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Decarbonizing aviation

A 2050 mirage?

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About this report

Aviation significantly contributes to global carbon emissions, accounting for 2.5% of total CO_2 emissions. With air traffic increasing by approximately 3.8% per year, this figure is expected to rise unless decisive action is taken. Beyond direct CO_2 emissions, aviation also produces non-CO_2 effects, such as condensation trails and nitrogen oxides (NOx), further contributing to climate change. Achieving net-zero CO_2 emissions by 2050 requires a combination of technological advancements, policy measures, and industry-wide collaboration.

This report outlines the key challenges and solutions for decarbonizing the aviation sector, including energy efficiency improvements, alternative fuels, traffic reduction, and regulatory interventions.

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Executive Summary

The aviation sector faces a critical and complex challenge: how to align with global climate goals while continuing to meet rising demand for air travel. Although aviation accounts for only ~2.5% of global CO_2 emissions, its total climate impact - including non-CO_2 effects such as contrails, NO_x, and water vapor - is estimated to be significantly higher, contributing ~3.5% to effective radiative forcing. With air traffic projected to grow 3-4% annually, decarbonizing aviation is both urgent and difficult.

This report provides an overview of the emissions landscape and offers a structured review of the key technological, operational, and policy levers available to achieve net-zero emissions. It highlights trade-offs, readiness levels, costs, and implementation barriers while underscoring that no single solution can meet the challenge alone :

New aerodynamic designs, lightweight materials, and advanced propulsion systems could reduce fuel burn by 15–25% in new aircraft by 2050. However, because aircraft development cycles are long (20–30 years), and supply chain constraints slow down fleet renewal, the pace of adoption across the global fleet will be gradual. As a result, many near-term efficiency gains remain incremental and are further constrained by trade-offs with NOx emissions or design complexity

Sustainable Aviation Fuels (SAFs) offer the most viable short- to medium-term solution. Second-generation biofuels (*e.g.*, HEFA-SPK, FT-SPK) and synthetic e-fuels (PtL) can achieve up to 80% GHG reduction depending on feedstock and process. SAFs are compatible with existing engines and infrastructure but face significant cost barriers (3-10× fossil jet fuel) and limited feedstock availability. Policy support and mandates are essential for scaling production.

Hybrid and battery-electric aircrafts are limited to short-range, low-capacity segments due to battery energy density constraints. Hybrid-electric systems are being explored for regional applications but will likely remain niche. Full electrification is not viable for commercial aircraft before 2050.

Hydrogen has long-term potential for zero-emission flight, especially for short- to medium-haul routes. Liquid hydrogen storage poses major challenges in weight, volume, and infrastructure. Key players (Airbus, Safran, ArianeGroup) are targeting 2035–2040 for first commercial hydrogen aircraft, but its climate benefit depends on clean hydrogen production and system-wide integration.

Operational measures such as continuous descent approaches (CDAs), AI-based routing, electric ground vehicles, and sustainable airport infrastructure can yield 5–10% GHG savings. Though relatively low-cost, their overall impact is limited unless paired with deeper systemic changes, such as airspace modernization or widespread adoption of low-emission aircraft.

Curbing demand growth through modal shifts (*e.g.*, rail substitution), travel behavior change, or corporate flight policies offers immediate emissions reductions. However, such strategies raise equity and economic concerns, especially in regions where air access is vital.

Carbon pricing, fuel mandates, and emissions trading systems (*e.g.*, EU ETS, CORSIA) are critical tools to internalize aviation's climate cost. These instruments can drive investment in low-carbon solutions and help close the cost gap for SAFs. Their success depends on scope, enforcement, and international alignment.

To address residual emissions, **Carbon Dioxide Removal (CDR)** approaches such as Direct Air Capture (DAC) and Bioenergy with CCS (BECCS) may be necessary. However, they face high costs, energy intensity, and scalability concerns. CDR should be viewed not only as a complement to aggressive emissions reductions, but also as a necessary input for producing synthetic fuels such as eSAF.

The report concludes that no single solution will decarbonize aviation. Instead, an **integrated and realistic approach combining technology deployment, demand management, cleaner fuels, and governance reform** is needed. While **achieving net-zero aviation by 2050 is highly ambitious** - and perhaps unrealistic under current trajectories - each sectoral advance brings the industry closer to climate alignment.

Introduction

The aviation industry is critical to global transportation, connecting economies, enabling trade, and supporting tourism. However, it also significantly contributes to climate change, accounting for approximately 2.5% of global CO_2 emissions (Ritchie, 2024). With air travel demand increasing by around 3.8% annually (IATA, 2024), emissions will surpass pre-pandemic levels sooner than one might think – 2025 (Khan, 2025), posing a major challenge to global decarbonization efforts.

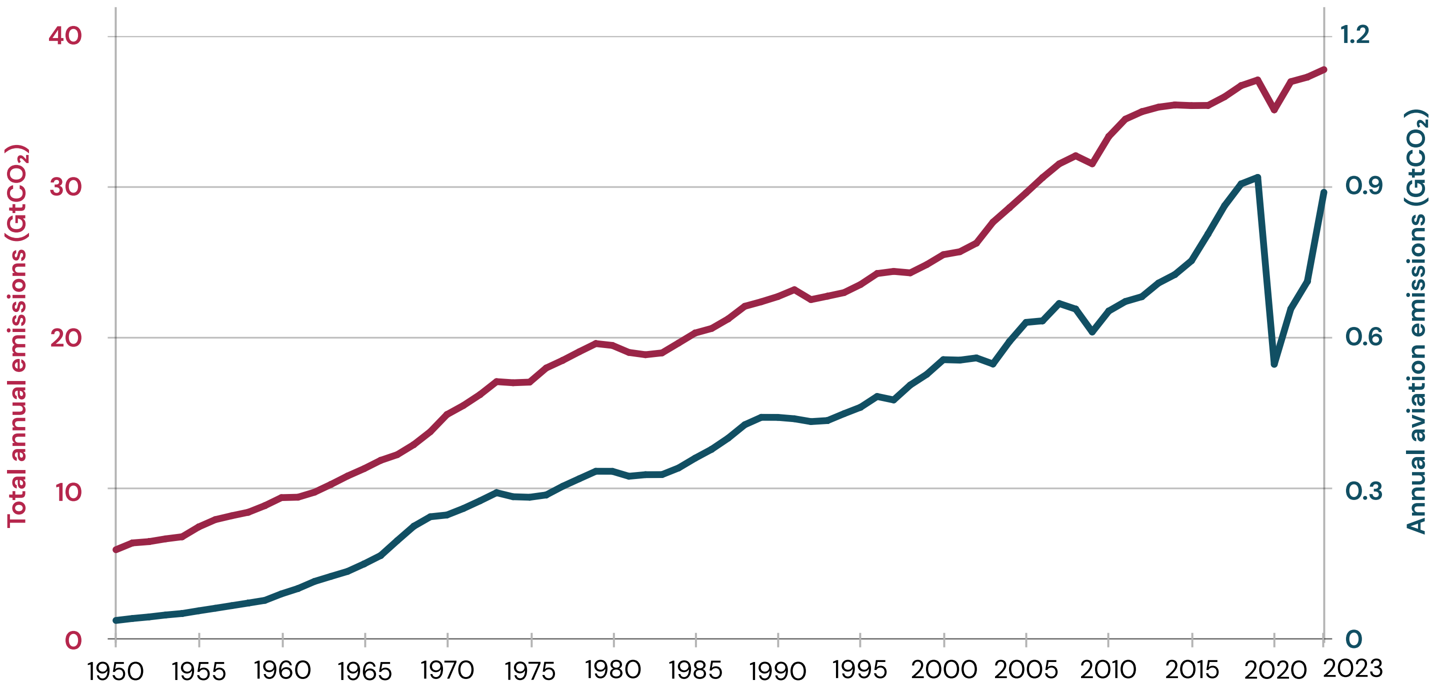


Fig. 1 – Global Aviation CO_2 Emissions vs. Total Global Emissions. (Our World in Data, 2025; Zenon 2025)

In addition to direct CO_2 emissions, aviation has non-CO_2 climate effects, such as condensation trails (contrails), and nitrogen oxides (NO_x), contributing to global warming beyond CO_2 alone. These combined effects make the overall environmental footprint particularly complex.

Decarbonizing aviation requires **technological innovation, robust policy frameworks, targeted investment, and coordinated international action,** all aligned with the objective of reaching net-zero emissions, regardless of projected traffic growth.

This report outlines the key challenges, strategies, and pathways for reducing aviation's environmental impact. The discussion is structured around the following key areas:

- Climate Impact of Aviation
- The Aviation Ecosystem
- Decarbonization Strategies: Energy efficiency, sustainable Aviation Fuels (SAF), alternative energy, demand reduction, and regulatory measures.
- Future Scenarios

1

Climate Impact of Aviation

Global CO_2 Emissions from Aviation
Non-CO_2 Climate Effects

Global CO_2 Emissions from Aviation

Projected Growth of Air Traffic to 2050

Global air traffic is on a long-term growth trajectory, even accounting for recent disruptions like the COVID-19 pandemic. Historically, air travel demand grew around 5% per year, roughly doubling every 15 years (Overton, 2022). After the pandemic dip, forecasts still anticipated a return to steady growth by the mid-2020s. Most industry and institutional projections estimate annual passenger traffic growth of about 3–4% in the coming decades, driven by rising incomes and expanding connectivity, especially in emerging markets. This implies a doubling or tripling of air travel demand by 2050 compared to pre-2020 levels (Gössling, Humpe, 2020). For instance, the International Civil Aviation Organization (ICAO) projects that by 2050 global traffic (measured in revenue passenger-kilometers, RPK) could reach approximately 2.5–3 times its 2019 level under business-as-usual trends (ACI, 2025). In concrete terms, one central scenario foresees over 10 billion passenger journeys per year by 2050, totaling about 22 trillion passenger-kilometers annually (BostonPartners, 2022) – a monumental increase from roughly 4 billion passengers and 8–9 trillion RPK in 2019. Even more conservative post-COVID forecasts expect robust growth: a joint ACI-ICAO outlook suggests global passenger traffic in 2050 will be about 144% higher than 2019 (i.e. roughly 2.5× 2019 levels) despite pandemic setbacks (ACI, 2025). Overall, unless checked by deliberate measures, air travel demand is poised to soar in the coming decades.

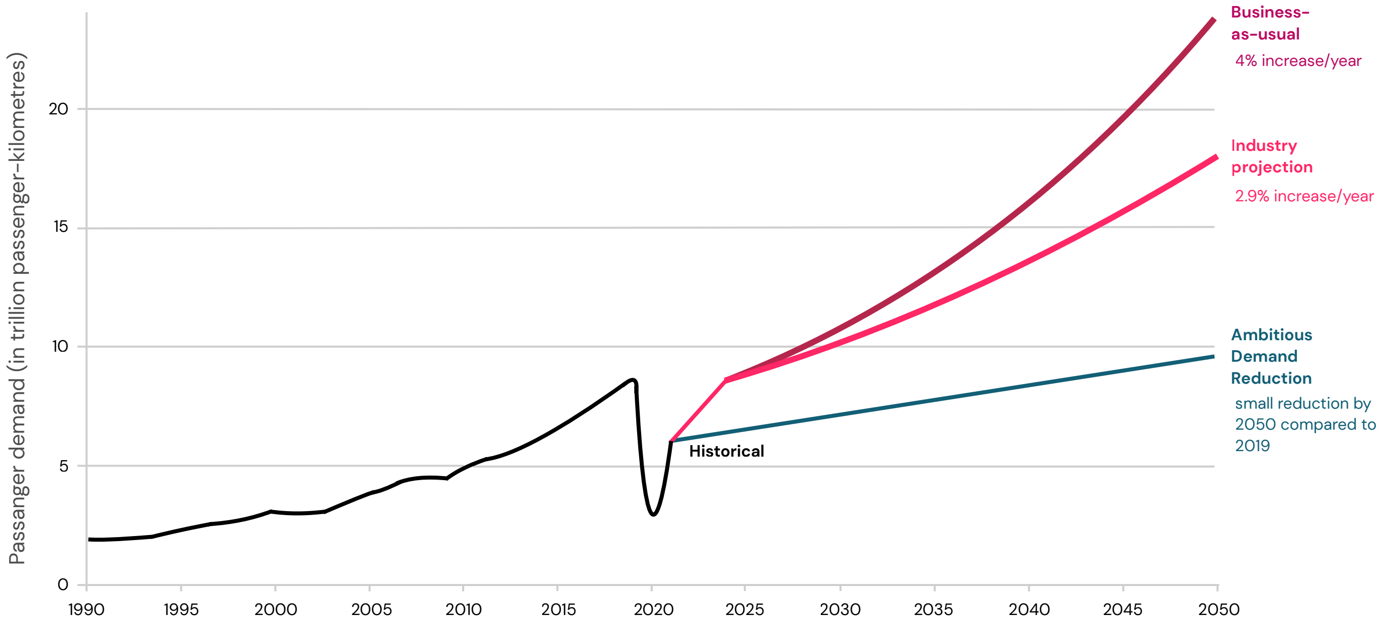


Fig. 2 - Global passanger aviation demand: historical and projections (Bergero *et al.*, 2023)

Importantly, forward-looking scenarios diverge on how this growth might be managed. In a business-as-usual (BAU) trajectory with no additional climate policies, air traffic expansion is essentially unconstrained,[1] following economic and population trends, which leads to the high-end growth figures noted above. In contrast, net-zero or climate-mitigation scenarios incorporate some demand-moderating strategies alongside technology shifts. For example, the International Energy Agency's Net Zero by 2050 scenario envisions "demand restraint" measures that slightly curb aviation growth (such as shifting short-haul trips to high-speed rail or reducing growth in business travel) (IEA, 2021). Even so, global air travel is still expected to grow significantly in mitigation pathways; the difference is that demand might grow a bit more slowly than in BAU. This relentless growth in flying – unless accompanied by aggressive decarbonization measures – poses a serious challenge for controlling aviation's carbon emissions.

