Allianz Trade

High hopes, heavy footprint: Aviation's quest for climate-neutral skies

02 December 2025

Allianz Research

Content

Executive Summary

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Aviation remains a cornerstone of our globalized economy, shrinking distances and accelerating the movement of people and goods, thereby enabling tourism and trade. But it is also one of the hardest sectors to align with global climate-neutrality goals by 2050. In 2023, aviation produced roughly 1 gigatonne of CO_2 – accounting for about 2.5% of all human-made CO_2 emissions, including land-use change. When accounting for non-CO_2 impacts such as contrails and nitrogen oxides, the sector's share of global warming rises to approximately 6%, underscoring the magnitude of the challenge.

Mitigating emissions requires a comprehensive set of measures spanning technology, fuels, operations and policy. A key pillar is the deployment of Sustainable Aviation Fuels (SAFs), which can lower CO_2 emissions by 60–90% and are compatible with existing fleets. Yet current deployment is far below what climate targets require: SAFs supplied only 0.3% of global jet-fuel demand in 2024, constrained by limited sustainable feedstocks, high production costs and slow infrastructure expansion. Scaling SAFs will require major investment in renewable electricity, diversified feedstocks and large-scale production facilities, supported by clear and stable policy mandates. However, scientific evidence also shows that SAFs alone cannot deliver full climate neutrality as non-CO_2 effects – contrails, NO_x and water vapor – continue to drive warming. SAFs remain essential, but must be complemented by broader technological, operational and regulatory measures. Efficiency improvements, such as retiring older aircraft, adopting more aerodynamic and fuel-efficient models, reducing cabin weight and introducing electric taxiing, further cut fuel burn. In parallel, novel propulsion technologies – hydrogen, battery-electric and hybrid-electric aircraft – offer long-term transformative potential, though they require major advances in infrastructure and energy systems.

Market-based mechanisms (carbon credits) can also help bridge the carbon gap. On one side, CORSIA allows airlines to offset a growing share of international emissions, with costs rising from negligible levels during the pilot phase (USD7–20/ton CO_2) to potentially USD100/ton by 2027, representing a financial burden of up to USD9.5bn (26% of the sector's net profits) as participation expands and obligations tighten. On the other side, the EU ETS imposes stricter, Europe-focused obligations, requiring airlines to purchase allowances, with projected needs of 70mn allowances by 2030 at EUR80–150/ton, translating to EUR5.6–10bn in costs. While carbon credits remain less expensive than the adoption of SAF, their cumulative cost is expected to rise, influencing operating margins or ticket pricing. Overall, these market-based mechanisms act as transitional tools, enabling airlines to offset unavoidable emissions while incentivizing long-term investment in SAF and low-emission technologies, supporting both compliance and the sector's sustainable growth.

These efforts will require around USD5.1trn in investment by 2050. This is largely for renewable electricity (40%) to power synthetic fuels and future hydrogen or electric aircraft. Another 38% must support scaling SAF production, while CO_2 capture and electrolysers account for 16% and next-generation aircraft for the remaining 6%. Despite the magnitude, the transition is economically favorable. Without mitigation, the sector would face nearly USD8trn in cumulative carbon costs under rising carbon prices. A transition pathway lowers this to USD2.6trn, eliminating carbon-price exposure after 2045 and strengthening long-term competitiveness and regulatory resilience.

Decarbonizing aviation also hinges on accelerating aircraft modernization and next-generation innovation. With global fleet retirement at just 1.7% in 2024 and the renewal rate at 3.7%, the average aircraft age has reached a record 15 years, while delivery backlogs hit 17,000 units, extending wait times from two to three years to nearly six. Retrofitting older jets – through cabin upgrades, avionics, engines and aerodynamic improvements like winglets (which have reduced CO_2 by over 100mn tons since 2000) – offers short-term efficiency gains, but meaningful decarbonization requires new aircraft. Current technology could cut fuel burn and emissions by ~20% by 2050, but only if manufacturers accelerate production, diversify suppliers, streamline certification and secure supportive government policies. Leading OEMs are investing heavily in R&D for SAF-compatible platforms, hybrid-electric and hydrogen propulsion and advanced aerodynamics. Yet, the CAPEX-to-revenue ratio remains low at 3–5% despite increases of +8% over the past decade and +67% since pandemic lows. To achieve step-change efficiency and align with net-zero targets, materially higher investments are essential to bring next-generation, energy-efficient aircraft into service at the scale and pace the industry – and the planet – require.

Demand-side measures also matter. Air travel has expanded from 0.4bn passengers in 1970 to almost 5bn in 2025, and global demand is projected to reach 12.4bn by 2050. Europe will grow more moderately – from 1.19bn passengers in 2023 to 1.81bn in 2050 – but even this +52% rise challenges net-zero pathways. Over 50% of EU passengers fly domestically or within the EU-27, and short flights present the clearest mitigation opportunity: routes under 300 km account for 19% of national travel, while routes below 500 km account for 45%. Rail is well placed to substitute these distances, but requires major upgrades. Europe plans to expand high- and very-high-speed rail from 12,000 km today to nearly 49,400 km by 2050, demanding over EUR890bn in investment by 2050. Complementary measures, such as aviation ticket taxes reducing intra-EEA demand by around 9%, can further accelerate a fair and effective modal shift.

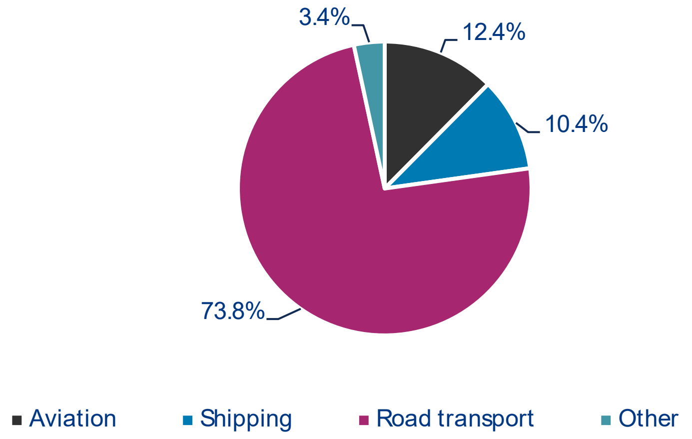
Aviation's emissions footprint – Where the sector stands today

Transport remains one of the most carbon-intensive sectors of the global economy, accounting for nearly one quarter of energy-related CO_2 emissions. Within this total, road transport overwhelmingly dominates, contributing close to three-quarters (74%) of global transport emissions in 2024 (Figure 1a). Shipping and aviation follow with 10% and 12%, respectively, while all other modes combined represent only a minor share. Although aviation's contribution appears modest in relative terms, its growth trajectory over the past five decades has been among the steepest in the sector. Since 1970, aviation-related CO_2 emissions have increased by roughly +180%, compared to +260% for road transport and +96% for shipping (Figure 1b). This pattern reflects both structural and behavioral dynamics. Road transport emissions surged as vehicle ownership expanded rapidly across emerging economies, while aviation growth has been driven by globalization, the spread of tourism and the rise of low-cost carriers. Shipping, by contrast, grew more slowly, thanks to efficiency gains and moderate trade growth in recent years.

Aviation plays a vital role in the global economy, enabling fast and reliable connectivity for passengers and goods across long distances. However, it also remains a notable and growing source of anthropogenic emissions contributing to climate change. In 2018, global aviation emitted approximately 1 gigatonne (Gt) of CO_2, accounting for around 2.5% of total anthropogenic CO_2 emissions, including land-use change . When non-CO_2 effects are considered, the sector's contribution to global warming increases to around 6%.

Figure 1: Aviation emissions in comparison to other transport modes: a) share of total transport emissions in 2024; b) growth of emissions by transport mode, 1970–2024

a)



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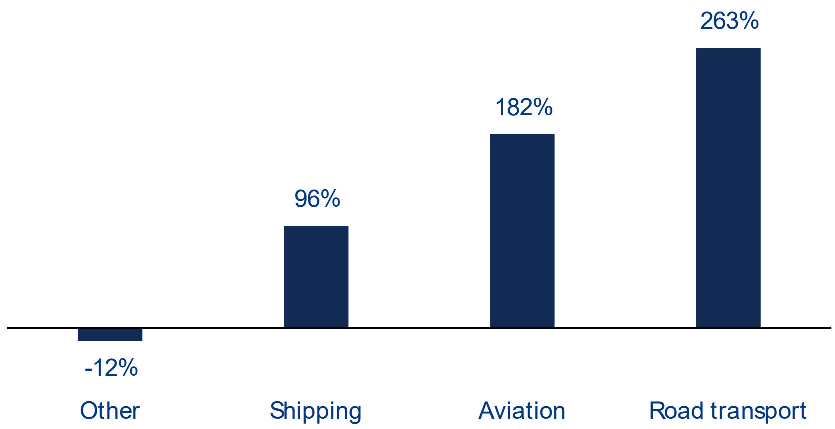


Sources: EDGAR, Allianz Research

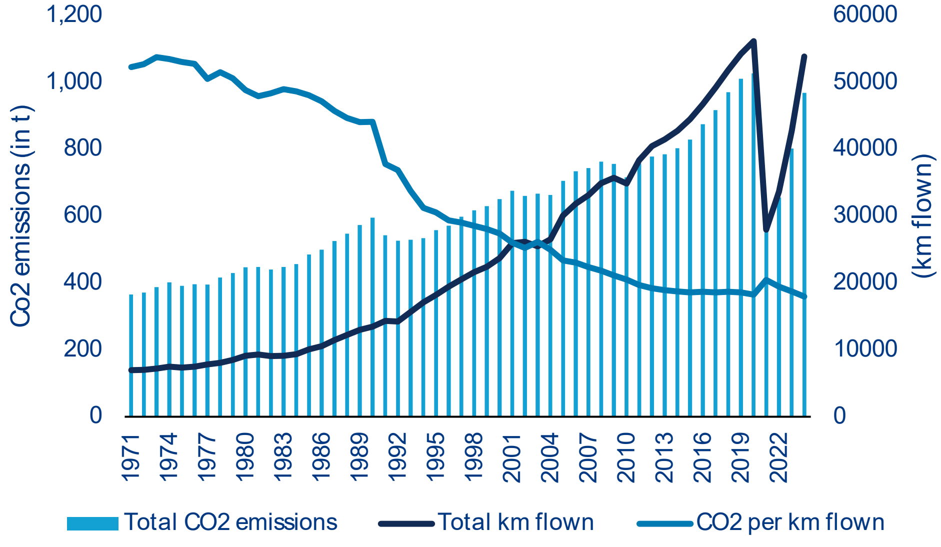
Over the past five decades, the aviation sector has undergone a remarkable transformation. Between 1970 and 2023, total CO_2 emissions from aviation increased by around +164%, reaching nearly 1 gigatonne (Gt), reflecting the sustained global appetite for air travel. This rise was primarily driven by the sharp increase in total kilometres flown, which expanded by almost seven times over the same period, as air connectivity became a cornerstone of globalization, tourism and trade. As a reference for sector's expansion, the global commercial aircraft fleet has increased from 14,000 planes at the beginning of the century to around 30,300 active units registered in mid-2025. Even more striking is the 13-times growth in passenger numbers, underscoring the structural shift of air travel from a privilege of the few to a mass transport mode serving billions annually (Figure 2).

Yet this expansion occurred alongside a major leap in energy efficiency. CO_2 emissions per kilometer flown declined by approximately -66% since 1970, a testament to technological progress in aircraft design, engine efficiency, air-traffic management and operational practices. Modern aircraft today consume roughly one-third of the fuel per passenger-kilometer compared to those in the 1970s. This decoupling between traffic growth and emissions intensity reflects continuous improvements, but not at a pace sufficient to offset demand growth.

The data illustrate the central paradox of aviation's climate challenge: efficiency gains have been outpaced by rising demand. While each kilometer travelled emits substantially less CO_2, the sheer multiplication of flights, routes and passenger volumes has driven aggregate emissions to record highs. In effect, the industry's carbon footprint continues to grow even as it becomes cleaner per unit of output. Looking ahead, this dynamic suggests that meeting net-zero goals will require not only further technological breakthroughs – such as SAF and next-generation aircraft – but also systemic measures to manage demand, improve operational efficiency and accelerate fleet renewal.

The evolution of aviation emissions has not been uniform across regions (Figure 3). Between 2013 and 2024, Asia recorded by far the strongest growth, with aviation-related CO_2 emissions rising by more than +50%, reflecting the region's rapid economic expansion, growing middle class and booming low-cost carrier market. North America and Europe also experienced increases of around +30% and +22%, respectively, but at a slower pace as their aviation sectors are mature and subject to stricter efficiency and climate regulations. In Europe, the EU Emissions Trading System (EU ETS)[1], in place since 2012, has imposed a carbon price on intra-European flights, while the ReFuelEU Aviation Regulation (2023)[2] mandates a gradual blending of SAF – starting at 2% in 2025 and rising to 70% by 2050 – creating long-term decarbonization incentives. In North America, participation in ICAO's CORSIA scheme[3], which requires airlines to offset emissions exceeding 2019 levels, has introduced a cap on growth-related CO_2 emissions for international flights (see pages 20-23 for ETS and CORSIA analysis). In contrast, Africa stands out with a decline of nearly -20%, partly due to weaker economic performance, limited air connectivity and slower fleet modernization.

