



Shell Scenarios | Sketch

The 2026 Energy Security Scenarios

Aviation and energy to 2100

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Key observations

This publication explores the future of aviation through three scenarios which recognise that the world is being shaped by national security agendas, competitiveness and climate concerns, with potentially world-changing technologies like artificial intelligence (AI) rushing headlong towards us.

At Shell, scenarios analysis plays a key role in understanding the longer-term energy system, technology, geopolitical and social trends. It is not an expression of Shell's strategy or business plan.

There are two exploratory scenarios in **The 2026 Energy Security Scenarios: Surge** and **Archipelagos**.

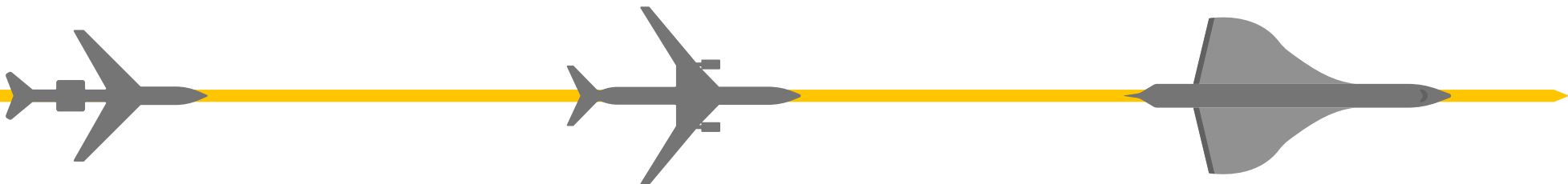
In **Surge**, an era of robust economic growth is ushered in by the rapid adoption of AI technologies, with higher economic growth and AI infrastructure driving up energy demand.

The **Archipelagos** scenario sees a world that reacts to the pressures of regional conflicts, increasing migration across multiple borders and uneven global trade patterns. Concerns mount over trade, reliable allies, a new superpower, resource availability, and the environment. In a world of uncertain and confusing signals, these concerns lead to both domestic prioritisation of key resources and new global alignments. Countries act as if global conflict is imminent, yet the scenario has no such outcome. The underlying driver within the scenario is a global realignment of influence.

Horizon, the third scenario, is normative and designed to understand the full depth and speed of change required to achieve net zero CO₂ emissions by 2050. It illustrates a rapid acceleration of the energy transition and the introduction of carbon-management practices, including for land use, to sharply reduce emissions.

- The global aviation industry is projected to exceed \$1 trillion in revenue in 2026, supporting some 865 million jobs and contributing over \$4 trillion to the global economy. Annual passenger numbers are expected to reach 5.2 billion in 2026.

- From a starting point in 1960 when global passenger aviation amounted to 100 billion passenger kilometres per year, demand increased tenfold by 1980 and nearly a hundredfold by 2020. In 2025, some 30,000 commercial aircraft were in service.
- In 2026, CO₂ emissions from commercial aviation could account for 2.3% of total anthropogenic CO₂ emissions, or more than 1 billion Mt. However, total aviation emissions (including CO₂, NO_x, soot, sulphate aerosols and water vapour) are potentially warming the climate at approximately three times the rate of that associated with aviation CO₂ emissions alone.
- The scenarios show strong growth in aviation demand over the century, with passenger demand more than doubling by mid-century and continuing to grow strongly in the second half of the century.
 - Developed countries have reached, or will soon reach, peak spend on aviation as a proportion of per capita GDP. Although absolute demand continues to rise, growth in the sector lags GDP per capita.
 - While overall demand is dominated by North America in the 2020s, this shifts to China by mid-century and then to India.



- Sectoral change will be measured in decades, not years. For example, in the rapid transition of the **Horizon** scenario:
 - It takes until 2058 for conventional jet fuel demand to fall by 50%.
 - The scaling of bio-SAF (sustainable aviation fuel) is dependent on cellulosic processing, which begins at scale in the late 2020s.
 - Synthetic fuels (e-SAF) are not in use at scale until 2040, limited by cost and the commercial development of direct air capture.
 - The first hydrogen aircraft enter service in 2040.
 - Small battery-electric planes enter service in 2030 but have little impact on sector CO₂ emissions.
- In **Surge** and **Horizon**, the demand for ethanol in passenger cars declines by at least a third by the mid-2040s as vehicles trend towards battery-electric operation. This frees up 30 million tonnes per year of ethanol globally. Aviation provides an opportunity to sell that fuel into a potentially higher-value market, but only after conversion to bio-SAF.
- In **Archipelagos**, domestic demand for biofuels in many countries is driven by security concerns. This leads to an overall growth in production, but tightens the availability for aviation due to competition from other sectors.
- In **Surge** and **Horizon**, sustainability criteria in regulated markets will demand that land use considerations are factored into the production of bio-SAF, which in turn will provide impetus to the nascent cellulosic route for ethanol production. The same trend eventually emerges in **Archipelagos**, but not until after mid-century.
- All airlines will require access to bio-SAF, but early production is highly skewed geographically. Particularly in **Surge**, book-and-claim systems allow major existing biofuel producers to leverage their scale and move quickly to build large facilities for cellulosic processing and converting ethanol to jet fuel, which in turn supports the rapid scaling of a nascent industry.
- e-SAF production is possible, but the technology faces considerable commercialisation and scale challenges. A single 10,000 barrel per day e-SAF facility, sufficient to meet the 1% blend ratio under the EU synthetic fuel mandate for 2030, would require 15 GW of solar photovoltaic (PV). This is equivalent to all the solar PV installed in Germany in 2024.
- e-SAF production is dependent on a ready source of atmospheric carbon, but direct air capture technology is very limited in the 2020s and is yet to be proven commercially viable at a scale that is material for global CO₂ management. e-SAF production using biogenic carbon helps the industry become established in **Surge** and **Horizon**. In **Archipelagos** the e-SAF industry fails to emerge.
- Given the increasing use of bio-SAF, the development of e-SAF, the constant improvement in fleet efficiency through technology change and fleet turnover and the introduction of novel propulsion aircraft, emissions are still likely to rise in the foreseeable future.
- With no scenario outcome showing aviation fuel use even close to net zero CO₂ emissions by 2050, CO₂ offsets will be required to reach that goal. These would likely be carbon removal units associated with long-term reforestation projects and the geological storage of CO₂.
- While offsets can be used to meet interim reduction targets, in **Surge** there is insufficient global availability of high-quality carbon removal offsets for aviation to reach net zero CO₂ emissions by 2050. In **Archipelagos**, some voluntary offsets are used, but progress towards net zero CO₂ emissions in aviation is not a global priority.
- In **Horizon**, aviation achieves net zero CO₂ emissions around 2050, given the scenario design forces the world on such a trajectory. However, the aviation sector would need to purchase about a fifth of the available global pool of carbon removal units to achieve the net zero target.

Aviation today

The global aviation industry is a massive sector with significant economic impact, projected to surpass \$1 trillion in revenue in 2026, supporting 86.5 million jobs and contributing over \$4 trillion to the global economy.

Annual passenger numbers are expected to reach 5.2 billion in 2026 and around a third of world trade by value is transported by air. Some 60% of all international tourists travel to their destinations by air.

In 2026, the global commercial aviation sector is expected to consume some 7.2 million barrels per day of liquid hydrocarbon fuel, compared with around 100 million barrels per day of oil production in total. Of the hydrocarbon fuel used by aviation, less than 1% is sustainable aviation fuel with bioenergy origins (bio-SAF).

Net carbon dioxide emissions from aviation amount to more than 1 billion tonnes per year, or 2.3% of total anthropogenic CO₂ emissions. While this is modest in the context of today, it becomes problematic as emissions in other sectors decline and demand for aviation continues to grow rapidly.

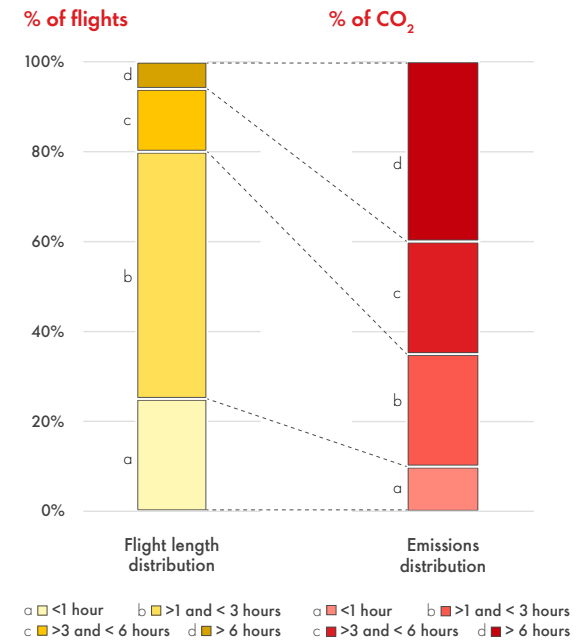
CO₂ emissions from aviation are also highly asymmetric, in that 20% of flights account for about 65% of emissions. This is because 80% of flights take less than 3 hours on smaller highly efficient planes (see References, item 2).

By 2050, CO₂ emissions from aviation could conceivably be more than 10% of the global total, given reductions in the global amount and increases in aviation demand. The sector is therefore under pressure to manage emissions and achieve net zero CO₂ emissions by 2050.

Scenarios analysis, making use of **The 2026 Energy Security Scenarios**, is an ideal approach to examine what those pathways and timelines might be.

At Shell, scenario analysis plays a key role in creating context and growing understanding around the energy system, technology, geopolitical and social trends. Scenarios are an exploration of how the world could possibly evolve under different sets of assumptions. But scenarios are not expressions of Shell's strategy or business plan. Shell scenarios are informed by data, constructed using models, and they contain insights from leading experts in relevant fields.

Estimated aviation flight length and emissions distribution in 2025



[See the accessibility description](#)

Aviation by the numbers

- There are over 30,000 commercial aircraft in active service worldwide in 2026.
- The global commercial aircraft market, dominated by Airbus and Boeing, is projected to see significant growth, with the global fleet expected to expand to more than 38,000 aircraft by 2035.
- The industry projects travel to touch 10 trillion revenue passenger kilometres in 2026.
- The airline industry is projected to exceed revenue of around \$1 trillion in 2026.
- In 2025 there were some 40 million flights carrying 5.5 billion passengers. The average flight distance is 1,400 km and the average number of passengers per flight is 165.
- Global air cargo demand is projected to reach 290 billion tonne kilometres in 2026. This equates to growth of around 3% per year through 2025 and 2026.
- Aviation CO₂ emissions could be more than 1 billion tonnes in 2026.
- Some 80% of flights take less than three hours, but these generate only 35% of aviation CO₂ emissions.
- Only about 5% of the global population travels internationally by air in a given year.



The 2026 Energy Security Scenarios

As the national security mindset dominates, and the global competitive landscape becomes more intense, national interests take precedence within political agendas.

These agendas are shaped by concerns over insipid economic growth, AI technologies that provide additional advantage to already advanced economies, growing militarism from traditional adversaries, and increasing climate pressures driven by extreme weather events.

Three scenarios emerge from the pressures facing nations: **Surge**, **Archipelagos** and **Horizon**.

In **Surge**, an era of robust economic growth is ushered in by AI technologies that are welcomed and not overly challenged, with economic growth and AI infrastructure driving up energy demand. The geopolitical landscape offers a spur for change as China and the USA compete for AI dominance.

The **Archipelagos** scenario sees a world that reacts to regional conflicts, increasing migration across multiple borders and uneven global trade patterns. The underlying driver within the scenario is a global realignment of influence. China is increasingly positioning itself as a technology leader. The shift in balance fractures the post-war pattern of US and European power, with the emerging economies following new money rather than old power bases. China leads not by replacing the USA as global hegemon, but by reshaping the terms of trade, technology and diplomacy.

Although China is ascendant, it is not triumphant. The USA is diminished, but not irrelevant. In the space left behind key middle powers scramble for advantage, navigating a fractured, unpredictable global order. They ride multiple currents rather than anchor to one and succeed in an increasingly transactional economic environment. Countries act as if global conflict is imminent, yet the scenario has no such outcome.

Horizon is illustrative of a rapid acceleration of the energy transition and introduction of carbon-management practices to sharply reduce emissions, both in response to a comprehensive policy framework with strong societal and political support.

Importantly, **Horizon** takes a normative approach aimed at a world that achieves two key things: net zero CO₂ emissions by 2050 and global warming limited to 1.5°C by the end of the century.

