Aviation

Pathways to net zero

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KEARNEY FORESIGHT | Energy Transition Institute

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About the FactBook: Aviation pathways to net zero

This FactBook assesses aviation pathways to net zero, highlighting its climate impact and emissions trajectory. It explores key climate impact mitigation levers, their technical and economic aspects, and related initiatives. The aviation ecosystem and regulatory landscape are examined for their influence on adoption rates. The FactBook summarizes market status, trends, and the environmental and social impacts of net zero solutions, outlining feasibility and scalability challenges.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Aviation: pathways to net zero

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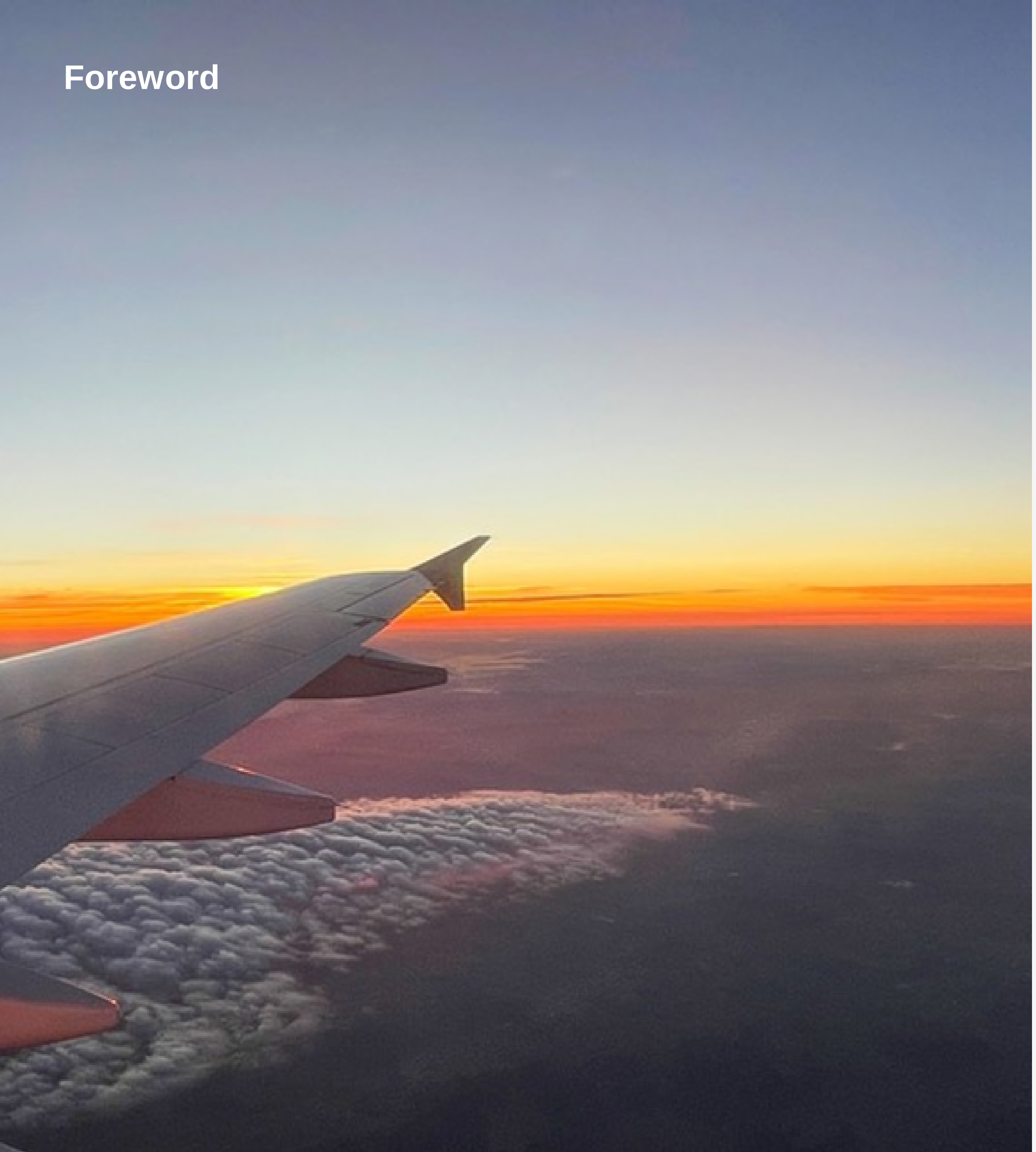
Foreword



The aviation sector stands at a **decisive crossroads**. Technological innovation has unlocked an **abundance of promising solutions**.

This report outlines the **many pathways to decarbonize aviation**. Levers range from improved airframe and more efficient propulsion to the use of low-carbon fuels and smarter air-traffic management that optimizes routings to cut fuel burn and reduce contrail formation. Each pathway carries its own potential to mitigate warming impact. Some are *mutually incompatible—or even competing*—while their climate benefits are **not generally additive**.

Choosing **the most promising pathway, or the right combinations of solutions**, remains under active debate. Decisions span the energy carrier (advanced biofuels vs. hydrogen), airframe architecture (blended-wing-body vs. truss-braced wing), and propulsion concepts (open-rotor/propfan vs. ultra-high-bypass-ratio turbofans), among others.

In the years ahead, manufacturers will **prune this solution tree**, discarding branches that pose greater industrial risk or prove less cost-effective at the sector level, considering their deployment potential and factoring in realistic boundaries. The process by which the industry selects and **sequences the technology building blocks** for new programs is at **least as important as the list of candidates itself.**

The mechanism by which these technologies are selected—*how trade-offs are assessed, how synergies are captured, and how risks are managed*—**will be as critical as the innovations themselves**. Recognizing this dynamic is essential to maintaining a rational and evidence-based outlook on aviation's decarbonization journey.

As this report illustrates, progress **toward net-zero flight** will depend not only on **the innovation of these advances but also on the rigor with which the industry selects and integrates them**, considering **infrastructure and fleet renewal constrains**, among other factors.

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1. Aviation and climate change

Aviation is a growing GHG emitter, though with a relatively minor global contribution that is hard to abate

Aviation's climate impact goes beyond CO_2

In 2024, aviation accounted for ~2.5% of global CO_2 emissions, but its overall contribution to climate change is higher (~4% of the total radiative forcing by all anthropogenic activities) due to non-CO_2 effects, namely contrails and indirect impact of NOx emissions.[1]

Aviation demand tripled from 2000 to 2024

Aviation demand tripled from 2000–2024 with a temporary drop-off due to the COVID-19 pandemic, driving emissions rise.

The full extent of emissions rise was curtailed by energy efficiency gains, reflected by falling carbon intensity from 0.23 kgCO_2e/km to 0.10 kgCO_2e/km, between 2000 and 2024.

Aviation is a hard-to-abate sector

Aviation's path to net zero is challenged due to its dependency on higher energy density fuels, long-lived assets, and global operations with few lower-carbon substitutes to decrease its contributions to climate change.

Efficiency and low-carbon fuels are key to limit aviation's climate impact

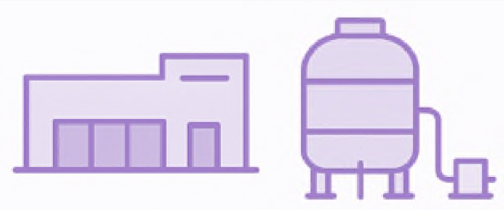
Further gains in efficiency are needed alongside uptake of electrification and/or low-carbon fuels to realize a significant reduction in aviation's environmental impact.

[1] Considering scope 1 and 2.
Source: Kearney Energy Transition Institute analysis

1.0 Chapter summary

Aviation activities generate emissions of greenhouse gases and other warming agents across the entire value chain

Upstream



Aircraft manufacturing
- From mining to assembling
- Emissions from the supply chain

Fuel production and supply
- Extraction, refining, and transport of jet fuel

Core aviation activity

Flight cycle (cruise, takeoff and landing, taxiing and parking)
- CO_2 emissions from the combustion of jet fuel
- Non-CO_2 effects at high altitudes (NOx, water vapor, contrails)

Ground operations
- Use of auxiliary power units (APUs), ground vehicles, and equipment
- Share of airport energy use for terminals

Maintenance and overhaul
- Parts replacement, engine testing, and facility operations
- Transportation of parts and logistics emissions

End-of-life
- Dismantling and recycling of aircraft

Focus of this report

Support infrastructure

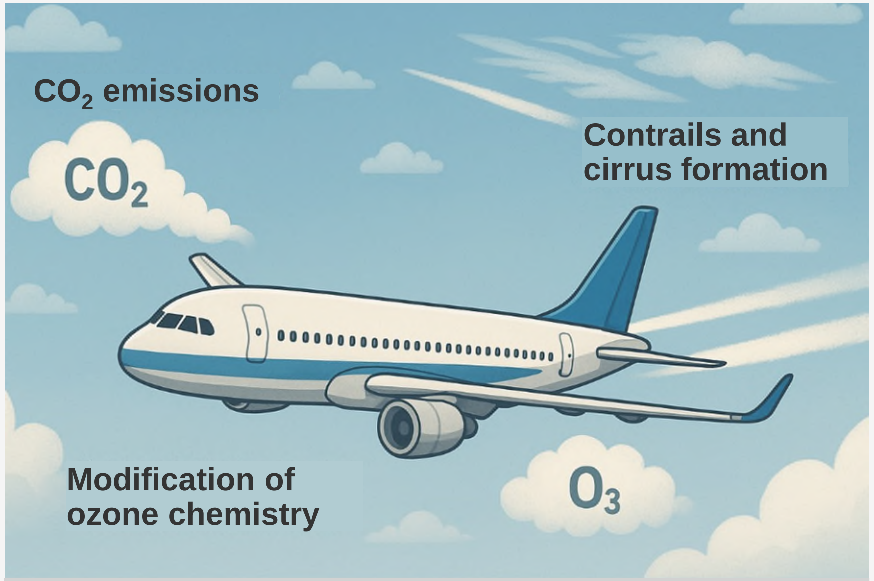
Airports and air navigation services
- Construction and maintenance of airports
- Energy for airport buildings, air traffic management systems