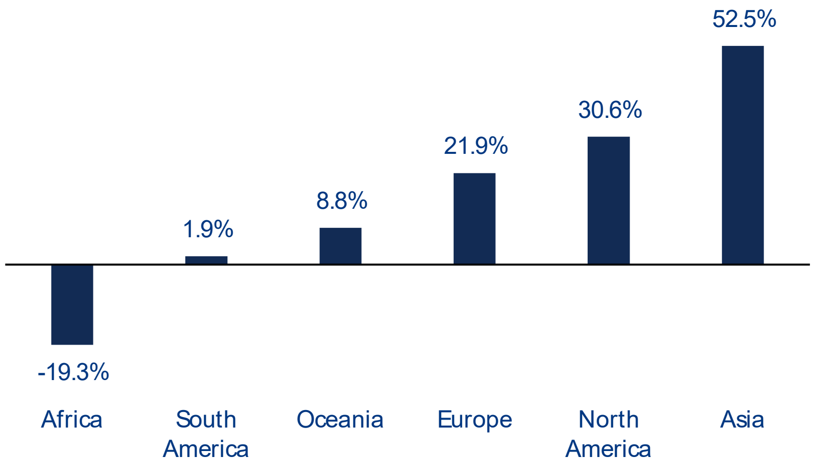
Figure 2: Development of CO2 emissions, flying demand and aircraft efficiency (1970 – 2023)



Sources: EDGAR, Allianz Research

[1] Reducing emissions from aviation - Climate Action - European Commission
[2] ReFuelEU aviation - Mobility and Transport - European Commission
[3] CORSIA

Figure 3: Growth of CO_2 emissions per region for the period 2013 – 2024



Sources: Our World in Data, Allianz Research

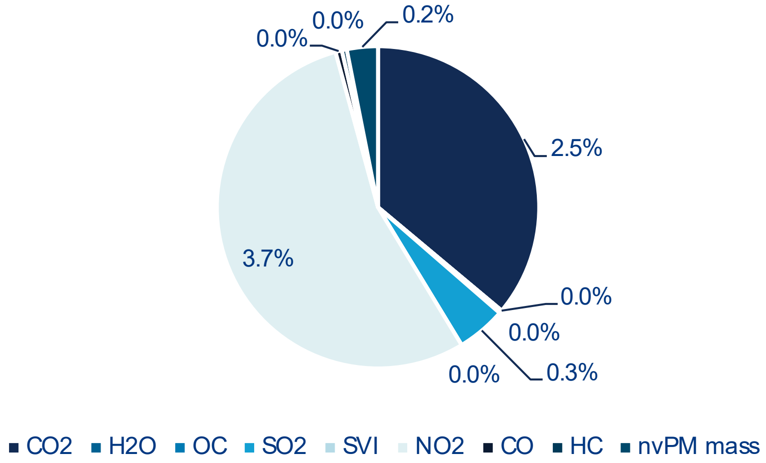
Aviation's smaller absolute share conceals its disproportionate climate impact: emissions occur at high altitudes and produce additional non-CO_2 effects such as contrails and nitrogen oxides, amplifying its total radiative forcing. Moreover, unlike road or maritime transport, decarbonization options for aviation remain limited, with sustainable aviation fuels (SAF) and next-generation aircraft technologies still at early stages of deployment. Consequently, while aviation is not the largest emitter within transport, it poses one of the hardest decarbonization challenges, requiring coordinated technological, regulatory and demand-side responses to align the sector with global net-zero objectives.

While CO_2 dominates in terms of emission mass, representing more than 70% of all aviation exhaust (893 Tg in 2019), other species such as water vapor (H_2O, 28%) and nitrogen oxides (NO_x, ~0.36%) play a disproportionately large role in determining the overall climatic impact of aviation (Figure 4a and 4b). Despite its small mass share, NO_x emissions are particularly influential because of their high radiative power per unit of emission and their chemical reactivity in the upper troposphere and lower stratosphere. When emitted at cruising altitude, NO_x promotes the formation of ozone (O_3) – a short-lived greenhouse gas that contributes a positive radiative forcing – while simultaneously accelerating the breakdown of methane (CH_4), a long-lived greenhouse gas, which exerts a cooling effect. The combined outcome is a net warming impact, making NO_x one of the largest non-CO_2 contributors to aviation's total climate forcing, despite its minimal share in total mass emissions.

Water vapor emissions, while abundant, exhibit altitude-dependent radiative effects. Near the surface, their contribution is negligible due to rapid removal from the atmosphere. But at high altitudes, where residence times are longer, they enhance greenhouse trapping. Similarly, soot (black carbon) and sulfur dioxide (SO_2) emissions – although representing less than 0.05% of aviation exhaust by mass – play an indirect yet critical role in contrail and contrail-cirrus formation. These artificial ice clouds can trap outgoing longwave radiation and create significant additional warming, particularly under nighttime conditions. Overall, the non-CO_2 components – principally NO_x, water vapor and contrails – account for nearly two-thirds of total aviation radiative forcing, highlighting the need for mitigation strategies that go beyond carbon reduction alone. Policies and technological innovations must therefore target both CO_2 and non-CO_2 emissions to achieve meaningful progress toward climate-neutral aviation.

Figure 4: CO2 and non-CO_2 aviation emissions (2019, pre-COVID): a) share in total global emissions reflecting radiative forcing; b) share within the aviation sector emissions

a)



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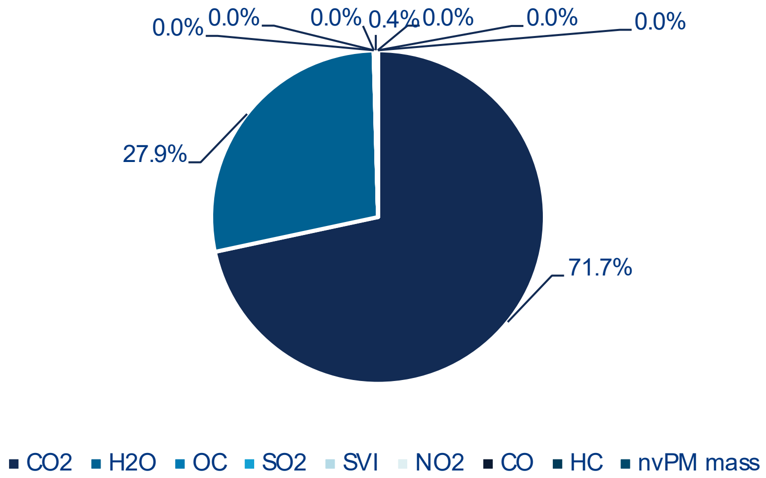
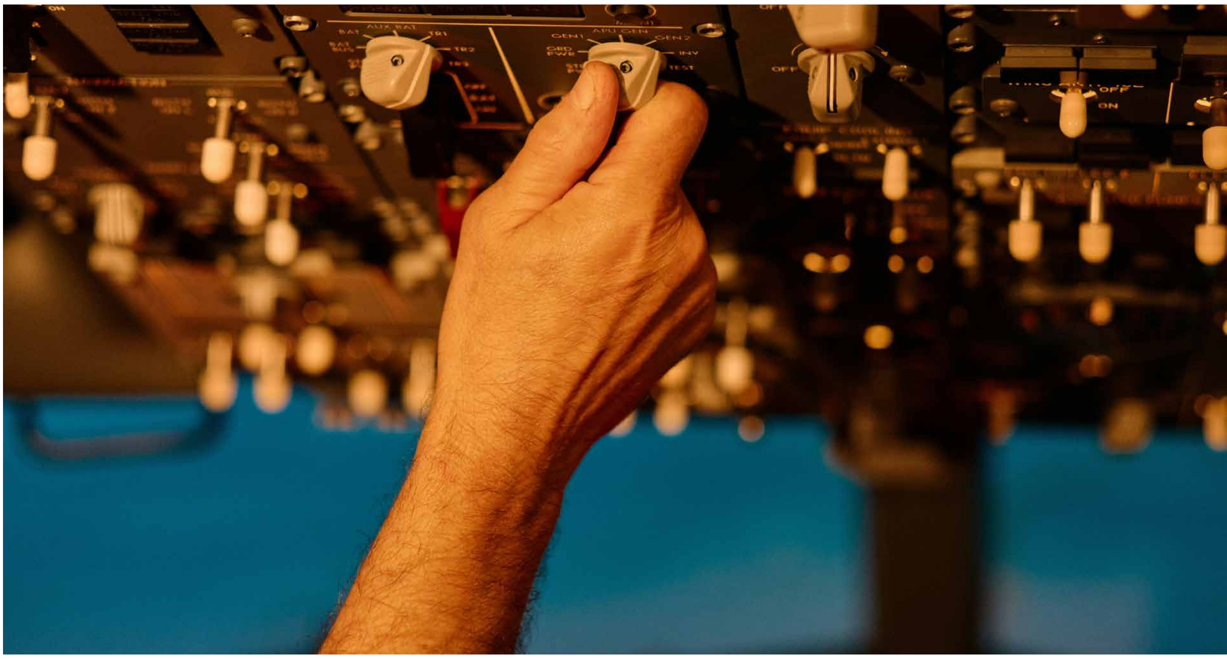


Sources: Teoh et al. (2024)[4], Allianz Research

[4] ACP - The high-resolution Global Aviation emissions Inventory based on ADS-B (GAIA) for 2019–2021

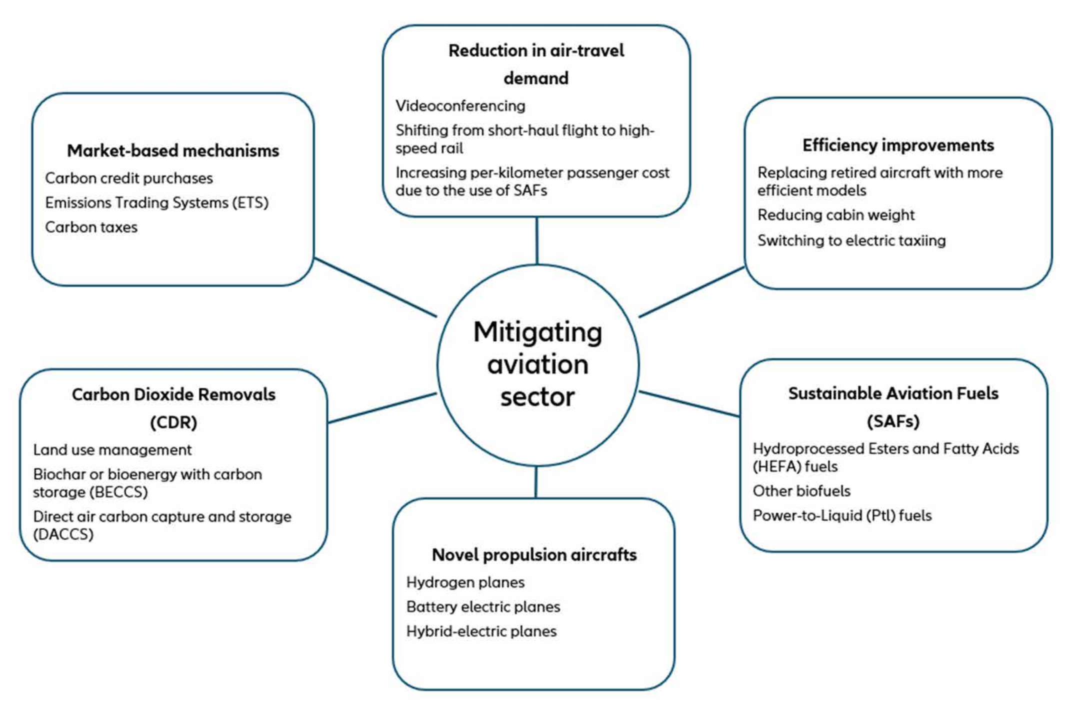


Roadmap to climate-neutral aviation

Achieving climate neutrality in aviation requires a multifaceted strategy that combines technological innovation, sustainable fuels, market incentives and demand management. As illustrated in Figure 5, mitigation options can be grouped into six complementary pillars addressing both emissions at the source and their compensation. Sustainable Aviation Fuels (SAFs) represent the most immediate and scalable pathway to reduce life-cycle CO_2 emissions. Current certified fuels such as Hydroprocessed Esters and Fatty Acids (HEFA) can achieve up to 80% emission reductions compared to conventional fossil jet fuel, while next-generation options such as Power-to-Liquid (PtL) fuels offer near-zero carbon intensity when produced with renewable electricity. Complementing fuel substitution, efficiency improvements such as fleet renewal, lighter aircraft materials and optimized routing continue to lower emissions per kilometer flown. A second technological frontier involves novel propulsion systems, including hydrogen-powered and battery-electric aircraft, which could eliminate direct CO_2 emissions in the long term, though they remain limited by infrastructure and energy-density constraints.

On the systemic side, market-based mechanisms can accelerate the decarbonization of the sector. Market solutions, such as the EU Emissions Trading System (ETS), carbon offsetting and potential aviation carbon taxes, internalize the environmental cost of flying and create economic incentives for decarbonization. Demand-side measures, such as promoting videoconferencing, shifting short-haul flights to rail and moderating air-travel growth, can further curb emissions when technological progress alone is insufficient. Finally, carbon dioxide removals (CDR), including land-based sequestration, biochar or direct air capture (DACCS), offer a means to neutralize residual emissions that cannot yet be abated.

Figure 5: Strategies for climate neutrality in aviation



Source: Allianz Research

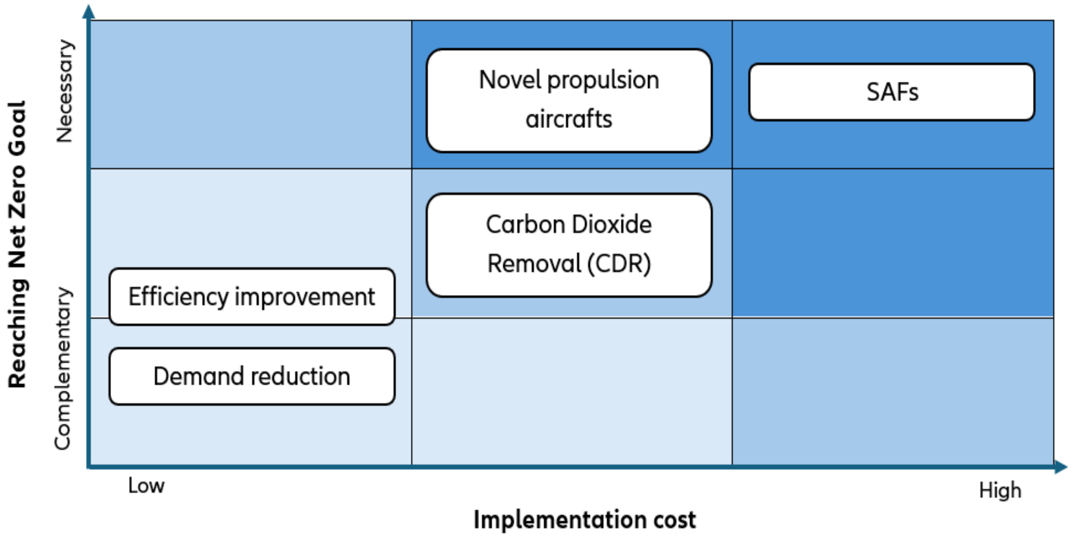
The transition to climate-neutral aviation requires balancing technological ambition with economic feasibility. Figure 6 illustrates both the cost–benefit hierarchy and the estimated mitigation cost per ton of CO_2 for key decarbonization strategies. Low-cost measures, such as efficiency improvements and demand reduction, remain the most cost-effective levers in the near term. Enhanced aircraft operations, lighter materials and optimized routing can deliver emission savings at negative abatement costs – around -USD300 per ton of CO_2 – reflecting net fuel-cost savings over time. Similarly, demand-side actions, such as shifting short-haul travel to rail or substituting business flights with digital meetings, have no costs, though they depend heavily on behavioral change and policy acceptance. Medium-cost options include carbon dioxide removal (CDR) and fleet renewal through more efficient aircraft. CDR solutions, such as biochar, BECCS or direct air capture, are estimated at roughly USD150 per ton, while introducing new aircraft generations lies around USD250 per ton. These approaches provide measurable progress but cannot achieve full sectoral neutrality alone.