Each scenario features a unique global growth trajectory. In **Archipelagos**, trade tensions and global decoupling result in a low-growth scenario, with the world economy smaller by approximately 8% in 2050 than in **Horizon**. The reduction in annual growth is more profound in the coming decade to 2035 than in the period 2035 to 2050.

Surge is built on the highest growth assumptions, with a boost in productivity emerging from deeper use of AI technologies in global supply chains. New goods and services also emerge, further boosting growth. A middle class emerges that aspires to greater wealth, travel and acquisition of material possessions, although not to the extent seen in Europe and the USA in the 20th century. New digital-based products also change consumer habits.

Horizon is a normative middle case, with global economic growth between 2.5% and 3% for the balance of the 2020s and just below 2% through to 2100.



Three distinct storylines in a period of apparent polycrisis

The scenarios explore the challenges the world faces as countries deal with aggressive neighbours and adversaries, face mounting trade issues and grapple with migration, while still attempting to reap the benefits of global technology developments like AI and manage rising greenhouse gas emissions.

Horizon

A normative scenario illustrates how long-term environmental security is delivered as the world reaches net zero emissions by 2050, while aiming for 1.5°C.

Archipelagos

Security through realignment is pursued as self-interest and security concerns become deeply rooted in the national psyche. Economic growth suffers and, while global conflict doesn't emerge, nations act as if it will.

Surge

Economic security emerges through growth and productivity improvements, with AI technologies reshaping society and driving rapid change in the energy system.



Generated by AI

Trends in demand for aviation

While commercial mail, freight and passenger uses for aviation date back well over a century, the modern era of rapid long-distance travel by jet started with the British De Havilland Comet, which first entered service in May 1952. But the real transformation came in 1958 with the reintroduction of the Comet 4 after metal fatigue issues had grounded the original Comet fleet in 1954, and the introduction of the Boeing 707 and its use for trans-Atlantic travel.

Passenger aviation

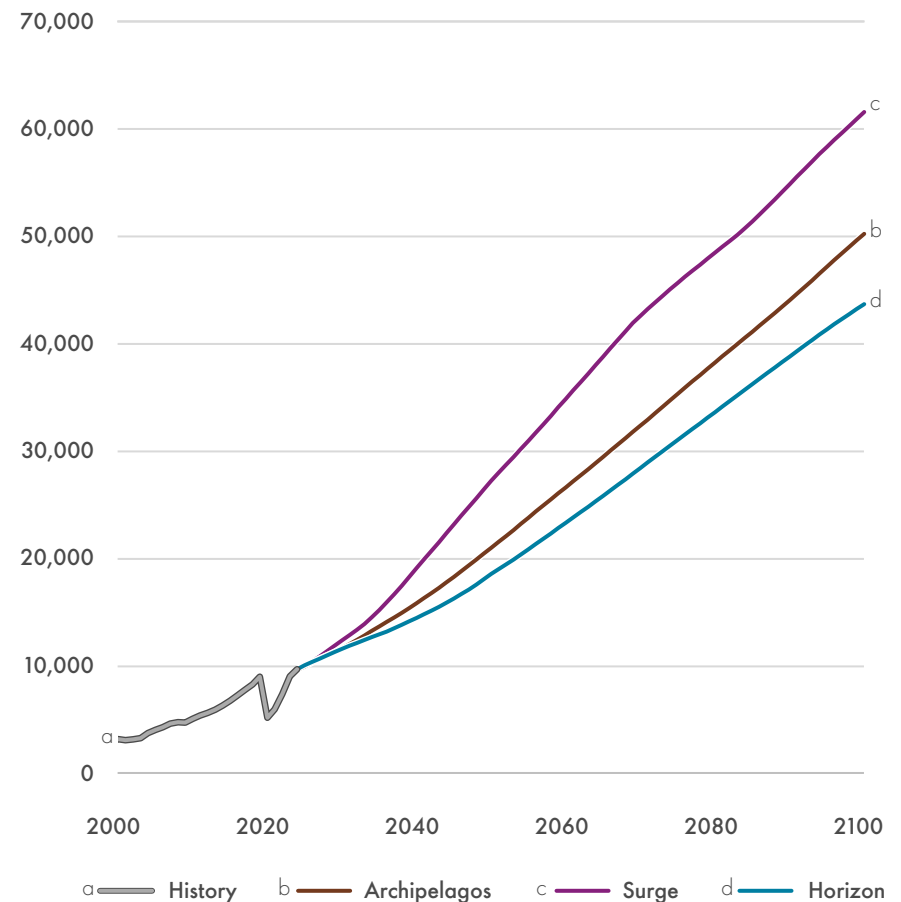
From a starting point in 1960 when global passenger aviation amounted to 100 billion passenger kilometres per year¹, demand increased tenfold by 1980 and nearly a hundredfold by 2020. In 2025, some 30,000 commercial aircraft were in service.

In all three scenarios, demand for passenger aviation continues to grow, not only in developing markets where aviation is relatively limited today, but also in the well-developed markets of Europe and North America.

¹Two Boeing 707-120 planes each with 160 passengers and each doing 400 return trips of 4,000 km – e.g. New York to Los Angeles – per year equates to one billion passenger kilometres.

A solid growth trend for aviation in all scenarios

Billion passenger kms per year



[See the accessibility description](#)

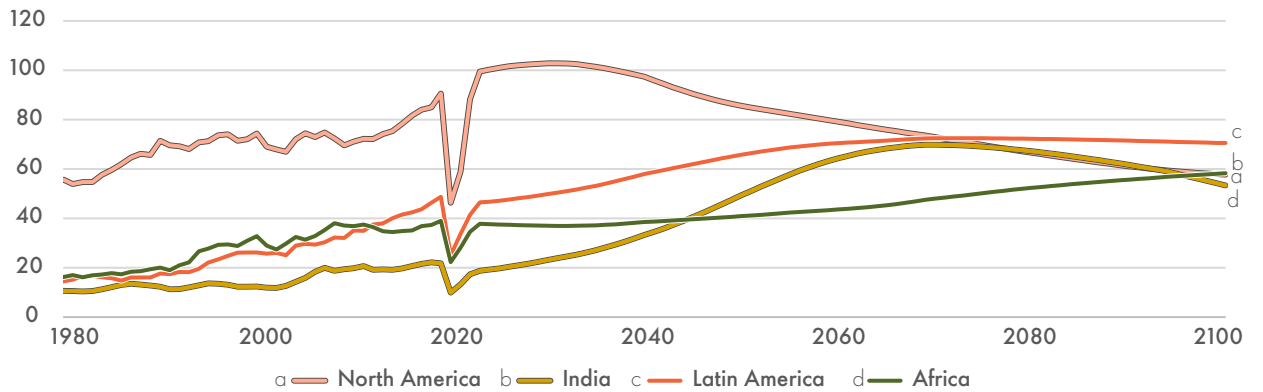
Surge exhibits the strongest growth, with demand tripling by the mid-2050s on the back of its stronger overall economic growth. In **Horizon**, growth is solid, but demand has only doubled by the mid-2050s, due to consumers shifting their behaviour in response to climate concerns and the further development of rail.

Within the growth trends, a more subtle undercurrent emerges. The developed countries have reached, or will soon reach, peak spend on aviation as a proportion of per capita GDP. Although absolute demand continues to rise, growth in the sector lags GDP per capita. This is driven by technology alternatives to travel and new options for discretionary spending. In the emerging economies, the trend reversal is either much later, flatter or not visible within this century.

While overall aviation demand is dominated by North America in the 2020s, this shifts to China by mid-century and then to India as illustrated in **Surge**.

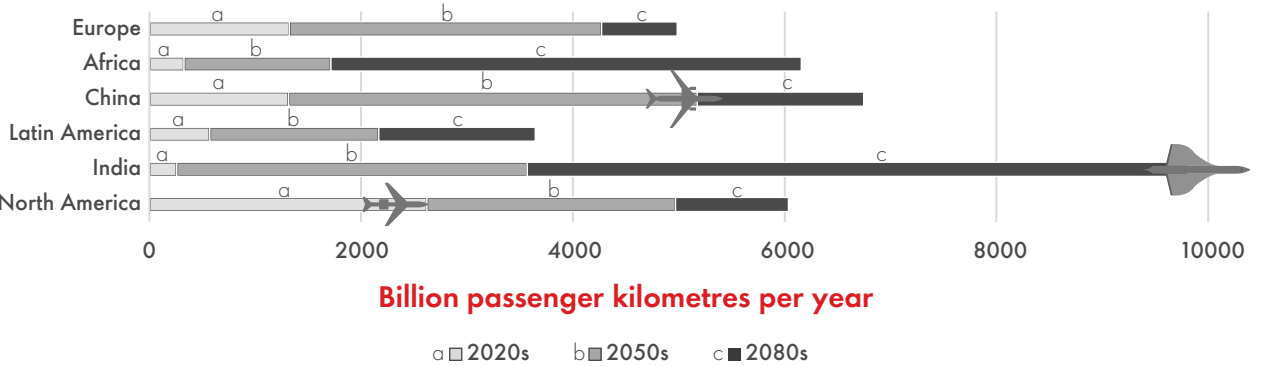
Aviation travel per unit of GDP in the **Surge** scenario

Flight kilometres per \$'000 of GDP per person



[See the accessibility description](#)

Passenger aviation market development by region in **Surge**



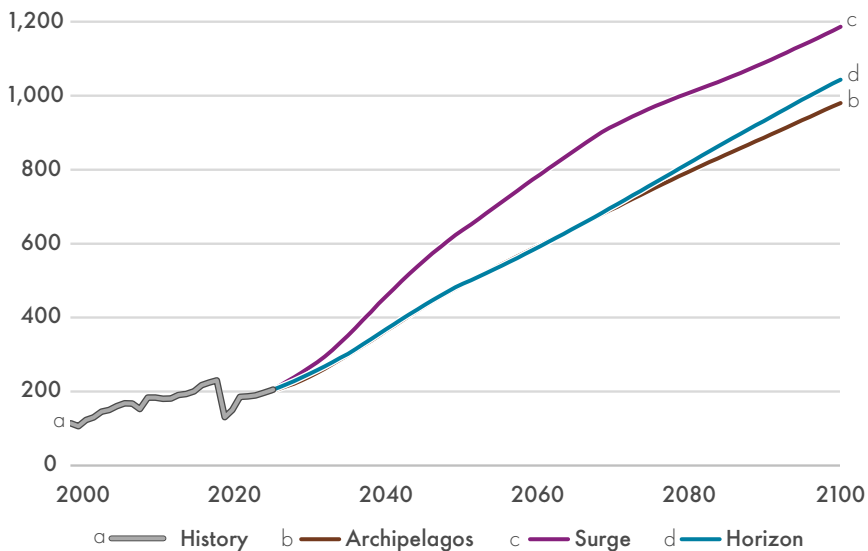
[See the accessibility description](#)

Air freight

Air freight was essentially non-existent in 1960, apart from within the military. By 2025, many passenger flights also carried freight and there were some 2,500 dedicated air-freight planes in operation. This could surpass 4,500 by the mid-2040s, resulting in 500 billion tonne-kilometres of air freight carried each year. All three scenarios expect this figure to reach 1 trillion tonne-kilometres by 2100.

Air freight development in the 21st century

Billion tonne-kilometres per year



[See the accessibility description](#)

Aviation and climate change

In 2026, CO₂ emissions from commercial aviation could account for 2.3% of total anthropogenic CO₂ emissions. Commercial aircraft could burn around 350 million metric tonnes of fuel, releasing over 1 billion metric tons of CO₂.

But global aviation operations also contribute to anthropogenic climate change through a complex set of processes that lead to net surface warming. While aviation emissions of CO₂ are important, the overall impact includes nitrogen oxides (NO_x), water vapour, soot and sulphate aerosols, and increased cloudiness due to contrail formation.

Research indicates that contrail cirrus, consisting of linear contrails and the cirrus cloudiness arising from them, yields the largest positive net (warming) effective radiative forcing (ERF) term followed by CO₂ and NO_x emissions. The formation and emission of sulphate aerosol yields a negative (cooling) term. For 2018, the net aviation ERF is +100.9 milliwatts (mW) per m² with major contributions from contrail cirrus (57.4 mW per m²), CO₂ (34.3 mW per m²), and NO_x (17.5 mW per m²). Non-CO₂ terms give a net positive (warming) ERF, with total aviation related emissions currently warming the climate at about three times the rate of that associated with aviation CO₂ emissions alone.

Contrail formation could be managed with future flight management protocols to avoid layers of air where contrail formation and persistence is more likely.

Source: D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, Volume 244, 2021, 117834, ISSN 1352-2310, doi.org/10.1016/j.atmosenv.2020.117834.