1 Though, in practice, there are suggestions that aircraft and pilot availability will slightly limit reaching such large traffic numbers.

CO_2 Emissions from Aviation: Drivers and Scenario Outlook

Aviation's carbon dioxide emissions are directly linked to fuel burn. When aircrafts burn jet fuel, they emit CO_2 in a fixed proportion – about 3.16 kilograms of CO_2 per kilogram of fuel consumed (Overton, 2022), based on typical kerosene composition. This emission factor can vary slightly depending on the hydrogen-to-carbon (H/C) ratio of the fuel; for instance, synthetic paraffinic SAFs generally have a higher H/C ratio, resulting in a slightly lower CO_2 emission factor per kilogram of fuel. Therefore, the key drivers of aviation CO_2 emissions are those factors that determine fuel consumption:

- **Air traffic volume:** More flights and longer distances (higher RPK) increase total fuel burn. Rapid demand growth means significantly more fuel will be consumed if all else remains equal.
- **Aircraft efficiency:** Technological improvements in aircraft and engines can reduce fuel burned per flight or per passenger-kilometer. Newer designs with improved aerodynamics, lightweight materials, and efficient engines allow airlines to operate the same routes with less fuel. However, the rate of fleet renewal is a critical constraint: replacing existing aircraft with more efficient models takes time, and current supply chain limitations may hinder both the scaling of production and the replacement pace, especially if global demand for air travel continues to rise. This creates a tension between growing capacity and accelerating decarbonization.
- **Operational practices:** How flights are operated also affects fuel use. Tactics such as optimizing flight routes and altitudes, minimizing holding patterns and delays, increasing aircraft occupancy (passenger load factor), and improving air traffic management can all trim a significant amount of unnecessary fuel burn.
- **Fuel carbon intensity**: While fuel consumption is the primary driver of CO_2 emissions, the type of fuel used also matters. Low-carbon fuels such as Sustainable Aviation Fuels or synthetic e-fuels can significantly reduce lifecycle CO_2 emissions per unit of fuel burned. For example, advanced biofuels and power-to-liquid fuels can offer 60–80% reductions in net GHG emissions compared to fossil kerosene, depending on the feedstock and production method. Therefore, fuel decarbonization is a critical lever for reducing aviation's CO_2 impact, alongside efficiency and demand management.

In simple terms, **CO_2 emissions = fuel burn × CO_2 per unit fuel**. The CO_2 per unit fuel is essentially constant for jet kerosene, so reducing emissions hinges on burning less fuel – either by flying less, flying more efficiently, or using fuels that produce less net carbon. This relationship explains why unchecked traffic growth directly translates into higher emissions and why efficiency gains are pivotal for mitigation.

Emissions Trajectories to 2050

Without intervention, aviation CO_2 emissions are poised to rise sharply alongside traffic. Industry analyses warn that, under a no-additional-improvements scenario, emissions from global aviation could roughly triple by 2050 relative to current levels. The Air Transport Action Group (ATAG) estimates that carrying billions of passengers in 2050 with today's technologies and fuels would produce on the order of **2 Gt CO_2 annually** - for context, pre-pandemic aviation emissions were about 0.9 Gt in 2019. Similarly, ICAO's trend assessment before the adoption of any long-term climate goal found that **international aviation CO_2 could increase 2 to 4-fold by 2050 compared to 2015** if no further action is taken (Overton, 2022). These BAU projections reflect the fact that expected efficiency improvements in this scenario are modest compared to traffic growth. Even if new aircraft get somewhat more fuel-efficient each year, the sheer increase in flights would push emissions upward. In the absence of new policies, **fuel consumption was projected to climb between 2.4 and 3.8 times** its 2015 level by 2050, tracking a nearly **3.9-fold increase in traffic (RTK)** over that period (Fleming *et al.* 2019). In other words, efficiency gains might slow the growth of fuel burn (*e.g.*, via ~1% per yearly fuel efficiency improvements), but **not enough to prevent a net increase** in total emissions. Indeed, ICAO's analysis noted that even under an optimistic technology scenario, the sector falls short of its historical **2% per year fuel efficiency improvement goal**, achieving only ~1.3% per year efficiency gains, which still leaves **global aviation fuel use doubling or more by 2050**. The takeaway is that **under business-as-usual trajectories, aviation CO_2 emissions would continue rising to 2050**, potentially reaching **around 2–3 Gt CO_2 per year** (figure 3) - which would represent a non-negligible portion of the remaining global carbon budget. As of 2025, the global carbon budget for limiting warming to 1.5 °C with a two-thirds probability—estimated at approximately 80 $GtCO_2$ from 2024 onward—has effectively already been consumed, according to recent analyses (IPCC, 2025; Forster *et al.*, 2023). For a 2 °C target, a larger but still limited budget of around 870 $GtCO_2$ remains.

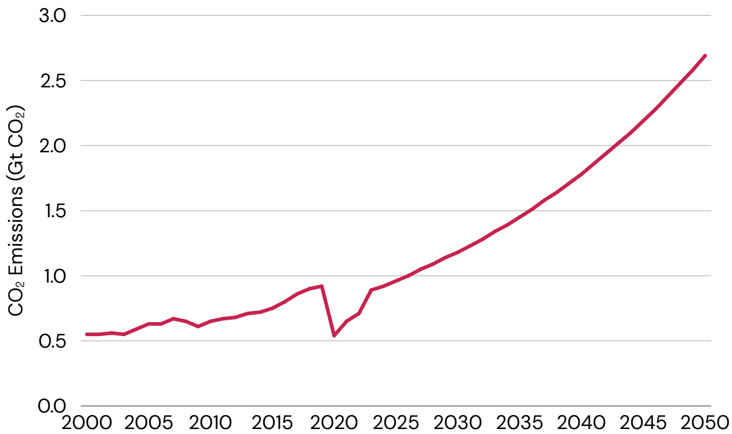


Fig. 3 - Historical and projected aviation CO_2 emissions (2000-2050) with a compound annual growth rate (CAGR) of 4.2% per year. (Our World in Data, 2025; Zenon, 2025)

The picture looks very different in **"net-zero" or mitigation scenarios**. In these pathways, a combination of **technological, operational, and fuel-related strategies** dramatically alters the emissions trend. The core approach is to reduce fuel burn and carbon intensity per flight enough to offset the growth in activity, ultimately driving emissions down to net-zero by 2050. For example, in the **IEA's Net Zero Emissions by 2050 (NZE)** scenario, aviation net emissions peak and then decline, thanks to aggressive deployment of new technologies and sustainable fuels. By 2050, conventional jet kerosene is largely replaced with low-carbon energy: the IEA projects that almost 80% of aviation's fuel use is met by sustainable aviation fuels or other advanced bio/synthetic fuels in 2050 under the NZE scenario (IEA, 2021).

This massive switch to SAF (along with continued improvements in aircraft efficiency and some demand moderation) means that the in-sector CO_2 emissions from aircraft are greatly **reduced**. However, because eliminating jet fuel combustion is very challenging, some residual emissions remain in 2050 in these scenarios, primarily from the last share of fossil-based fuel or imperfect lifecycle emissions of alternatives. For instance, hard-to-abate sectors like long-haul aviation are expected to still emit a few hundred Mt of CO_2 globally in 2050, even in ambitious mitigation pathways. To achieve "net-zero," those **residual emissions** must be counteracted by **carbon removal or offsets**. The IEA scenario assumes that any remaining aviation CO_2 in 2050 is neutralized by measures such as bioenergy with CCS or direct air capture. The net result is that, instead of rising to 2–3 Gt in a BAU scenario, aviation's net emissions in 2050 would be effectively zero in a successful mitigation scenario.

Other aviation-specific roadmaps echo this contrast between BAU and net-zero futures. **ATAG's Waypoint 2050** report, for example, lays out multiple scenarios to reach net-zero CO_2 by 2050. In those pathways, improvements in aircraft and engine design, more efficient operations, and extensive use of sustainable aviation fuel (and possibly new propulsion like hydrogen for short-haul) collectively enable the sector's emissions to peak and decline (ATAG 2021). Any emissions gap is expected to be closed with market-based measures or offsets in the interim. In essence, the "net-zero by 2050" scenario for aviation bends the emissions curve from a steep rise to a downward trajectory, even as traffic grows. This requires unprecedented changes: for instance, one analysis suggests on the order of **330–445 Mt of SAF** will be needed **annually** by 2050 to enable aviation decarbonization, alongside new aircraft technologies (ATAG & ICF, 2021). It also assumes policy support and industry action at a level far beyond historical precedent, given that producing sustainable fuels at such scale is a massive undertaking (Fleming *et al.* 2019).

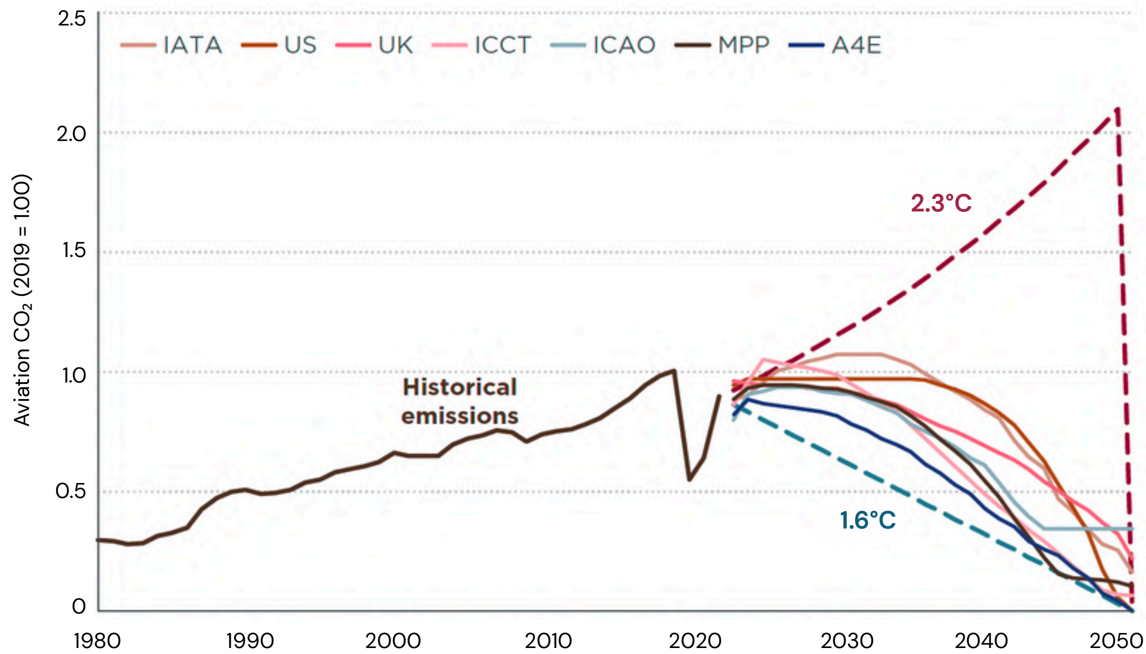


Fig. 4 - Historical and projected CO_2 emissions from aviation, 1980 to 2050, normalized to 2019. (ICAO, 2023)

Figure 4 illustrates possible aviation CO_2 trajectories under various net-zero strategies, normalized to 2019 levels. Temperature outcomes range from 1.6 °C (early decline) to 2.3 °C (late drop), assuming aviation maintains its 2019 share of global CO_2. Most roadmaps, including ICAO, ICCT, and Destination 2050, require emissions to peak before 2025 to align with a 1.75 °C pathway (Graver et al. 2022; ICCT 2023).

The main drivers of aviation CO_2 emissions – demand, efficiency, operational measures and fuel type – will **determine which trajectory the sector follows**. If air traffic grows unabated and fossil jet fuel remains dominant, emissions are projected to double or triple by 2050; and conversely, in ambitious mitigation scenarios, a combination of slower demand growth, fuel-efficiency gains (from both new aircraft and better operations), and a transition to low-carbon fuels can lead to approaching net-zero CO_2 by 2050. Additionally, offsetting and direct carbon capture would be needed for the remaining "residual" - and quite substantial - emissions in all the presented scenarios. Achieving that outcome will require that improvements outpace demand growth: for example, holding 2050 fuel consumption near or below today's levels despite much higher traffic. The latest scenarios from authoritative bodies illustrate these divergent futures: a "business-as-usual" future of rising emissions vs. a "net-zero" future where 2050 emissions are negligible. Policymakers and the aviation industry are now tasked with making the net-zero vision attainable by addressing each of the emission drivers through innovation and international cooperation. Only by simultaneously curbing fuel demand growth and adopting new technologies/fuels can aviation square its growth with global climate objectives (IEA, 2021).