At the higher end of the cost spectrum are SAFs and novel propulsion aircraft. Today's Power-to-Liquid (PtL) fuels exceed USD1,400 per ton of CO_2 avoided, although technological learning could reduce this to USD250 per ton of CO_2 by 2050. Hydroprocessed Esters and Fatty Acids (HEFA) and other biofuels currently range between USD300 and USD500 per ton. Hydrogen or battery-electric aircraft also fall into the "high-cost but necessary" category, given the infrastructure and R&D investment required.

In sum, cost-effective pathways will initially rely on efficiency and behavioral measures. SAFs and novel propulsion systems represent the indispensable but capital-intensive solutions for achieving net-zero aviation by mid-century. Combining these complementary strategies ensures both economic realism and long-term climate alignment.

Figure 6: The economics of climate neutrality in aviation: a) cost-benefit representation; b) costs of different solutions in USD per ton of CO_2

a)



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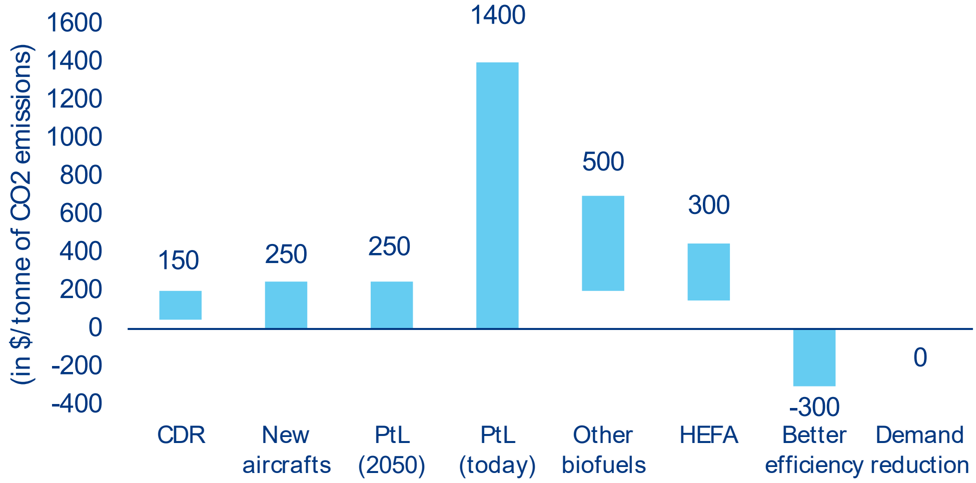
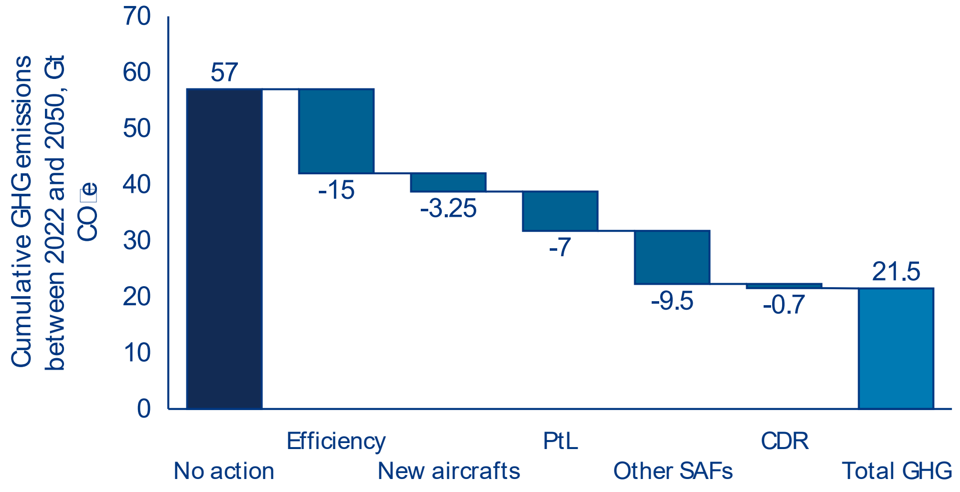


Sources: MPP, Allianz Research

The combined implementation of efficiency improvements, technological innovation and sustainable fuels could substantially curb greenhouse gas (GHG) emissions from aviation by mid-century. As illustrated in Figure 7, cumulative emissions in a no-action scenario would amount to roughly 57 Gt CO_2e between 2022 and 2050. Implementing efficiency measures could reduce this total by around 15 Gt CO_2e, representing the largest single mitigation contribution. The deployment of new aircraft technologies adds a further 3.25 Gt CO_2e reduction, reflecting ongoing fleet renewal and aerodynamic advances.

The introduction of Power-to-Liquid (PtL) fuels and other SAFs would jointly abate close to 16.5 Gt CO_2e, demonstrating their critical role in long-term decarbonization despite high production costs. In contrast, carbon dioxide removal (CDR) measures offer only a modest contribution (around 0.7 Gt) due to technological and scalability constraints. In total, these combined actions could cut cumulative aviation emissions by over -60%, lowering the sector's cumulative footprint to roughly 21.5 Gt CO_2e between 2022 and 2050.

Figure 7: Cumulative greenhouse gas (GHG) emissions reduction in the aviation sector (2022 – 2050)

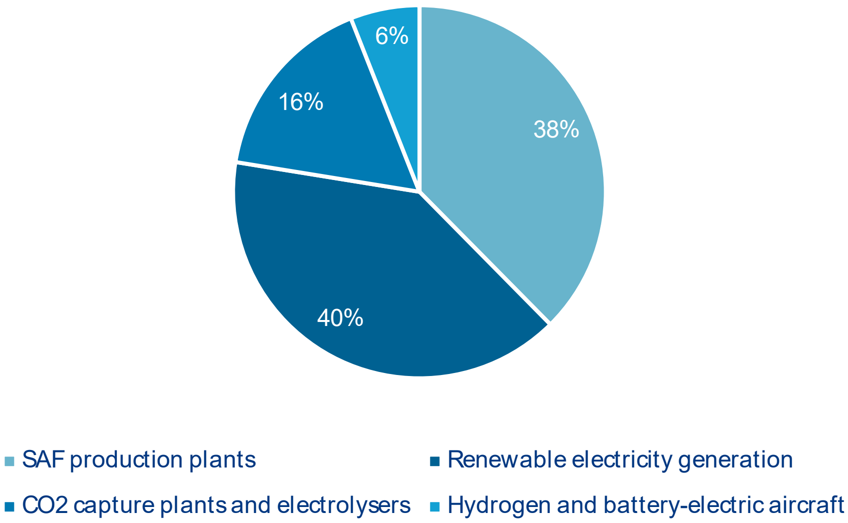


Source: MPP, Allianz Research

Realizing these mitigation pathways will require an important investment effort, estimated at nearly USD5.1trn between 2022 and 2050. As shown in Figure 8, the largest share of this financing, around 40%, must be directed toward renewable electricity generation, reflecting the sector's dependence on clean power to produce synthetic fuels and supply future hydrogen and electric aircraft. Another 38% is needed for building SAF production facilities, which represent the backbone of near and medium-term decarbonization. CO_2 capture plants and electrolysers account for roughly 16% of total investment needs, essential for generating low-carbon hydrogen and capturing carbon for Power-to-Liquid (PtL) fuel synthesis. The remaining 6% will be required for the development of hydrogen and battery-electric aircraft, a technology frontier expected to mature only after 2040. These figures highlight that achieving climate neutrality in aviation will depend on the capital-allocation question, requiring coordinated action from governments, investors and the private sector to mobilize long-term financing at scale.

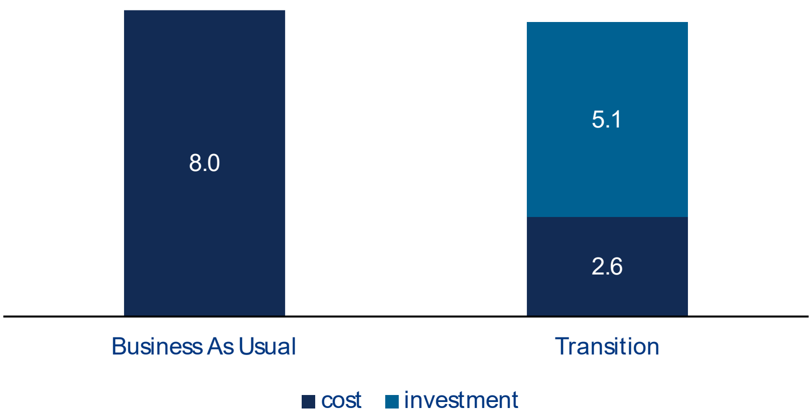
While the investment required to decarbonize aviation is substantial, the long-term economic calculus remains clearly in favor of the transition. As shown in Figure 9, under a Business-as-Usual (BAU) scenario, where no mitigation measures are implemented, the aviation sector would continue to emit large volumes of CO_2, facing rising carbon tax liabilities averaging USD176 per ton between 2025 and 2050. This results in an estimated USD8trn cumulative cost from carbon pricing alone over the period, with emissions projected to keep rising beyond mid-century. In contrast, a transition scenario would significantly reduce emissions, bringing the cumulative carbon cost down to around USD2.6trn, and effectively near zero by 2045 as the sector approaches net-zero. Achieving this, however, would require USD5.1trn in cumulative investments across SAF production, renewable electricity, carbon capture and new propulsion systems. Taken together, the total financial outlay under the transition – around USD7.7trn – is slightly lower than the cost of inaction. Yet the implications extend far beyond cost parity. Under the transition pathway, aviation would eliminate its carbon price exposure from 2045, while maintaining long-term economic competitiveness and regulatory resilience.

Figure 8: Decomposition of the investment needed to decarbonize the aviation sector

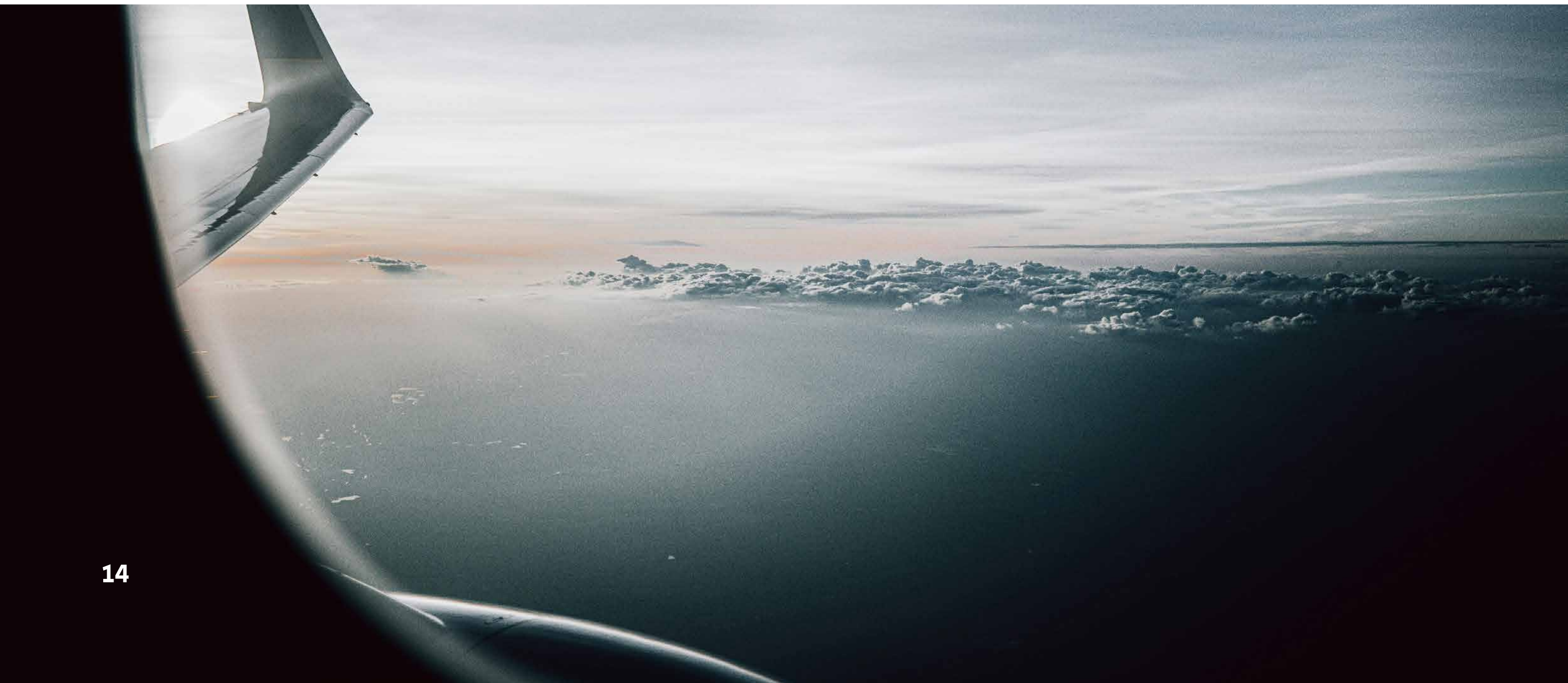


Source: Allianz Research

Figure 9: Decomposition of the investment needed to decarbonize the aviation sector



Sources: MPP, Allianz Research



The role of SAF in achieving net-zero aviation

The energy sector plays a pivotal role in the decarbonization of the aviation industry, serving as both a critical enabler and a potential bottleneck in the transition to net-zero flight. Given that the vast majority of aviation emissions stem from the combustion of fossil-based jet fuels, the development and large-scale deployment of low-carbon energy alternatives, such as SAF, green hydrogen and renewable electricity, are essential to meaningfully reduce the sector's climate impact. Indeed, it is estimated that by 2050 the overall consumption of aviation fuel is expected to climb by +75% from 2024's level. This is why SAF is recognized as a crucial lever in achieving the industry's net-zero target, potentially contributing to 65% of the necessary emissions reductions.