Potential aviation technology developments

The aviation sector, while highly commercial in nature, is essentially a technology journey. Its birth is a function of technology development and its success and growth have relied on advanced technology development. Looking forward, technology will have an even larger role in the sector as it seeks a pathway towards net zero CO₂ emissions and ultimately an end to sectoral dependency on fossil fuels. Such a shift will require advanced fuel pathways, novel engine and airframe technology and further improvements in efficiency. These all feature in the three scenarios, but the way in which the various technologies develop is highly dependent on the underlying political, environmental and societal pressures.

Efficiency

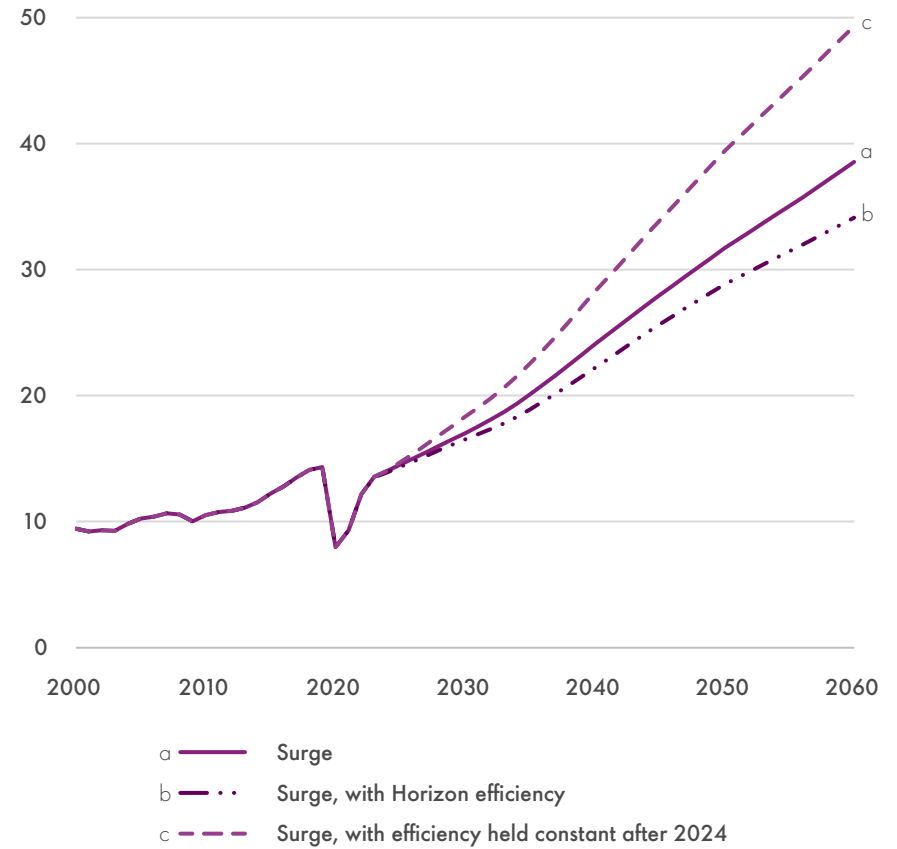
In 1965, a Boeing 707-120 used around five to six litres of fuel per 100 km per person. Sixty years later in 2025, an Airbus A350-1000 uses less than 2.5 litres of fuel per 100 km per person. Modern planes carry more people, fly longer distances and have greater reliability than the Boeing 707-120 in 1965, even though it was a leap ahead in aviation technology at the time.

Over the next 35 years, there is evidence that further gains in aviation efficiency can be achieved, with **Surge** assuming a 30% improvement, equivalent to a wide-body plane such as the Airbus A350 or Boeing 787 operating at less than 1.7 litres of fuel per 100 km per person. Improvements include:

- Advanced turbofan engine design
- New wing shapes
- Lighter construction materials in the airframe
- Improved routing and traffic management
- Data analysis using AI techniques leading to predictive maintenance, better scheduling and faster turnaround times

Aviation final energy demand profiles under varying efficiency assumptions

Final energy, EJ per year



[See the accessibility description](#)

Bio-SAF for aviation

The sustainable aviation fuel (SAF) business is in its infancy today. Global production of bio-SAF could pass two million tonnes in 2026, or 0.7% of total jet fuel production. There are many certified pathways to make SAF, but the HEFA method (hydrotreated esters and fatty acids, such as used cooking oil, animal fats) is expected to account for around 80% of production through to 2030.

New commercial pathways are emerging for fuel production. Promising among these is the conversion of ethanol to jet fuel, capitalising on the significant production of corn and sugar-cane ethanol in the USA and Brazil.

In **Surge** and **Horizon**, the demand for ethanol in passenger cars declines by at least a third by the mid-2040s, as vehicles trend towards battery-electric operation. This frees up 30 million tonnes per year of ethanol globally. In **Archipelagos**, domestic demand for biofuels in many countries is driven by security concerns. This leads to an overall growth in production, but tightens the availability for aviation due to competition from other sectors.

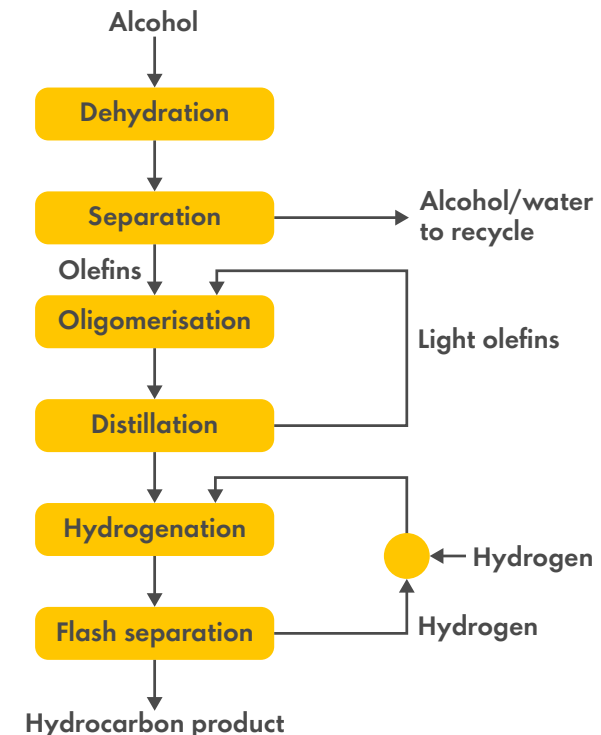
Aviation provides an opportunity to sell ethanol into a potentially higher-value market, but only after conversion. However, diverting conventional agricultural ethanol from the passenger-vehicle market will meet only a limited part of the current 345 million tonne per year fuel demand in the aviation sector.

Sustainability criteria in regulated markets will demand that land use considerations are factored into the production of aviation biofuels, which in turn will provide impetus to the nascent cellulosic route for ethanol production. This route makes use of materials such as agricultural waste, incorporating the breakdown of these raw materials into glucose with enzymes. The glucose is then fermented to make ethanol.

Significantly scaling up bio-SAF production will likely depend on processing routes which do not place additional demands on food crops. In **Surge** and **Horizon**, land use sustainability concerns are a catalyst for change in the biofuel industry, but in **Archipelagos** domestic energy production needs become a higher priority. Cellulosic processing eventually emerges at scale, but not until after mid-century.

Using ethanol to make aviation jet fuel

Alcohol-to-jet fuel processes convert alcohols such as ethanol, which can be easily produced from renewable resources, into the hydrocarbon fuels necessary for jet turbines. The process is based on three catalytic reactions: alcohol dehydration to make ethylene, olefin oligomerisation, and hydrogenation. This is then followed by separation of the synthetic hydrocarbon product to produce jet fuel, diesel fuel for trucks and marine fuel for ships.



Synthetic aviation fuels

With most air travel almost certainly requiring hydrocarbon fuels for much if not all of this century, routes to production other than from fossil fuels become increasingly important as the pressure to manage the global carbon balance increases. One route forward is through the production of synthetic fuels, starting with carbon and hydrogen (H₂) building blocks obtained through the direct air capture of CO₂ or making use of biogenic CO₂ and electrolysis of water respectively. Two synthesis methods are of interest:

First method: Fischer-Tropsch Synthesis

The CO₂ is converted to carbon monoxide (CO) through one of several available processes, such as hydrogen-enabled chemical conversion (the reverse water-gas shift reaction) or a direct electrolysis process. The development of co-electrolytic processes can result in the production of both H₂ and CO from a single electrolyser fed with water and CO₂. The H₂ and CO are then used in a Fischer-Tropsch synthesis step to produce hydrocarbons with a high yield of product suitable as jet fuel.

Second method: Synthesis via Methanol

Methanol is produced as an intermediate product, which can be further converted to jet fuel as described above for ethanol or can be used directly as a fuel for shipping. This route therefore has important demand flexibility. There are two methods for converting CO₂ to methanol. One is to reduce CO₂ to CO as described above and then reduce CO with hydrogen to make methanol. The second method,

which is still evolving, is direct hydrogenation of CO₂ with hydrogen over a catalyst through a one-step process that converts CO₂ directly to methanol.

Synthetic aviation fuels (e-SAF) are an important consideration for the sector in that they can be used directly in existing aircraft (as can bio-SAF) and there should be no concerns relating to land use change and competition with the agricultural food sector. However, several of the process steps involved are very energy intensive and still emerging. Although Fischer-Tropsch synthesis and methanol production have been developed over many years, capturing CO₂ (particularly from the air) and producing hydrogen by electrolysis remain relatively expensive.

A 10,000 barrel per day e-SAF facility, sufficient to meet the demand for the EU synthetic fuel mandate for 2030, would require 15 GW of solar photovoltaic (PV) power. This is equivalent to all the solar PV installed in Germany in 2024.

Hydrogen as a fuel

A longer-term option for aviation could be the development of an alternative fuel and airframe combination. Since the 1950s, liquid hydrogen has been considered a fuel possibility, although serious consideration of this pathway has only emerged in recent years. Liquid hydrogen is very energy dense on a weight basis, which is important for aviation, but it falls short on a volume basis compared to jet fuel. This may require a different airframe design.

While the various technologies required to make use of hydrogen in aviation all exist, the process of design, prototype development, construction, testing, certification and delivery to commercial customers, including the development of suitable airport infrastructure, could easily take two decades.



Battery-electric planes

Recent rapid improvements in battery energy density, with units potentially exceeding 1000 watt-hours (Wh) per litre and 500 Wh per kg well before 2040, open the possibility of battery-electric aviation. Initial models would be short haul for 20 to 50 passengers, operating as commuter flights or bringing regional passengers into larger hub airports for longer-distance travel.

A 1.5 megawatt-hour (MWh) battery, which could weigh 3 tonnes, would allow 20 to 30 passengers to fly around

250 km, sufficient for a short regional flight. A variety of such planes are under development in 2026, although all are dependent on the expectation of improved battery technology. Examples of new battery chemistries that could be promising for aviation applications include solid-state batteries and lithium-sulphur batteries, both of which offer the higher energy densities needed to enable longer-range flights. Recent solid-state battery developments are edging into the energy density range that battery-electric aviation would require.

Short-haul electric planes may also emerge as vertical take-off and landing designs, which could deliver an entirely new business model for commuting.

Very rapid recharging will also be important for the commercial viability of electric aviation, with a 1.5-2 MWh battery capable of being fully recharged in less than 30 minutes between flights.