Non-CO_2 Climate Effects

Non-CO_2 factors are significant: the historical cumulative warming impact of aviation's non-CO_2 effects (such as contrails, nitrogen oxides, and water vapor) is estimated to be of **the same order of magnitude** as that of CO_2 emissions (Lee *et al.*). This suggests that non-CO_2 effects currently contribute a comparable level of warming to CO_2, though future proportions may vary depending on flight altitude, engine design, and mitigation measures. Overall, when both CO_2 and non-CO_2 effects are accounted for, aviation is estimated to contribute approximately 3.5% of global effective radiative forcing, compared to ~2% from CO_2 alone (EASA, 2020; Lee *et al.*, 2021). Understanding these effects is crucial, as they reinforce the warming impact of aviation beyond what CO_2 emissions cause.

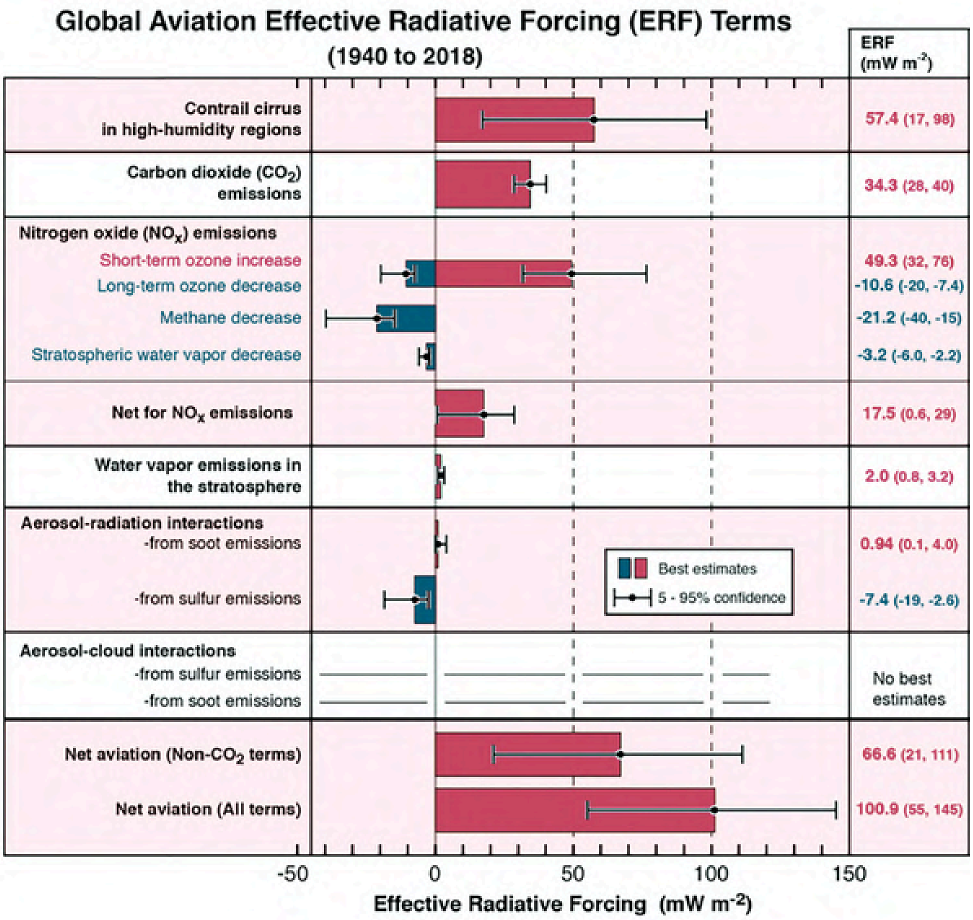


Fig. 5 - Global Aviation Effective Radiative Forcing (ERF) Terms (1940-2018). (Lee, 2021)[2]

How Non-CO_2 Emissions Affect the Climate

Major non-CO_2 impacts from aviation include contrail formation, NO_x emissions, water vapor, and particulate soot/aerosols. Each affects the climate through different physical processes:

- **Contrails and Contrail Cirrus:** Aircraft often form condensation trails (contrails) – line-shaped clouds of ice crystals – in cold, humid upper-air conditions. Contrails occur when water vapor in the exhaust condenses and freezes onto soot particles from the engine. If the atmosphere is sufficiently cold (around -30 °C or below) and humid, these contrails can persist and spread into broader contrail cirrus clouds (Lee *et al.*, 2021). High-altitude contrail cirrus reflect some incoming sunlight (a cooling effect) but also trap outgoing heat (infrared radiation) from Earth's surface, much like natural cirrus clouds (CATF, 2023). Their net effect is warming, since the heat-trapping outweighs the daytime reflection. A persistent contrail-cirrus cloud, can last on the order of hours (up to ~18 hours averaging ~8 hours), and during that time, it warms the atmosphere by preventing heat from escaping (Newinger, 2012). Contrail cirrus is currently considered the largest contributor to non-CO_2 climate effects from aviation in terms of effective radiative forcing (ERF). ERF is a measure of the energy imbalance in Earth's atmosphere caused by a given emission, expressed in watts per square meter (W/m^2), and serves as a proxy for potential warming (Singh, 2024). The ERF from contrail cirrus may range from approximately half to up to three times that of aviation CO_2, depending on atmospheric conditions and modeling assumptions (Lee *et al.*, 2021). While CO_2 emissions have persistent, long-term effects, contrails exert strong but short-lived forcing over several hours. Because of this, focusing on ERF allows us to assess their instantaneous climate impact without conflating it with long-term temperature change, which involves different time dynamics.

[2] Global aviation's best estimations of climate forcing terms between 1940 and 2018. The 5–95% confidence intervals and ERF best estimates are displayed by the bars and whiskers, respectively. Warming terms are indicated by red bars, whereas cooling phrases are indicated by blue bars.

- **NO_x Emissions (Ozone and Methane effects):** NO_x (nitrogen oxides) produced by high-temperature combustion in jet engines play a complex role in climate. In the upper a greenhouse gas that causes warming. At the same time, NO_x increases levels of hydroxyl radicals (OH), which accelerate the breakdown of methane (CH_4), another potent greenhouse gas[3]. Methane reduction is a cooling influence (Köhler *et al.,* 2013). NO_x emissions also lead to small reductions in background stratospheric water vapor and long-term ozone, which are additional minor cooling effects (Skowron *et al.,* 2013). Overall, NO_x emissions from aircraft engines trigger chemical reactions that lead to both ozone formation (a short-lived greenhouse gas) and methane depletion (which has a cooling effect). Currently, the warming effect from increased ozone generally outweighs the cooling from methane reduction, resulting in a net positive effective radiative forcing (Terrenoire *et al.*, 2022). However, the magnitude and sign of this impact depend on atmospheric background levels of ozone and methane, which are influenced by emissions from other sectors and natural sources. As a result, the climate impact of aviation NO_x is context-dependent and may evolve in the future. Moreover, these effects are shorter-lived than CO_2's, persisting on timescales of weeks to years, in contrast to the century-long impact of CO_2 (Freeman *et al.*, 2018).
- **Water Vapor:** Jet engines emit water vapor as a byproduct of hydrocarbon combustion. While water vapor is itself a greenhouse gas, its climate impact from aviation depends strongly on where it is released. In the humid upper troposphere, where most commercial subsonic aircraft cruise, additional water vapor has a relatively small radiative effect, since the atmosphere is already near saturation (Wilcox *et al.,* 2012). In contrast, emissions into the dry stratosphere (as would occur with supersonic or hypersonic aircraft) can have a larger and longer-lived warming impact, because water vapor injected into a dry layer more significantly alters local radiative balance (Matthes et al., 2022). Although such flights are rare today, a future resurgence of high-altitude aviation could worsen this impact, making water vapor a more critical non-CO_2 climate factor (Frömming et al., 2012).
- **Soot and Sulfate Aerosols:** Aircraft exhaust contains soot (black carbon) particles and trace sulfur that forms sulfate aerosols. Soot particles absorb solar radiation (causing warming) and also serve as nuclei for contrail ice crystals (directly influencing contrail formation[4]) (Terrenoire *et al.*, 2022). Sulfate aerosols, in contrast, reflect sunlight and tend to cause a slight cooling effect (Myhre *et al.,* 1998). Overall, the direct climate forcing from aviation soot and sulfate is small – soot contributes a minor warming, while sulfate causes a minor cooling[5].

Net impact: When all non-CO_2 effects are considered - including contrails, ozone from NO_x, water vapor, and soot particles - they appear to increase aviation's climate impact significantly. Importantly, these effects come with large scientific uncertainties, especially in areas like aerosol-cloud interactions, where no best estimate or uncertainty range was provided by Lee et al. (2021) due to insufficient evidence. Despite this, based on current knowledge, most non-CO_2 processes are believed to contribute net positive effective radiative forcing, meaning they add to aviation-induced warming. As such, while exact quantification remains difficult, the collective impact of non-CO_2 effects is substantial and must be accounted for in aviation climate strategies.

[3] Methane breakdown: NO_x leads to an increase in OH radicals, which react with CH_4 to form water vapor (H_2O), carbon monoxide (CO), and eventually CO_2. This chain shortens CH_4's atmospheric lifetime and reduces its greenhouse effect—but the CO_2 produced still contributes weakly to long-term warming.

[4] For kerosene, soot particles are the drivers of contrail formation.

[5] There is still some uncertainty in how aviation aerosols might alter natural cloud properties – a subject of active research.

Mitigation Strategies for Non-CO_2 Effects

Because non-CO_2 emissions are such a large part of aviation's climate footprint, mitigation measures are being explored to address these effects alongside CO_2 reductions. Key strategies include operational changes, technological innovations in engines, and cleaner fuels:

- **Contrail Avoidance:** Current estimates suggest that around 80% of contrail-related warming is caused by just 3% of flights operating in specific atmospheric conditions (T&E, 2024). The idea behind contrail avoidance is to adjust flight trajectories—for instance by changing cruising altitude by a few thousand feet or slightly rerouting - to avoid cold, humid air layers where persistent contrails are likely to form (DLR, 2023). However, it is important to note that not all contrails contribute equally to climate forcing: while avoiding contrail formation is technically feasible, accurately predicting which flights will create high-radiative-forcing contrails remains a challenge. Still, based on current knowledge, contrails remain the most promising non-CO_2 mitigation target, with some flights producing hundreds of tonnes of CO_2-equivalent warming from a single long-lived contrail. Targeted mitigation through contrail-aware flight planning could offer significant near-term climate benefits, especially if focused on the minority of high-impact flights (AMELIA, 2024; T&E, 2024).
- **Low-NOx Engine Design:** Reducing NO_x emissions at the engine source remains a relevant mitigation pathway — though its climate impact is currently considered less significant than that of contrails, particularly in terms of short-term radiative forcing. NO_x is formed under the high-temperature conditions of jet engine combustors. To address this, engine manufacturers are working on advanced designs such as lean-burn combustion, staged combustors, and innovative fuel injectors that limit NO_x formation. These approaches have already delivered improvements under regulatory pressure over past decades (Miake-Lye *et al.*, 2022). However, technical trade-offs are inherent: efforts to improve fuel efficiency (which reduces CO_2 emissions) typically involve higher pressure and temperature, which in turn increase NO_x formation. Similarly, reducing NO_x may worsen particulate emissions. Thus, balancing NO_x, particulate matter, and CO_2 emissions is a core challenge in engine development. Researchers are exploring long-term solutions, including alternative thermodynamic cycles and post-combustion treatments, but such technologies are unlikely to reach commercial deployment before 2050.

  Adding further complexity, the climatic effect of NO_x is sensitive to background methane levels, which may evolve under global warming scenarios (*e.g.*, methane released from thawing permafrost). This introduces additional uncertainty into the net radiative forcing of aviation NO_x. As a result, while NO_x mitigation remains a useful target, its relative priority and impact are more limited compared to contrail reduction strategies.
- **Cleaner Fuels (SAF and Hydrogen):** Changing the fuel itself can mitigate non-CO_2 effects. Sustainable Aviation Fuels (SAF) – such as biofuels or synthetic fuels – tend to contain fewer aromatics and impurities than conventional jet fuel, which means they burn cleaner (with less soot). Less soot generally leads to fewer ice nuclei for contrails, which in turn can reduce contrail formation and thickness. As long as there are enough soot emissions, reducing soot leads to a decrease in contrail formation, but when soot emissions get very low, other particles take over (Dischl *et al.* 2025; Voigt *et al.* 2025). Experimental flights have demonstrated significant benefits: a NASA/DLR study found that using a 50% biofuel blend in a jet engine cut soot particle emissions by 50–70%, yielding correspondingly fewer ice crystals in contrails (Gipson, 2021). Different SAF types have different aromatic and sulfur contents —HEFA and synthetic e-kerosenes are especially low, while some alcohol-to-jet (ATJ) or Fischer–Tropsch SAFs may vary. These variations influence both soot and NO_x emissions: lower flame temperatures and cleaner burn profiles can reduce NO_x slightly, though effects are still under study.