SAF represents the most immediate and scalable pathway to decarbonize the aviation sector, offering a "drop-in" alternative to fossil-based jet fuel that can leverage existing aircraft and airport infrastructure. SAFs are derived from renewable feedstocks – ranging from lipid-based materials, biomass and municipal waste, to synthetic sources using captured CO_2 and green hydrogen. Although still at an early stage of market deployment, SAFs can achieve 60–90% reductions in life-cycle greenhouse gas (GHG) emissions, depending on the feedstock, process and energy input.

The main SAF families differ by feedstock, conversion technology and technological readiness (Table 1). Hydroprocessed Esters and Fatty Acids (HEFA-SPK) dominate current commercial production, using used cooking oils and animal fats. With TRL 9 and a blend limit of 50%, HEFA fuels can cut up to 80% of GHG emissions but are constrained by limited sustainable lipid availability and competition with food and feed markets. Fischer–Tropsch (FT-SPK/A) fuels convert biomass or municipal waste into hydrocarbons and offer the highest theoretical GHG savings (up to 90%) and full drop-in compatibility; however, they are capital-intensive and depend on large-scale gasification infrastructure.

Other pathways are advancing toward maturity. Alcohol-to-Jet (ATJ) fuels, derived from ethanol or isobutanol, show solid progress (TRL 8–9) and can reduce emissions by 60–85%, though conversion costs remain high. Synthetic Iso-Paraffins (SIP), based on microbial fermentation of sugars, have demonstrated up to 70% GHG reductions but face scalability and cost limitations, with production largely discontinued. Meanwhile, Power-to-Liquid (PtL) fuels, produced via Fischer–Tropsch synthesis using captured CO_2 and renewable hydrogen, are viewed as the long-term net-zero solution, despite current production costs exceeding USD1,000 per tonne of CO_2 abated. Finally, Algal Oils (HAO-SPK) offer strong long-term potential due to their high energy yield and minimal land-use impact, but remain at an early research stage (TRL 5–7).

Table 1: Sustainable airline fuels, their key benefits and main challenges

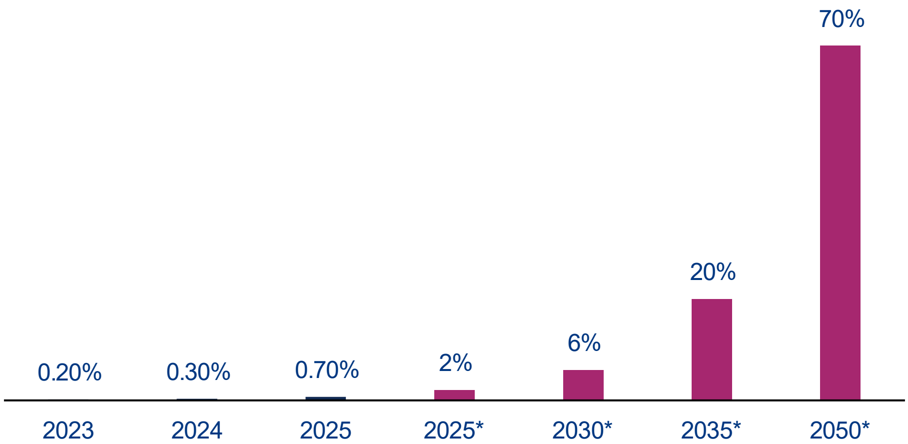
Type of SAF	Feedstock & Production Process	Key Benefits	Main Challenges	Technological & Market Readiness (2025)
Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	Hydrotreatment of lipid-based feedstocks (vegetable oils, used cooking oil, animal fats, tall oils). Oxygen is removed and hydrocarbons are cracked into jet-range alkanes.	Most mature SAF pathway; up to 80% GHG reduction; drop-in compatible; low sulfur and aromatics.	Limited sustainable lipid feedstock availability; competition with food/bio-diesel sectors; high hydrogen demand.	TRL 9 (commercial scale); blend limit: 50%; cost ~2–3× fossil jet fuel.
Fischer–Tropsch Synthetic Paraffinic Kerosene (FT-SPK / FT-SPK-A)	Gasification of biomass, municipal waste, or natural gas into syngas (CO + H_2), followed by Fischer–Tropsch synthesis into liquid hydrocarbons.	Sulfur-free; high thermal stability; can use diverse feedstocks; up to 90% GHG reduction potential.	Capital-intensive; large plant size required; complex gas cleanup; carbon efficiency <60% without CCUS.	TRL 8–9; blend limit: 50%; suitable for PtL integration.
Synthetic Iso-Paraffin (SIP / HFS-SIP)	Fermentation of sugars (sugarcane, corn, cellulosic biomass) using engineered microorganisms to produce farnesane (iso-paraffin).	Renewable biochemical route; low freezing point; clean combustion; up to 70% GHG reduction potential.	High sugar feedstock cost; land-use footprint; limited scalability and yields; small-scale production.	TRL 7–8 (demo); blend limit: 10%; production largely discontinued due to economics.
Alcohol-to-Jet (ATJ-SPK)	Conversion of ethanol, isobutanol, or methanol into jet fuel via dehydration, oligomerization, and hydroprocessing.	Flexible feedstocks; compatible with existing ethanol infrastructure; 60–85% GHG reduction.	High conversion cost; dependence on low-carbon alcohol feedstocks; catalyst optimization ongoing.	TRL 8–9; up to 50% blend; scaling 2026–2030.
Power-to-Liquids (PtL / e-SAF / FT-SPK-A)	Synthesis of renewable hydrogen (via electrolysis) and captured CO_2 into synthetic hydrocarbons using Fischer–Tropsch or methanol-to-jet routes.	Near-zero lifecycle emissions; fully compatible with current infrastructure; essential for long-term net-zero aviation.	Very energy-intensive (5–8 MWh/t fuel); costly renewable H_2 and CO_2 capture; limited demo scale.	TRL 6–8; blend limit: 50%; focus of ReFuelEU mandate.
Algal Oils / Hydroprocessed Algal Oils (HAO-SPK)	Cultivation of microalgae, extraction of lipids, followed by hydrotreatment into jet-range hydrocarbons.	High theoretical yields; non-arable land use; strong CO_2 uptake potential.	High energy and nutrient input; expensive cultivation; scalability challenges.	TRL 5–7; pilot to demo; not yet ASTM-certified; potential cost decline with photobioreactors.

Sources: Khujamberdiev and Cho (2024)[5], Allianz Research

[5] Biofuels in Aviation: Exploring the Impact of Sustainable Aviation Fuels in Aircraft Engines

According to the International Air Transport Association (IATA), the development of SAF remains disappointingly slow, far behind what is needed to align with global decarbonization targets. In 2024, global SAF production reached 1mn tons, slightly higher than the output of 2023 (+0.1pp) but still only representing 0.3% of global jet-fuel demand. While SAF production is expected to double in 2025, it will still only represent 0.7% of global jet-fuel consumption (Figure 10). By contrast, policy roadmaps such as the EU ReFuelEU Aviation Regulation envision SAF blending shares of 2% by 2025, 6% by 2030, 20% by 2035 and as much as 70% by 2050. This stark gap underscores the scale of the challenge. The current production capacity and feedstock availability are far from sufficient to meet rising demand. The aviation sector needs rapid investment in production infrastructure, renewable electricity and feedstock diversification to meet its net-zero milestones.

Figure 10: The slow development of SAF



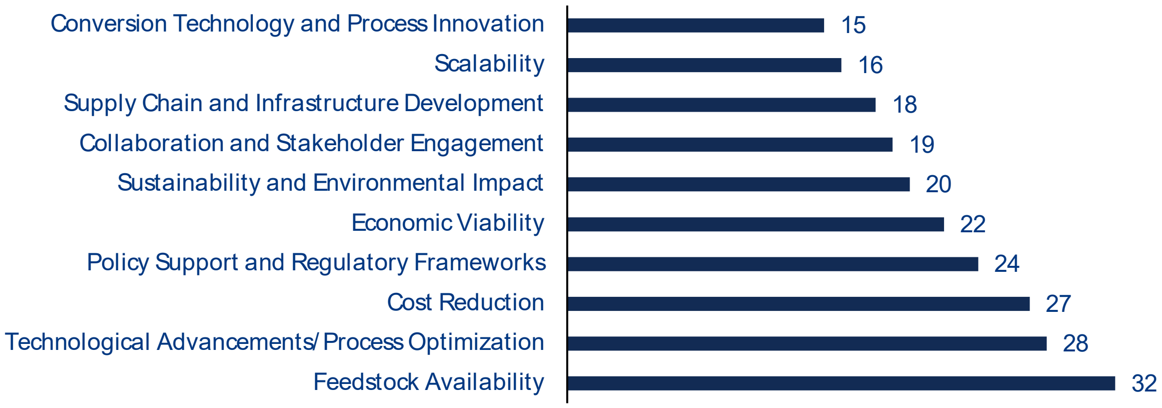
Source: ReFuelEU, Allianz Research

The development and large-scale deployment of SAF face a complex set of interrelated challenges that span the technological, economic, regulatory and logistical dimensions of the energy transition (Figure 11). According to the literature review and meta-analysis of over 50 peer-reviewed studies (Wandelt et al, 2025), feedstock availability emerges as the most frequently cited barrier. The limited supply of sustainable lipid-based feedstocks – such as used cooking oil, animal fats and agricultural residues – is constrained by land competition, seasonal variability and logistical inefficiencies. Moreover, as SAF demand increases, competition from the food and biofuel industries is expected to further tighten supply chains and raise prices, undermining scalability.

Technological advancement and process optimization represent the second most significant challenge. Existing SAF pathways, such as Fischer–Tropsch synthesis, Hydroprocessed Esters and Fatty Acids (HEFA) and Alcohol-to-Jet (ATJ) processes, remain energy-intensive and costly. Breakthroughs in catalysis, reactor efficiency and process automation are critical to achieving the required cost reductions and emissions performance. Related to this, cost reduction is a central concern as most SAFs remain substantially more expensive than fossil jet fuel, with abatement costs currently exceeding USD1,000 per ton of CO_2 for some pathways. Achieving cost parity will depend on scaling up production, improving efficiency and establishing clear and stable policy incentives.

Indeed, policy support and regulatory frameworks are another recurring theme. Fragmented global standards, inconsistent carbon pricing and the absence of binding mandates hinder investor confidence and delay deployment. Coordinated policy tools, such as subsidies, tax credits and blending obligations, are essential to de-risk private investment and drive industrial scaling. Further challenges include economic viability (the "chicken-and-egg" problem of low demand and high prices), supply-chain and infrastructure development and scalability, all of which require substantial capital investment and international coordination. Finally, sustainability concerns, such as indirect land-use change, biodiversity impacts and lifecycle emissions, underscore that not all SAF pathways are equally green. Addressing these interlinked challenges holistically is essential for SAFs to evolve from a niche innovation into a cornerstone of climate-neutral aviation.

Figure 11: Number of studies identifying key challenges in SAF production



Sources: Wandelt et al. (2025)[6], Allianz Research

While SAFs are often described as the most promising near-term solution to decarbonize aviation, recent scientific evidence suggests that their climate benefits may be more limited than widely assumed. According to Boerboom et al. (2025)[7], when accounting for the full "well-to-wake" climate impact – including both CO_2 and non-CO_2 effects such as nitrogen oxides (NO_X, water vapor and contrails – the total emission reduction potential of SAFs rarely exceeds -50% compared to conventional jet fuel. This finding challenges the prevailing perception that SAFs can deliver near-carbon neutrality simply through feedstock substitution.

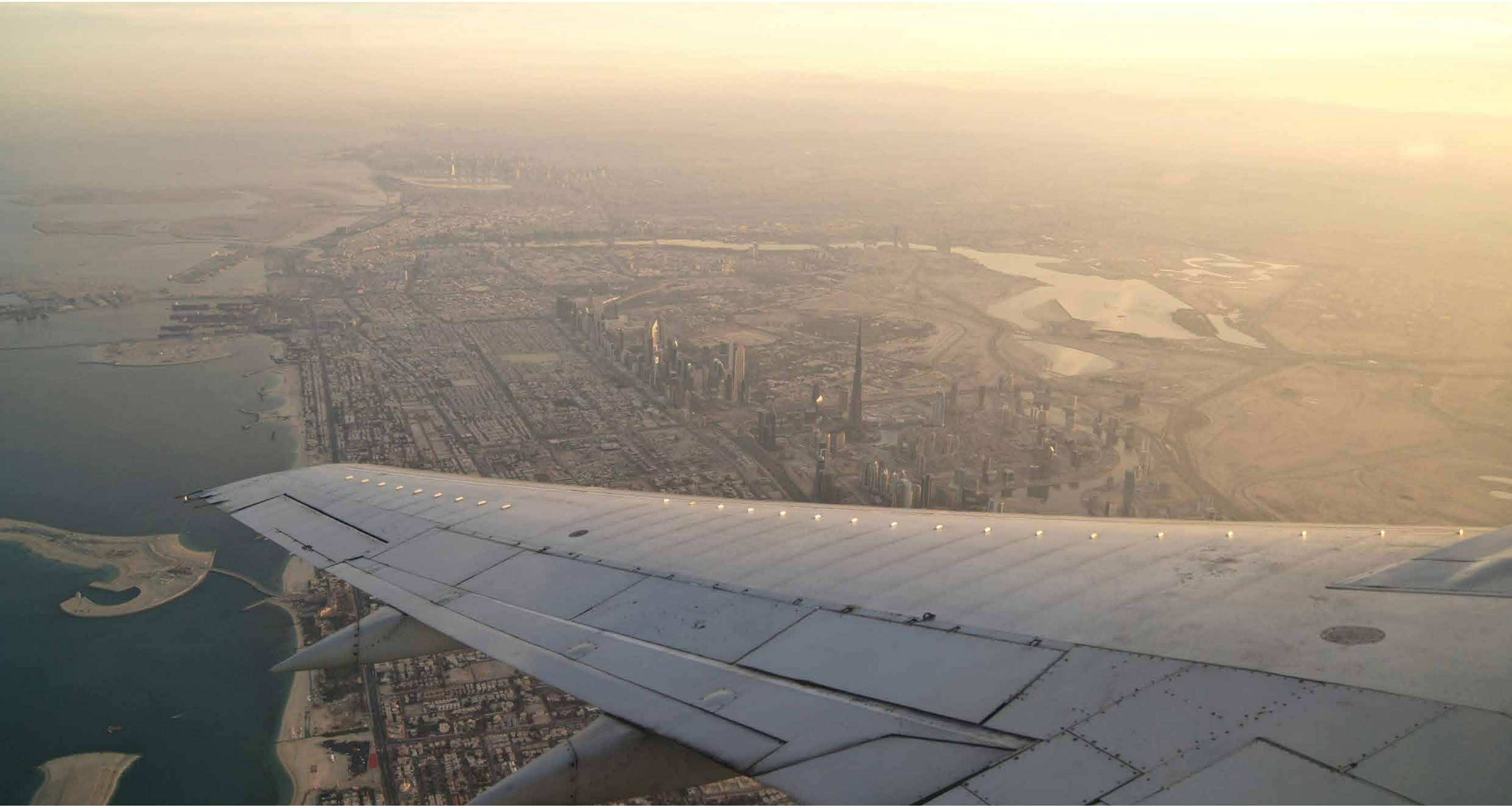
One key limitation lies in the persistent in-flight non-CO_2 effects, which represent roughly two-thirds of aviation's total radiative forcing. Even when SAFs achieve near-zero CO_2 lifecycle emissions, their combustion still produces NO_X and water vapor at high altitudes, contributing to ozone formation, methane depletion and contrail-induced cirrus clouds. These processes have complex warming and cooling dynamics, but the net effect remains positive radiative forcing, meaning continued warming. The magnitude of these effects depends strongly on flight altitude, humidity and atmospheric conditions, making mitigation difficult to standardize.