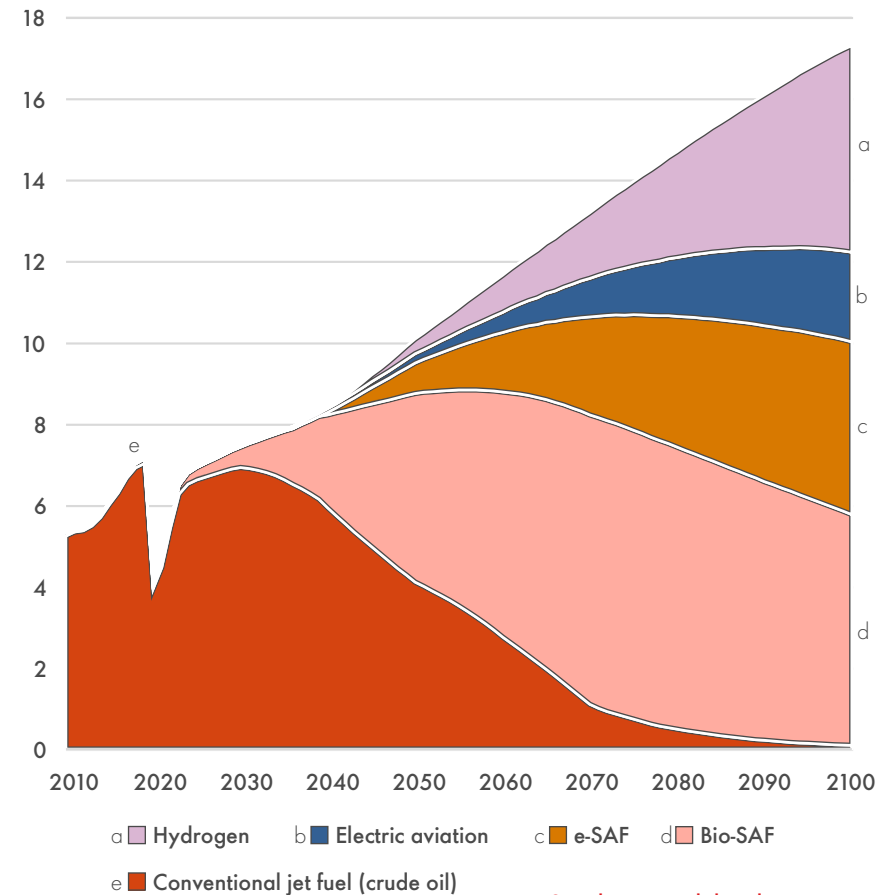
A shifting fuel and technology mix

In 2026, aviation is dependent on oil-derived products – and remains so for several decades – even though the fuel mix begins to shift. The **Horizon** scenario illustrates a maximum potential rate of change in the sector, allowing for the emergence of supporting business models, the development and commercialisation of new technologies and the construction of production facilities. In the case of radical change, such as hydrogen-fuelled aircraft, the time taken for safety testing, government approval, refitting of airport infrastructure and the construction of new aircraft must be considered. **Horizon** also features a rapid shift in aircraft fuel efficiency and a muted increase in demand for aviation as climate concerns shift consumer behaviour and cause governments to invest in alternatives, such as rail infrastructure. Of note in **Horizon**:

- It takes 32 years (until 2058) for conventional jet fuel demand to fall by 50%, and 50 years for a decrease of 90%. But fossil fuel demand hardly increases from 2026.
- Synthetic fuels (e-SAF) are not in use at scale until 2040. This is limited by both high costs and the commercial development of direct air capture (DAC).
- The first hydrogen aircraft test flights start in the mid-2030s, with commercial operation starting in China in 2040 as some 60 planes enter service.
- The scaling of bio-SAF is dependent on cellulosic processing, which begins in the late 2020s and outpaces conventional bio-SAF before 2040.
- Small battery-electric planes enter service in 2030, with more than 1,000 in operation globally by 2040.

The shifting fuel mix for aviation in **Horizon**

Fuel demand, million barrels of oil (equivalent) per day



[See the accessibility description](#)



Surge and **Archipelagos** show different development pathways with overall demand in both scenarios much higher than in **Horizon**.

In **Surge** there is a strong trend towards synthetic fuels after 2040, catalysed by the rapid cost reduction of DAC. With two fuel alternatives (bio-SAF and e-SAF) and ongoing developments in battery technology, hydrogen never emerges as a serious contender.

Instead, the hydrogen is used to make synthetic fuels, without any need to change the underlying aviation infrastructure.

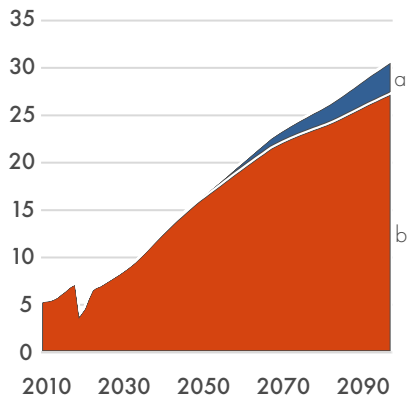
In **Archipelagos**, decarbonisation of the aviation sector is sluggish, lacking priority in a world focused on near-term security issues. Although biofuel production increases globally, demand competition from road transport and ships curtails the use in aviation.

The emergence of a large scale cellulosic processing route is delayed by over a decade, with simpler first generation processes dominating until well into the second half of the century. Similarly, ethanol conversion to jet fuel is slow to scale.

With the DAC industry vanishing in the late 2020s in **Archipelagos**, e-SAF is never established so the liquid-fuel demand splits between conventional jet fuel and bio-SAF.

Aviation fuel demand in **Surge**

Million barrels of oil equivalent per day

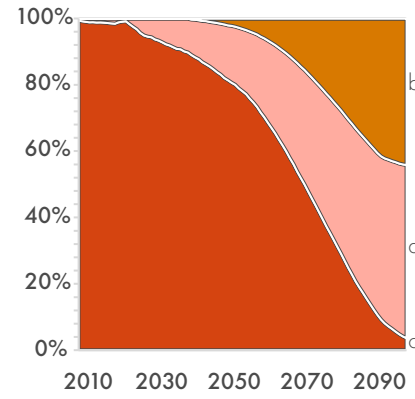


a ■ Electric aviation
b ■ Conventional jet fuel (crude oil)

[See the accessibility description](#)

Liquid fuel mix in **Surge**

Fraction of the liquid fuel mix, %

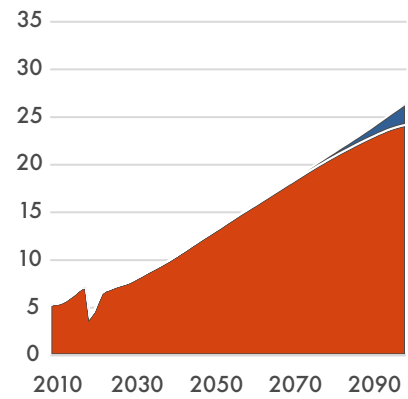


a ■ Bio-SAF b ■ e-SAF
c ■ Conventional jet fuel (crude oil)

[See the accessibility description](#)

Aviation fuel demand in **Archipelagos**

Million barrels of oil equivalent per day

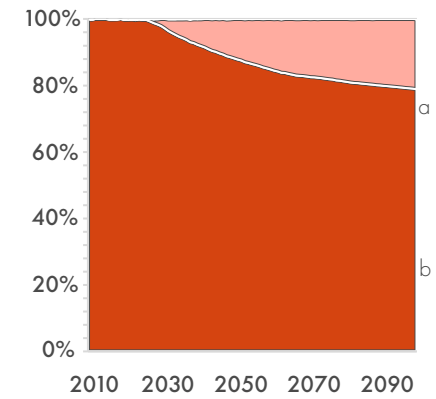


a ■ Electric aviation
b ■ Liquid hydrocarbon fuels

[See the accessibility description](#)

Liquid fuel mix in **Archipelagos**

Fraction of the liquid fuel mix, %



a ■ Bio-liquids b ■ Fossil liquids

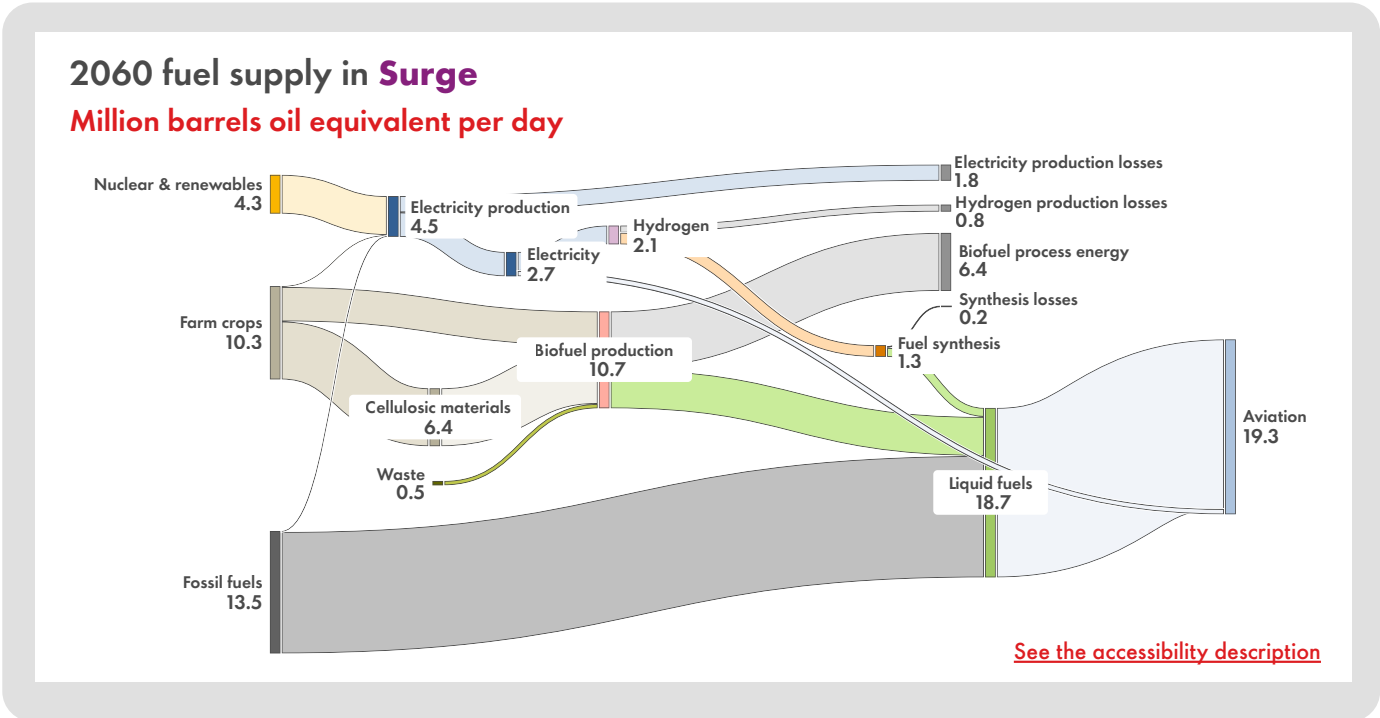
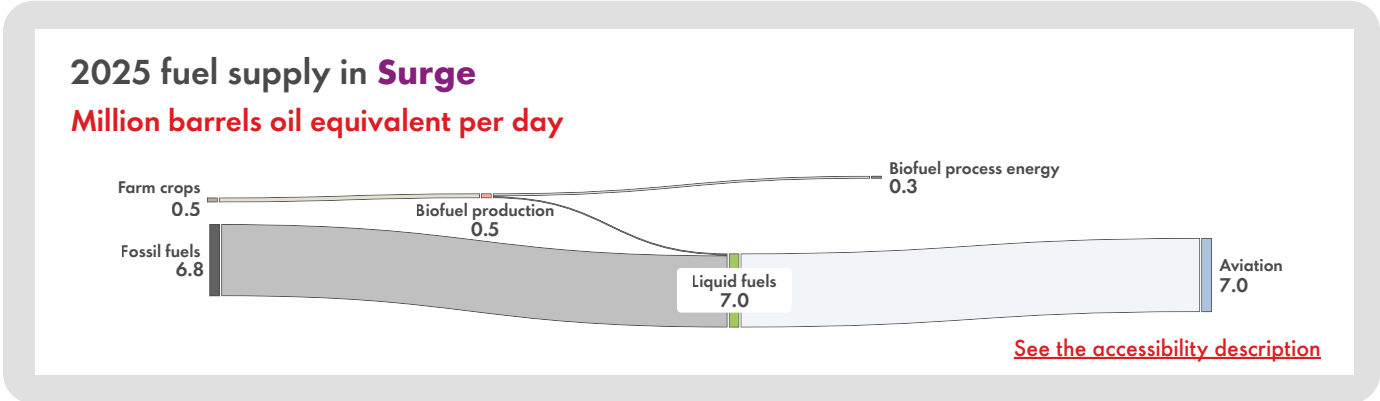
[See the accessibility description](#)

As illustrated in the adjacent charts for 2025, 2060 and 2100, **Surge** offers an example of the development of the aviation fuel system.