Hydrotreated fossil fuels (such as desulfurized or hydrogenated kerosene) can also offer benefits similar to SAF, with reduced sulfur and aromatics. While not renewable, they may help mitigate contrail and aerosol-related effects in the short term.

The contrails that did form with biofuel were composed of larger ice crystals that were predicted to fall out faster, shortening the cloud's lifetime. Overall, this suggests SAF use can reduce contrail cloudiness and warming. In addition, SAF typically has very low sulfur content, which minimizes sulfate aerosol production and associated effects.

Looking further ahead, hydrogen is being explored as a zero-carbon aviation fuel. Hydrogen combustion produces no CO_2 or soot – only water vapor and some NO_x, since the air's nitrogen can still form NO_x at high flame temperatures. If hydrogen were used in jet turbines, it would eliminate CO_2 emissions and could reduce contrail formation due to the lack of soot particles[6]. A key challenge is that hydrogen flames run hotter, so without special combustor designs, NO_x emissions could increase (Horizon Europe, 2023). Research programs (*e.g.*, Airbus "ZEROe" and others) are working on hydrogen engines with ultra-low NO_x technologies to avoid this issue. Another possibility is hydrogen fuel cells (producing electric propulsion), which would emit only water and no NO_x at all. While hydrogen and electrified aircraft are still in development and likely limited to future mid-century deployment, probably on the regional aviation segment, they represent a path to virtually eliminate both CO_2 and soot emissions from aviation, thereby greatly reducing long-term climate impacts[7].

6 Though the higher water output means contrails could still occur and could increase the forcing exerted by stratospheric water vapor injection. They are an active research topic (Airbus 2023).

7 With the remaining concern being water/contrail effects that might be managed through operational strategies.

Beyond CO_2: Understanding Aviation's Climate Effect

While CO_2 is the most well-known greenhouse gas, aviation emits several other substances at high altitudes that significantly influence the climate. These non-CO_2 effects can double aviation's effective radiative forcing and must be addressed alongside CO_2.

Contrail cirrus

Persistent Ice Clouds Behind Aircraft

- **Driver:** Water vapor + soot particles in cold, humid air
- **Effect:** High-altitude clouds trap outgoing infrared radiation
- **Climate Impact:** Strong short-term warming
- **Uncertainty:** High – radiative forcing estimates 0.5–3× that of aviation CO_2
- **Mitigation:** Contrail-avoidance routing, soot reduction via SAFs

Nitrogen Oxide (NO_x)

Formed in high-temp combustion

- **Effects:**
    - Creates ozone (O_3): short-lived warming
    - Reduces methane (CH_4): cooling
- **Net Effect:** Warming (but dependent on atmospheric conditions and methane background)
- **Uncertainty:** Moderate – context-dependent
- **Mitigation:** Low-NO_x engine design, altitude optimization

Water Vapor

Combustion product

- **Effect:** Adds greenhouse gas directly into the upper troposphere/lower stratosphere
- **Impact:** Small warming, except for supersonic aircraft in the stratosphere (larger effect)
- **Uncertainty:** Low to moderate
- **Mitigation:** Avoid stratospheric flight

Soot particles

Black carbon emitted by jet engines

- **Effect:** Acts as nucleation site for contrails
- **Impact:** Indirect warming through contrail formation
- **Uncertainty:** Moderate
- **Mitigation**: Use of low-aromatic fuels (SAF), engine optimization

Sulfur Oxides (SO_x)

From sulfur in jet fuel

- **Effect:** Form sulfate aerosols; possible cooling by reflecting sunlight
- **Uncertainty:** High – aerosol-cloud interactions not well constrained
- **Mitigation: SAFs have very low sulfur content**

These effects operate on different timescales and altitudes, complicating mitigation.

Contrail and NO_x mitigation may offer high-impact short-term climate benefits.

Policy and technology must address both CO_2 and non-CO_2 effects for credible climate action.

2

The Aviation Ecosystem: Key Stakeholders

Energy Producers
These companies (*e.g.*, Shell, TotalEnergies) supply the raw materials—fossil fuels today, and increasingly sustainable aviation fuels (SAF), green hydrogen, and renewable electricity. Their shift toward low-carbon fuels is foundational, as it determines the emissions potential of the entire supply chain. If they delay SAF or hydrogen production at scale, decarbonization stalls.

Fuel Manufacturers
Refiners like Neste and World Energy convert feedstocks into aviation-ready fuels. They are central to scaling and developing bioSAF and eSAF that reduce lifecycle CO_2. They are also responsible for storing and transporting fuels to airports which requires an organizational and logistical framework. Without their innovation, massive investments and cost reduction, sustainable fuels remain niche.

Original Equipment Manufacturers (OEMs)
In the aviation ecosystem, OEMs are companies that design, manufacture, and supply aircraft and aircraft components. Companies such as Airbus and Boeing design more efficient, SAF-ready aircraft and are developing next-generation hydrogen and electric models. They play a key role in reducing CO_2 per passenger and enabling the shift to alternative energy sources.

Engine Manufacturers
Engine makers (*e.g.*, GE, Safran) develop propulsion systems that lower fuel burn, cut CO_2, and reduce non-CO_2 impacts like NO_x and soot. They are also pioneering engines compatible with 100% SAF and hydrogen combustion, which is vital for the sector's long-term transition.

Airlines
Airlines operate fleets and decide on aircraft selection, fuels, and flight operations. Many (*e.g.*, Air France, Lufthansa, United) are investing in SAF, and in line with ATMs and ANSPs, optimizing flight efficiency, and testing contrail-avoidance strategies. Their choices directly affect emissions and set market signals across the ecosystem.

Airports
Airports like Heathrow and Schiphol support decarbonization by enabling SAF supply, installing electric ground equipment, improving air traffic flow, and cutting their own operational emissions. They also serve as critical hubs for the introduction of future hydrogen or electric aircraft.

Air Traffic Management (ATM) / Air Navigation Service Providers (ANSPs)
ATM and ANSPs systems optimize flight trajectories, reduce holding patterns, and enable continuous climb and descent operations. Initiatives like SESAR (Europe) or NextGen (U.S.) aim to modernize ATM infrastructure through digitalization and satellite-based navigation, cutting unnecessary fuel burn and emissions. Companies like Thales and Indra are technology providers in this space, delivering advanced ATM systems to enhance efficiency and coordination. ANSPs also facilitate contrail avoidance strategies and support collaborative airspace management, essential for both short-term efficiency gains and long-term integration of low-emission aircraft.

Governments
Policymakers establish emission standards, SAF mandates, carbon pricing, R&D support, sustainability frameworks, and international agreements (*e.g.*, ICAO's net-zero goal, EU's ReFuelEU). Governments are key enablers, shaping the pace and scale of aviation's decarbonization transition.

Passengers & Businesses
Travelers and companies influence demand for sustainable aviation. Corporate alliances (like SABA) are buying SAF, and some consumers increasingly favor airlines with strong climate commitments. Reducing unnecessary flights and supporting green options are important contributions.

Each stakeholder has a crucial role in decarbonizing aviation. No single actor can achieve net-zero alone, but combined, they can drive the innovation, investment, and system change needed to reduce both CO_2 and non-CO_2 impacts.

The aviation industry consists of multiple interdependent stakeholders, each playing a role in the transition to sustainability.

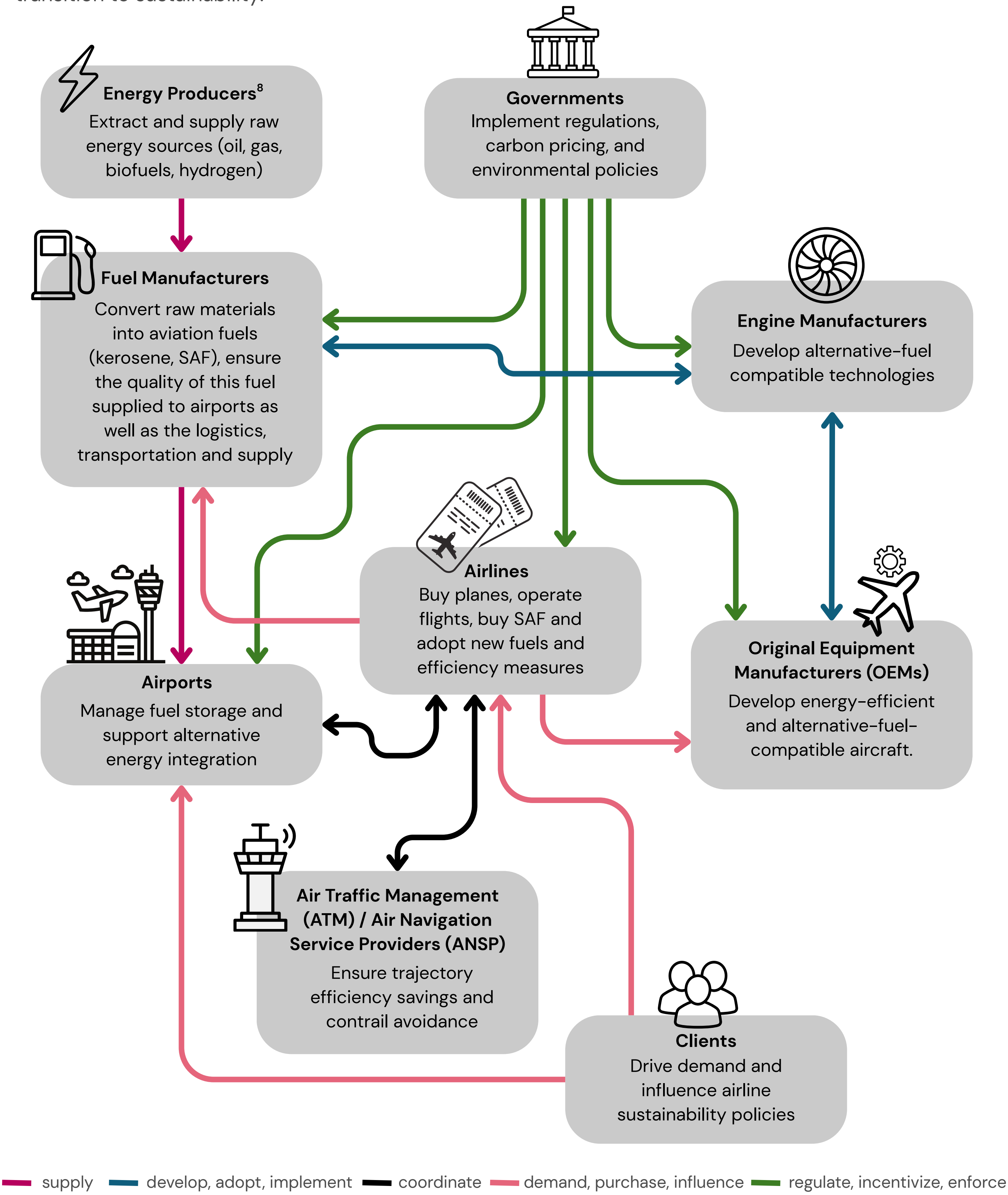


Fig. 6 – Key stakeholders of the aviation ecosystem and their respective impact and influence

[8] Actors involved in carbon dioxide removal (CDR) – including those developing BECCS, Direct Air Capture (DAC), or supplying captured CO_2 for eSAF – are not explicitly represented in this ecosystem diagram. While essential to the future of sustainable aviation, these stakeholders do not produce energy per se, but rather enable negative emissions or synthetic fuel production. Their integration into the aviation value chain remains emerging and indirect.

3

Key Decarbonization Strategies

CFM RISE Program – Open fan engine
Credit image: Aérovolet

Decarbonizing aviation involves a wide range of complementary strategies that target different components of the sector. These include improving aircraft and engine efficiency, switching to sustainable fuels, changing operational practices, and managing demand. A simplified way to view these levers is by dissecting a flight:

Improving Energy Efficiency

Technological upgrades to aircraft design, propulsion, and materials can reduce fuel burn, though fleet renewal timelines limit near-term impact.

Transitioning to Sustainable Aviation Fuels (SAF)

SAFs—derived from biogenic or synthetic sources—offer significant lifecycle CO_2 reductions and compatibility with existing aircraft, but face cost and scale-up constraints.

Hybrid/Electric Aircraft

Battery-electric propulsion enables zero in-flight emissions for short-range flights, but energy density limits restrict applications to small aircraft and regional routes.

Hydrogen-Powered Aircraft

Hydrogen combustion or fuel cell systems could enable near-zero emissions flight, particularly for short- to medium-haul, but require new aircraft designs, infrastructure, and fuel production capacity.

During the flight

Before the flight

After the flight

Increasing Aircraft Load Factors & Fleet Utilization

Flying fuller aircraft, reducing empty legs, and using newer, more efficient aircraft more often improves overall emissions per passenger-kilometer.