[6] Sustainable aviation fuels: A meta-review of surveys and key challenges - ScienceDirect
[7] A comprehensive well-to-wake climate impact assessment of sustainable aviation fuel | Scientific Reports

A second limitation concerns the heterogeneity of SAF feedstocks and production pathways. Boerboom et al. (2025) highlight that life-cycle CO_2 performance varies widely – from around 150 to 250 g CO_2e/MJ – depending on feedstock type, process energy source and land-use change assumptions. For instance, fuels derived from waste lipids (HEFA-SPK) offer higher GHG savings than crop-based biofuels, while Power-to-Liquid (PtL) fuels have the lowest potential emissions but are constrained by renewable electricity supply and high production costs. This variability complicates both regulatory accounting and market comparability.

Furthermore, the temporal dimension of climate impact matters. The "average temperature response" analysis shows that short-lived non-CO_2 effects (e.g., contrails) dominate near-term warming, while CO_2 reductions only materialize over decades. Thus, SAFs perform better in long-term climate stabilization scenarios (100-year timeframes) than in short-term mitigation goals, an important consideration for policies aiming at near-2050 net-zero targets.

In short, while SAFs play an indispensable role in aviation's transition, they are not a silver bullet. Their effectiveness depends on addressing non-CO_2 effects, ensuring truly sustainable feedstocks and coupling fuel substitution with technological, operational and policy innovations that target the full climate footprint of flight.



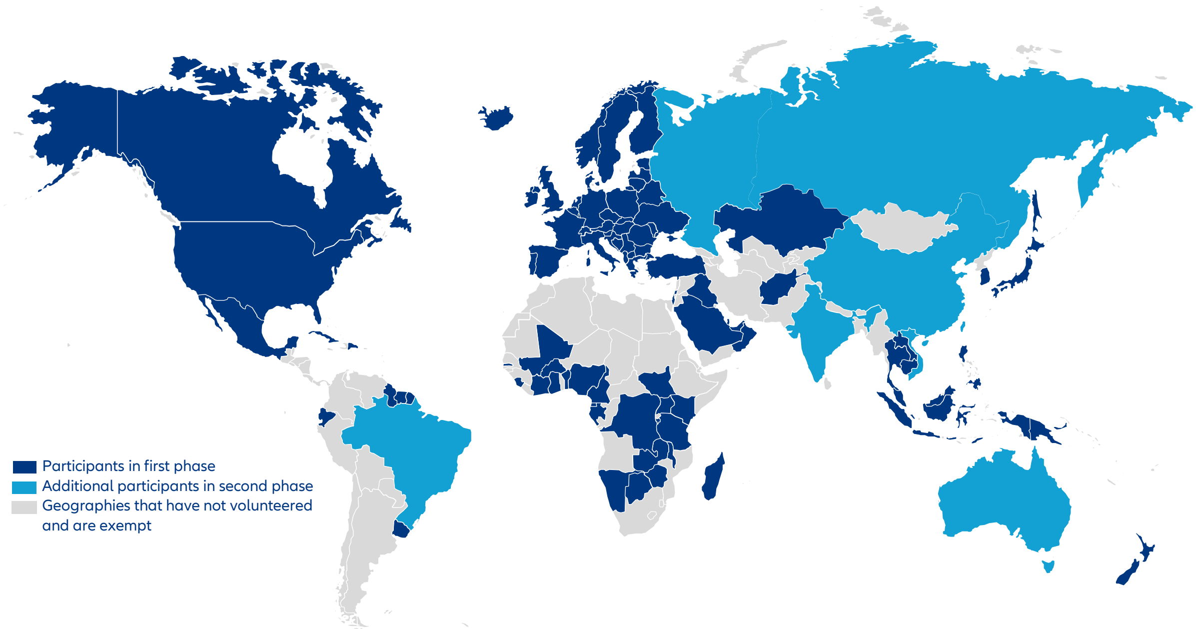
Carbon credits: a solution with financial implications

Greening aviation takes more than fuel – market-based mechanisms can also help bridge the carbon gap. Carbon credit initiatives are also emerging as a complementary solution to the sector's greening pathway. As of today, two major policy instruments are largely recognized: CORSIA[8] (Carbon Offsetting and Reduction Scheme for International Aviation) and the EU Emissions Trading System (ETS). Both are key carbon-credit mechanisms designed to achieve a rapid transition, allowing airlines to offset part of their CO_2 emissions by financing verified carbon-reduction projects elsewhere.

Although both tools have similar goals, they differ in scope and approach. CORSIA represents the first globally-agreed market-based offsetting mechanism for international aviation (flights between two states). The project started with a pilot phase (2021-2023), followed by a first phase (2024-2026). For both, participation is voluntary (Figure 12), but they differ in how the airline's offsetting requirements are determined by the state. The pilot phase allowed states to choose how to calculate airlines' offsetting obligations (using actual yearly emissions or 2019 levels) and used a baseline equal to 100% of 2019 emissions. But the first phase uses only actual annual emissions, removes the 2019-emissions option and tightens the baseline to 85% of 2019 emissions, increasing expected offsetting. For the second and last phase of implementation (2027-2035), all states[9] whose individual share of international aviation activity in 2018 was above 0.5% of total activity, or whose cumulative share reaches 90% of total activity, are included, i.e. most International Civil Aviation Organization (ICAO) states.

[8] Officially created in 2016 by the International Civil Aviation Organization (ICAO), and operating in practice since 2021
[9] Least developed countries, small island developing states and landlocked developing countries are exempted for participation.

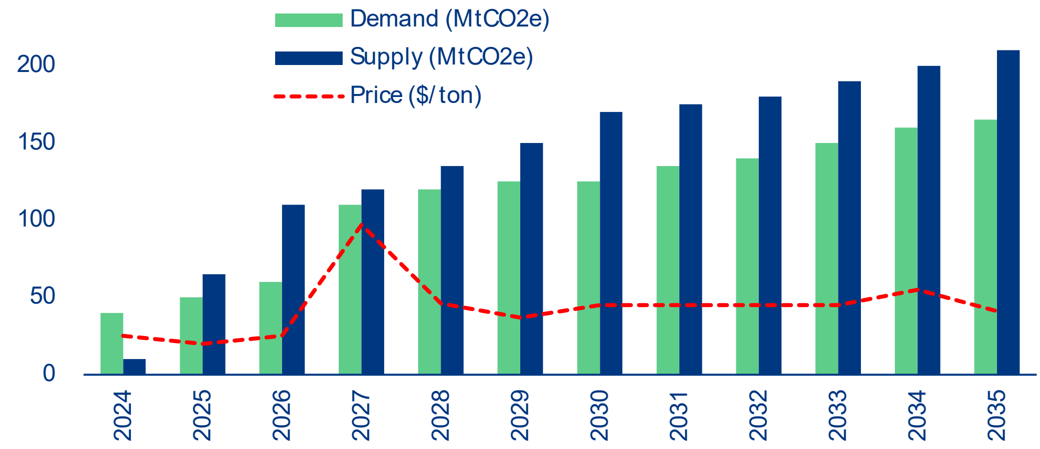
Figure 12: CORSIA's participation



Sources: Bloomberg NEF, ICAO, Allianz Research

In the pilot phase, CORSIA imposed negligible costs on airlines. But a higher financial burden is looming for 2027. The cost of emission units varies widely, influenced by factors such as the project type, the certification standard applied and prevailing market conditions. As of October 2025, one carbon credit costs on average USD20/ton of carbon emissions removed (vs USD7/ton during the pilot phase). Indeed, during 2021-2023, CORSIA had almost no impact on airlines' costs. The scheme's emissions baseline (set at 2019 levels) meant that, for many carriers, actual emissions fell within or below this reference point. Consequently, the obligation to acquire carbon offsets did not apply in practice, resulting in minimal financial burden during these early years. In 2024, it is estimated that airlines spent around USD1bn on credits (with prices averaging USD25/ton). This represents only 3% of the sector's USD32bn net profit recorded last year. As we approach the start of the second phase (2027), more states are starting to join the program. The number of participants is expected to jump from 88 countries in 2021 to 130 next year, with additional big players such as Russia, China, India and Brazil joining the project soon. Therefore, demand for CORSIA credits is expected to increase by +20% y/y in 2026 and to almost double in 2027 (Figure 13). With demand set to soar, carbon credit prices are expected to rise, particularly from 2027 onwards, when CORSIA obligations are projected to cover roughly 85% of international aviation emissions – reflecting the share of the industry required to participate. This upward pressure is further supported by the even higher cost of alternative solutions such as SAF. Carbon prices are projected to approach USD100/ton in 2027 (+290% vs now), particularly driven by demand doubling while supply should grow by only around +10%. Assuming airlines need to offset between 80-110mn tons (Mt CO_2) that year, this could represent a financial burden of around USD9.5bn or 26% of the sector's current net profits. Beyond that, as offsetting projects development accelerates and supply expands faster than sector demand, prices will likely ease, and CORSIA could become a more reasonable cost to absorb. Clearly, the impact will not be homogeneous across all airlines as it will fall more heavily on those with greater exposure to the international (long-haul) segment and on carriers that are lagging in SAF adoption or operating less efficient, higher-emitting fleets.

Figure 13: Supply, demand and price forecast of CORSIA credits, per year



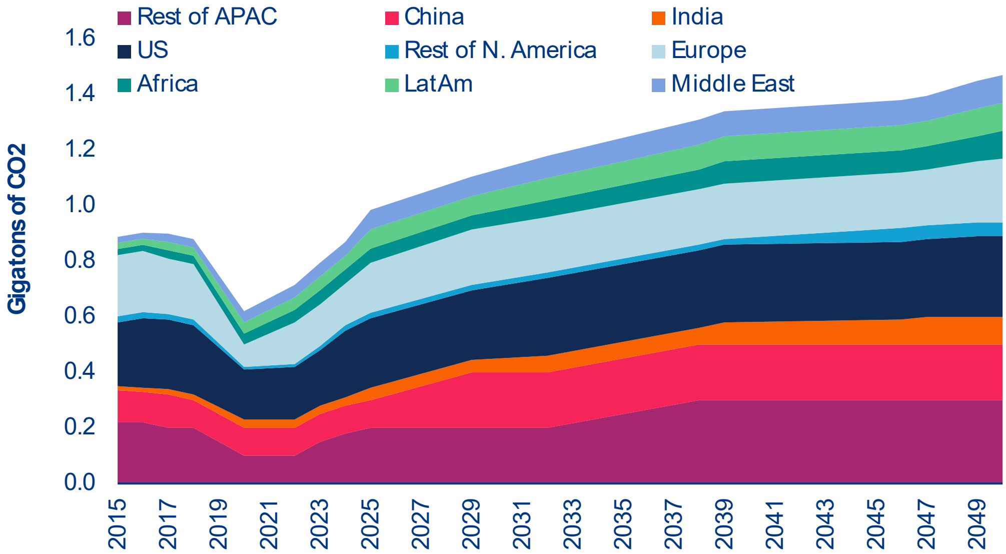
Sources: Bloomberg NEF, Allianz Research. Note: Chart shows BloombergNEF's base case outlook.

In contrast to CORSIA's looser global offsetting approach, the EU ETS makes airlines pay for all verified CO_2 emissions within Europe under a strict cap-and-trade system. EU ETS represents one of the most significant regulatory pressures on the European airline industry as it places a direct and increasing price on carbon emitted by flights operating within the European Economic Area[10]. Under this cap-and-trade scheme, airlines must monitor, report and verify their CO_2 emissions annually, and then surrender a corresponding number of emissions allowances. While a portion of allowances was historically allocated for free, these are being phased out rapidly, meaning carriers must increasingly purchase them on the market, exposing them to carbon-price volatility. Key milestones include the progressive tightening of the emissions cap, the reduction of free allowances to zero by 2026 and the alignment of aviation with the EU's broader "Fit for 55" decarbonization agenda. In practice, the ETS incentivizes airlines to accelerate fuel-efficiency improvements, fleet renewal, SAF adoption and operational optimization, since every ton of CO_2 avoided directly reduces compliance costs and competitive risk.

The EU is phasing out free ETS allowances for aviation in a gradual manner, which has given the sector some breathing room in the past two years. Airlines received a -25% reduction in free allocations in 2024 and a -50% reduction in 2025. From 2026 onward, all allowances must be fully purchased, traded or auctioned. In other words, airlines will have to purchase a larger share of their required credits on the market next year. Although Europe is not the region with the highest CO_2 emissions from the aviation sector (Figure 14), this year its carriers are expected to need around 45mn allowances in total, with current prices hovering around EUR80/ton of CO_2, which represents a total cost of EUR3.6bn. As allowance needs will increase progressively, reaching up to 70mn by 2030, this financial obligation could increase up to EUR5.6bn, ceteris paribus, or EUR10.5bn if prices jump up to EUR150/ton by then. While carbon credits are generally less expensive than sustainable aviation fuel, their cumulative cost is expected to rise as emission caps tighten and carbon prices increase. This will directly impact operating costs and profit margins if airlines choose to absorb the expense. Alternatively, these costs could be passed on to passengers, potentially affecting ticket prices.