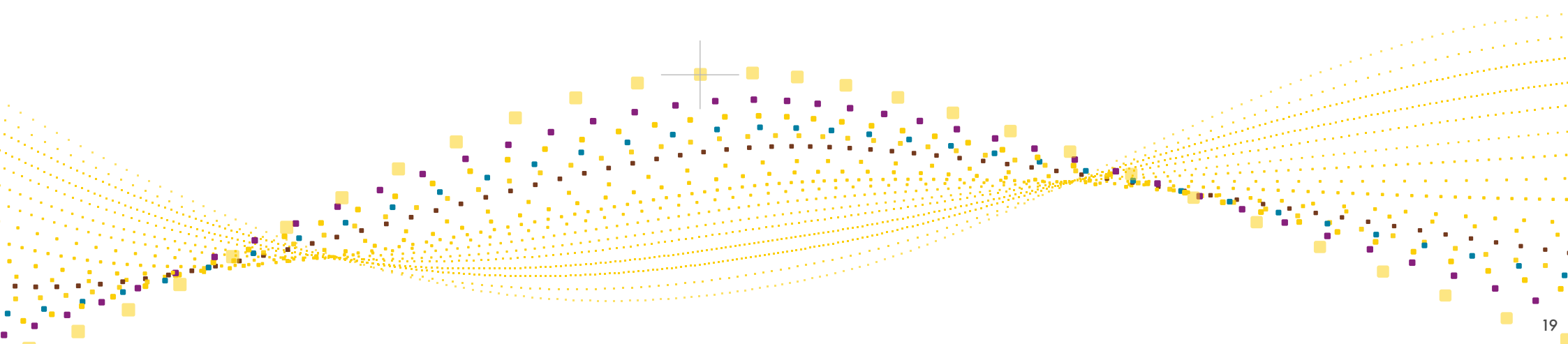
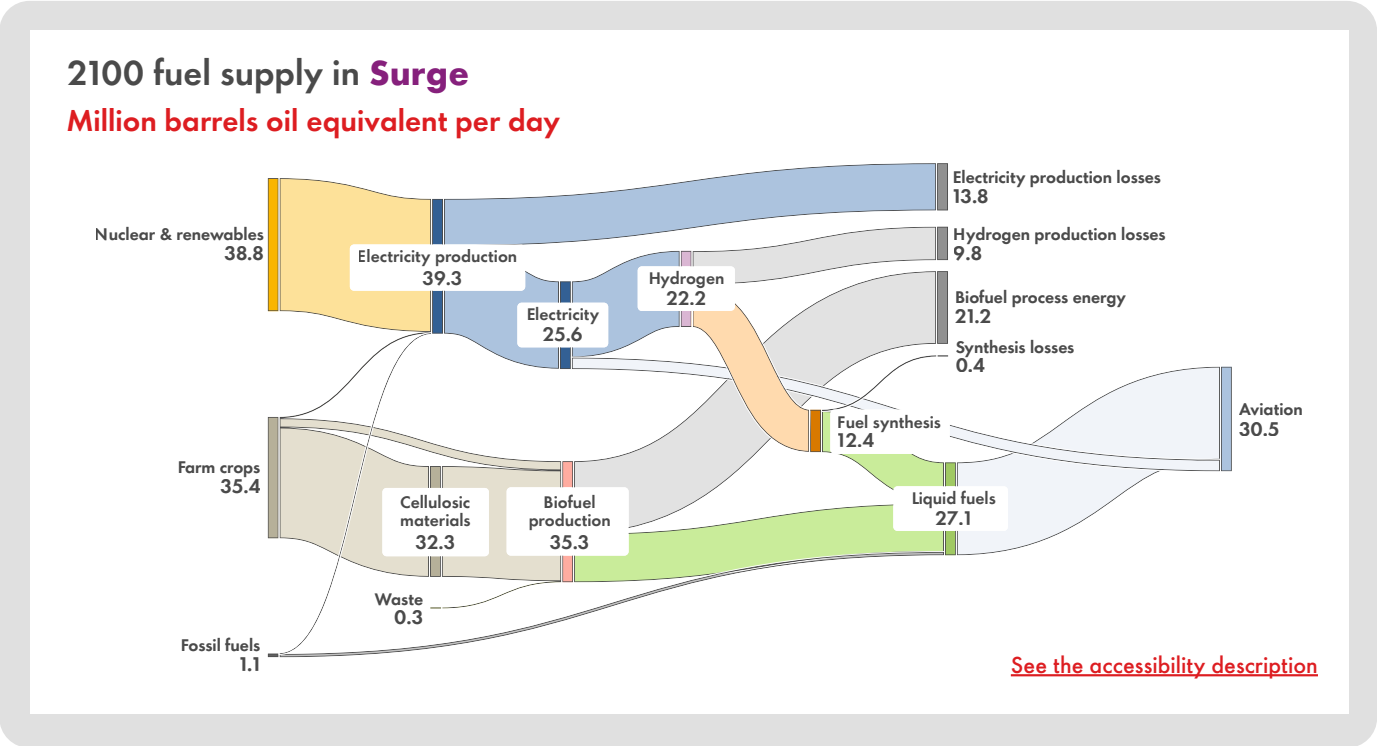
The system is relatively simple in the 2020s when nearly 100% of the energy requirement is derived from fossil fuels. By 2100, fossil fuels have been largely removed from the aviation fuel pool, but the supply pathways have diversified considerably and the system size increased by a factor of five.

In the case of **Surge**, the fuel supply to the plane is largely unchanged throughout the century, remaining as a liquid hydrocarbon middle distillate. For short commuter and hub travel, electric planes emerge from 2040, but even in 2100 liquid fuels dominate.

The shift to alternative fuel pathways has started with bio-SAF and in all scenarios this gains momentum but fails to overtake fossil fuel demand until after mid-century. By 2060 in **Surge**, more than 70% of jet fuel is still derived from fossil-fuel sources.



Unlike **Archipelagos**, **Surge** features the use of synthetic fuels, or e-SAF, from 2040 onwards, but this remains relatively small until much later in the century. By 2100, aviation fuels are largely supplied by bio-SAF and e-SAF in equal amounts. A key determinant in the evolving fuel mix for aviation is the overall growth in demand. It is so rapid in **Surge** that it outpaces the supply of low-carbon alternatives, with fossil fuel use rising until the 2060s. This then becomes a major challenge for the industry given its net zero CO₂ ambition for 2050.





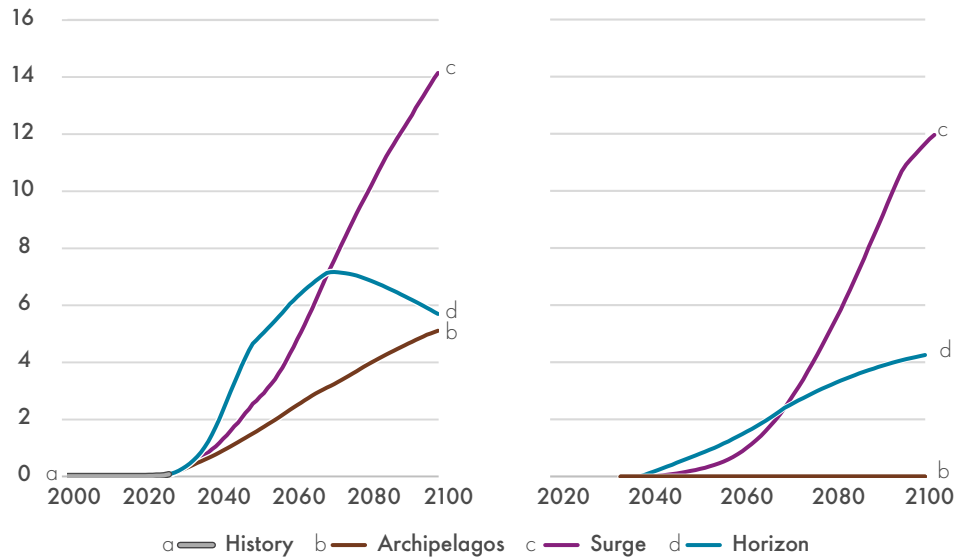
While aviation in **Surge** and **Archipelagos** remain a predominantly liquids-based jet fuel market, **Horizon** branches towards hydrogen to create the fastest decarbonisation pathway. This is led by China, starting in 2040. By 2060, more than 60% of global hydrogen use for aviation is in China and by the 2070s the country is using

12 million tonnes per year of hydrogen for aviation, with most domestic flights using the fuel. By the late 2070s, 3,500 hydrogen planes are operating in China.

Hydrogen appears as a limited option in **Surge** for certain remote flight-paths, but not at all in **Archipelagos**.

The global demand for biofuels for aviation in three scenarios

Bio-SAF, million barrels oil (equivalent) per day



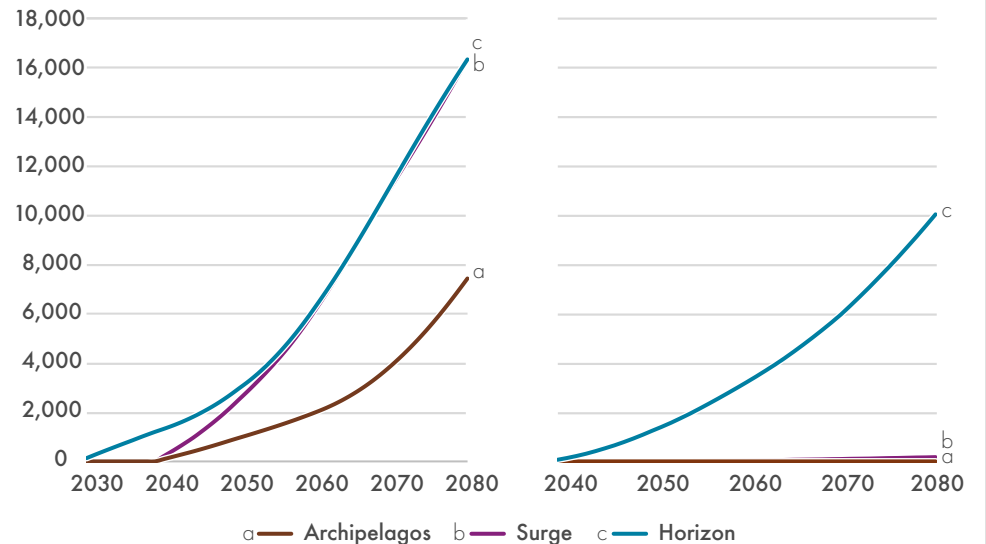
[See the accessibility description](#)

Global synthetic fuel use for aviation

Number of electric commuter planes deployed globally

(<100 passengers, range from 500 km to 1200 km by 2100)

Global hydrogen fleet (number of planes)



[See the accessibility description](#)



Securing jet fuel to meet rising demand

While alternative aviation fuel solutions progress at different pace in the three scenarios, jet fuel derived from crude oil remains the dominant energy source for aviation until the 2070s in **Surge** and for all the century in **Archipelagos**.

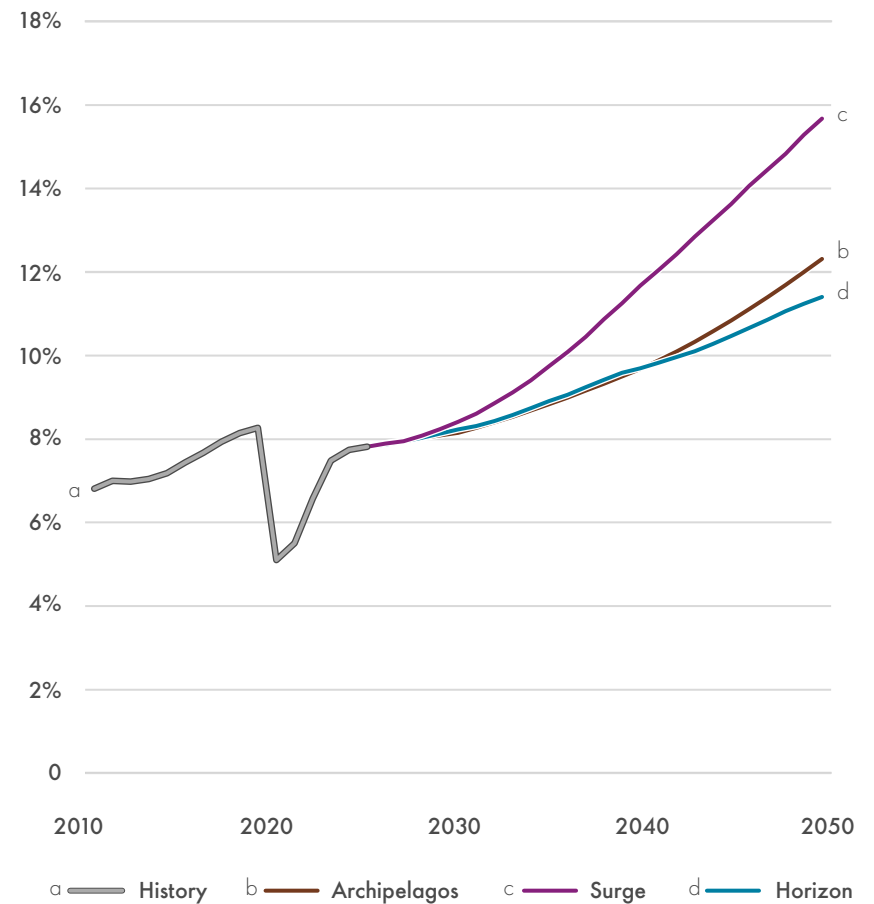
With the continued trend of refining capacity shifting from Europe, Japan and North America towards the Middle East, Asia and China, supply security for jet fuel increasingly becomes a strategic theme, especially for Europe.