Logistics and passenger transport
- Emissions from passengers and cargo traveling to/from airports

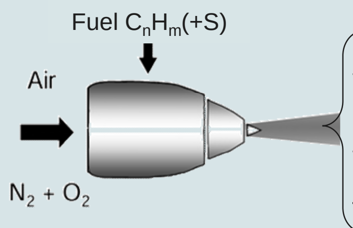
Source: Kearney Energy Transition Institute analysis

Aircraft exhaust gases and particles emissions, including soot, contribute to climate change via increased radiative forcing induced by altered atmospheric composition

Aircraft operations contribute to climate change through direct greenhouse gases emissions



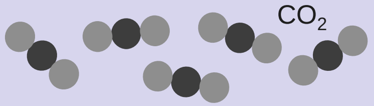
Released chemical components from jet fuel combustion



- Greenhouse gases: CO_2, H_2O, N_2, O_3, NOx, SOx, unburned hydrocarbon (CH_4)
- Other gases: CO
- Particles: Soot, sulfate particles (SOx)

The **non-CO_2 climate impact of aviation is typically assessed using radiative forcing rather than GWP** (Global Warming Potential) because emissions from aviation include short-lived climate forcers—such as contrails and NO_X-induced effects—that create a wide range of impacts over relatively shorter timescales. In contrast, GWP is more suitable for longer-lived GHG gases that remain in the atmosphere for decades or centuries, such as CO_2.

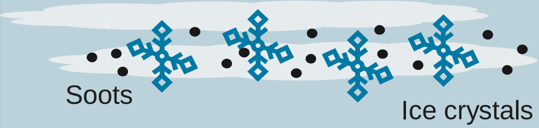
CO_2 emissions



CO_2 absorbs and reemits infrared radiation from Earth's surface, reducing efficiency with which heat escapes to space and trapping energy within lower atmosphere.

GHG related

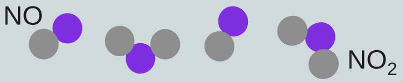
Contrails and cirrus formation



Contrails form from water vapor and soot in cold and humid conditions, **exerting warming or cooling effect by trapping outgoing infrared radiation or reflecting incoming solar radiation,** respectively; they evolve into cirrus-like clouds when persistent, modifying natural cloud cover and influencing overall radiative balance.

Contrails/cirrus/ polar stratospheric clouds

Modification of ozone chemistry



At cruise altitudes, NO_X emitted by aircraft enhances O_3 formation, **leading to short-term warming effect while reducing atmospheric concentration of CH_4 simultaneously,** producing a longer-term cooling effect.

Atmospheric chemistry

Source: IPCC, 2018, Special report: Aviation and the global atmosphere; Kearney Energy Transition Institute

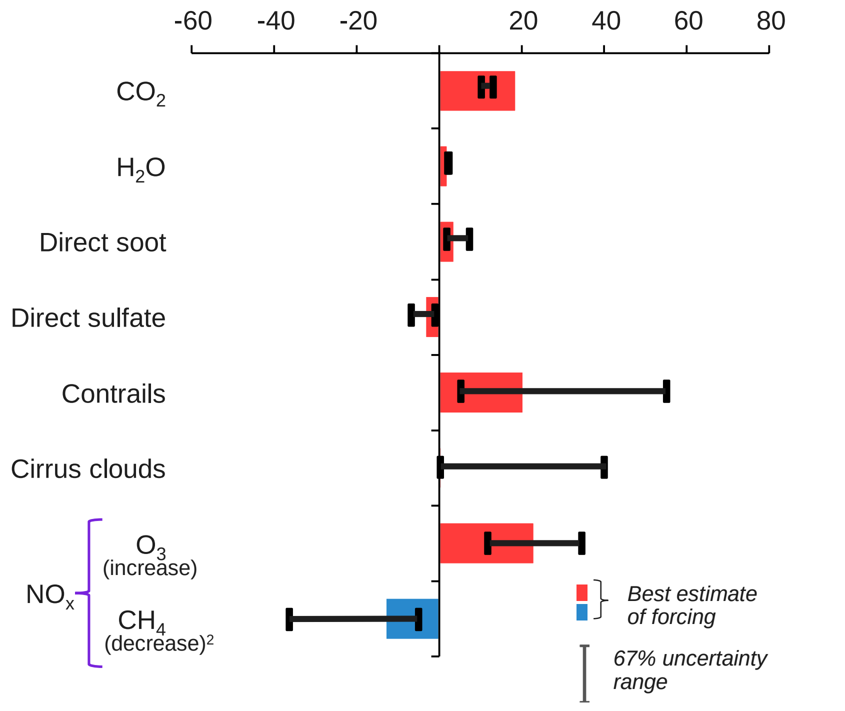
The combined effect of aircraft contrail formation and NO_x emissions can double the radiative forcing attributed to direct greenhouse gas emissions; however, high uncertainties remain

Species contributing to climate change

Emitted species	Zone	Process	Mechanism	Impact
CO_2	Troposphere/stratosphere	GHG emissions	Direct radiative forcing	Warming
H_2O	Troposphere	GHG emissions	Direct radiative forcing	Warming
		Contrail formation	Radiative forcing	Warming
	Stratosphere	GHG emissions	Direct radiative forcing	Warming
		Enhanced PSC formation	O_3 depletion	Enhanced UV-B
		O_3 chemistry	O_3 depletion	Enhanced UV-B
SO_x and H_2SO_4	Troposphere	Enhanced sulfate aerosol conc.	Direct radiative forcing	Cooling
		Contrail formation	Radiative forcing	Warming
		Increased cirrus cloud cover	Radiative forcing	Warming
	Stratosphere	O_3 chemistry	O_3 depletion	Enhanced UV-B
Soot	Troposphere	GHG emissions	Direct radiative forcing	Warming
		Contrail formation	Radiative forcing	Warming
		Increased cirrus cloud cover	Radiative forcing	Warming
		O_3 chemistry	O_3 depletion	Enhanced UV-B
	Stratosphere	O_3 chemistry	O_3 depletion	Enhanced UV-B
NO_x (NO and NO_2)	Troposphere	O_3 chemistry	Radiative forcing	Warming/reduced UV-B
		Decrease in CH_4	Less radiative forcing	Cooling
	Stratosphere	O_3 chemistry	O_3 formation <18-20 km	Reduced UV-B
		O_3 chemistry	O_3 formation >18-20 km	Enhanced UV-B
		Enhanced PSC formation[1]	O_3 depletion	Enhanced UV-B

GHG related · Chemical balance · Contrails/cirrus/polar stratospheric clouds · Warming impact · Cooling impact

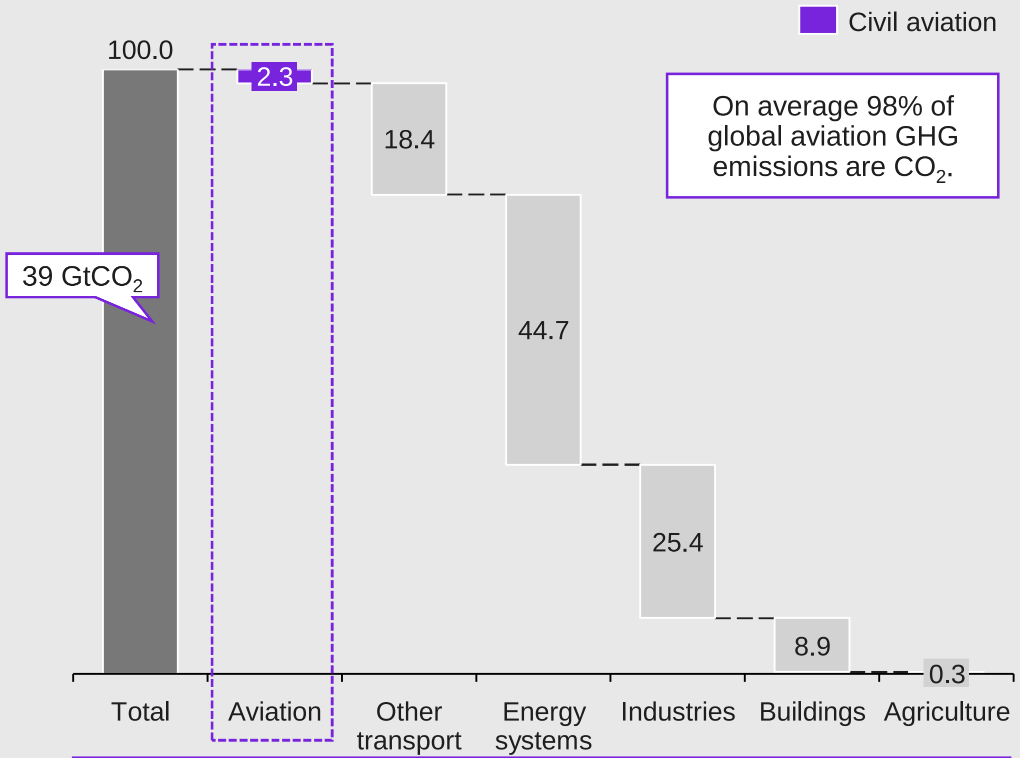
Radiative forcing (mW/m²)



Note: Radiative forcing occurs when the quantity of energy entering the atmosphere exceeds the quantity leaving, accumulating and raising temperatures, e.g., greenhouse gas effect.
[1] Polar stratospheric cloud; [2] NOx emissions increases atmospheric concentration of hydroxyl that breaks down CH_4, reducing its concentration and creating a net negative radiative forcing contribution.
Sources: ISAE Supaero, 2021, Aviation et climat; IPCC, 2018, Special report: Aviation and the global atmosphere; Kearney Energy Transition Institute analysis