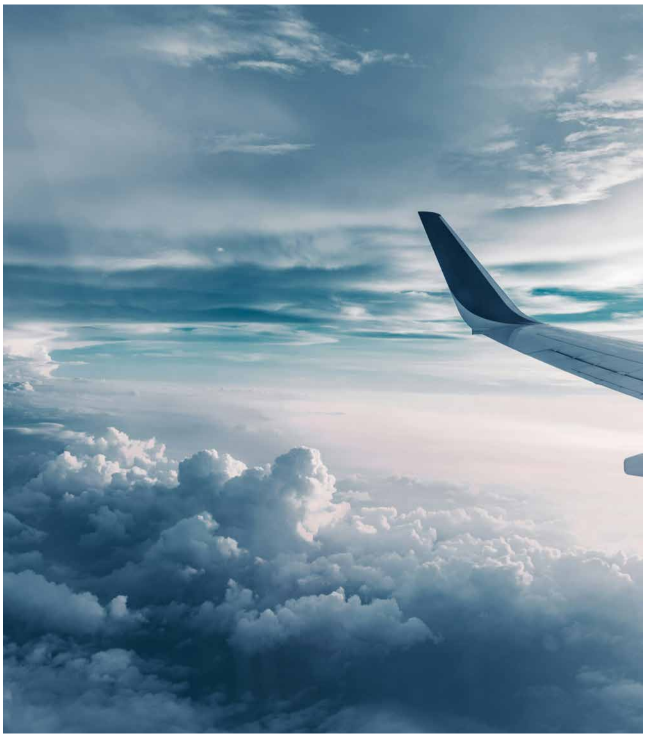
[10] EU ETS applies for flights within and between countries in the European Economic Area, as well as departing flights to Switzerland and to the UK, while applying CORSIA for flights to and from third countries.

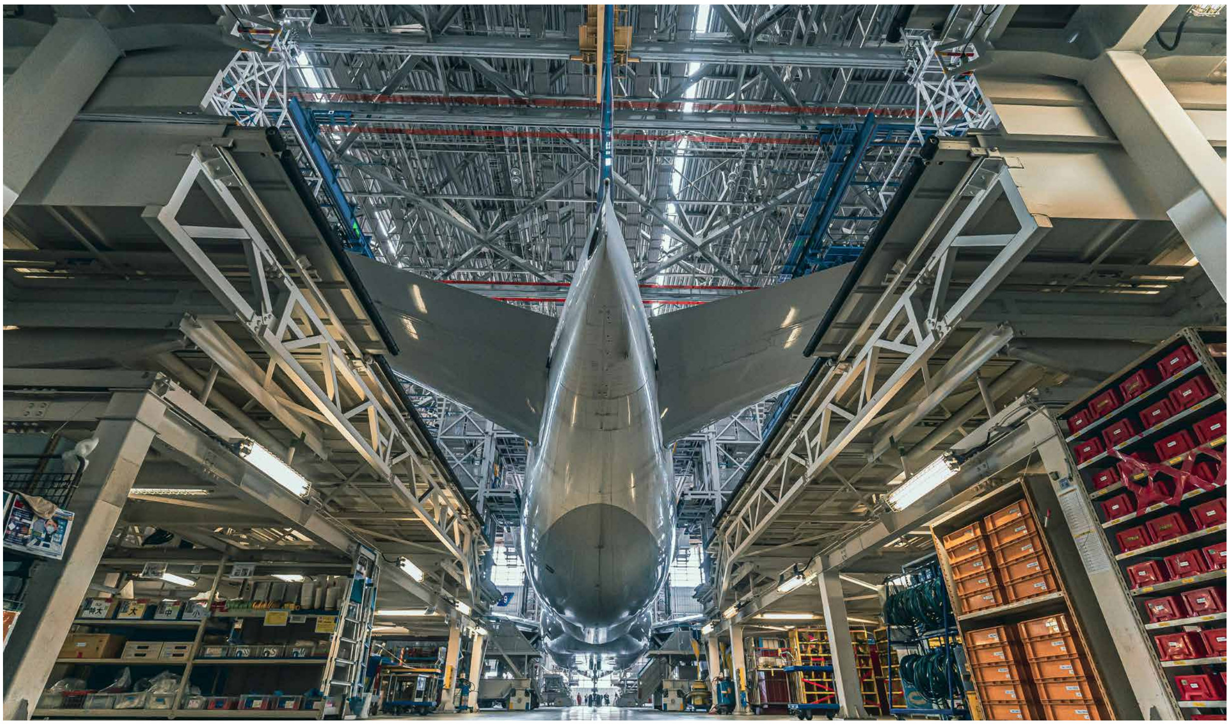
Figure 14: Airlines' CO_2 emissions outlook, by region



Sources: BloombergNEF, International Energy Agency (IEA), International Civil Aviation Organization (ICAO), Allianz Research. Note: Includes sustainable aviation fuels

All in all, airlines should treat carbon credits under CORSIA and the ETS as both a compliance obligation and a strategic cost component in their sustainability and financial planning. These credits serve as a transitional mechanism, allowing airlines to offset unavoidable emissions while cleaner technologies and sustainable aviation fuels are scaled up. In the short to medium term, carbon credit systems help the sector limit its climate impact without disrupting operations. From a profitability perspective, absorbing these costs internally may affect margins, whereas passing them on could influence ticket pricing, depending on an airline's business strategy. Over the longer term, the cumulative cost of carbon credits is likely to incentivize greater investment in SAF and low emission technologies, reducing reliance on external offsets and supporting a more sustainable, competitive aviation sector.

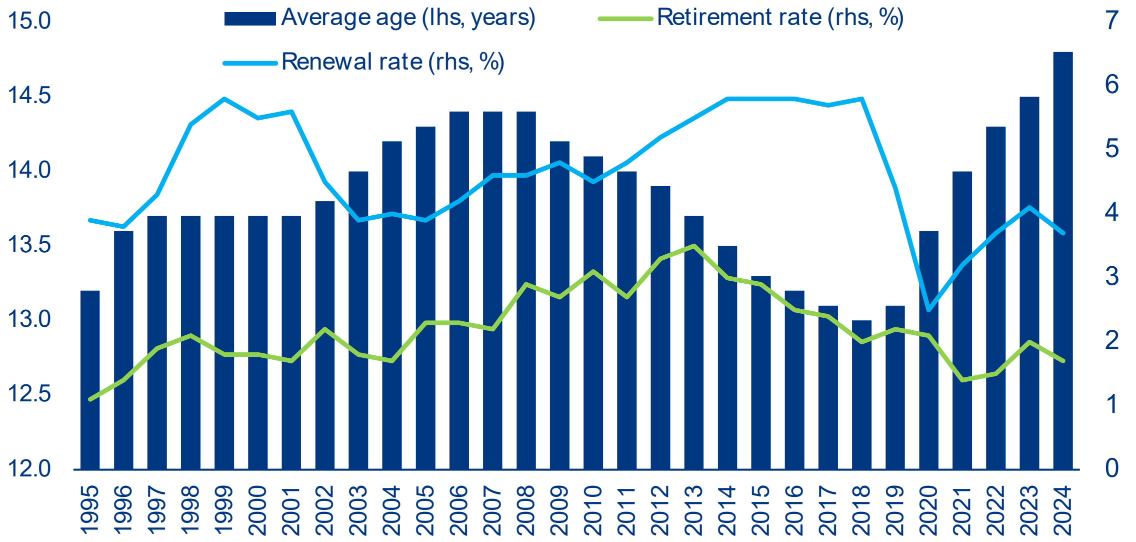




Reinventing propulsion: The game-changing role of aircraft manufacturers

Decarbonizing the aviation industry is a collective challenge that extends well beyond the operational and financial efforts of airlines. Plane makers also have a big role to play. Two fundamental challenges emerge from the perspective of aircraft manufacturers: how to accelerate new aircraft deliveries so that airlines can modernize aging and less energy-efficient fleets as soon as possible, and how to allocate additional resources to accelerate innovation and the development of the next-generation aircraft. With aircraft retirement rates remaining very low (at 1.7% in 2024) and renewal rates only at 3.7% (Figure 15), the global fleet is aging more rapidly than ever, rising from a pre-pandemic average age of 13 years to a record high of nearly 15 years. As airlines increase their reliance on older aircraft equipped with less fuel-efficient engines, operating costs climb and efforts to decarbonize are further set back. In other words, the benefits of adopting sustainable aviation fuels, purchasing carbon credits and implementing other operational efficiencies are being partially offset by persistent delivery challenges within the manufacturing segment of the supply chain.

Figure 15: Average age of global aircraft fleet, fleet retirement rate, and renewal rate



Sources: IATA Sustainability and Economics, Allianz Research

The aircraft manufacturing industry is highly consolidated, with very few well-established dominant producers that hoard a significant market power. As of June 2025, the worldwide commercial fleet consists of 35,550 aircraft. The two biggest plane manufacturers produced around 80% of the current active fleet, while the top five represent almost 95% of all aircraft in service around the world. While the remarkable development and expansion of air transportation is largely attributable to this duopoly, the sector – as well as related beneficiary industries such as tourism – remains heavily dependent on their ability to scale production. Persistent and multifaceted supply-chain disruptions in the post-pandemic era have extended aircraft delivery times from two to three years to almost six years (longer for widebody aircraft and shorter for regional aircraft), driving the global commercial aircraft backlog to climb to about 17,000 units in 2024, from an average of 10,800 between 2017 and 2019.

With this scarcity having limited short-term solutions, airlines are now looking for efficiencies through plane retrofitting. The situation of fewer new jets available is driving up maintenance and retrofitting costs for airlines. Retrofitting older aircraft is emerging as a compelling alternative to waiting for new deliveries. By refurbishing cabins, upgrading avionics or converting passenger jets into freighters, airlines can extend the useful lives of existing airframes. Retrofitting also implies lower depreciation and financing costs than purchasing a brand new plane. Commercial aircraft are most frequently retrofitted in their cabins, avionics systems, engines and airframe components. The highest-demand upgrades include cabin modernizations and densification, next-generation avionics packages and enhanced passenger connectivity. Energy-efficiency improvements typically come from aerodynamic additions like winglets, lightweight interior materials upgraded APUs and engine performance packages that refine control systems and core components. Aerodynamic enhancements on winglets, for instance, allow airlines to achieve fuel savings exceeding 4% while also lowering aircraft noise and nitrogen oxide (NOx) emissions. Since 2000, more than 9,000 aircraft have been equipped with winglets, collectively reducing CO_2 emissions by over 100mn tons, according to IATA.

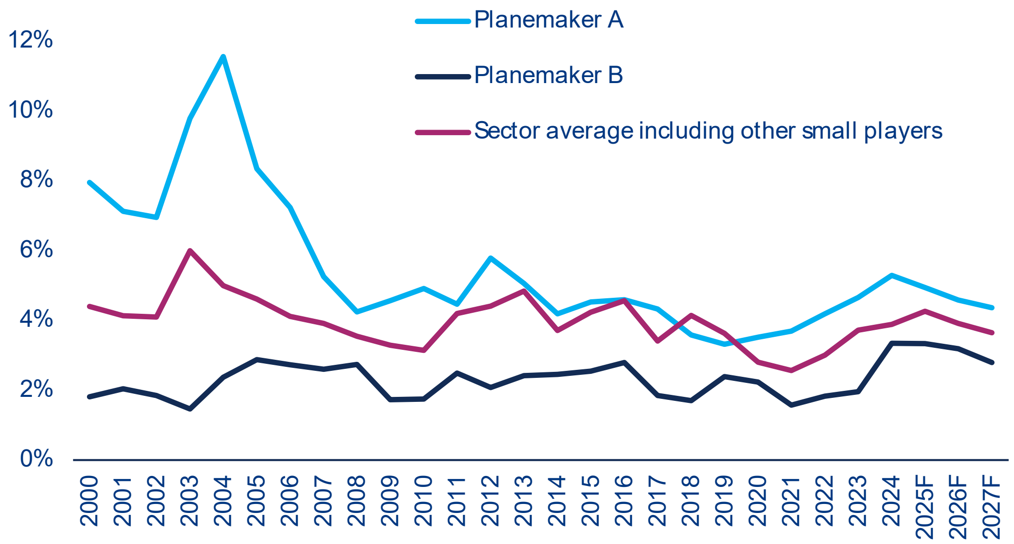
While retrofitting is a valuable bridge solution, it cannot substitute the impact of deploying new-generation aircraft. Upgrades can improve efficiency at the margins, but older airframes remain structurally constrained by legacy designs, higher weight and less advanced propulsion systems. By contrast, newly built aircraft integrate step-change technologies – lighter composite structures, next-generation engines, optimized aerodynamics and digital systems – that deliver substantially lower fuel burn and emissions. Therefore, although retrofits help mitigate short-term delivery bottlenecks, meaningful and sustained decarbonization ultimately depends on accelerating the introduction of new, inherently more efficient aircraft into the global fleet.

Accelerating new aircraft deliveries requires a coordinated industry response that tackles capacity constraints across the entire aerospace supply chain. First, manufacturers need to stabilize and diversify their supplier bases, especially for engines, aerostructures and critical avionics, by qualifying additional tier-2 and tier-3 suppliers and investing in long-term contracts that create visibility and financial resilience. Second, expanding production capacity – through new final-assembly lines, automation in component manufacturing, additive-manufacturing applications and digital-twin–enabled quality control – can shorten build cycles and reduce rework. Third, OEMs and regulators must streamline certification and conformity processes, using more digital certification tools and risk-based oversight to prevent bottlenecks. Fourth, governments can accelerate deliveries by offering targeted industrial incentives (tax credits, export-financing support, workforce training programs) that help suppliers ramp up quickly. Finally, airlines themselves can contribute by sharing more stable, long-horizon demand signals and adopting standardized configurations that reduce customization and enable faster throughput. Taken together, these measures create a more resilient, scalable manufacturing ecosystem that can deliver new, energy-efficient aircraft at the pace required for meaningful fleet modernization and decarbonization.