Optimizing Air Traffic & Airport Operations

Improved routing, efficient descent procedures, and cleaner ground operations could cut emissions by 8–10% through operational refinements.

Carbon Dioxide Removal (CDR)

Engineered and nature-based CDR approaches can offset residual emissions that cannot be abated, but their high cost and limited capacity make them a last-resort solution.

Demand side

Regulatory and Market-Based Measures

Carbon pricing, SAF blending mandates, emissions trading, and international agreements (*e.g.* CORSIA, EU ETS) are critical to aligning incentives and accelerating uptake of cleaner options.

Demand Reduction & Traffic Management

Curbing unnecessary air travel, shifting to rail alternatives, or limiting airport capacity can slow emissions growth, though politically sensitive and logistically complex.

Improving Energy Efficiency

One of the most immediate and effective ways to reduce emissions is by improving aircraft fuel efficiency. According to ADEME and ICAO projections, energy efficiency improvements in aircraft design, engines, and operations could lower fuel burn and associated CO_2 emissions by roughly 25% by 2050, compared to BAU trajectories. Several technological strategies are under development, each at a different stage of maturity:

Technological strategy	Description	TRL/Status	Companies
New Aerodynamic Designs	Example: *Blended-wing body* aircraft, which reduce drag and improve lift-to-drag ratio.	**4–6** (prototype/demonstration)[9]	Airbus (*e.g.* MAVERIC prototype), NASA + Boeing (X-48 program). These aircraft demonstrated controlled flight and aerodynamic benefits, but no full-scale BWB passenger aircraft is under development.
Lighter Materials	Using carbon-fiber composites and next-generation aluminum-lithium alloys to reduce aircraft weight and fuel consumption.	**8–9** (widely deployed on commercial aircraft)	Boeing (787 Dreamliner ~50% composite), Airbus (A350) (extensive carbon composites and Al-Li alloys)[10]
Ultra-Efficient Engines	Open-rotor or geared turbofan engines promise 10 - 20% fuel savings at the motor level	**5–7** (advanced test phase)	CFM (RISE program - open fan engine)[11], Pratt & Whitney (GTF engines) (RTX, 2025)
Hybrid & Electric Propulsion	Electric-assisted propulsion systems reduce fuel use during taxiing, certain phases during the flight and takeoff	**4–6** for commercial-scale applications	Airbus (EcoPulse project with Daher & Safran)[12], Rolls-Royce + Tecnam (hybrid-electric commuter aircraft)

9 The technology is considered TRL 4–6 because it has moved from wind tunnel and ground tests (TRL 4) to flight-demonstrated subscale prototypes (TRL 5–6), but has not yet reached system-level integration in an operational environment (Airbus, 2020), (Arnaud, 2025).

10 The materials are TRL 9, having been fielded extensively and passed through the full cycle of testing, certification, and long-term airline use. Their use continues to expand across next-generation aircraft (Boeing, 787 Tech specs), (Bachman *et al.*, 2017), (Alcoa, 2014).

11 Open-rotor or open-fan engines are still in development. CFM has tested scale models and plans full-scale demonstrator flights around 2026 (Airbus, 2025). Thus, open-fan technology is currently TRL 5–6 (validated in component-level testing and subscale prototypes). The range TRL 5–7 reflects that while GTF is mature, open-rotor engines - the focus of "ultra-efficient engines" - remain in advanced test and pre-flight stages.

12 These systems are TRL 4–6, as core subsystems (batteries, electric motors, controllers) are validated in relevant environments (ground and flight), but have not yet been integrated into certified commercial aircraft. For 9–19 seat classes, hybrid-electric aircraft may reach certification in the late 2020s, but they remain non-commercial today (Airbus, 2024).

While many of these innovations are promising, aircraft development, certification processes and fleet renewal cycles are long, often 20–30 years. This means today's R&D must be accelerated to ensure impactful deployment by 2050.

Transitioning to Sustainable Aviation Fuels (SAF)

Sustainable aviation fuels (SAF) are among the most promising near-term solutions for decarbonizing aviation. They can reduce life-cycle greenhouse gas emissions by up to 80% compared to conventional fossil jet fuel, depending on the feedstock and production process (IATA, 2024). Critically, SAFs are drop-in compatible[13] with existing aircraft and fueling infrastructure, allowing airlines to decarbonize without waiting for new aircraft or engine technologies.

1st Gen Biofuels

e.g., corn, sugarcane, vegetable oils using HEFA (hydroprocessed esters and fatty acids)

Foodstock (examples)

Food crops (starches, sugars, vegetable oils)

Production Process

Ferment sugars/starches to ethanol (for alcohol-to-jet conversion) or extract oils for biodiesel/HEFA. Requires upgrading (*e.g.*, ATJ or hydrotreating) to meet jet fuel specifications.

Typical Life-Cycle GHG Reduction vs Fossil Jet

Low–moderate (often ~20–60% net GHG reduction vs fossil jet (Calderon *et al.*, 2024); sugarcane on higher end). Indirect emissions from land-use change can reduce benefits.

TRL (2023–24)

Commercial tech for primary fuel production (ethanol, biodiesel) – TRL 9. Jet fuel conversion pathways (*e.g.*, Alcohol-to-Jet (ATJ) from ethanol) are ASTM-approved and demonstrated (TRL ~8–9).

Feedstock Supply Considerations

Relies on edible crops (finite arable land). Competes with food supply; expansion can cause deforestation or other land-use change. Subject to sustainability limits (*e.g.*, EU restricts first-gen biofuels) (Morciani, 2025).

Estimated Production Cost

~$1–2 per liter (roughly 2–4× the cost of fossil jet fuel) (Ozkan *et al.*, 2024). Often requires policy support or subsidies to be economical.

2nd Gen Biofuels

e.g., HEFA, FT-SPK, ATJ

Foodstock (examples)

Non-food & waste biomass; *e.g.*, used cooking oil, tallow, agricultural residues (straw, bagasse), woody biomass, municipal solid waste.

Production Process

Various advanced pathways: HEFA – hydrotreat waste oils/fats into drop-in kerosene; Fischer–Tropsch (FT-SPK) – gasify biomass to syngas then synthesize hydrocarbons; Alcohol-to-Jet (ATJ) – ferment cellulosic sugars to alcohol then upgrade to jet fuel.

Typical Life-Cycle GHG Reduction vs Fossil Jet

High potential reductions (typically 60–80% lower GHG vs fossil) (Braun *et al.*, 2024). Waste oil-based HEFA ~80% less CO_2 (SAFRAN), and some pathways (forestry/agri residues) can exceed 80% savings.

TRL (2023–24)

Mature for some pathways: HEFA is in commercial use (TRL 9); ATJ has pilot plants/commercial demos (TRL ~8–9). FT-based biofuels are slightly behind (first commercial-scale projects underway, ~TRL 7–8) (Zemanek *et al.*, 2020).

Feedstock Supply Considerations

Uses waste or non-food inputs – avoids food competition. Feedstock availability is limited: *e.g.*, global used cooking oil supply ~1 Mt/year (trivial relative to jet fuel demand) (O'Malley *et al.*, 2021). Agricultural/forestry residues are more abundant, but collection and sustainability constraints apply. Overall, first- and second-gen bio feedstocks alone cannot scale to full aviation demand.

Estimated Production Cost

Currently ~2–5× cost of conventional jet fuel (even the cheapest waste-oil SAF is ~$0.8–1.5/L). Continued cost premium necessitates incentives or blending mandates.

13 SAFs require additives to be drop-in and that ultimately negates potential contrail reductions from these fuels.

Synthetic SAF

Power-to-Liquid e-fuels

Foodstock (examples)

Captured CO_2 (from air or industrial flue gas) and low carbon H_2 (from water electrolysis using low carbon electricity).

Production Process

Often referred to as e-SAF, Power-to-Liquid (PtL) synthesis combines green hydrogen with CO_2 to produce syngas, then converts to synthetic hydrocarbons (via Fischer–Tropsch or methanol-to-jet process). Entire process is driven by low carbon energy; output is drop-in e-kerosene.

Typical Life-Cycle GHG Reduction vs Fossil Jet

Very high potential reduction: ~90–100% net CO_2 reduction if the process is powered by low-carbon energy and uses renewable inputs (Batteiger *et al.,* 2022). However LCAs indicate that actual GHG savings depend on the carbon intensity of electricity and may not fully reach 100%, NO_x and system losses accounted for.

TRL (2023-24)

Pilot/demonstration stage for full PtL fuel production. Key steps are proven (electrolysis, FT), but integrated plants are just starting (overall system TRL ~6–7) (Batteiger *et al.,* 2022). First demo e-fuel facilities (*e.g.,* Ineratec Frankfurt) are producing limited volumes. Commercial rollout target by late 2020s.

Feedstock Supply Considerations

Not constrained by bio-feedstock volume – feedstock CO_2 and water are virtually unlimited. Scalability depends on massive renewable electricity supply for H_2 and CO_2 capture. In principle can scale to meet huge volumes, but requires large investments in clean energy and carbon capture infrastructure.

Estimated Production Cost

Highest cost: currently ~5–10× more expensive than fossil jet (e-kerosene production on the order of $5–10 per liter) (Seymour *et al.,* 2024). Costs should fall with cheaper low carbon power and scale, but near-term uptake relies on subsidies or carbon pricing.

Emerging / 3rd Generation

e.g., algae, lignin, CO_2-to-jet

Foodstock (examples)

Novel/experimental feedstocks: microalgae (algae cultivated using sunlight, CO_2, and nutrients), lignin-rich residues (*e.g.,* waste from cellulosic biorefineries), and recycled carbon (CO_2) via new pathways.

Production Process

Multiple early-stage technologies. Algae: grow algae in ponds or bioreactors, extract oils or convert whole algae (*e.g.,* hydrothermal liquefaction) into biocrude, then upgrade to jet. Lignin-to-jet: depolymerize or gasify lignin and upgrade the bio-oil/syngas to fuel. CO_2-to-jet: experimental catalytic or microbial methods that convert CO_2 and green hydrogen into jet-range hydrocarbons. (Note: e-SAF from PtL processes is categorized under Synthetic SAF rather than 3rd-gen.)

Typical Life-Cycle GHG Reduction vs Fossil Jet

Potentially large GHG savings (>80%) if processes are powered by clean energy. Algae fuels recycle CO_2 during growth (~50–70% lifecycle CO_2 reduction vs fossil kerosene in best cases) (AFDC, 2024). With optimal technology, some pathways could approach carbon-neutral operation. (Actual GHG benefit depends on process energy inputs.)

TRL (2023-24)

Low technological maturity. Most concepts in early pilot or lab stage. Algae-to-jet has reached ~TRL 6–7 in pilot projects (but many algae biofuel innovations remain at TRL 3–5). Lignin and CO_2-to-fuel pathways are similar in R&D; not yet proven at scale (roughly TRL 4–6 currently) (NREL, 2024; Borrill *et al.,* 2024).

Feedstock Supply Considerations

Feedstocks are theoretically abundant: algae can be grown at scale using non-arable land and waste CO_2; lignin is a sizable byproduct stream from forestry and bio-refining; CO_2 is virtually unlimited. Advanced solid waste and carbon feedstocks could provide large volumes. However, significant practical challenges (*e.g.,* low yields in algae cultivation, feedstock collection and processing issues, nutrient and energy needs) must be overcome for scalability (WorldEnergy, 2024; Bhuchar *et al.,* 2025).

Estimated Production Cost

Currently extremely high and undetermined at commercial scale. Pilot-scale algae fuels have ranged from ~$0.88 to $5.68 per liter (i.e., ~$140–$900 per barrel), making them 5–30× more expensive than fossil jet. Major breakthroughs and scaling are needed to bring costs down.

While current and planned production capacity (figure 7) appears sufficient to meet demand through 2027, a growing gap emerges beyond 2030, as demand accelerates under net-zero scenarios. This gap could exceed 25% by 2040, highlighting the need to accelerate production. However, future demand remains uncertain due to potential changes in air travel growth and ticket prices.

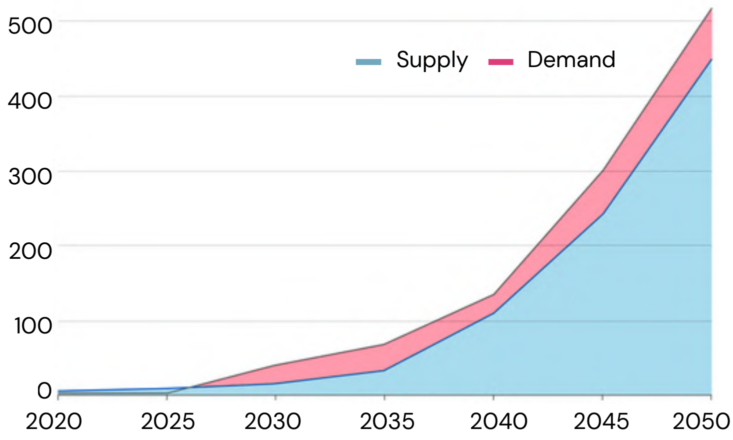


Fig. 7 - Global predicted SAF demand, 2022-2050 (Mt). (TOPSOE)

Sustainable Aviation Fuels (SAFs) are crucial to the aviation industry's decarbonization plan. They provide a practical alternative to fossil-based jet fuel while ensuring compatibility with current aircraft and infrastructure. In contrast to electric or hydrogen-powered planes, which demand extensive technological innovations and new infrastructure, SAFs serve as a straightforward "drop-in" replacement for traditional jet fuel. Thus, airlines can lower their carbon emissions without major fleet alterations.