In addition, the trend towards electrification of road transport in combination with strong growth in aviation demand challenges the global refining system to deliver a higher share of jet fuel in the product mix.

The required change in refinery jet fuel yield can be largely accomplished by investing in additional hydrocracking capacity to convert heavy crude oil molecules into middle distillates, including jet fuel. In addition, further investment for more effective separation of jet fuel molecules from adjacent refined products will be required. In **Surge**, the combined investment doubles the jet fuel yield from crude oil in 25 years, rising from 8% of refined products to 16%. Without such investments, refiners will need to process additional crude to meet future jet fuel demand.

Refinery yield of jet fuel from crude oil

Expressed as a fraction of refined product demand (Yield, %)



[See the accessibility description](#)

Land-use considerations

In 2026, global biofuel production requires about 80 million hectares (Mha) of land. Nearly half of this is in Brazil and the USA with the balance widely distributed across many countries. This production is primarily for road transport.

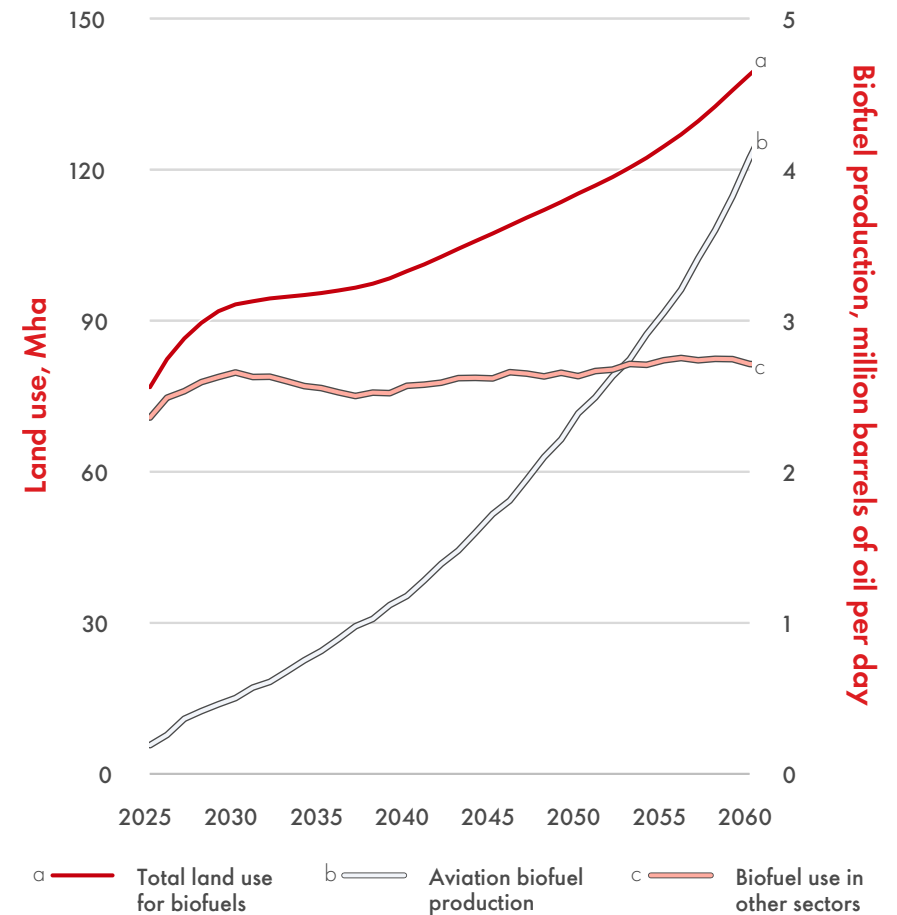
As biofuel production trends towards aviation and overall demand rises, total biofuel production rises from 2.5 million barrels per day (Mb/d) in 2025 to 5 Mb/d in 2050 and to nearly 15 Mb/d for aviation alone by the end of the century. Land use change rises too, but much less so. By mid-century, the requirement is approaching 120 Mha.

The key change in **Surge** is the early emergence of advanced biofuel technologies, such as cellulosic processing. For example, rather than produce a fuel such as ethanol directly from sugar cane, the sugar-cane bagasse is also processed. In such a process, the lignocellulosic bagasse is pretreated to free the cellulose from the lignin seal and its crystalline structure to render it accessible for further treatment. The cellulose is then converted to C5 and C6 sugars through an enzyme-based process known as saccharification. Finally, the sugars can be fermented to produce ethanol.

This is a more complex process than standard sugar-cane ethanol production, but it means that both higher yields and a lower land and therefore carbon footprint of the product are the result. According to the US Department of Energy, cellulosic ethanol production can deliver greenhouse gas reductions between 88% and 108% compared with gasoline and diesel production and use.

Cellulosic processing is slow to emerge in **Archipelagos**, putting greater pressure on land use through the century.

Land use required for increasing aviation biofuel production in **Surge**



[See the accessibility description](#)

Reaching net zero CO₂ emissions

Following on from the Paris Agreement and aligned with the Glasgow Climate Pact, the commercial aviation industry has established a goal to reach net zero carbon (CO₂) emissions by 2050. The goal has been ratified by both the International Civil Aviation Organisation (ICAO) and the International Air Transport Association (IATA).

The goal is overseen by the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) under the auspices of the ICAO, but some regional and national legislative fuel mandates and carbon pricing mechanisms now also cover aviation. Examples are the EU Emissions Trading System and the ReFuelEU Aviation regulation which are part of the EU's efforts to reduce emissions.

ICAO: Montréal, 7 October 2022 – Culminating two weeks of intensive diplomacy by over 2,500 delegates from 184 States and 57 organizations at the 41st ICAO Assembly, ICAO Member States adopted a collective long-term aspirational goal (LTAG) of net zero carbon emissions by 2050.

IATA: Boston, 4 October 2021 – At the 77th IATA Annual General Meeting a resolution was passed by IATA member airlines committing them to achieving net zero carbon emissions from their operations by 2050. This pledge brings air transport in line with supporting efforts of the Paris Agreement's temperature goal.

Aviation emissions

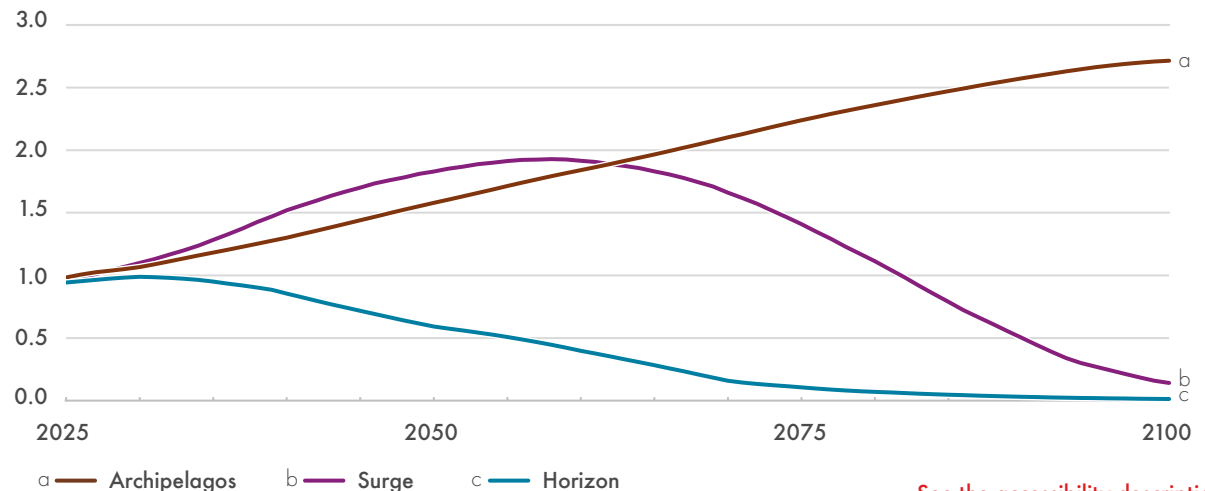
Even with the increasing use of bio-SAF, the development of e-SAF, the constant improvement in fleet efficiency and the introduction of novel propulsion aircraft, CO₂ emissions are likely to rise in the foreseeable future. Demand for aviation eclipses the good progress in **Surge** until after mid-century, and in **Archipelagos** the somewhat insipid efforts are no match for rising demand.

Only in **Horizon**, with a somewhat muted increase in demand and its accelerated deployment of fuels and technology, do CO₂ emissions fall from the mid-2030s onwards. The scenario also requires considerable infrastructure investment in passenger rail networks, nearly quadrupling global capacity in 75 years. Nevertheless, by 2050, aviation emissions are 0.6 Gt, which will require an offset for net zero emissions.

Global aviation CO₂ emissions in three scenarios

Bio-SAF and e-SAF are reported as net zero CO₂ and any use of offsets is not shown

Emissions, Gt per year



[See the accessibility description](#)

Book-and-claim

Bio-SAF is the only technology available to the sector to reduce emissions in the shorter term, with the more advanced fuel and propulsion technologies not emerging until after 2040. Further, in 2040 in **Horizon**, at least half of the global bio-SAF is produced in the USA and Brazil, yet those countries account for only 20% of aviation emissions, with most in the USA.

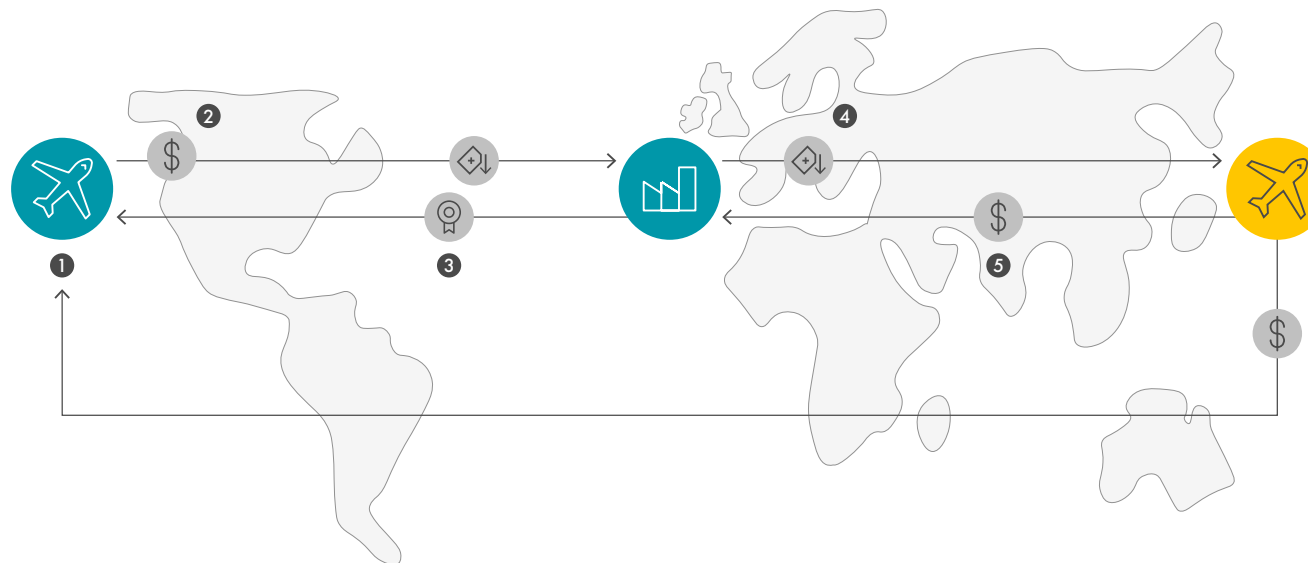
This poses a significant distribution issue for bio-SAF in that all airlines will require some, but production is highly skewed geographically. A solution to this issue, other than moving small quantities of liquid fuel over

potentially large distances, is to employ a book-and-claim approach to emissions reduction. The bio-SAF is mainly consumed by airlines close to production centres, exceeding the immediate needs of those airlines in their journey to net zero greenhouse gas emissions, with the excess CO₂e reduction benefit transferred through a system known as book-and-claim. In essence, a book-and-claim system decouples the environmental benefits of a lower carbon product (like SAF) from its physical delivery.