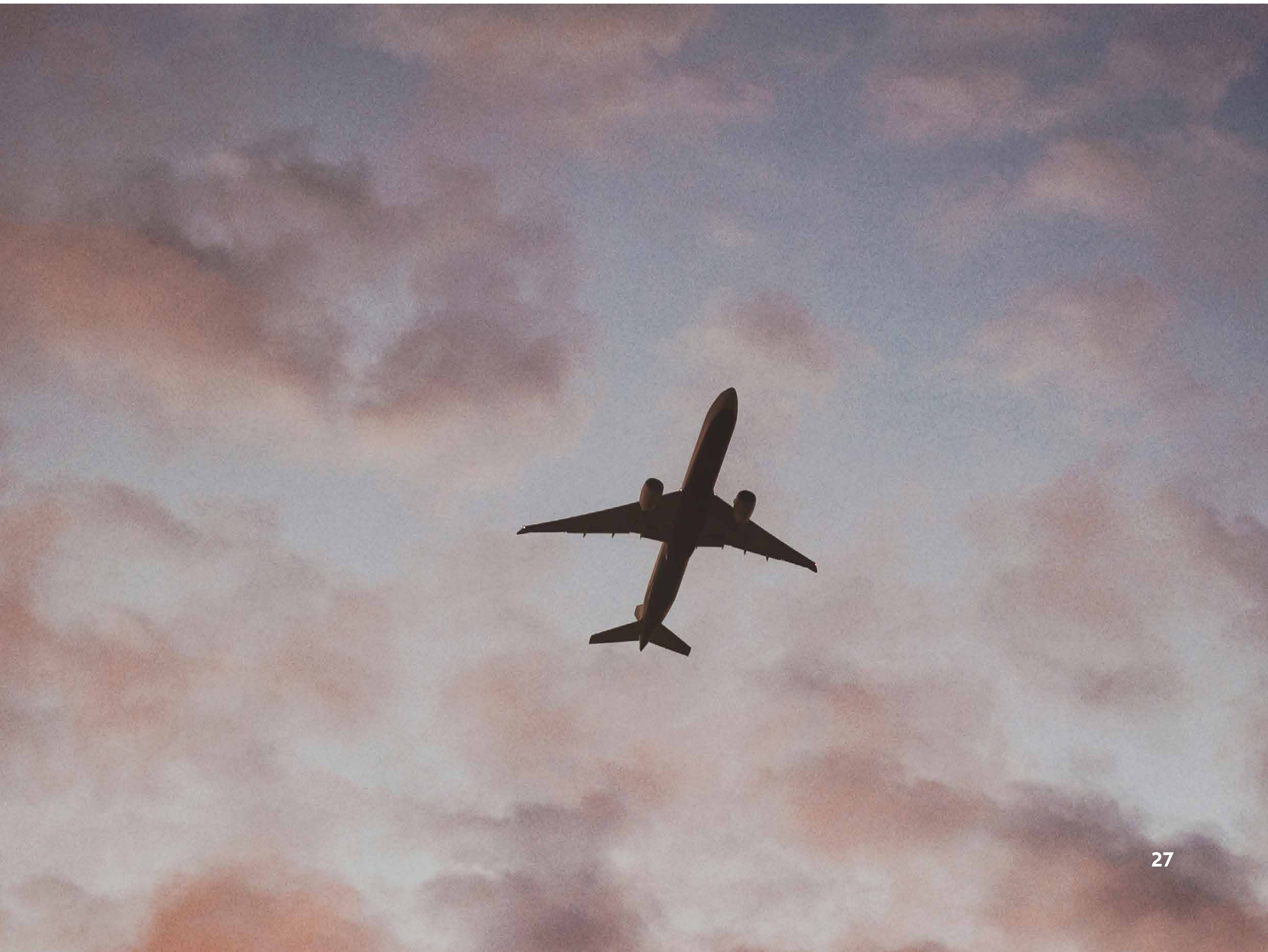
It is estimated that advances in aircraft technology could cut fuel use and CO_2 emissions by about -20% by 2050, but first things first: CAPEX must accelerate to get there. Looking ahead, airlines' ability to achieve meaningful carbon reductions will increasingly hinge on the pace of technological innovation delivered by aircraft and engine manufacturers. ICAO projections suggest that improvements in aircraft technology could reduce fuel consumption and CO_2 emissions by around -20% by 2050 relative to baseline levels. Beyond incremental efficiency gains from the most recent models, the sector's long-term decarbonization will be driven by the development of new aircraft platforms and propulsion technologies – ranging from ultra-efficient narrowbodies to hybrid-electric, fully electric and hydrogen-powered designs. As these next-generation technologies mature and enter commercial service (with ultra-efficient and hybrid-electric models arriving through the 2030s, and hydrogen-powered commercial aircraft projected for the late 2030s to 2040s), they will provide the step-change in energy efficiency that existing fleets and retrofit solutions cannot achieve, positioning airlines to accelerate their decarbonization trajectories. Undoubtedly, advancing these innovations requires substantial and sustained capital expenditures. Recent CAPEX among leading aircraft manufacturers has been heavily focused on decarbonization and next-generation propulsion technologies, with a significant portion directed toward R&D on new aircraft platforms that support SAF adoption, as well as investments in synthetic e-SAF and bio-SAF pathways. At the same time, manufacturers are advancing hydrogen-based propulsion systems and hybrid-electric powertrains, funding the development of hydrogen fuel-cell aircraft and associated infrastructure, while also pursuing advanced aerodynamic and engine designs – such as open-fan engines capable of running on 100% SAF – to drive long-term efficiency gains. These investments reflect a strategic shift: not merely improving existing models, but fundamentally transforming how aircraft are powered, with a strong emphasis on sustainability and reducing lifecycle emissions. To align with global net-zero targets, the aviation industry must continue prioritizing R&D and allocating greater resources to clean technology development, ensuring that the aircraft of the future enable airlines to meet their decarbonization commitments.

Even with these efforts, current CAPEX levels remain insufficient. Although investments have increased by +8% over the past decade, and by +67% relative to pandemic lows, the CAPEX-to-revenue ratio of the industry remains very low, between 3% and 5% (Figure 16). For a sector tasked with delivering a scale of transformation necessary to meet climate goals, business-as-usual investment levels are far below what is required. To accelerate decarbonization meaningfully, aircraft manufacturers and their investors must commit to materially higher CAPEX, ensuring that next-generation technologies are developed and deployed at the pace the industry – and the planet – demands.

Figure 16: Plane makers' historical and forecast capex-to-revenue ratio



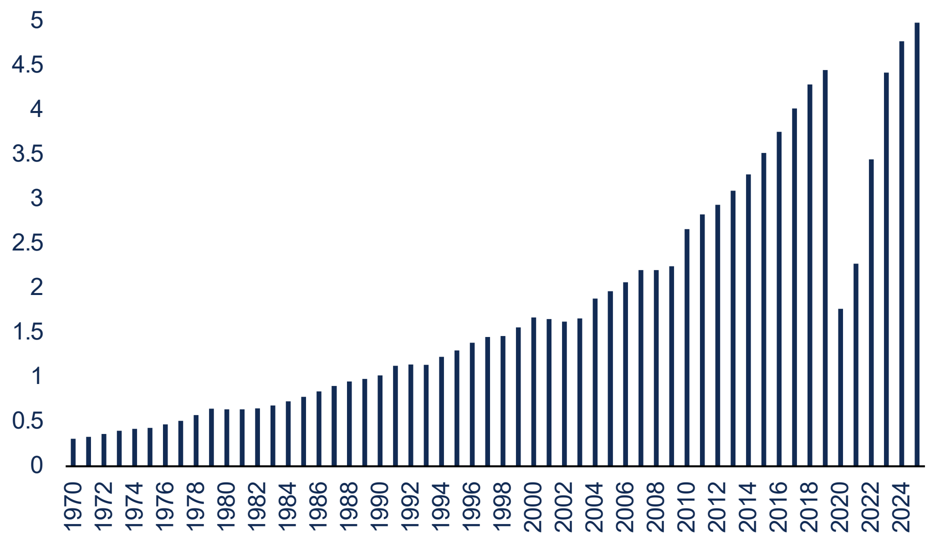
Sources: Bloomberg, Allianz Research



Aligning aviation demand with climate goals

Air travel demand has expanded at an extraordinary pace over the past five decades. Global passenger numbers rose from fewer than 0.4bn in 1970 to almost 5bn in 2025, an unprecedented 16-fold increase (Figure 17). This long-run growth reflects structural drivers such as rising incomes, falling ticket prices, globalization of supply chains and the expansion of tourism. It also highlights the sector's strong resilience: shocks such as 9/11, the 2008 financial crisis and particularly Covid-19 caused abrupt declines, yet demand rebounded rapidly each time. The major shock of Covid-19 was fully made up for in 2024, when the number of passengers already crossed its 2019 level. However, this continued growth presents a major challenge for decarbonization: Even with efficiency gains and low-carbon fuels, rising passenger volumes risk outpacing technological progress.

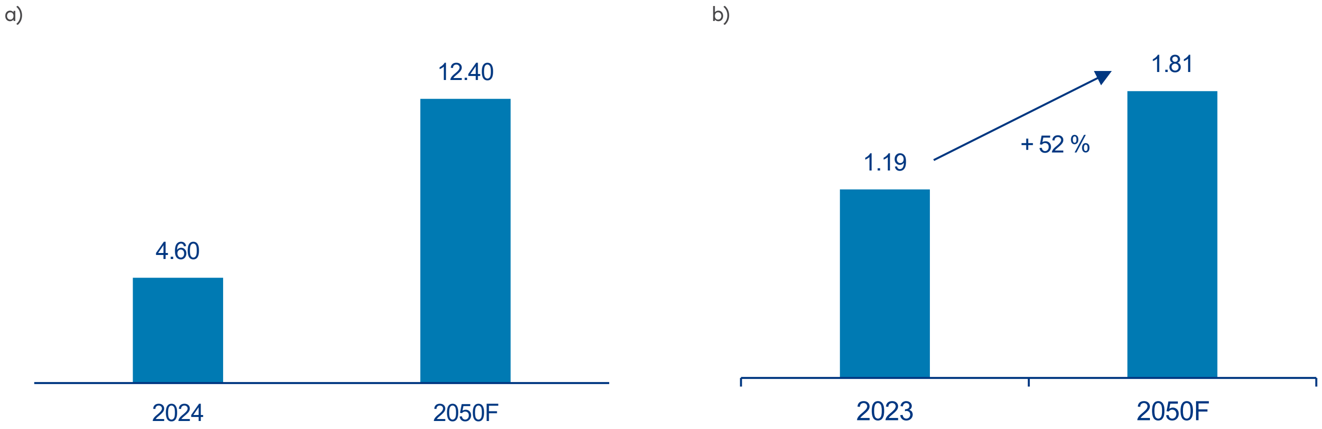
Figure 17: Evolution of air transport passengers from 1970 to 2025 in billion



Sources: World Bank, IATA, Allianz Research

The rapid growth in global air travel over the past five decades is expected to continue, albeit with significant regional variation (Figure 18). Worldwide passenger numbers are projected to rise from 4.6bn in 2024 to 12.4bn by 2050, an almost three-fold increase. This surge reflects sustained income growth in emerging economies, expanding tourism and the integration of developing regions into global markets. In Europe, by contrast, growth is expected to be more moderate. Passenger traffic is projected to increase from 1.19bn in 2023 to 1.81bn in 2050, a +52% rise. This slower trajectory reflects a more mature market, denser alternative transport networks and stronger policy-driven constraints (e.g. ETS I). Nevertheless, even Europe's more modest demand expansion will challenge the ability of existing climate strategies to keep emissions on a net-zero pathway by 2050.

Figure 18: Projection of the evolution of air transport passengers by 2050 (in billion) globally (a) and in Europe (b)



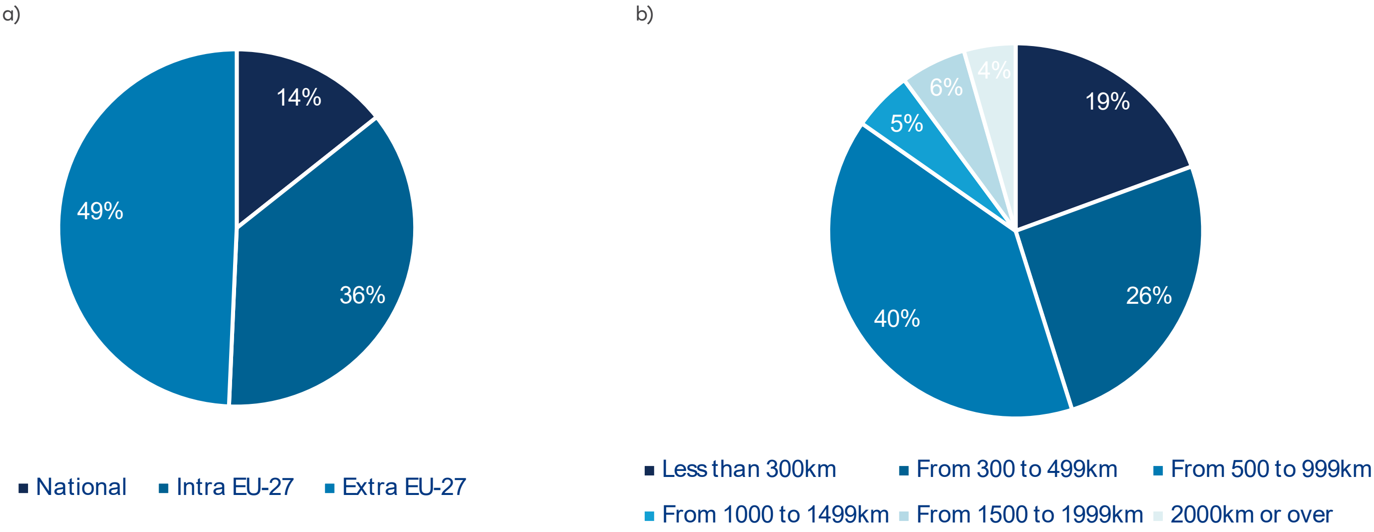
Sources: Allianz Research based on JRC EDGAR, Energy Institute, Global Carbon Budget, World Bank, IRENA, NGFS

Air travel patterns within the EU reveal significant opportunities for demand-side mitigation. In 2024, more than half of all EU passengers flew either domestically or within the EU-27, underscoring that much of Europe's aviation demand is concentrated on relatively short distances where competitive low-carbon alternatives already exist (Figure 19a). High-speed rail networks, night trains and improved cross-border services can play a substantial role in reducing the need for short-haul flights without compromising connectivity.