Figure 8 compares the well-to-wake greenhouse gas emissions of various SAF pathways, expressed in grams of CO_2-equivalent per megajoule (gCO_2e/MJ). Well-to-wake refers to the full life-cycle emissions of a fuel, from the extraction or production of raw materials (the "well") to the combustion in aircraft engines (the "wake"). This comprehensive metric captures emissions from feedstock cultivation or CO_2 capture, fuel processing and refining, transportation, and final use.

The lowest emissions come from e-fuels synthesized from captured CO_2 and renewable electricity. For instance, CO_2-to-SAF via bioethanol or corn stover can result in just 5–6 gCO_2e/MJ. Other CO_2-to-SAF routes using direct air capture or point-source CO_2 (*e.g.*, cement or natural gas power plants) perform relatively well too, ranging from 10 to 42 gCO_2e/MJ depending on the process. In contrast, HEFA fuels (made from fats and oils like soy or rapeseed) tend to have higher emissions due to land-use and agricultural impacts (33–40 gCO_2e/MJ), and SPK from corn ethanol reaches nearly 50. For comparison, conventional fossil jet fuel emits around 84 gCO_2e/MJ, while synthetic fuel derived from natural gas (FT-Jet) can exceed 100. This analysis shows that not all SAFs are equal; only certain pathways deliver deep decarbonization potential, especially when paired with clean electricity and sustainable feedstocks.

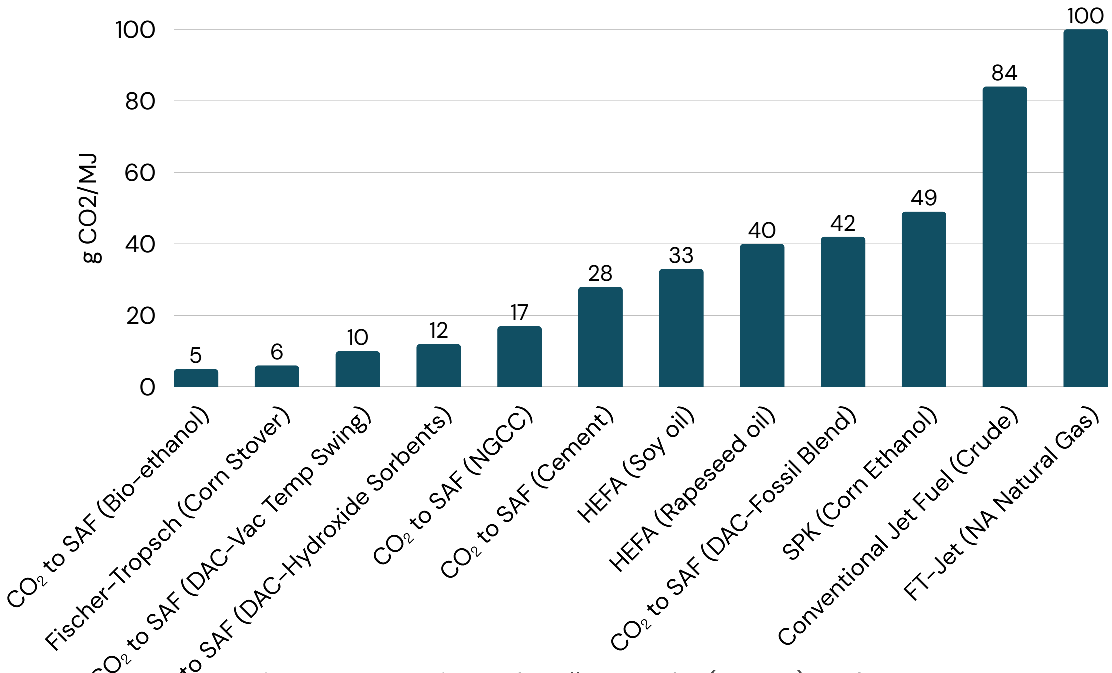


Fig. 8 - Comparison of Well-to-Wake (WTWa) Carbon Intensity values across SAF pathways. (Grim *et al.*, 2022)

Certification and Industrial Scaling

To be approved for commercial aviation use, all sustainable aviation fuels (SAFs) must undergo a rigorous certification process governed by ASTM International under standard ASTM D7566 (IATA, 2024). This certification ensures that SAFs meet strict safety, performance, and material compatibility criteria, allowing them to be blended with conventional Jet A fuel and used in existing aircraft without modification. The approval process typically involves multi-year testing in collaboration with aircraft and engine manufacturers to evaluate combustion behavior, cold flow properties, and long-term engine impacts.

There is no notion of sustainability in ASTM, which means that this aspect needs to be added, via mechanisms such as CORSIA, RED or voluntary certifications such as RSB/ISCC. As of 2024, seven SAF production pathways have been certified under ASTM D7566, including HEFA-SPK, FT-SPK, ATJ-SPK, and others. This process is essential to ensure that SAFs can be seamlessly integrated into the global aviation fuel supply chain while maintaining flight safety and performance.

Future Outlook and Policy Considerations

As the aviation industry moves towards net-zero emissions by 2050, SAFs are expected to play a central role, covering up to 35% of aviation fuel demand. However, policy frameworks and market incentives will determine their ultimate success.

Some key considerations include:

- **Mandatory SAF blending quotas**, such as those introduced in the EU and the UK.
- **Financial subsidies or carbon pricing mechanisms** to make SAF economically competitive with fossil fuels, like innovation funds, ReFuelEU, the EU Emissions Trading System (EU ETS), Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the Inflation Reduction Act (IRA), etc.
- **Research and development investments** to improve production efficiency and expand feedstock options.

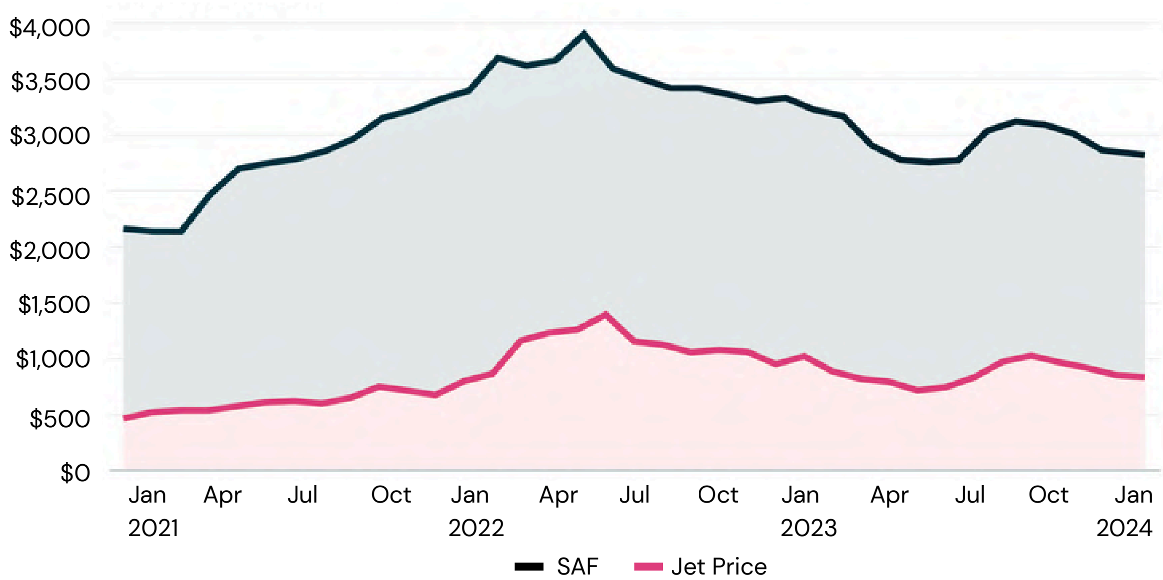


Fig. 9 - SAF vs Jet Price (in $/Mt). (Vitol, 2024)

Figure 9 shows that SAF remains over three times more expensive than conventional jet fuel from 2021 to 2024. This high cost is due to limited feedstock availability, with SAF making up only 0.1% of global jet fuel use in 2022. As feedstocks become scarcer, prices could rise further, highlighting the economic challenge of scaling SAF without strong policy support (Vitol, 2024).

SAFs represent the most immediate and scalable solution for reducing aviation's carbon footprint. However, for them to reach their full potential, regulatory alignment, infrastructure investments, and cost-reduction strategies must be accelerated.

Hybrid/Electric Aircraft

Suitable for short-haul flights as battery weight limits range (~500 km).

Battery-electric aircraft use onboard batteries to power electric motors, eliminating direct emissions during flight, while hybrid-electric designs combine battery-driven propulsion with conventional engines or generators for extended range or efficiency.

Currently, these technologies are limited to small aircraft: several prototypes and planned commuter airplanes (typically under ~30 seats) have been flown or ordered, such as the 9-passenger Alice (approximately 402 km range) (CATF, 2024), which is also aiming for a 1,000 km range. This is impressive for a battery-powered aircraft, but battery weight remains a major limitation at the moment.

Advances in battery technology are crucial to making electric aircraft viable for longer distances. It is not just about increasing capacity but also about reducing weight and improving energy density. There are promising breakthroughs on the horizon, such as solid-state batteries and other next-generation technologies.

As mentioned previously, battery weight is currently a limitation, but researchers are making real progress in battery technology. Heart Aerospace is developing an electric aircraft or a fully electric plane, and is also exploring a hybrid range-extender unit for longer flights. This is essentially a small engine that activates when battery power alone is insufficient. The 30-seat ES-30 regional hybrid aircraft (200 km battery range plus a reserve hybrid mode) (Pullen, 2023). However, battery energy density and weight remain critical constraints: today's advanced lithium-ion batteries store around 250-300 Wh/kg, compared to 12,000 Wh/kg for jet fuel (kerosene), meaning batteries provide roughly 40-50 times less energy per kilogram than conventional fuel (Research and Markets, 2024; IEA, 2023).

Electric aircraft provide several advantages such as quieter flights, zero in-flight emissions, and potentially lower operating costs. Electric aircraft have immense potential, especially for regional routes.

Even with hybrid systems, the improvements in range and fuel savings are incremental and come with added complexity. Thus, through 2030 the realistic use cases for electric flight remains limited: short-range hops (a few hundred kilometers at most) using small aircraft (from two-seat trainers and eVTOL air taxis up to ~30-seat regional commuters), with multiple projects aiming - with noticeable struggles - for certification and entry into service by the late 2020s.

Hydrogen-Powered Aircraft

Zero-carbon emissions, but requires significant infrastructure development.

Hydrogen is certainly a strong contender, especially for long-haul flights, where battery weight remains a major obstacle. Liquid hydrogen, which is much denser than its gaseous form, is considered the most viable option for aviation. However, storing liquid hydrogen requires extremely low temperatures (-254°C) or in high-pressure containers, posing a significant logistical and safety challenge (Massaro *et al.*, 2023). Furthermore, hydrogen storing takes up a lot more space than jet fuel (about 3–4 times more volume is needed to store the same amount of energy) and therefore requires an entirely revised architecture of the plane (no reservoirs in the plane wings, complex integration in the structure of the plane itself, managing the center of gravity, etc.) There are major technological hurdles to overcome, not to mention the need for an entirely new infrastructure for producing, transporting, and storing liquid hydrogen.

In the near term (before 2035), hydrogen propulsion will likely be limited to smaller aircraft and demonstrators. For example, startup ZeroAvia has flown a 19-seat Dornier 228 testbed with one of its engines powered by a 600 kW hydrogen fuel-cell powertrain (first flight in January 2023) (Perry, 2025). This prototype completed multiple test flights up to 5,000 feet altitude, and ZeroAvia is aiming to certify its hydrogen-electric system by 2026–2027. Such fuel-cell-based hydrogen engines could enter service on short regional routes in the late 2020s.

Large commercial aircraft will take longer. Airbus's ZEROe program initially unveiled concept designs for a hydrogen-fueled turboprop, a turbofan, and even a blended-wing body, targeting entry into service by 2035 (Airbus, 2025). However, due to technology and infrastructure hurdles, Airbus has postponed its hydrogen airliner timeline. The company's goal of introducing a ~100-seat hydrogen aircraft by 2035 has been pushed back by at least 5–10 years (Hepher, 2025), now pointing toward the 2040s for entry into service. In 2023, Airbus selected hydrogen fuel cells (over combustion turbines) for its first ZEROe aircraft and successfully ran a 1.2 MW fuel-cell engine prototype on the ground – a major step in scaling up the technology.

Looking ahead to the long term, hydrogen propulsion is expected to play a role in short- to medium-haul aviation post-2035, once technical challenges are resolved. Airbus, engine makers, and airlines are continuing R&D, with the aim of achieving truly zero-emission flight on a commercial scale in the decades to come. Each milestone, from small regional hydrogen aircraft in this decade to potential hydrogen-powered single-aisle airliners in the 2040s, will contribute to decarbonizing aviation if the supporting fuel infrastructure and regulatory framework can keep pace.

