impact Accelerator



Conclusion

It is crucial to recognise that most existing aviation net-zero pathways mistakenly assume a smooth transition to net-zero, with multiple technologies coexisting beyond 2050. History shows that technological transitions are rarely smooth; competing technologies typically vie for dominance until one prevails and displaces the others. This misperception of a smooth transition is harmful, as it creates the illusion that delaying action will result in only a minor increase in emissions by 2050. The findings of this report, supported by the Aviation Impact Accelerator (AIA) model, clearly demonstrate that this assumption is flawed. Without bold intervention today, the opportunity to transform the aviation industry will be lost.

This report outlines an ambitious five-year plan to set the aviation sector on a path to achieving net-zero by 2050. It establishes four key Sustainable Aviation Goals for 2030, each targeting critical leverage points. If these goals are not immediately implemented and achieved by 2030, the window for transformation will close, leaving the world to face the escalating climate consequences of a rapidly expanding aviation industry, which is projected to at least double by 2050. The urgency of this moment cannot be overstated.

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Citing this report

Aviation Impact Accelerator, 2024. Five Years to Chart a New Future for Aviation: The 2030 Sustainable Aviation Goals [R.J. Miller, E.N. Whittington, S. Gabra, P.J. Hodgson, J. Green, J. Kho, J.R. Smith, D. Singh]. AIA, University of Cambridge. doi: 10.17863/CAM.112375.

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Partners

We would like to thank our partners for supporting and funding the AIA. Without their support this report would not have been possible: 4AIR, Boeing, Emirates, Flexjet, Quadrature Climate Foundation, Reviate at Breakthrough Energy, Rolls-Royce, Stratos, the Sustainable Markets Initiative, the Royal Air Force, UK Department for Energy Security and Net Zero, UK Department for Transport, Massachusetts Institute of Technology, University of Melbourne, and University College London.

Transatlantic Sustainable Aviation Partnership

The organisations who attended the inaugural meeting of the Transatlantic Sustainable Aviation Partnership at the Massachusetts Institute of Technology (MIT) in April 2023, hosted jointly by the University of Cambridge and MIT, where the original concepts for the four Goals were conceived included: Aerospace Technology Institute (ATI), EU Clean Aviation, Massachusetts Institute of Technology (MIT) Laboratory for Aviation and the Environment, National Aeronautics and Space Administration (NASA), Penn State University, UK Department for Business & Trade (DBT), UK Department for Transport (DfT), University College London (UCL), Air Transport Systems Lab, University of California San Diego, University of Cambridge Aviation Impact Accelerator, USA Federal Aviation Administration (FAA), and Washington State University.

It should be noted that the views published in this report are those of the Aviation Impact Accelerator and do not represent the specific views of those attending the workshop.

Acknowledgments

We would like to acknowledge the contributions of the following people to the report, the underlying model, and the Transatlantic Sustainable Aviation workshop and roundtable: Mansoor Abulhoul, Omer Aiuby, Caleb Akhtar Martinez, Florian Allroggen, Jill Ashcroft-Campion, Beth Barker, Nils Barner, Steven Barrett, Kilian Bartsch, Phoebe Bendall, Peter Bennett, Mark Bentall, JoeBen Bevirt, Dirsha Bohra, Paul Bond, Samuel Brockie, Jean-Francois Brouckaert, Lucy Bruzzone, Ghenadie Bulat, Freya Burton, Johnston Busingye, King Charles III, Nathan Clark, Richard Clarkson, Polly Courtice, James de Salis Young, John Dennis, Haldane Dodd, Nicole Didyk Wells, Sebastian Eastham, Liz Edwards, Jenifer Elmslie, Gary Fitzgerald, Lara Fowler, Henry Free, George Freeman, Steve Freeman, Gene Gebolys, Maja Glavin, Jordi Gomez-Alberti, Jon Gordon, Matthew Gorman, Holly Greig, Ewan Gribbin, Paul Griffiths, Chez Hall, John Hansman, Shaun Harris, Eric Hendricks, James Hileman, Malcolm Hillel, Ian Henderson, Gim Huay Neo, Eisaku Ito, Shaun Ho, John Holland-Kaye, Lindsay Hooper, Jerome Jarrett, Jennifer Jordan-Saifi, Julia King, Richard Knighton, Axel Krein, Joyce Light, Prem Lobo, Lorraine Lorimer, Nateri Madavan, Angela McLean, Anmol Manohar, Charalampos Michalakakis, Matteo Mirolo, Alan Mitchell, Paul Monks, David Morgan, Adam Morton, Herve Morvan, Abby Munson, Massimiliano Nardini, Andy Neely, Anna Oldani, Anil Padhra, Ralph Percival, Oriel Petry, Annie Petsonk, Ben Petty, David Pitchforth, Prakash Prashanth, Deborah Prentice, Matt Prescott, Tony Purnell, Miruna Rapeanu, David Reiner, Kennedy Ricci, Alex Routh, Richard Sandberg, Dinesh Sanekommu, Andreas Schafer, Marc Shapiro, Grant Shapps, Vidhi Sharma, Sarah Sharples, Raymond Speth, Noli Shelala, James Stephens, Marc Stettler, Andrew Sweeney, Jack Swerdlow, Katharina Tegethoff, Neil Titchener, Nigel Topping, Mark Turner, Adam Twidell, Patrick Vallance, Maria Vera-Morales, David Victor, Grazia Vittadini, Edgar Waggoner, Richard Wahls, Ian Waitz, Kevin Welsh, Andrew Wheeler, Michael Wolcott, Tom Yorke, and Brian Yutko.

About

The Aviation Impact Accelerator

The Aviation Impact Accelerator (AIA) is a global initiative jointly led by the University of Cambridge's Whittle Laboratory and Institute for Sustainability Leadership (CISL), bringing together experts from across the sector and beyond to accelerate the transition to climate-neutral aviation. Our mission is to develop evidence-based tools and insights to allow decision makers to map, understand and embark on the pathways towards sustainable flight.

To find out more about how to get involved, contact us at info@aiazero.org.

The Whittle Laboratory

The Whittle Laboratory at the University of Cambridge is one of the world's leading laboratories working on reducing the climate impact of aviation and power generation. The Lab has partnered with industries such as Rolls-Royce, Mitsubishi Heavy Industries, Siemens and Boeing for over 50 years successfully translated hundreds of primary research ideas into industrial products. Its research has been awarded the American Society of Mechanical Engineers highest honour, the 'Gas Turbine Award' 15 times, more than any other institution or company. In 2026, the New Whittle Laboratory will open, housing the Bennett Innovation Laboratory and the UK National Centre for Propulsion and Power.

The University of Cambridge Institute for Sustainability Leadership

CISL is an impact-led institute within the University of Cambridge that activates leadership globally to transform economies for people, nature and climate. Through its global network and hubs in Cambridge, Cape Town and Brussels, CISL works with leaders and innovators across business, finance and government to accelerate action for a sustainable future. Trusted since 1988 for its rigour and pioneering commitment to learning and collaboration, the Institute creates safe spaces to challenge and support those with the power to act.

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