The distance breakdown confirms this high decarbonization potential. Short flights under 300 km account for 19% of all national air travel, i.e. nearly one in five passengers. When extending the range to 500 km, these flights represent 45% of the total, almost half of all domestic journeys (Figure 19b). These are precisely the distances where rail is generally faster once door-to-door travel time, security procedures and airport access are considered. Moreover, expanding night train networks can effectively replace flights in the 500–1,000 km range, which still represent a significant share of demand. Prioritizing alternative modes for these short and medium distances could therefore deliver rapid emission reductions at limited societal cost. Such a shift is facilitated by Europe's existing infrastructure, dense population centers and policy momentum. France is already restricting ultra-short flights where rail connections under 2.5 hours exist[11].

[11] Air Passenger Market Analysis

Figure 19: Decomposition of air travel in the EU (2024): a) by boarders (domestic boarders (National), within EU countries (Intra) or outside EU boarders); b) by distance for national travel including overseas

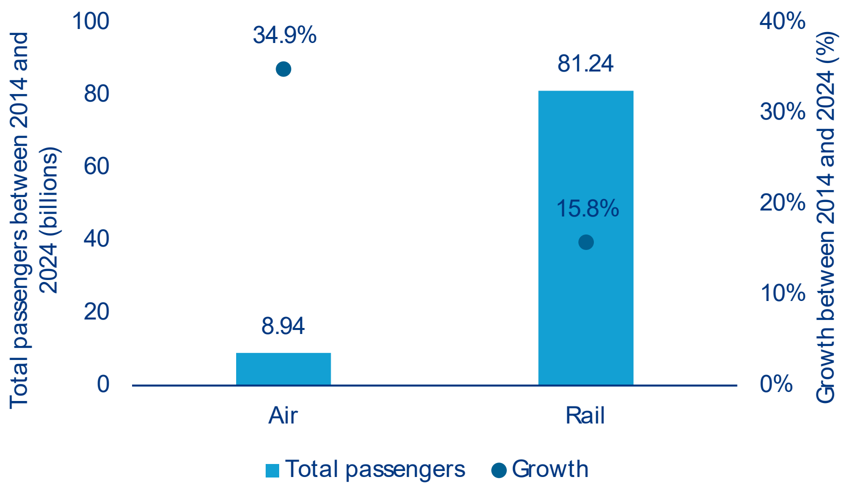


Sources: Eurostat, Allianz Research

The evolution of rail demand in Europe over the past decade reinforces the potential for modal shift as a key strategy for reducing aviation emissions. Between 2014 and 2024, railways transported 81.2bn passengers, compared with 8.9bn transported by air over the same period (10 times less). Although air travel recorded much faster growth (+34.9%), driven by low-cost carriers and the expansion of tourism, rail still achieved a robust +15.8% increase in passenger numbers (Figure 20). This expansion reflects steady improvements in rail service quality, cross-border connections and the revival of night trains across several European corridors, e.g. the night train between Berlin and Paris.

However, Europe's railway system faces several structural challenges that limit its competitiveness with air travel. One of the most critical gaps is speed performance. Compared with leading Asian high-speed networks, European trains remain significantly slower (Figures 21a and 21b). For example, the journey from Munich to Rome covers 917 km in 570 minutes (9 hours 30 minutes), yielding an average speed of 1.6 km/min. In contrast, the Beijing–Shanghai high-speed connection covers 1,213 km in just 270 minutes (4 hours 30 minutes), achieving an average of 4.5 km/min, almost three times faster. This persistent technological lag in high-speed rail infrastructure reduces the attractiveness of rail for medium-distance intra-European travel, where passengers may still prefer flying despite its higher carbon intensity. In addition, punctuality remains a systemic weakness. Since the Covid-19 pandemic, delays have increased across major European rail operators (Figure 21c): On-time performance (arrival within five minutes) has fallen to around 90%, compared with approximately 95% in the pre-pandemic years. This decline further undermines trust in rail reliability – an essential factor for a modal shift toward low-carbon transport.

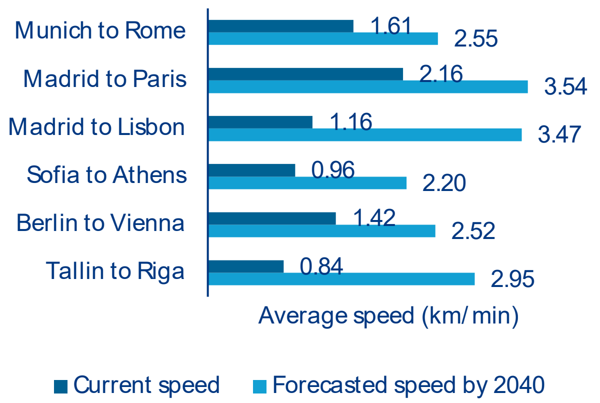
Figure 20: Evolution of demand in air transport and railways in Europe (2014 – 2024)



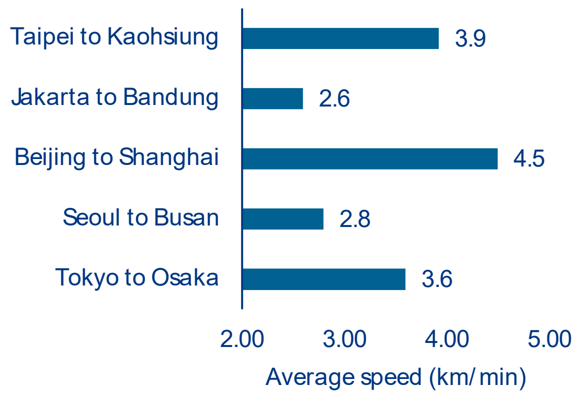
Sources: Eurostat, Allianz Research 1L7AU4

Figure 21: Challenges of European railways: a) European real train speed in 2024 and 2040 (km per minute), b) Asian real train speed in 2024, c) Within 5 minutes train punctuality in major EU countries (2015 – 2023)

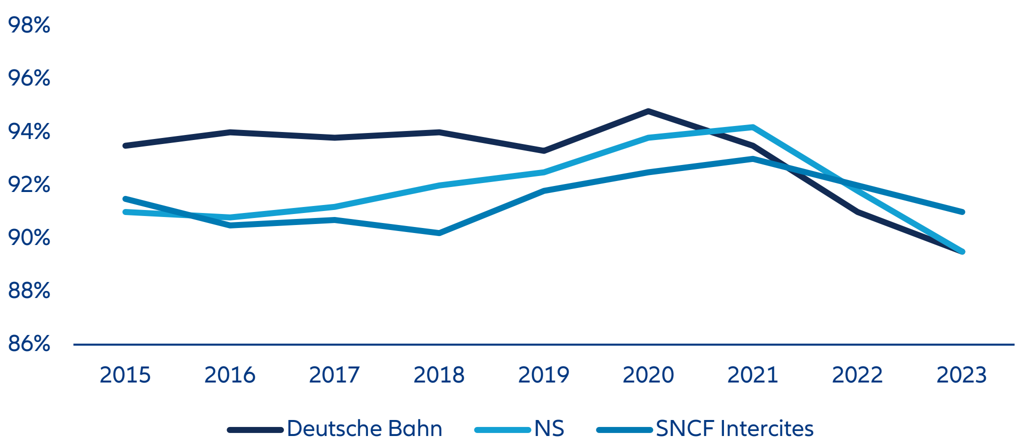
a)



b)



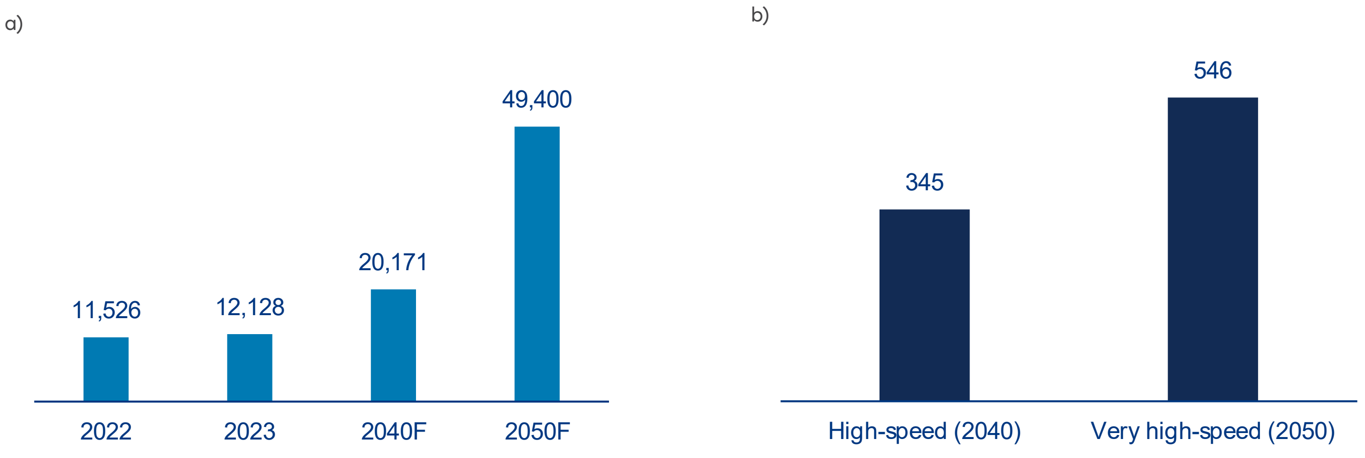
c)



The transformation required to make rail a competitive alternative to aviation also hinges on substantial investment in Europe's rail infrastructure, particularly in high-speed and very-high-speed networks. Figure 22 illustrates both the planned expansion of track length and the financial effort associated with this shift. Between 2022 and 2050, the total length of high- and very-high-speed railways is projected to more than quadruple, rising from around 12,000 km today to nearly 49,400 km by 2050. This represents an unprecedented scaling effort aimed at closing the technological gap with Asian frontrunners and enabling rail to offer faster connections for long-distance and cross-border travel. Meeting this ambition requires significant capital expenditure. By 2040, investment needs for high-speed rail alone are estimated at EUR345bn, while by 2050, very-high-speed rail development could demand up to EUR546bn. Ensuring stable long-term financing, with cross-European borders cooperation, will be essential to deliver this infrastructure on time and unlock the modal shift necessary for supporting the climate neutrality of the air transport sector.

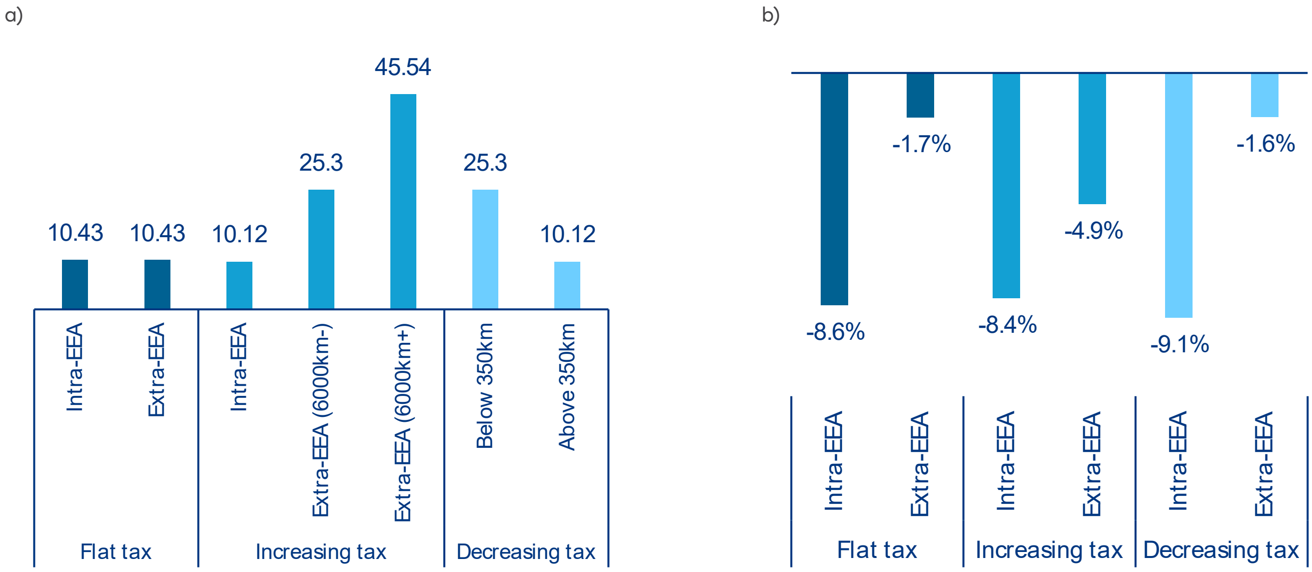
Another policy option to curb demand for substitutable flights, particularly short and medium-distance trips, is the introduction of direct taxation on flight tickets. As illustrated in Figure 23a, several tax designs could be implemented. A flat tax applies a uniform levy to all tickets, whereas a progressive tax increases with distance, reflecting the rising carbon footprint of longer flights. A digressive tax, by contrast, decreases with distance, acknowledging the higher social and economic role of long-haul connectivity in an increasingly globalized world. Each taxation mode generates different impacts on ticket prices and passenger behavior (Figure 23b). Overall, such measures are estimated to reduce demand within intra-EEA routes by around 9%, with impacts ranging from 8% to 10% depending on the tax model. These effects highlight the potential of targeted fiscal instruments to shift travelers away from aviation when viable alternatives exist. However, to ensure fairness and maximize behavioral change, aviation taxes should be complemented by parallel investments in low-carbon mobility, particularly rail. Making trains more affordable, through subsidies (for instance, using revenues from flight ticket taxes to lower rail fares) or price-integration mechanisms across European countries, would strengthen the incentive for passengers to choose climate-friendly transport options rather than simply absorbing higher airfares.

Figure 22: Investment in railway network: a) High- and very-high-speed railway development (2040 and 2050, in Km); b) Investment in high- and very-high-speed railways (2040 and 2050, in EUR bn)



Sources: Eurostat, Allianz Research

Figure 23: Tax on flight tickets: a) Different models of air transport taxation applied in 2025 (in EUR); b) Impact of taxation on reducing air transport demand by 2030 (in %)



Sources: Ricardo International, European Commission, Allianz Research

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