Demand Reduction & Traffic Management

Reducing air traffic growth is necessary to meet climate goals. However, rather than restricting aviation outright, some smart demand management strategies can be implemented such as:

Carbon Pricing: Higher taxes on fossil jet fuel to make sustainable options more attractive.

Frequent Flyer Levies: Higher fees for passengers who fly multiple times per year.

Corporate Travel Policies: Encouraging businesses to reduce non-essential flights in favor of virtual meetings.

Promoting Alternative Transport: Strengthening rail networks as a viable alternative for short-haul flights (<800 km).

It should be noted that there is a strong regional and behavioral character to reducing air travel demand. The majority of the anticipated increase in flight numbers will occur outside of Europe, where many countries do not consider reducing their air travel and lack alternative infrastructure (such as high-speed trains). Additionally, there is the element of inter-generational and inter-regional justice at play. Furthermore, there is a challenge in balancing environmental goals with economic accessibility, and ensuring that policies do not disproportionately affect low-income travelers and tourism-dependent economies.

Optimizing Air Traffic & Airport Operations

Operational inefficiencies in Air Traffic Management (ATM) and airport ground operations currently contribute significantly to avoidable emissions. Addressing these issues can yield immediate carbon reductions (on the order of 8–10% by 2050 according to ADEME estimates) without waiting for new technology. Key inefficiencies and solutions include:

Optimized Flight Routes: Using AI and satellite-based ATM to reduce fuel-intensive detours and holding patterns.

Continuous Descent Approaches: Adjusting landing procedures to minimize fuel burn during descent.

Electric Ground Support Equipment: Replacing diesel-powered airport vehicles with electric alternatives.

Sustainable Airport Infrastructure: Using solar power, energy-efficient terminals, and green hydrogen hubs at major airports.

These improvements can deliver immediate benefits, complementing longer-term technological shifts.

Key inefficiencies and solutions include:

- **Fragmented Airspace & Indirect Routing:** Europe's fragmented airspace management leads to longer flight paths and holding patterns, wasting fuel. To address this, the Single European Sky initiative (SESAR) is unifying ATM and enabling more direct routes, aiming to cut per-flight CO_2 emissions by ~10% (Eurocontrol, 2020). Free-route airspace trials already demonstrate ~6–12% fuel savings[14] from optimized routing (SESAR, 2021).
- **Inefficient Approaches & Holding:** Traditional stepwise descents and arrival delays cause excessive fuel burn near airports. Continuous Descent Operations (CDO) and improved approach sequencing (*e.g.,* extended arrival management) allow aircraft to descend at idle thrust, minimizing fuel use. These procedures are now deployed by many European ANSPs (*e.g.*, DSNA in France at Paris-CDG, Lyon and Toulouse) (Gillermet, 2021). Each optimized approach can save ~150 kg of CO_2 per landing (EUSPA, 2024), and better sequencing has cut holding times by ~1 minute per flight at busyhubs – avoiding ~5,000 tonnes CO_2 annually in one London Heathrow tria.

14 Note that contrail avoidance would offset a fraction of that gain.

- **Ground Taxiing & Delays:** Prolonged taxi-out and queueing with engines running lead to unnecessary fuel burn, especially on short-haul flights, where in extreme cases, up to one-third of total fuel can be consumed on the ground (SESAR, 2021). Airports are mitigating this with improved ground traffic management (*e.g.*, Airport Collaborative Decision Making) and single-engine taxi procedures. At Paris-CDG, optimized taxiing practices reduced average taxi time by ~10% and fuel burn per flight by ~10%, while a 5-minute single-engine taxi on a widebody can save ~65 kg of fuel (OpenAirlines, 2023).
- **Auxiliary Power & Ground Support Equipment:** At the gate, aircraft often run onboard auxiliary power units (APUs) and airports use diesel ground vehicles, creating avoidable emissions. Replacing APUs with gate electric power and electrifying ground support equipment (GSE) or using cleaner fuels can virtually eliminate these sources. For example, APUs burn 150–400 kg of jet fuel per hour versus <20 kg using centralised electric power (OpenAirlines, 2023), and Paris-Orly Airport is targeting zero net CO_2 emissions from ground operations by 2030 (ADP, 2024). These operational improvements deliver immediate emissions benefits, complementing longer-term technological shifts.

Increasing Aircraft Load Factors & Fleet Utilization

Many commercial flights operate below full capacity, leading to wasted fuel and unnecessary emissions. Increasing passenger load factors (the percentage of available seats filled) from 85% to 95% could cut emissions by 5-8%.
Key strategies include:

- **Dynamic Pricing & Seat Optimization:** Encouraging airlines to maximize passenger capacity per flight. This solution guarantees that no seats are left empty, and that passengers can book flights more efficiently and easily depending on the pricing.
- **Fleet Modernization:** Retiring older, less efficient aircraft sooner and standardizing fleet types to improve efficiency. Modernizing an airline's fleet can help in reducing operating costs and reduce emissions due to the higher aircraft efficiency. Increase in energy costs might eventually lead to fleet modernization, with carriers aiming for more environmentally friendly operations (Oliviera et al. 2022).

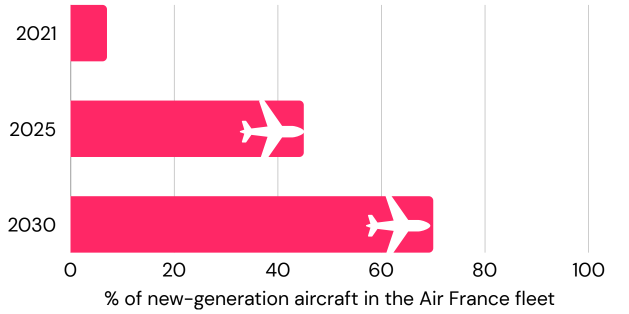


Fig. 10 - Fleet renewal Air France objectives. (Air France, 2022)

- **Encouraging Use of Larger Aircraft:** Using wide-body aircraft on busy routes instead of multiple smaller flights. In this case however, there seems to be a lot of discussion surrounding profitability for airline companies. Airline companies already have a low profit margin (2-3%) (IATA, 2023) and so using larger aircrafts is a financial risk.[15] So while this solution makes sense from an ecological perspective, it would be a difficult decision for airline companies to make, in order to remain competitive in the market and actually make a profit.

While these changes may seem incremental, collectively, they offer significant emissions reduction.

Regulatory & Market-Based Measures

Stronger emissions regulations can incentivize green technologies.

Carbon pricing can encourage airlines to invest in sustainability (detailed later in section 5).

Public-private partnerships can accelerate research and development.

15 Also, even if the frequency of these long-haul flights using larger aircrafts is reduced to the bare minimum to guarantee that the number of passengers is complete, there is still a financial risk in the case of cancellation, delay or other technical issues that might hinder the flight actually taking off. In this case the airline company is completely liable and has to financially compensate all passengers.

Carbon Dioxide Removal (CDR)

Even with major gains in efficiency, sustainable aviation fuels (SAF), and operational improvements, a portion of aviation's CO_2 emissions remains difficult to eliminate (IATA, 2025). Carbon Dioxide Removal (CDR) is therefore needed to neutralize these residual emissions on the path to net-zero. CDR methods can be engineered or nature-based. Engineered solutions like direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) use technology to extract CO_2 from the atmosphere and permanently sequester it (often by injecting CO_2 into geological formations).

CDR is increasingly recognized as a necessary component of any credible net-zero strategy for aviation—not merely as a last resort, but as a strategic necessity to balance the persistent CO_2 from fossil-derived jet fuels. Its role is to neutralize residual emissions—particularly from long-haul and hard-to-abate segments—after all feasible in-sector reductions have been deployed. Until fossil fuel use is fully eliminated, aviation will continue to accrue a CO_2 debt that must be offset through durable carbon removals.

Technologies & Challenges

- **Direct Air Capture with Carbon Storage (DACCS)** is the most discussed engineered option, but it remains technologically immature, energy-intensive, and costly (typically $500–1,000 per tonne of CO_2 removed) (Höglund, 2024). Large-scale deployment also requires secure and verifiable geological storage capacity, which is geographically and politically constrained.
- **Biological removals (like BECCS or biochar)** face similar land-use, scalability, and permanence concerns. Their global potential is modest compared to aviation's long-term emissions.
- Evidence suggests that relying on future removals to offset emissions today is **a high-risk climate strategy.** Several studies emphasize the uncertainty in durability, additionality, and deployment speed of CDR technologies (Lamb et al., 2024; Smith et al., 2023).

A Limited Role

- Even optimistic techno-economic scenarios do not foresee CDR covering more than 5–15% of aviation emissions by 2050 (Brazzola *et al.*, 2025; Lamb *et al.*, 2024).
- If overused or misrepresented, CDR can delay more systemic changes and create moral hazard, undermining aggressive emission reductions where they are technically possible.
- While CDR may become a compliance mechanism in carbon accounting frameworks, it must not be viewed as a license to maintain business-as-usual trajectories (Simpliflying, 2024).

4

Economic and Policy Challenges in Decarbonizing Aviation

- Key Barriers to Achieving Net-Zero Aviation
- Future Scenarios for 2050
- Is Net-Zero Aviation by 2050 Achievable?

The transition to sustainable aviation will require massive investments across the industry. The key question remains: Who will finance this transformation? This is where economic and political realities come into play.

Achieving aviation decarbonization will demand substantial financial commitments from aircraft manufacturers, airlines, fuel producers, and governments.

Key Barriers to Achieving Net-Zero Aviation

Decarbonizing aviation will require substantial investment, and these efforts may not yield immediate financial returns. While sustainable options are often more expensive than fossil-based alternatives, this comparison shifts when accounting for the negative externalities of conventional aviation, such as climate impacts, air pollution, and noise. One potential outcome of transitioning to cleaner technologies is an increase in ticket prices. This raises an important question: how can the sector reconcile affordability and broad access to air travel with the imperative of environmental sustainability? It is ultimately up to policymakers and industry leaders to define and manage this balance.

Ensuring that sustainable aviation is not only environmentally viable but also economically feasible is important. The industry must find financial mechanisms to support this transition without placing an excessive burden on airlines or passengers, especially if indefinite growth proves neither realistic nor desirable in the long term.

The Cost of Sustainability: A Major Challenge

- Sustainable aviation technologies are significantly more expensive than conventional options.
- Making them cost-competitive is essential to ensure widespread adoption.

Long Development Timelines

- The aviation industry operates on long innovation cycles; developing and certifying new aircraft can take decades.
- Hydrogen-powered and electric aircraft, while promising, may not reach commercial viability before 2040-2050.

Addressing Non-CO_2 Climate Effects

- Even if aviation eliminates CO_2 emissions, non-CO_2 factors such as contrails and NOx emissions must also be mitigated.
- A holistic approach is necessary to address the full climate impact of aviation.

Future Scenarios for 2050

Despite the challenges, there is a projected path forward. The Air Transport Action Group (ATAG) has developed a comprehensive report, "Waypoint 2050", which outlines a structured roadmap for aviation decarbonization.

The strategy involves a multi-faceted approach, integrating:

- Continuous efficiency improvements in aircraft design and operations.
- The development and deployment of electric and hydrogen-powered aircraft.
- A large-scale expansion of Sustainable Aviation Fuel (SAF) production.
- Carbon offsetting mechanisms to neutralize residual emissions.

Rather than relying on a single breakthrough technology, Waypoint 2050 proposes a combination of solutions working in parallel. This approach is ambitious and aspirational, and could be achievable, provided that all industry stakeholders collaborate effectively. There are four different scenarios that could be followed:

Sc. 0: baseline/continuation of current trends.

Continues current technological trends with limited improvements; emissions rise steadily.

Sc. 1: pushing technology and operations

Focuses on aircraft and operational efficiency; no low-carbon fuels included.

Sc. 2: aggressive sustainable fuel deployment

Adds aggressive SAF deployment to tech gains; cuts emissions significantly.

Sc. 3: aspirational and aggressive technology perspective

Combines tech, SAF, and market tools; only pathway that achieves net-zero.