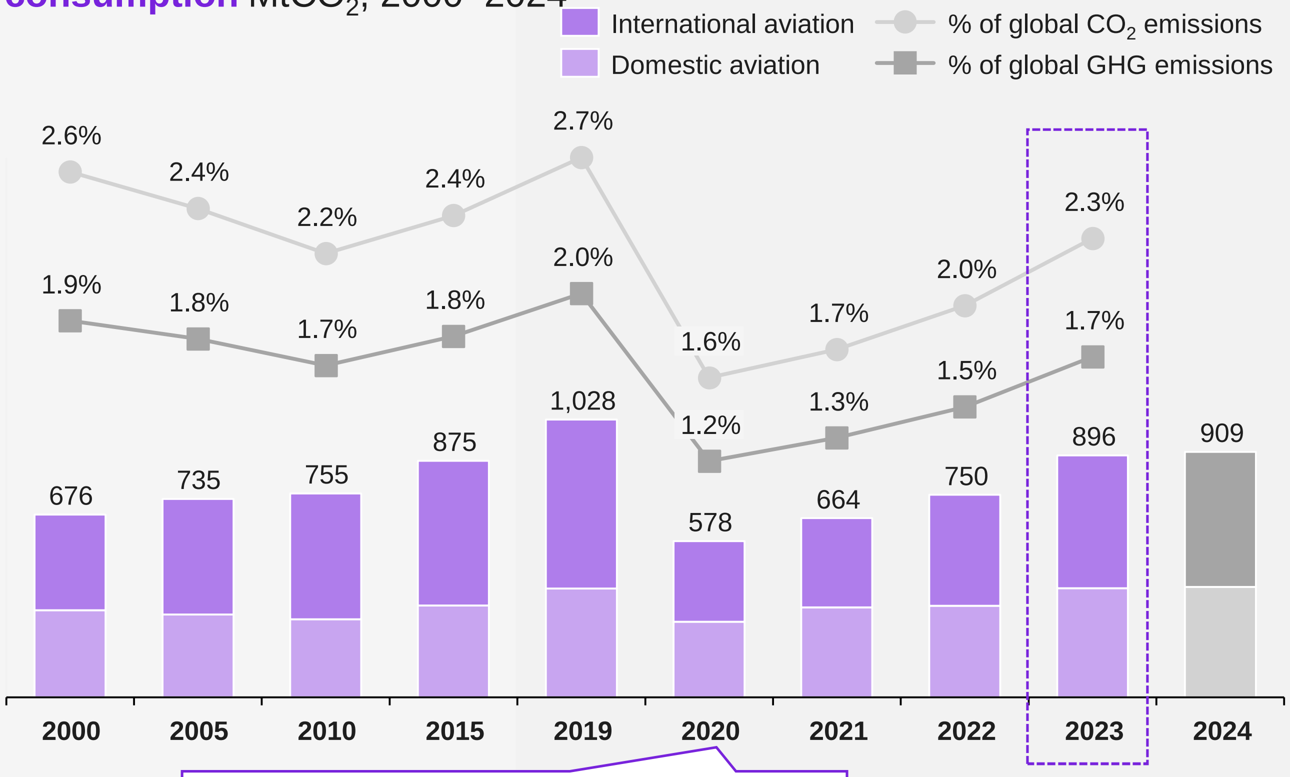
Although absolute CO_2 emissions from aviation have continued to increase, exceeding 900 $MtCO_2$ in 2024, the share of the global anthropogenic total has stabilized at ~2% since 2000

Global CO_2 emissions by sector
Share %, 2023, by sector



Tracking other emissions (NOx, CH_4) is challenging and there is no agreed methodology to estimate these.

Evolution of global commercial aviation CO_2 emissions from fuel consumption $MtCO_2$, 2000–2024

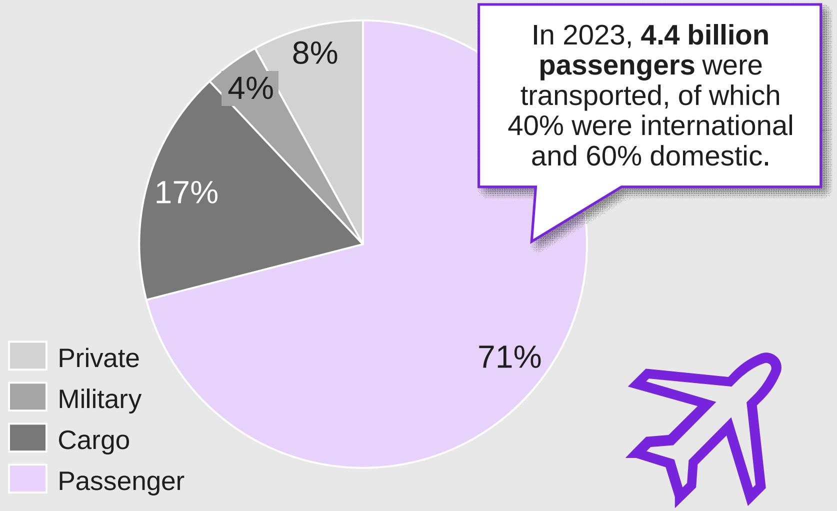


Drop-off in 2020 demand and emissions due to COVID-19, but quickly rebounding

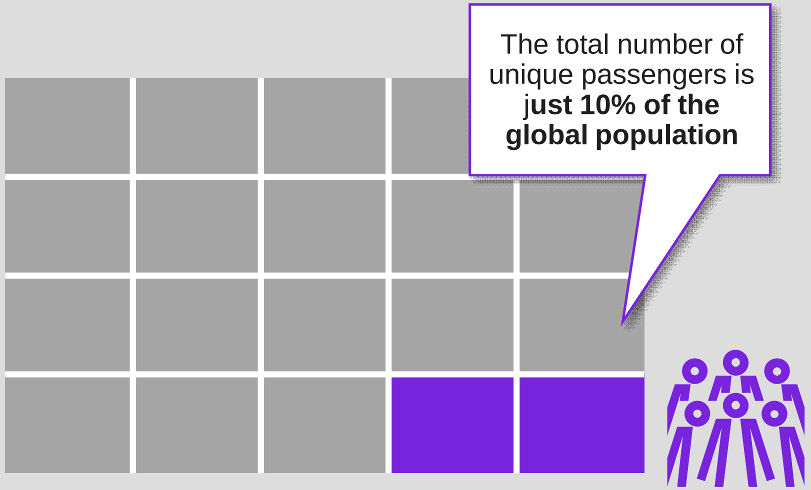
Sources: IEA, Transport, accessed March 2025; European Commission, 2023, Joint Research Center, GHG emissions of all world countries; World Meteorological Organization, 2024, Record carbon emissions highlight urgency of Global Greenhouse Gas Watch; Kearney Energy Transition Institute analysis

The increase in aviation demand has outpaced the decarbonization rate, creating a net negative impact on climate change

Share of CO_2 emissions by aviation type
2023

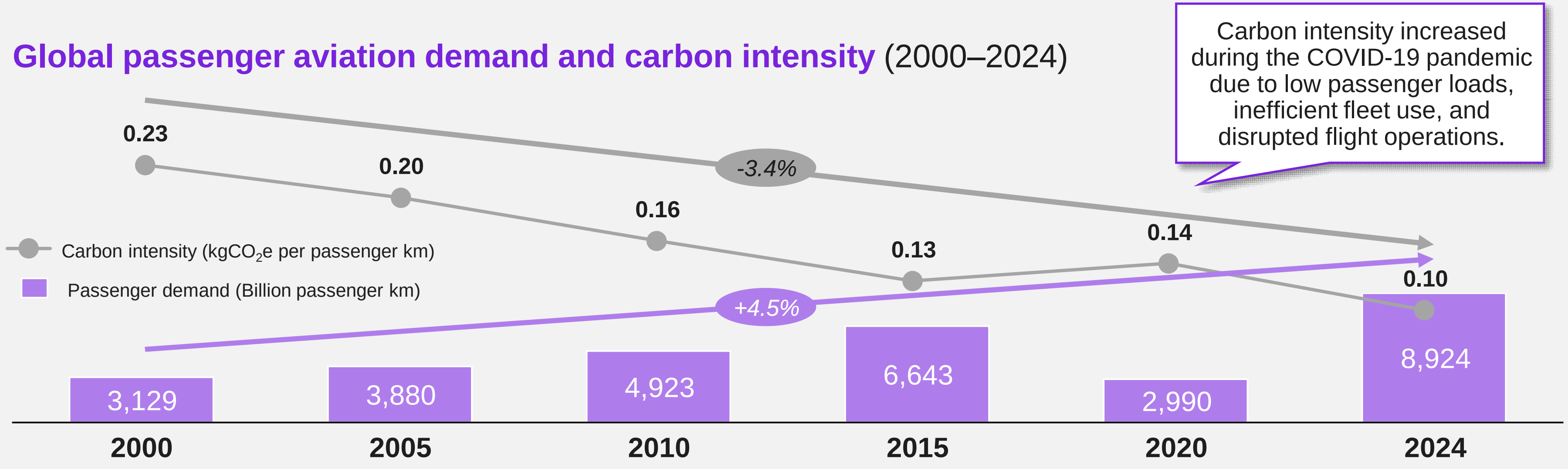


Share of global population flying



In 2020, aviation's carbon intensity rose mainly due to COVID-19, as lower passenger load factors, longer non-direct routes from airspace restrictions, older aircraft use, and more cargo flights on passenger planes increased emissions per passenger-kilometer.