Book-and-claim systems allow major biofuel suppliers to leverage their scale and move quickly to build larger,

lower-cost facilities for cellulosic processing and converting ethanol to jet fuel. This in turn supports the rapid scaling of a nascent industry by providing wider access to the greenhouse gas benefits of bio-SAF across the aviation value chain. In the long-term, realising the full potential of book-and-claim will require robust standards and guidelines, and recognition under corporate sustainability reporting frameworks. These standards and guidelines require clear consensus on terminology, accuracy and transparency in emissions accounting, and opportunities for independent verification.

- 1 Airline A wants to buy SAF, but there is none available on the routes they fly.
- 2 Airline A pays the higher price for SAF to a producer in a different geography.
- 3 Instead of transporting the SAF to an airport used by Airline A, they receive standard jet fuel and documented verification for the SAF, which may allow them to claim the emission reduction.



- 4 The SAF is then used with Airline B, however, they are not able to claim the emission reduction because that has already been allocated to Airline A through the documentation.
- 5 Airline B only has to pay the standard market price for jet fuel, even though they receive SAF, because they are not able to claim the benefit.

[See the accessibility description](#)

Carbon removal offsets

With no scenario outcome showing aviation fuel use even close to net zero CO₂ emissions by 2050, CO₂ offsets will be required to reach that goal. These would likely be carbon removal units associated with long-term reforestation projects and the geological storage of CO₂.

Given the general level of scrutiny that the sector is subject to, a scenario working assumption is that only offsets from verified long-term carbon removal projects would be used for reaching net zero CO₂ emissions by the aviation sector. This could include direct air capture of CO₂ with geological storage (DACCS), bioenergy processing combined with carbon capture and storage (BECCS) and land reforestation.

Based on these offset types, the goal of net zero CO₂ emissions by 2050 remains challenging. DACCS doesn't deploy at scale until 2040, and only in **Surge** and **Horizon**.

BECCS is only a large-scale option in **Horizon**, with little activity in **Archipelagos** and the potential activity in **Surge** eclipsed by the enthusiasm for DACCS, which preferentially draws in the investors. Reforestation projects, while relatively abundant, are hampered in **Surge** and **Archipelagos** by a slower adoption of land use change practices than in **Horizon**.

The table shows that in **Surge** and **Archipelagos**, there is insufficient global availability of carbon offsets for aviation to reach net zero CO₂ emissions by 2050.

In **Surge**, with CO₂ emissions from the sector not starting to fall until after 2060, chasing net zero with a growing but barely sufficient stock of offsets (the sector would need all), does not appear to be a viable strategy until about 2060. But offsets could be used to meet various interim reduction targets.

A similar story emerges in **Archipelagos**, but with an even smaller supply of removal offsets. The strategy for the sector would require a broadening of offsets to include avoidance units.

Horizon can achieve net zero CO₂ emissions in 2050, given that the world does in the scenario. However, the aviation sector would need to purchase about a fifth of the available global pool of carbon removal units.

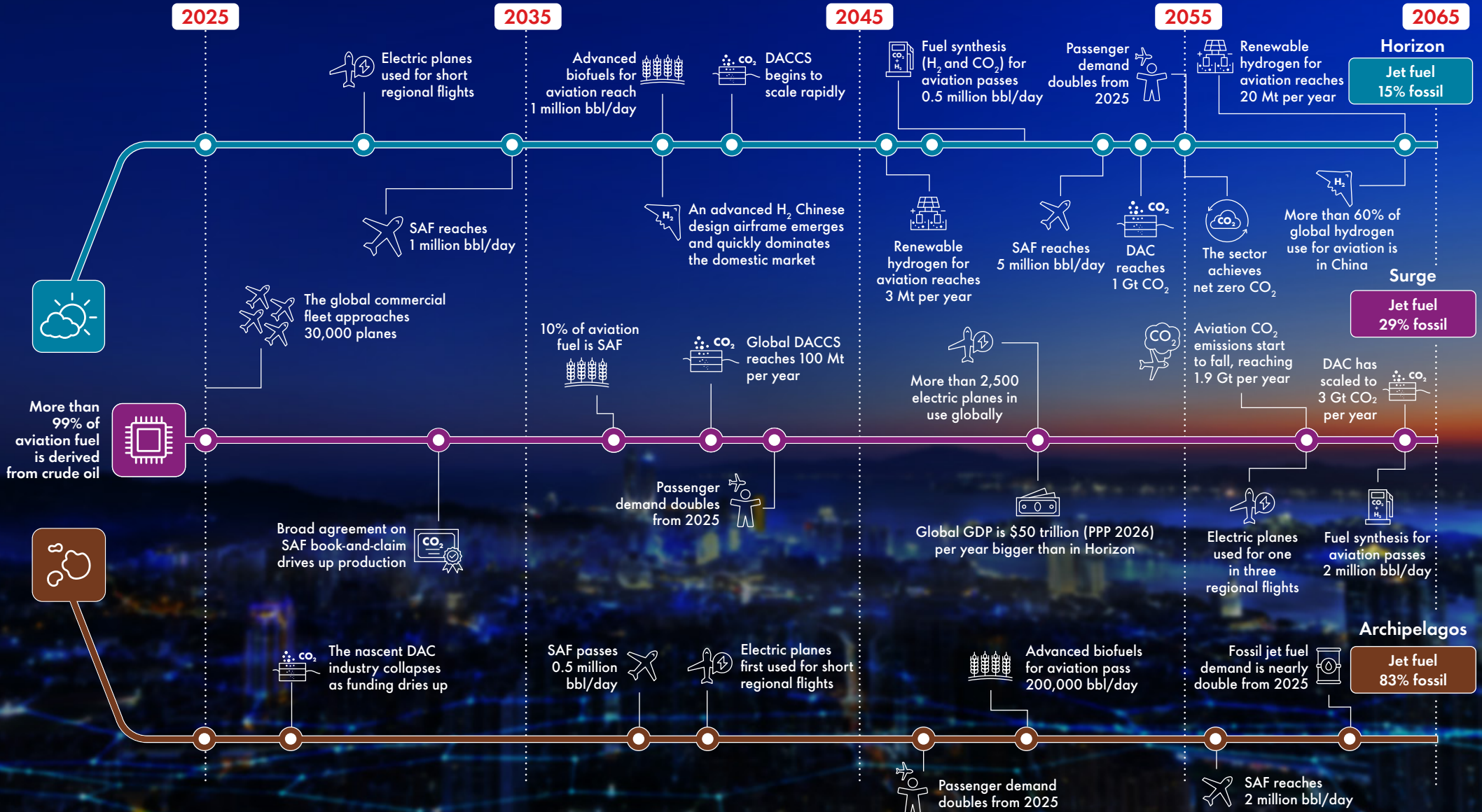
Scenarios	Sector emissions, Mt CO ₂ per year in 2050	Maximum availability of DACCS and BECCS, Mt CO ₂ per year in 2050	Maximum availability of reforestation credits, Mt CO ₂ per year in 2050
Surge	1,830	1,140	780
Archipelagos	1,580	80	110
Horizon	590	1,870	1,200

Final thoughts

The broader energy transition is now at a tipping point; the question at hand is not whether aviation can reach net zero CO₂ emissions, but when can it reach net zero and which fuels and technologies might take it there. Bio-SAF will likely play a major role in the nearer term, but from there the direction is less certain. But what is clear is that the sector will need to embrace new technologies, be prepared for different cost structures and make use of tools such as book-and-claim to reach its goal. The decades ahead will see considerable change.



Forty years of change for aviation



DAC - direct air capture
 DACCS - direct air capture and (geological) storage
 bbl/d - barrels per day (liquid fuels)

Mt - million tonnes
 GDP - gross domestic product
 Gt - gigatonne (or billion tonne)

PPP - purchasing power parity
 SAF - sustainable aviation fuel

[See the accessibility description](#)

Accessibility descriptions

Estimated aviation flight length and emissions distribution in 2025

A grouped bar chart with two panels for 2025: the left panel shows % of flights by duration; the right shows the % of CO₂ they produce. Short-haul flights (<3 hours) make ~80% of flights but only ~35% of CO₂, whereas the longest flights (the minority) account for a disproportionately large share (~65%) of emissions. Context in the caption notes ~7.2 million barrels/day of aviation fuel use in 2025 (out of just under 100 million bbl/day of total oil production), and ~1.1 Gt CO₂ from commercial aviation – about 2.7% of anthropogenic CO₂. The point is that most flights are short, but most emissions come from longer flights.

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A solid growth trend for aviation in all scenarios

A line chart with historical data and three scenarios (**Surge**, **Archipelagos**, **Horizon**). The y-axis ranges 0–70,000 billion passenger-km/year. History: ~100 billion pkm in 1960; ~10× by 1980; ~100× by 2020 (≈ 10,000 billion pkm). From 2025 (with ~30,000 commercial aircraft and >5 billion annual passengers), all scenarios grow: **Surge** is steepest (demand triples by the mid-2050s), **Archipelagos** is moderate, **Horizon** grows slowest (roughly doubling by mid-century). The key message is strong structural growth in all cases, with **Surge** highest and **Horizon** lowest by 2100.

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Aviation travel per unit of GDP in the **Surge** scenario

A multi-line chart showing how aviation intensity – measured as flight kilometres per \$'000 of GDP per person – evolves across regions from 1980 to 2100. Lines for North America, India, Africa, and Latin America show aviation intensity over time (flight-km per \$'000 GDP per person). North America starts highest (mature market) and declines; India, Latin America, and Africa rise steadily from a low base, with India slowly declining after 2070. Context: the sector expected 9.4 trillion passenger-km in 2025 globally and ~1.1 Gt CO₂ that year, indicating large absolute activity even as rich regions decouple intensity from GDP.

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Passenger aviation market development by region in **Surge**

A grouped set of stacked horizontal bars comparing total passenger-kilometres by region in three time slices: the 2020s, 2050s, and 2080s. The regions are Europe, Africa, China, Latin America, India, and North America. By the 2020s, North America is the largest market, with Europe and China following. By the 2050s, China overtakes North America, and India's segment expands significantly. By the 2080s, India becomes the largest market, with Africa also growing noticeably, while North America and Europe shrink

in relative share. The visual highlights a geographic shift in aviation demand from mature markets to emerging economies over the century.

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Air freight development in the 21st century

A three-line chart showing global air freight demand in billion tonne-kilometres per year from 2000 to 2100 under the **Surge**, **Archipelagos**, and **Horizon** scenarios. The x-axis spans 2000–2100; the y-axis runs from 0 to 1,200 billion tonne-km. In 2025, freight demand is already significant, with 2,500 dedicated freighters operating and many passenger flights carrying cargo. By the mid-2040s, demand reaches ~500 billion tonne-km, and by 2100, all scenarios approach or exceed 1 trillion tonne-km, with **Surge** highest. This chart highlights that freight grows strongly and adds to the sector's energy and emissions challenge.

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Aviation final energy demand profiles under varying efficiency assumptions

A line chart comparing three cases for aviation energy demand in the **Surge** scenario, measured in exajoules per year (EJ). One line assumes efficiency freezes after 2024, leading to the steepest rise, surpassing 40 EJ by 2050. Another assumes continued efficiency gains, moderating growth. A third applies **Horizon**-level efficiency to **Surge** demand, flattening the curve further. The narrative explains why: modern aircraft like the Airbus A350-1000 already achieve <2.5 L/100 km per passenger, down from 5–6 L in 1965, and **Surge** assumes another 30% improvement to <1.7 L/100 km. The chart shows that efficiency is a critical lever for controlling energy demand even as traffic grows.

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The shifting fuel mix for aviation in **Horizon**

A stacked area chart showing aviation energy by carrier type (conventional jet, bio-SAF, e-SAF, hydrogen, electric aviation) from 2010 to 2100. In 2025, nearly 100% was conventional jet fuel. By 2058, conventional fuel falls by 50%, and by 2100, it's replaced by bio-SAF and e-SAF. Additional demand is supplied via electric aviation as well as hydrogen. Even in 2100, liquids dominate, but they are mostly low-carbon. The chart shows a gradual but profound diversification of aviation energy.

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Aviation fuel demand in **Surge**

This chart shows aviation energy demand by fuel type from 2010 to 2090 in the **Surge** scenario. The vertical axis runs from 0 to 35 million barrels of oil equivalent per day, and the horizontal axis spans 2010 to 2090. Total demand grows faster and higher than in **Archipelagos**. Conventional jet fuel remains large for decades, while electric aviation becomes visible after 2050, growing little later in the century. The key message is that rapid demand growth delays the impact of low-carbon fuels, keeping fossil liquids significant until late in the century.