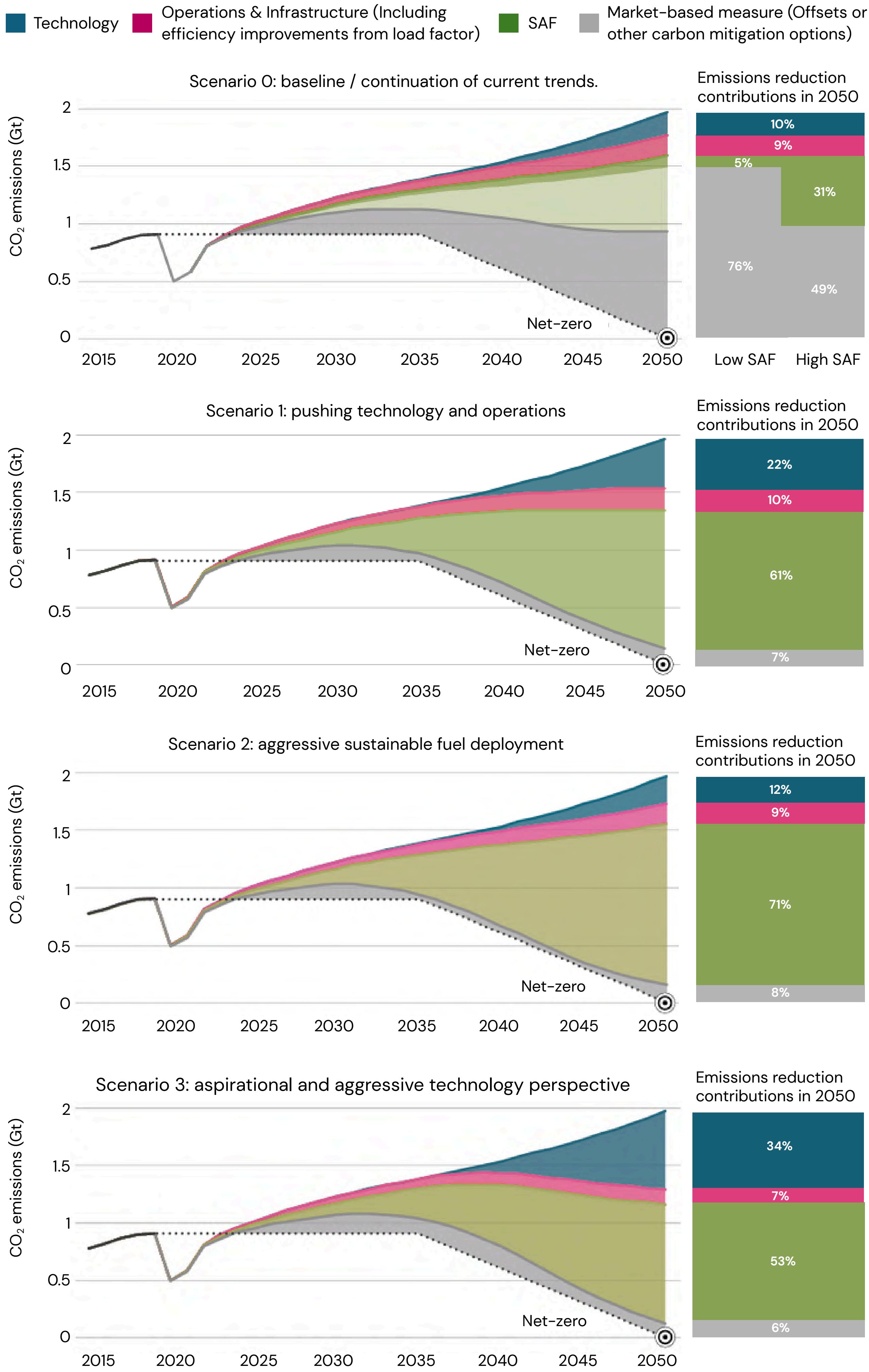


Fig. 11 – Different decarbonization pathways (Waypoint 2050)

The four scenarios differ primarily in their strategic emphasis. Scenario 0 serves as a baseline, illustrating the emissions trajectory if no further mitigation efforts are pursued, effectively a reference case. Scenario 1 pushes for aerodynamic and operational improvements but does not assume major breakthroughs in fuel switching, making it dependent on incremental gains. Scenario 2 focuses on the rapid and large-scale deployment of SAF to decarbonize the existing fleet, but it presumes less technological innovation in aircraft design. In contrast, Scenario 3 is the most ambitious, combining cutting-edge aircraft technologies with aggressive SAF scale-up, and relies on coordinated policy and investment to achieve full-sector transformation.

These scenarios highlight different levers, but it is also notable that these scenarios each focus on different technological solutions, without taking into account any demand reduction or moderation.

Is Net-Zero Aviation by 2050 Achievable?

Achieving net-zero emissions in aviation by 2050 is a widely stated ambition, but reaching this target appears highly unlikely under current trends. While many decarbonization solutions are technically feasible, scaling them in time to offset the projected growth in air traffic presents a formidable challenge.

The lifetime of commercial aircraft, typically 25-30 years, means that planes entering service in the 2030s will still be flying well into the 2050s. Unless a radical shift occurs in aircraft design, energy systems, and global policy, much of the 2050 fleet will still be powered by conventional jet engines. Furthermore, constraints in SAF production capacity, supply chains, airport retrofits, and regulatory alignment all add to the timeline required for transformative change.

Even under optimistic assumptions, including rapid SAF scale-up, technological advances, and efficiency gains, these measures alone are not expected to fully decarbonize the sector by mid-century.

Therefore, a pragmatic climate strategy must:

- Prioritize mature, high-impact solutions now (*e.g.,* SAFs, efficiency, ATM)
- Anticipate and manage residual emissions through credible, permanent removals
- And prepare for a decarbonization pathway that likely extends beyond 2050.

The challenge is not a lack of technical options, but the pace, scale, and coordination required to implement them globally. Aviation's climate strategy must therefore balance ambition with realism, pursuing immediate reductions while planning for a longer-term transformation.

5

Governmental and regulatory policies and mechanisms

- Market-Based Financial Mechanisms for Sustainable Aviation
- The Role of Governments in Driving Decarbonization
- A Collective Effort for a Sustainable Future

Market-Based Financial Mechanisms for Sustainable Aviation

Several financial and regulatory mechanisms can help accelerate the shift toward decarbonization. Among them, carbon pricing systems play a crucial role in making pollution financially unattractive, thereby encouraging investment in cleaner technologies.

The EU Emissions Trading System (ETS)
One key approach is cap-and-trade systems such as the European Union's Emissions Trading System (EU ETS). This system sets a limit (cap) on the total greenhouse gas emissions allowed for certain industries, including aviation (to be reviewed in 2026).

- Companies must purchase carbon allowances for every ton of CO_2 they emit.
- This effectively places a price on carbon emissions, making it increasingly costly for airlines to operate without reducing their environmental footprint.
- As the cap is progressively lowered over time, the system incentivizes greater efficiency and investment in low-carbon alternatives.

The Global CORSIA Program
Another mechanism is CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), a global market-based program designed to offset CO_2 emissions from international flights.

- Airlines purchase carbon offsets to compensate for emissions growth beyond 2020 levels.
- While CORSIA does not directly reduce emissions, it ensures that airlines take financial responsibility for their environmental impact.
- The system encourages investment in sustainable projects, such as reforestation and renewable energy initiatives, helping to balance aviation's carbon footprint.

While CORSIA is a step in the right direction, it remains a compensation mechanism rather than a direct emissions reduction strategy. A large fraction of compensation schemes have turned out to be ineffective, or offer non-permanent CO_2 offsetting (US Treasury, 2024). A broader combination of market-based policies and regulatory measures will be required to drive meaningful progress.

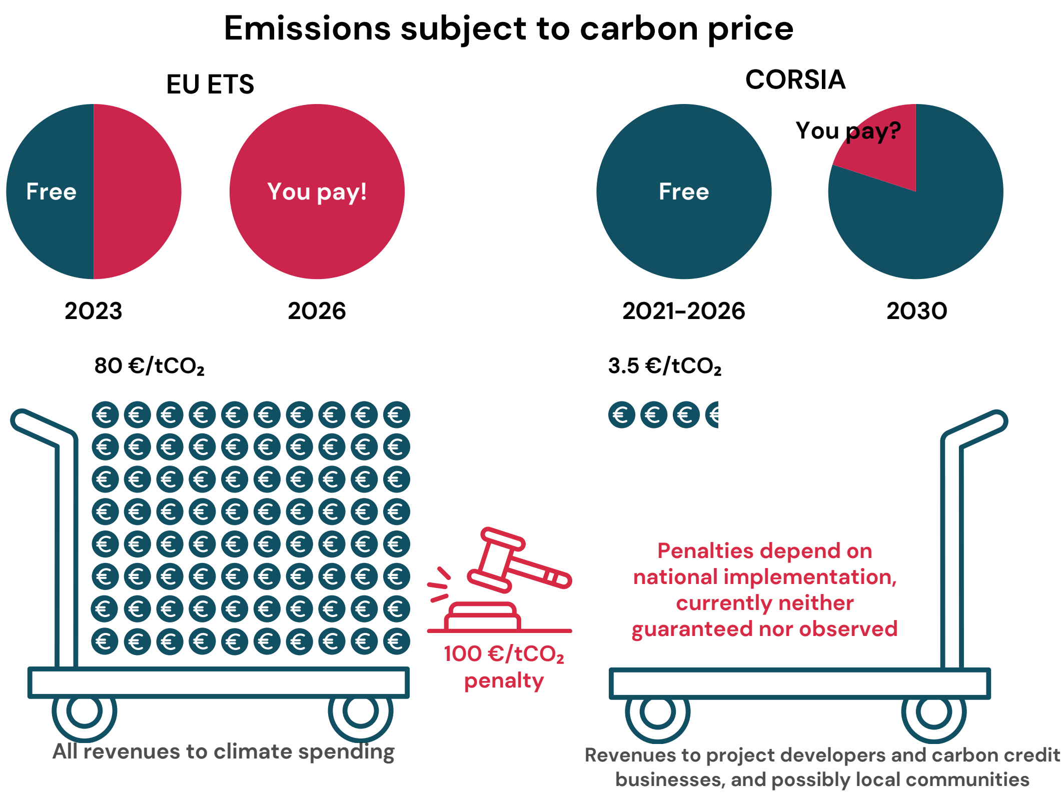


Fig. 12 - Comparison of Carbon Pricing and Offsetting Mechanisms. (Carbon Market Watch, 2024)

The Role of Governments in Driving Decarbonization

The success of sustainable aviation depends significantly on government intervention. Policymakers play a crucial role in:

- Establishing a favorable regulatory environment to accelerate the adoption of low-carbon technologies.
- Providing financial incentives such as tax breaks, subsidies, and direct funding for SAF production and hydrogen infrastructure.
- Ensuring fair market conditions, preventing green technologies from being undercut by cheaper fossil fuel alternatives.

Government support is critical in bridging the cost gap between sustainable aviation solutions and traditional fossil-based fuels. By fostering strong public-private partnerships, governments can help ensure that the transition to net-zero aviation remains both feasible and competitive.

A Collective Effort for a Sustainable Future

Despite these challenges, there is growing momentum for sustainable aviation. The industry is increasingly aware of the urgency of decarbonization as aviation emissions keep on rising, and significant technological progress is already underway.

- Collaboration is the key to success—governments, industry leaders, and research institutions must work together to drive innovation.
- Market-based incentives and regulatory frameworks will play a decisive role in ensuring that sustainable aviation becomes economically viable.
- The transition will take time, but the foundations for change are already in place.

A cleaner, more sustainable future for aviation is within reach. However, bold action is required today to ensure that future generations can continue to benefit from air travel without compromising the environment.

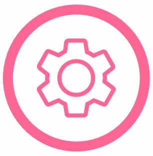
6

Recommendations

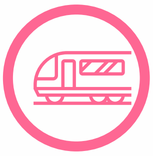
Recommendations

To accelerate the transition to sustainable aviation, stakeholders should:

Increase investment in SAF production[16] to lower costs and improve availability.



Enhance aircraft efficiency through advanced aerodynamics and engine improvements.



Promote alternative transport for short-distance travel to reduce unnecessary flights.

Develop Carbon Dioxide Removal technologies, and putting in place a clear legislative and regulatory framework.

Implement carbon pricing and incentives to drive airline sustainability initiatives.

Encourage international cooperation for harmonized regulations and infrastructure development.

While decarbonizing aviation is technically possible in the long term, reaching full net-zero by 2050 appears unlikely without transformative breakthroughs, massive investment, and structural demand shifts. Therefore, climate strategies for aviation must also plan for managing residual emissions, prioritizing the most effective mitigation pathways now, and preparing for a decarbonization timeline that realistically extends beyond 2050.

By adopting these measures, the aviation industry can take meaningful steps toward achieving net-zero emissions and a more sustainable future, but nowhere near the 2050 mark. If we take into account the growing air traffic and the lifetime of an airplane, an airplane sold and delivered in 2030 (which is closer than we think), will still be operational by the time we reach 2050. This means that even under optimistic deployment scenarios, much of the global fleet in 2050 will still rely on conventional propulsion and emit CO_2.

16 The major barrier to SAF investment is uncertainty around a return on investment (Harrison-Byrne *et al.*, 2024). In recent news, Bangchak corporation anticipates an ROI of 5-7 years on its SAF investment, revisiting its initial frame from three to five years (Hussain, 2025).

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About Zenon Research

Zenon Research is the think tank for climate innovations and technologies and a low-carbon world.

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Gérard Feldzer - **Aviation sans frontières**
Jérôme du Boucher - **T&E**
Marc Delcourt - **Global Bioenergies**
Mariano Berkenwald - **Breakthrough energy**
Sandra Combet & Kevin Guittet - **DGAC**
Raphaël Cario - **Consultant for AFEN**
Yannick Bonnaire - **SAFRAN**
Yannael Billard - **Aéroport de Paris**