Global passenger aviation demand and carbon intensity (2000–2024)



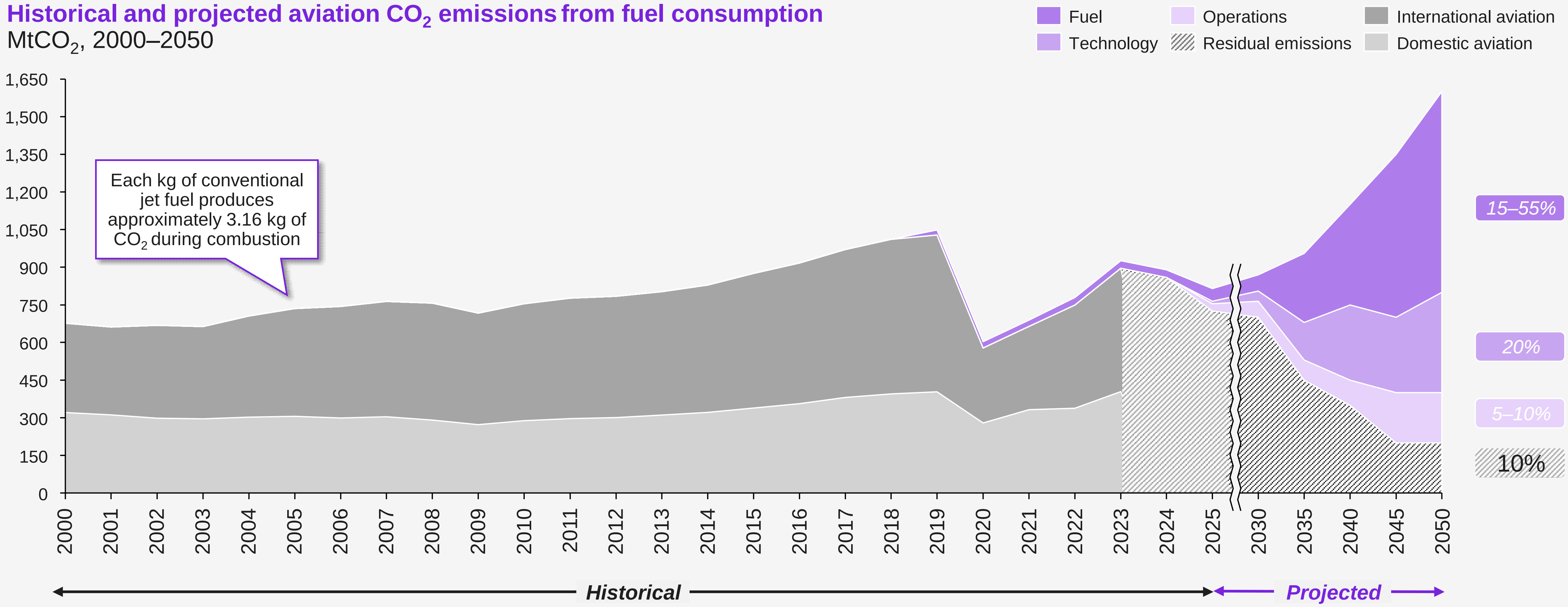
Sources: ISAE Supaero, 2021, Aviation et Climat; Bergero et al., 2023, Pathways to net zero emissions from aviation; Global Carbon Budget, 2024; IATA, 2025, Global Air Passenger Demand Reaches Record High in 2024; ICAO, 2024, LTAG Integrated Scenario; ADEME, 2022, Elaboration de scenarios de transition écologique du secteur aérien; Kearney Energy Transition Institute analysis

1.3 CO_2 emissions

CO_2 emissions from aviation fuel consumption are expected to fall following adoption of low-carbon fuels and deployment of technological advances in fuel burn efficiency

Historical and projected aviation CO_2 emissions from fuel consumption

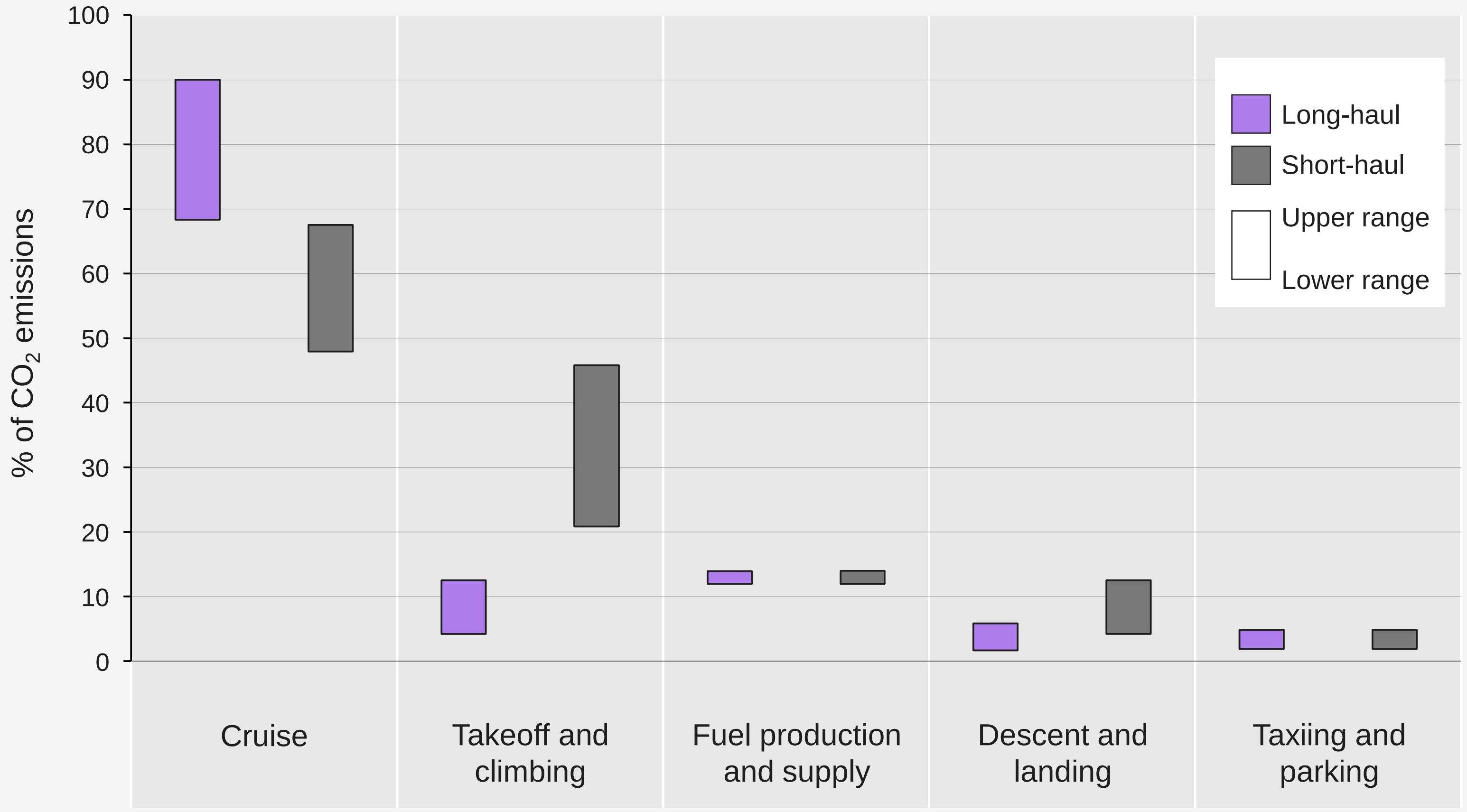
$MtCO_2$, 2000–2050



Sources: ICAO, LTAG Integrated Scenario 3; ISAE Supaero, 2021, Aviation et climate; Kearney Energy Transition Institute analysis

The quantity and proportion of CO_2 emissions from flight cycle vary significantly depending on several factors

CO_2 emissions ranges from flight cycle for long-haul and short-haul



- The quantity and proportion of fuel consumed by the different phases of the flight cycle—such as taxiing, takeoff, cruise, and landing—depend on the aircraft type, flight distance (short-haul or long-haul), and operational procedures.
- Although the cruise phase typically accounts for the majority of CO_2 emissions, the proportion from takeoff and climb decreases as flight time increases.
- Additionally, emissions from fuel production and supply are substantial yet frequently overlooked in emissions assessments.

Sources: IEA, 2025, Aviation; Kearney Energy Transition Institute analysis

Atmospheric conditions and volume of soot emitted by the aircraft determine contrail formation

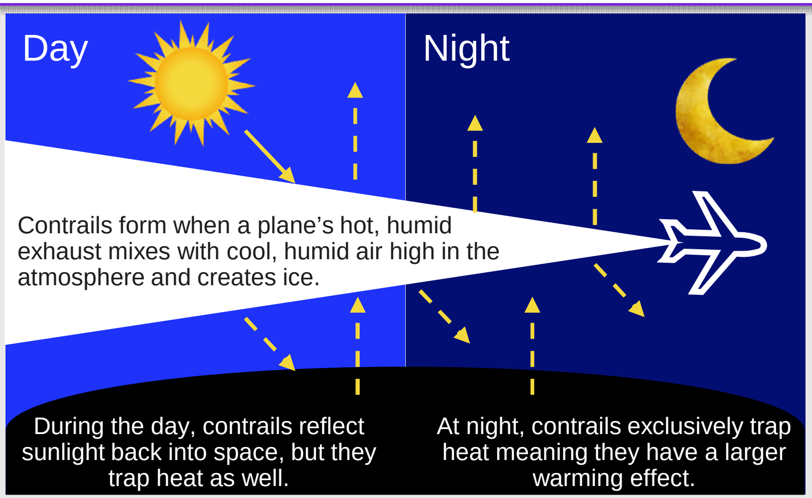
From 1940–2018, **contrail cirrus have contributed to aviation ERF by a quantity 0.5–2.5x greater than the better-known CO_2 contribution;** while CO_2 accumulates over time, the effects of contrails are immediate and fade within hours or days.[1]