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Liquid fuel mix in **Surge**

This composition chart shows only the liquid portion of aviation energy in the **Surge** scenario from 2010 to 2090, summing to 100% and split into conventional jet fuel, bio-SAF and e-SAF; in the early period (2010–2030) the mix is almost entirely fossil, by 2060 more than 70% of jet fuel is still fossil-derived, while bio-SAF has grown steadily and e-SAF begins to appear after about 2040, and by the end of the century (as corroborated by the 2100 fuel-supply Sankey) the liquid pool is largely low-carbon, with bio-SAF and e-SAF supplying most of the liquids and fossil shrinking to a minority share.

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Aviation fuel demand in **Archipelagos**

This chart shows aviation energy demand by fuel type from 2010 to 2090 in the **Archipelagos** scenario. The vertical axis runs from 0 to 35 million barrels of oil equivalent per day, and the horizontal axis spans 2010 to 2090. Demand grows steadily, dominated by conventional jet fuel for most of the century. Electric aviation is minimal, only appearing slightly after 2070. Overall, the transition is slow, and liquid hydrocarbon fuels remain dominant.

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Liquid fuel mix in **Archipelagos**

This composition chart for **Archipelagos** shows fractional shares of fossil liquids and bio-SAF across time, with e-SAF absent because direct air capture collapses in the late 2020s in this scenario. The early years (2010–2030) are almost entirely fossil, bio-SAF grows after 2030 to about 20% in 2090.

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2025 fuel supply in Surge

This Sankey diagram presents inputs on the left, conversion stages in the centre and outputs on the right for 2025, all in Mboe/d; the inputs are fossil fuels at 6.8 and farm crops at 0.5, biofuel production processes 0.5 using 0.3 of process energy, and the system delivers 7.0 of liquid fuels that flow entirely to aviation, indicating a simple, fossil-dominated supply chain with only a small bio component at this date and no contribution from electricity or hydrogen pathways.

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2060 fuel supply in Surge

This Sankey diagram presents inputs on the left, conversion stages in the centre and outputs on the right for 2060, all in Mboe/d. This larger, more complex Sankey for 2060 shows scaled inputs and multiple conversion routes; inputs include fossil fuels at 13.5, farm crops at 10.3, of which cellulosic materials are 6.4, waste at 0.5, and electricity production at 4.5 supplied by nuclear and renewables at 4.3, while conversions comprise biofuel production at 10.7 (with 6.4 process energy), hydrogen at 2.1 (with 0.8 production losses), fuel synthesis at 1.3 (with 0.2 synthesis losses) and electricity at 2.7 (with 1.8 production losses), yielding 18.7 of liquid fuels to an aviation demand of 19.3, which demonstrates that non-fossil pathways have become significant but aviation remains predominantly liquid-fuelled and still partly fossil at mid-century.

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2100 fuel supply in Surge

This Sankey diagram presents inputs on the left, conversion stages in the centre and outputs on the right for 2100, all in Mboe/d. This end-of-century Sankey depicts a very large, diversified system with fossil inputs near elimination; inputs are fossil fuels at 1.1, farm crops at 35.4, of which cellulosic materials are 32.3, waste at 0.3 and electricity production at 39.3 (nearly all from nuclear and renewables at 38.8), while conversions include electricity at 25.6 (with 13.8 production losses), hydrogen at 22.2 (with 9.8 production losses), biofuel production at 35.3 (with 21.2 process energy) and fuel synthesis at 12.4 (with 0.4 synthesis losses), producing 27.1 of liquid fuels and meeting 30.5 for aviation, thereby showing aviation still relies mainly on liquids but those liquids are predominantly low-carbon (bio-SAF and e-SAF) supported by massive clean-power and hydrogen flows.

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The global demand for biofuels for aviation in three scenarios (Left)

This chart shows the projected use of biofuels for aviation from 2000 to 2100 under the **Surge**, **Archipelagos**, and **Horizon** scenarios. The horizontal axis spans 2000 to 2100, and the vertical axis measures energy in million barrels of oil equivalent per day. In the 2040s bio-SAF exceeds 2 million barrels per day in **Surge** but is less than half that for **Archipelagos**. In **Horizon**, biofuel

use grows earliest and steadily, while in **Surge** it expands later but reaches the highest absolute levels by the end of the century, with milestones such as 14 million barrels per day. **Archipelagos** shows slower, steady growth without synthetic fuels, making bio-SAF the main low-carbon option in that scenario.

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Global synthetic fuel use for aviation (Right)

This chart shows projected use of synthetic aviation fuel (e-SAF) from 2020 to 2100 under the **Surge**, **Archipelagos**, and **Horizon** scenarios. The horizontal axis spans 2020 to 2100, and the vertical axis measures energy in million barrels of oil equivalent per day. e-SAF remains negligible until after 2040 in all scenarios. In **Surge**, it rises sharply in the second half of the century as direct air capture and low-carbon electricity scale, eventually becoming a major contributor. **Horizon** sees earlier but smaller growth because overall demand is lower. **Archipelagos** remains at zero because DAC technology fails. A reference point in the text notes that a 10,000-barrel-per-day e-SAF plant requires about 15 gigawatts of solar power, illustrating the energy intensity of this pathway.

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Number of electric commuter planes deployed globally (Left)

This line chart tracks the global fleet of battery-electric commuter aircraft (typically under 100 passengers) and their range; entry into service begins in 2030 for short regional flights under 700 kilometres, more than 1,000 electric planes are in operation by 2040, the fleet exceeds 16,000 in 2080 in the **Surge** and **Horizon** Scenario, and range improves to more than 1,400 kilometres by 2100, indicating that electric propulsion progressively reshapes short-haul connectivity and reduces local fuel burn while leaving long-haul segments largely dependent on liquid fuels. **Archipelagos** is slower, with almost 8,000 planes globally by 2080.

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Number of hydrogen power planes deployed globally (Right)

This line chart shows hydrogen aircraft (80+ passengers) progressing from test flights in the mid-2030s to around 60 planes in commercial service in China by 2040 in **Horizon** and scaling to approximately 3,500 aircraft in China by the late 2060s, with Chinese aviation using about 12 million tonnes of hydrogen per year and accounting for more than 60% of global aviation hydrogen use by 2060, which highlights the long lead times for airframe redesign and airport infrastructure as well as the initially concentrated geographic adoption.

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Refinery yield of jet fuel from crude oil

This line chart presents historical data and scenario projections for refinery jet fuel yield from 2010 to 2050, expressed as the percentage of refined-product demand met by jet fuel. The historical series, shown in grey, begins just above 7% in 2010, rises slightly toward 8% by the mid-2010s, then dips sharply to around 6% near 2020 before recovering to converge with the scenario trajectories at roughly 8% in the early 2020s. From that point forward, three scenario pathways – **Archipelagos**, **Horizon**, and **Surge** – track upward with differing steepness. **Archipelagos** climbs gradually to about 12% by 2050, while **Horizon** increases slightly faster to roughly 11–12% over the same period. **Surge** shows the most pronounced rise, surpassing 10% by the mid-2030s and reaching approximately 16% by 2050. Together, the lines illustrate a transition in which jet fuel yield becomes a growing share of refinery output across all scenarios, with the **Surge** pathway indicating a particularly strong shift toward higher jet fuel production in the long-term.

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Land use required for increasing aviation biofuel production in **Surge**

This paired chart tracks global land used for biofuels (million hectares) alongside aviation biofuel output (million barrels per day) and biofuel use in other sectors; about 80 million hectares are used in 2025 (roughly half in the USA and Brazil), land use approaches about 120 million hectares by 2050 as total biofuel output rises from below 0.5 Mb/d in 2025 to about 4 Mb/d by 2050.

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Global aviation CO₂ emissions in three scenarios

This chart shows projected CO₂ emissions from global aviation from 2025 to 2100 under the **Surge**, **Archipelagos**, and **Horizon** scenarios. The horizontal axis spans 2025 to 2100, and the vertical axis measures emissions in gigatonnes per year from 0.0 to 3.0. In 2025, emissions are about 1 gigatonne, roughly 2.3% of global anthropogenic CO₂. In **Surge** emissions peak after mid-century and fall to a low level by 2100, but in **Archipelagos** there is a constant rise towards almost 3 Gt in 2100. In **Horizon**, emissions peak in the 2030s and then decline, but by 2050 they are only about 40% lower than today, showing that even in the most ambitious scenario, deep cuts are challenging without major technology shifts and offsets.

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Book-and-claim

This graphic explains how a book-and-claim system allocates the emissions-reduction benefit of sustainable aviation fuel (SAF) separately from the physical fuel. On the left, SAF is produced mainly in a few regions; for example, in the **Horizon** scenario for 2040, at least half of global bio-SAF is produced in the USA and Brazil, while those countries account for only ~20% of aviation emissions (most in the USA). The diagram shows local physical use of SAF by nearby airlines, with any excess environmental benefit booked to a central registry; claims are then transferred to airlines elsewhere that purchase the documentation, that may allow them to count the associated CO₂ reduction even though the fuel was not delivered to them. In the long-term, realising the full potential of book-and-claim will require robust standards and guidelines, and recognition under corporate sustainability reporting frameworks. These standards and guidelines require clear consensus on terminology, accuracy and transparency in emissions accounting, and opportunities for independent verification.

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Forty years of change for aviation

The figure is a horizontal, multi-row timeline with labels at 2025, 2035, 2045, 2055, and 2065. Each row represents one scenario – **Surge**, **Archipelagos**, or **Horizon** – and marks major milestones for aircraft technologies, fuel supply, hydrogen and electricity use, CO₂ management, and the residual share of fossil jet fuel by 2065. The chart is read left-to-right as a progression of dated events rather than a scale with a numeric vertical axis.

In **Surge** the economy expands fastest and aviation demand grows strongly. In 2025, the global commercial fleet approached 30,000 planes. Before 2035, there is broad agreement on SAF book-and-claim usage, which drives up production. After 2035, 10% of aviation fuel is supplied as SAF, with global DACCS reaching 100 Mt per year a few years later. Around 2040, passenger demand doubles from 2025 and around 2050 more than 2,500 electric planes globally are in use. By then, global GDP is expected to be \$50 trillion (PPP 2026) per year bigger than that in **Horizon**. In 2060, electric planes are used for one in three regional flights and Aviation emissions start to fall. Just before 2065, DAC has scaled to 3 Gt CO₂ per year. Finally, in 2065, jet fuel will remain 29% fossil based.

In **Archipelagos** the energy transition is constrained by geopolitics and security priorities. The nascent DAC industry collapses in the late 2020s as funding dries up, so e-SAF never establishes at scale along this pathway. Around 2040, SAF passes 0.5 million bbl/day, followed by the first usage of electrical planes for short regional flights. After 2045, passenger demand doubles from 2025 and around 2050, advanced biofuels for aviation pass 200,000 bbl/day. After 2055, SAF reaches 2 million bbl/day and fossil jet fuel demand is nearly double that from 2025. The fossil jet fuel share remains at 83% in 2065.

Horizon is the rapid-transition case that is designed to reach net zero aviation CO₂ by ~2050. Early in the period, around 2030, electric planes are used for short and regional flights and just before 2035, SAF reaches 1 million bbl/day. Around 2040, advanced biofuels for aviation reach 1 million bbl/day, an advanced hydrogen Chinese design airframe emerges and quickly dominates the domestic market, as well as DACCS beginning to scale rapidly. After 2045, renewable hydrogen for aviation reaches 3 Mt per year, fuel synthesis for aviation surpasses 0.5 million bbl/day, SAF reaches 5 million bbl/day and DAC reaches 1 Gt CO₂. In 2055, passenger demand doubles from 2025 and the sector achieves net zero CO₂.

Just before 2065, renewable hydrogen for aviation reaches 20 Mt per year and more than 60% of global hydrogen use for aviation is in China. This leaves the fossil jet fuel share to only 15% in 2065.

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References

1. Numerous statistics relating to the current shape and scale of the aviation sector are cited, brought together from Air Transport Action Group – Facts and Figures, International Air Transport Association (IATA) Pressroom and Fact Sheets, World Economic Forum Net zero Industry Tracker 2024 – Aviation, International Energy Agency – Aviation, Bloomberg NEF 2025 Aviation Fuel Outlook, Boeing, Airbus, the International Civil Aviation Organisation and IATA Global Outlook for Air Transport December 2025.
2. The high-resolution Global Aviation emissions Inventory based on ADS-B (GAIA) for 2019–2021, Teoh et. al., Atmos. Chem. Phys., 24, 725–744, 2024.
3. All projections from 2025 onwards relating to aviation demand, fuel supply and carbon credits emerge from [The 2026 Shell Energy Security Scenarios](#).

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