1.4 Non-CO_2 emissions

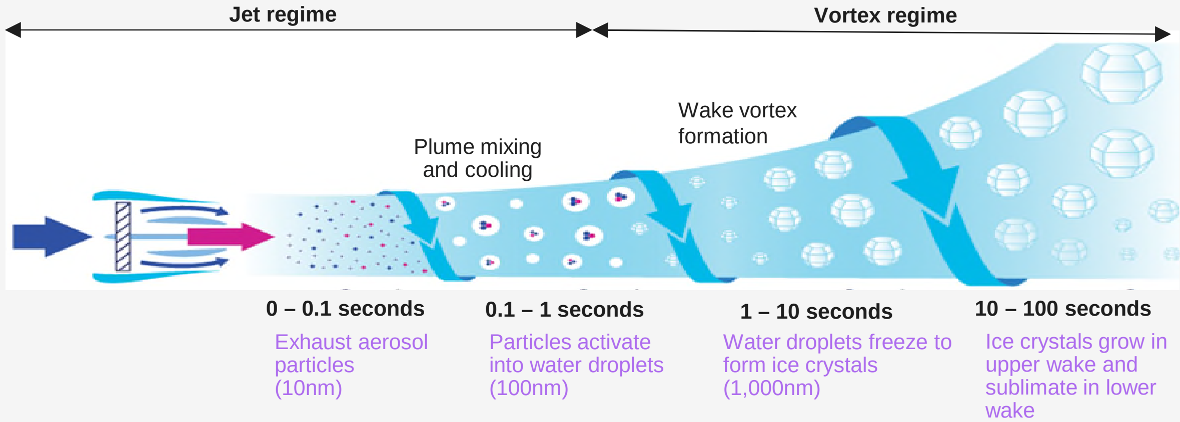
Contrails form due to the release of exhaust particles in specific weather conditions

- **Aircraft exhaust releases CO_2, water vapor, soot, and other particles.**
- **In cold (commonly under 233 K ≈ -40 °C) and humid conditions,** generally above 8 km, **water vapor condenses** around these particles, forming ice crystals that create long, linear-shaped clouds, which are known as contrails (condensation trails).
- **If the aircraft passes through ice-supersaturated regions (ISSRs), the contrails can persist**, spread, and evolve into cirrus clouds that linger in the atmosphere.

Altitude, temperature, and humidity contribute to contrail formation. Contrails' effects depend on their optical thickness and environmental conditions.



Processes and timescales of contrail formation



- **Contrail occurrence can be predicted with confidence**, if ambient pressure, relative humidity, water vapor, heat emissions, and propulsive characteristics of aircraft engines are known.
- However, this thermodynamic approach is not capable of predicting formation (nucleation) pathways and microphysical properties of ice crystals in contrails.

[1] ERF is effective radiative forcing. The difference between ERF and radiative forcing (RF) is that ERF includes all tropospheric and land surface adjustments, whereas RF only includes the adjustment due to stratospheric temperature change.

Sources: IATA, 2024, Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions; RMI, 2024, Understanding Contrail Management: Opportunities, Challenges, and Insights; Karcher, 2018, Formation and radiative forcing of contrail cirrus; Kearney Energy Transition Institute analysis

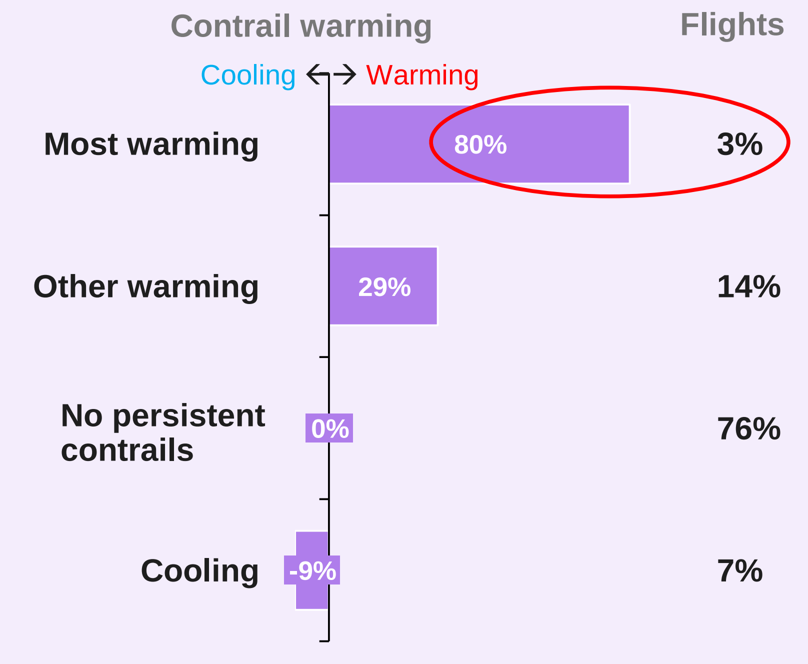
Contrail formation is unevenly distributed across regions and global fleet

Warming due to contrail cirrus is a localized phenomenon; diversion of a small number of flights can significantly reduce contribution to aviation ERF.

Less than a quarter of flights generate persistent contrails

Only **3% of flights cause 80% of contrail warming,** while 76% have no warming or cooling effect.

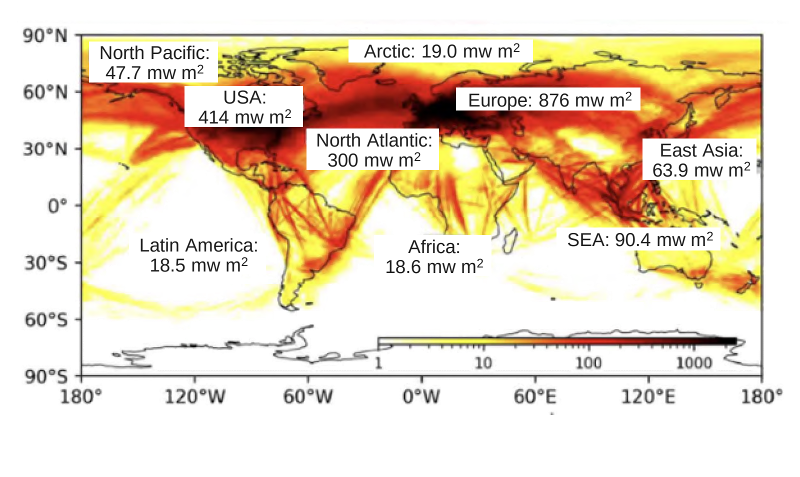
Mapping of contrail warming to flights
(% of global total)



This distribution varies regionally. For example, in Europe, **5% of flights account for 80% of the total contrail warming in the region**.

The impact of contrails on radiative forcing differs across the globe

- Europe (876 mW/m²) and the US (414 mW/m²) experience the **highest radiative forcing due to contrail formation.**
- In contrast, East Asia (64 mW/m²) and China (62 mW/m²) are near the global average (62 mW/m²) due to **lower cruising altitudes, where persistent contrails rarely form.**
- **Consequently, airlines in certain regions contribute more to contrail-induced warming** with flights at higher altitudes more likely to form warming contrails.



Estimating an ERF value for contrails is challenging due to climate model limitations in capturing the climate impact of small, short-lived clouds or cloud clusters.[1]

Note: Radiative forcing occurs when the quantity of energy entering the atmosphere exceeds the quantity leaving, accumulating and raising temperatures, e.g., greenhouse gas effect.
[1] ERF is effective radiative forcing. The difference between ERF and radiative forcing (RF) is that ERF includes all tropospheric and land surface adjustments, whereas RF only includes the adjustment due to stratospheric temperature change.
Sources: IATA, 2024, Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions; RMI, 2024, Understanding Contrail Management: Opportunities, Challenges, and Insights; Transport & Environment, 2024, Contrail avoidance: aviation's climate opportunity of the decade; Kearney Energy Transition Institute analysis

NO_x emissions from aviation contribute to radiative forcing and warming via a complex series of indirect atmospheric processes

Non-exhaustive

Warming impact | Cooling impact

Aircraft NO_x emissions occur primarily at cruise altitudes between **9 and 12 kilometers** in the upper troposphere and lower stratosphere where **atmospheric chemistry operates** under distinctly **different conditions than at ground level.**

1.4 Non-CO_2 emissions

Radiative forcing impact of NO_x emissions

Warming impact (Positive forcing)	**Cooling impact** (Negative forcing)
Formation of tropospheric O_3 In the troposphere, photolysis of NO_2 leads to O_3 formation, which is a greenhouse gas (GHG). This process is particularly efficient in the presence of volatile organic compounds (VOCs) and sufficient sunlight at higher altitudes. The impact of NO_x on stratospheric ozone is more complex and depends on the specific altitude within the stratosphere.	**Methane (CH_4) reduction** Aircraft NO_x increases hydroxyl radical (OH) production through direct reaction of NO with hydroperoxyl radicals and through increased photolysis of O_3. Enhanced OH levels accelerate CH_4 (GHG) oxidation. This also leads to reduction in background O_3 (as CH_4 is a pre-cursor to O_3) and stratospheric H_2O. **Aerosol formation** Potentially cooling effect from sulfate and nitrate particles formation (under research).

Net effect

Based on the current research, NO_x emissions from aviation result in **slightly positive net forcing.** However, this is subject to a **high degree of uncertainty** and future changes in atmospheric composition could potentially shift the balance toward a net cooling effect especially due to an increase in methane oxidation

[1] Lower latitude emissions cause ozone and methane radiative forcing effects that are approximately six times larger than those from higher latitude emissions as the southern hemisphere is more sensitive to changes due to lower background NO_x concentration.
Sources: Copernicus, 2022, Impact of present and future aircraft NOx and aerosol emissions on atmospheric composition and associated direct radiative forcing of climate; Kearney Energy Transition Institute analysis

Variations lead to high uncertainty in estimating impact

1 Atmospheric composition

– Background CH_4 and NO_x concentrations strongly influence O_3 production efficiency leading to regional variance.[1]

2 Temporal variance

– Short-term warming from O_3 (lifetime hours to weeks) formation is followed by longer-term cooling from CH_4 (lifetime 11.8 years) reduction.

3 Seasonal and altitude variance

– Stronger effects are observed in summers.
– Higher altitudes generally lead to greater O_3 production efficiency.

Radiative forcing impact of H_2O, soot, and sulfate emissions stems from direct effects as well as indirect atmospheric chemical reactions

Non-exhaustive

Warming impact | Cooling impact

H_2O

Aircraft engines emit water vapor as the byproduct of fuel combustion at cruising altitudes (9-13 km), although molecules persist longer than at lower altitudes.

Water vapor is a potent **greenhouse gas** and even small increases can have a disproportionately large warming effect due to the low background humidity at high altitudes.	Warming
It may contribute to **contrail and cirrus cloud formation** which have their own radiative forcing impacts.	Warming
Enhances **ozone reduction** by participating in catalytic cycles which break down ozone into oxygen in presence of other chemical species and formation of PSC.[1]	Cooling

Net warming effect

Soot particles

Aircraft jet engines directly emit solid soot, also referred as black carbon particles, encompassing all carbon-containing products from incomplete combustion.

Soot particles **absorb incoming solar radiation**, warming the surrounding air and contributing to positive radiative forcing.	Warming
Soot particles can act as ice nuclei which may contribute to **contrail and cirrus cloud formation.**	Warming
Soot particles provide surfaces for heterogeneous chemical reactions that can alter the balance of **ozone-producing and ozone-destroying compounds.**	Cooling

Net warming effect

Sulfates

Aviation emits SO_2, which oxidizes in the atmosphere to form H_2SO_4, condensing into tiny droplets and forming sulfate aerosols.

Sulfate aerosols are **highly reflective** and scatter incoming solar radiation back into space.	Cooling
Sulfate aerosols act as efficient cloud condensation nuclei which leads to formation of more but smaller cloud droplets. Such clouds are more reflective and exhibit **enhanced cloud brightness (albedo) effect.**	Cooling
Heterogeneous reactions on sulfate aerosols can alter the balance of **ozone-producing and ozone-destroying compounds.**	Cooling
Large number of sulfate particles increases the number of ice nucleation sites, leading to **denser and more persistent contrails.**	Warming

Net cooling effect

[1] PSC is polar stratospheric cloud.
Sources: Hong, Z., Li, Z., and Liu, Z., 2024, Comparison of Emission Properties of Sustainable Aviation Fuels and Conventional Aviation Fuels: A Review; Wang et al, 2022, Significant formation of sulfate aerosols contributed by the heterogeneous drivers of dust surface; Kearney Energy Transition Institute analysis

Core aviation activity can transition to net zero via three primary levers with the support of appropriate policies and regulations

Climate impact mitigation levers in aviation

Non-exhaustive

1 Sustainable aviation fuels

Replacement of fossil fuels with sustainable aviation fuels

- IBN SPK[1]
- PtL[2]
- G-FT[3]
- AtJ[4]
- HEFA[5]

Developed in Chapter 2

2 Technology improvements

Efficiency improvements including aerodynamics and engine performance

Airframe design
- Existing: Winglets, Composites
- Next-gen: New wing designs, Laminar flow

Engine concepts
- Existing: Geared turbofans, UHBR[6]
- Next-gen: Open rotor, Boundary layer ingestion

New propulsion systems
- Hybrid
- Electric
- Hydrogen

Developed in Chapter 3

3 Operation and routes efficiency

Optimizing airspace, routes, ground operations, maintenance practices, and load factor to reduce fuel burn

Traffic/airspace optimization
- Collaborative decision-making
- Continuous descent/climb
- Flexible use of military airspace
- Single European sky/SESAR
- Next-gen projects
- Advanced navigation
- Trajectory-based operations

Improved practices
- Weight and load optimization
- Aircraft condition and maintenance

Flight/trajectory optimization
- Flight planning
- Optimized trajectories
- Wake energy retrieval
- Space-based navigation

Ground operations
- Engine and taxiing
- Stationary energy mgmt.

Developed in Chapter 4

4 Policy and regulations

Using offsets and carbon regulation to bridge the gap to net zero

Emission cap
- ETS[7]
- Offsets

Indicative examples: EU ETS, CORSIA[8]

SAF mandates

Engine standards

Financing

[1] Isobutene synthetic paraffinic kerosene; [2] Power to Liquid; [3] Gasification Fischer–Tropsch; [4] Alcohol-to-Jet; [5] Hydroprocessed esters and fatty acids; [6] Ultra high bypass ratio engines [7] Emission trading system; [8] Carbon Offsetting and Reduction Scheme for International Aviation.
Source: Kearney Energy Transition Institute analysis

Developed in Chapter 5

SAF adoption offers the greatest GHG reduction potential of any lever by directly displacing traditional fossil-based aviation fuel…

⌗ Greatest impact solution per lever (shown with a dashed outline)

Mitigation lever	Sub-lever	Fuel efficiency improvement potential	GHG reduction potential (gCO_2e/MJ)
1 SAF	**PtL**	*N/A, fuel displacement rather than efficiency improvement*	**80-90**
	G-FT		70-80
	IBN SPK		50-60
	HEFA		50-60
	AtJ		50-60
2 Technology improvement	**New propulsion systems**	**25–95%**	**22-90**
	Engine concepts	3-5%	2.7-4.5
	Airframe design	1-5%	0.9-4.5
3 Operation and routes efficiency	**Flight/trajectory optimization**	**3-5%**	**2.7-4.5**
	Traffic/airspace optimization	1-5%	0.9-4.5
	Ground operations	1-3%	0.9-2.7
	Improved practices	~1%	~0.5
4 Policy and regulations	*Not quantified in the scope of this technology-focused report*		

See appendix for breakdown of technological and operational solution sub-levers

Source: Kearney Energy Transition Institute analysis

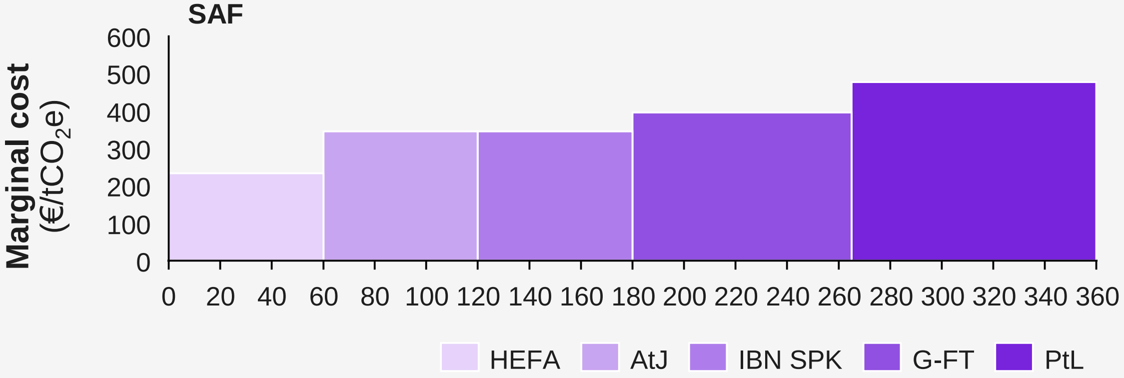
1.5 Aviation climate impact mitigation levers

…however, SAF alone is insufficient to achieve net-zero aviation, requiring supplementary and more cost-effective energy efficiency measures

Non-exhaustive; illustrative

Low-carbon fuel substitution potential – *Best estimate*

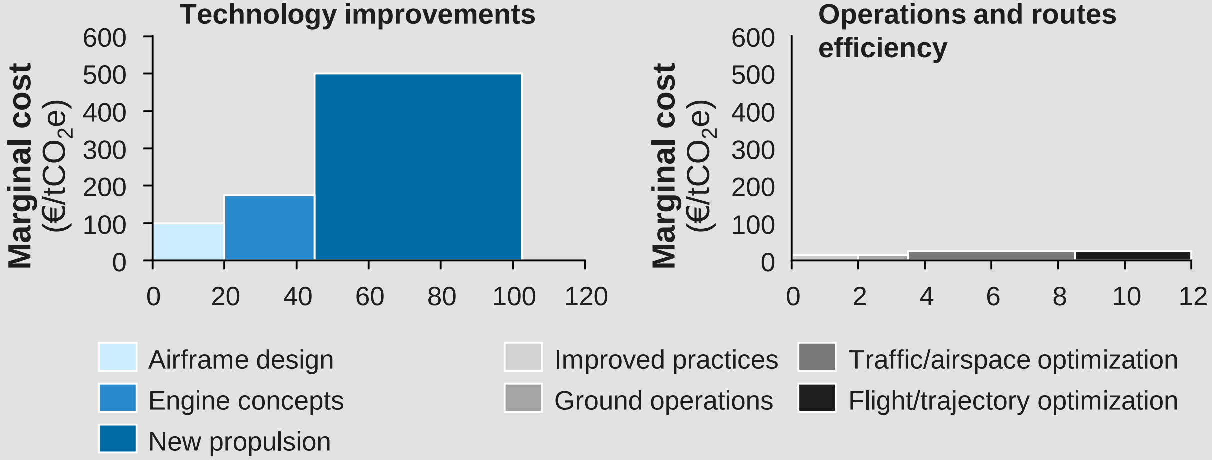
(€/tCO_2e - % emissions reduction per MJ relative to jet fuel, 2025)



- **SAF** (and new propulsion systems) **are required to displace traditional jet fuel and further reduce the carbon footprint of aviation,** realizing larger emissions reduction but entailing greater abatement cost (235-480 €/tCO_2e for BtL and ~500 €/tCO_2e for PtL, respectively).
- Most commercially viable **SAF, HEFA,** complements quicker-win efficiency gains. **On the longer-term, emerging synthetic SAF, PtL,** will be required to substitute traditional aviation fuel considering projected traffic growth.
- **Since low-carbon fuel are not 100% carbon neutral, compensation measures (e.g., BECCS, nature-based solutions) will be needed to achieve net-zero aviation.**

Energy efficiency gain solutions

(€/tCO_2e - % fuel consumption reduction, 2025)



- **Operational and route efficiency measures are the cheapest and quickest wins,** offering up to ~10% abatement at very low (or even negative) cost (maximum ~25 €/tCO_2e).
- **Simpler technology improvements** (airframe design and engine concepts) **can cut emissions by a further ~40%** at a moderate cost of 100-175 €/tCO_2e. While **new propulsion systems** provides higher potential but at a higher cost.
- **Energy efficiency solution** (operational efficiency and basic technology improvements) **alone cannot achieve net zero aviation; they could** cumulatively achieve up to about ~50% of CO_2 emissions abatement.

The percentage reduction in emissions per megajoule (MJ) relative to jet fuel and the percentage reduction in fuel consumption are not cumulative, since not all solutions will be applied simultaneously.
Sources: Cerulogy, 2024, Vertical Take-Off?; ICAO, 2025, SAF rules of thumb; RMI, 2024, Fueling Up Sustainable Aviation; Seymour et. Al, 2023, Future cost of power-to-liquid sustainable aviation fuels; Kearney Energy Transition Institute analysis

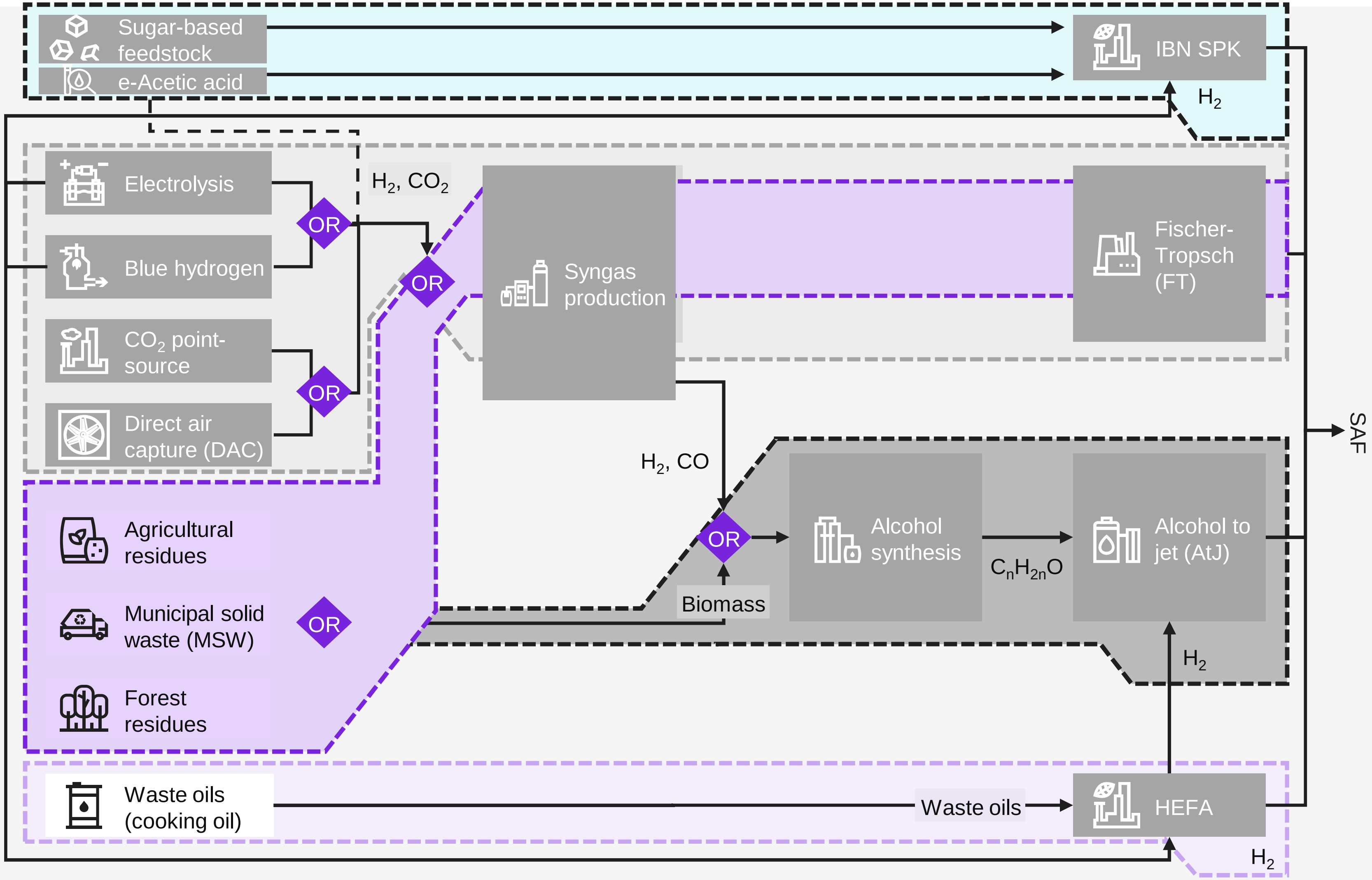
2. Sustainable aviation fuels

Sustainable aviation fuel is a key solution for aviation decarbonization; however, its widespread adoption may be hindered by feedstock availability and high production costs

Climate impact mitigation	**SAF effectively reduces emissions of CO_2, soot, and contrails,** although impact on NO_x and H_2O is minimal; no emitted species are completely removed relative to business-as-usual.
Production pathways	Of the five key SAF production pathways today, only HEFA is currently produced at scale. These five pathways have the potential to **reduce CO_2 emissions by 25–99%.**
Eligible feedstock	**SAF can be produced from four biomass generations**, each varying in origin, value chain maturity, production pathway suitability, and competing uses, such as food production.
Production capacity	Despite multiple announced projects, the estimated production capacity of **~19 million tons per year by 2030** is expected to fall short of meeting SAF demand.
SAF application	**SAF** is aromatic-free, making it incompatible with existing aircraft engines and fuel infrastructure in its pure form; therefore, it is currently **blended with conventional jet fuel at ratios of up to 50%.**
SAF cost	**Costs are up to 15x higher than conventional jet fuel** where HEFA and PtL are currently the most and least economically competitive; by 2050, PtL is expected to experience greatest cost decline.
Technology selection	Selecting the right SAF technology depends on **technology maturity and cost**, which are influenced by regional factors like **energy prices and feedstock availability.**

Source: Kearney Energy Transition Institute analysis

Among the various certified sustainable aviation fuels, the HEFA route is currently the primary commercial pathway



These five synthesis routes are commonly regarded as **the most promising**

Bio- and e-SAF

1. IBN SPK (isobutene synthetic paraffinic kerosene)

The IBN SPK process involves **the fermentation of sugar-based or acetic acid feedstocks into isobutene,** subsequently converted into alkanes.

Synthetic SAF

2. PtL (power to liquids, e-fuel or synthetic fuel):

The **PtL** jet fuel production process also employs **FT synthesis**, but **the syngas components are green hydrogen and captured carbon.**

3. G-FT (gasification Fischer–Tropsch):

The **G-FT process takes any carbon-**containing material and breaks it into **individual building blocks in a gas form** (synthesis gas). **FT synthesis** then combines these building blocks into **SAF and other fuels**.

4. AtJ (Alcohol-to-jet)[1]:

The AtJ technology converts alcohols into SAF by removing the oxygen and linking the molecules together to get the desired carbon chain length.

Bio-SAF

5. HEFA (hydroprocessed esters and fatty acids):

The HEFA process involves the **hydrogenation of vegetable oils and/or animal lipid feedstocks. HEFA** is commercially available today and powered **over 95% of all SAF** flights to date.

- Isobutene synthetic paraffinic kerosene (IBN SPK)
- Power to liquid (PtL)
- Alcohol-to-jet (AtJ)
- Biomass gasification (G-FT)
- Hydroprocessed esters and fatty acids (HEFA)

[1] Currently, only technologies that convert ethanol (C_2) into SAF are either under development or in the scale-up phase. The alternative pathway using butanol (C4) has been discontinued.

Sources: Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences; Kearney and Airports of Tomorrow, 2024, Scaling Up Sustainable Aviation Fuel Supply; Kearney Energy Transition Institute analysis

Adoption of SAF effectively reduces CO_2, soot, and contrails, although minimal change to NO_x and H_2O; no emitted species are completely removed relative to business-as-usual

Solution	Emitted species[1]					GHG reduction	Commentary
	CO_2	*Contrail*	*NO_x*	*Soot*	*H_2O*		
SAF blend	Decrease	Decrease	~	Decrease	~	**25-105 gCO_2e/MJ**	Decreased CO_2 emissions depending on the blend ratio and sustainability of sourcing/production; reduced soot formation in turn reduces contrail formation; minimal change in NO_x and H_2O.

[1] Change in emissions volume per molecule relative to business-as-usual aviation; Source: Kearney Energy Transition Institute analysis

Legend: Complete removal · Decrease · ~ No impact · Increase

A variety of raw materials are available for SAF production, each with different geographic origins and value chain maturities, and suitable for specific production pathways

Non-exhaustive; illustrative

● High ○ low

Feedstock	Generation	Origin	Value chain maturity	Technology served
Sugarcane, sugar beet, corn (edible)	1st	Brazil, Canada, China, India, United States, Vietnam	◑	AtJ / IBN SPK
Vegetable oils: soybean, palm oil, camelina, rapeseed, sunflower (edible)	1st	Brazil, Canada, China, Indonesia, Malaysia, United States	◕	HEFA
Vegetable oils: jatropha, macaúba, carinata, pennycress, castor (non-edible)	2nd	Argentina, Brazil, Canada, China, EU (selective), India, United States, Vietnam, global	◔	HEFA
Waste vegetable oils, animal oils and fats	2nd	Australia, Brazil, China, EU, Malaysia, South Korea, United States, global	◔	HEFA
Municipal solid waste	2nd	Large cities with mature waste management infrastructures	◑	G-FT / AtJ
Energy crops, forestry and agricultural residues: switchgrass, miscanthus, wood chips, sawdust, straws, bagasse	2nd	Brazil, EU, India, Canada, global	◑	G-FT / AtJ / IBN SPK
Electricity, CO_2 and H_2O	3rd	Theoretically unlimited feedstock (but potential supply constraints of green electricity, H_2, and CO_2)	◔	PtL / IBN SPK
Algae and aquatic plants	3rd	Nascent market	◑	HEFA
Genetically modified crops	4th	Nascent market	○	HEFA / AtJ / IBN SPK

Sources: Global Bioenergies, 2023, A growing player of the environmental transition; Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences; Mission Possible Partnership, 2022, Making Net-Zero Aviation Possible: An industry-backed, 1.5°C-aligned transition strategy; Kearney Energy Transition Institute analysis

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Each SAF production pathway exhibits specific process characteristics, opportunities, and technology maturities

● Mature ◕ Commercial deployment ◑ Commercial pilot ◔ In development (no FID)

	HEFA[1]	G-FT[2]	AtJ[3]	PtL[4]	IBN SPK[5]
Detailed process description	– Removal of oxygen fraction of the feedstock by **hydrotreatment** – Split of feedstock in different hydrocarbons (mainly diesel and kerosene) through **hydrocracking**	– **Gasification** of the solid biomass at elevated temperatures to obtain "syngas" – **Purification** of the gas and synthesis of kerosene and other hydrocarbons in a **catalytic reaction** known as the Fischer-Tropsch process	– **Dehydration of alcohol feedstock** (ethanol, butanol) to produce **olefins** – **Oligomerization** of olefins to **form longer hydrocarbon chains** – **Hydroprocessing and isomerization** to refine hydrocarbons into SAF	– Combination of **hydrogen** and **captured CO_2** to produce **syngas** – **Conversion of syngas into liquid hydrocarbons**, including kerosene, through the **Fischer-Tropsch synthesis** – **Hydroprocessing and fractionation** to refine the hydrocarbons into **SAF**	– **A bacterial fermentation** process converts the **sugar-based and acetic acid feedstocks** into **isobutene (IBN) gas** – The **IBN** undergoes **catalytic processing to** produce **synthetic paraffinic kerosene** (IBN-SPK)
Opportunity description	Already implemented at large scale but **not scalable due to feedstock availability** and logistical constraints	**Financing of the first large scale** plant projects ongoing, however significant **techno-economical uncertainty**	**Financing of the first large scale** plant projects ongoing, however significant **techno-economical uncertainty**	**First small-scale pilot plant starting**, primarily where **cheap high-volume electricity** is available	**First large-scale plant** in **operation toward 2030,** however significant **techno-economical uncertainty**
Technology maturity	2025 deployment ●	2030 deployment ◔	2030 deployment ◑	2035 deployment ◔	2030 deployment ◑
GHG reduction[6] (%)	55-65 (50-60 gCO_2eq/MJ)	80-90 (70-80 gCO_2eq/MJ)	55-65 (50-60 gCO_2eq/MJ)	90-100 (80-90 gCO_2e/MJ)	55-65 (50-60 gCO_2eq/MJ)

[1] Hydroprocessed esters and fatty acids; [2] Gasification Fischer–Tropsch; [3] Alcohol-to-Jet (LanzaJet plant); [4] Power to Liquid; [5] Isobutene synthetic paraffinic kerosene; [6] Relative to current state for fuel burn.
Sources: Global Bioenergies, 2023, A growing player of the environmental transition; Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences; ADEME, 2022, Elaboration de scenarios de transition écologique du secteur aérien; ICAO, 2024, CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels; Kearney Energy Transition Institute analysis

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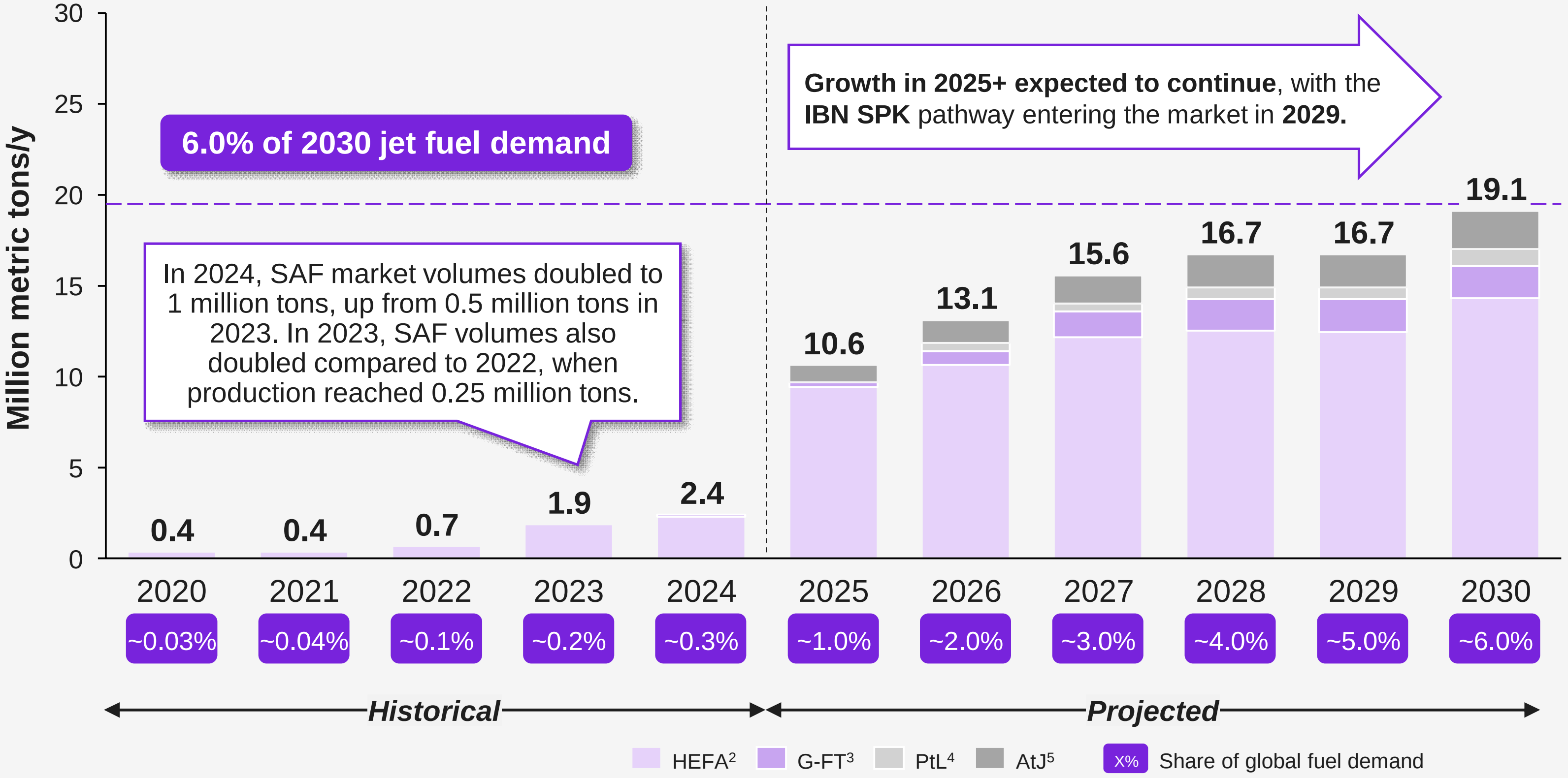
Announced SAF production facilities are mostly based on the bio-based HEFA process, which is expected to represent 6% of global market share by 2030

Cumulative global SAF nameplate production capacity by technology[1]



[1] SAF production yields are flexible and can vary greatly, from a default of around 15% to 50% or more of nameplate capacity;
[2] Hydroprocessed esters and fatty acids; [3] Gasification Fischer–Tropsch; [4] Power to liquid; [5] Alcohol-to-jet.
Sources: BNEF, 2024, United Airlines Is Betting Big on a Pricey Green Aviation Fuel; Global Bioenergies, 2023, A growing player of the environmental transition; Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences; Kearney Energy Transition Institute analysis

Key insights

- **Most** current **activities** still **focus** on **HEFA-based processes, but the availability** of sustainable, economic **feedstock** is increasingly affecting **project viability.**
- **AtJ and FT-based** processes using **bio / agricultural wastes and residue** are **gaining** traction toward **2025–2026.**
- **PtL-based production is expected** to expand, though its development heavily depends on green hydrogen and CO_2 capture technologies.
- **New projects** are emerging in diverse regions, such as **Brazil**, where large-scale **AtJ** plants are under development.
- **The growing geographic and technological diversity** of planned capacity suggests **developers are strategically optimizing project placement and timing** rather than moving away from renewable fuels.

Singapore and the United States account for 60% of the current global SAF production

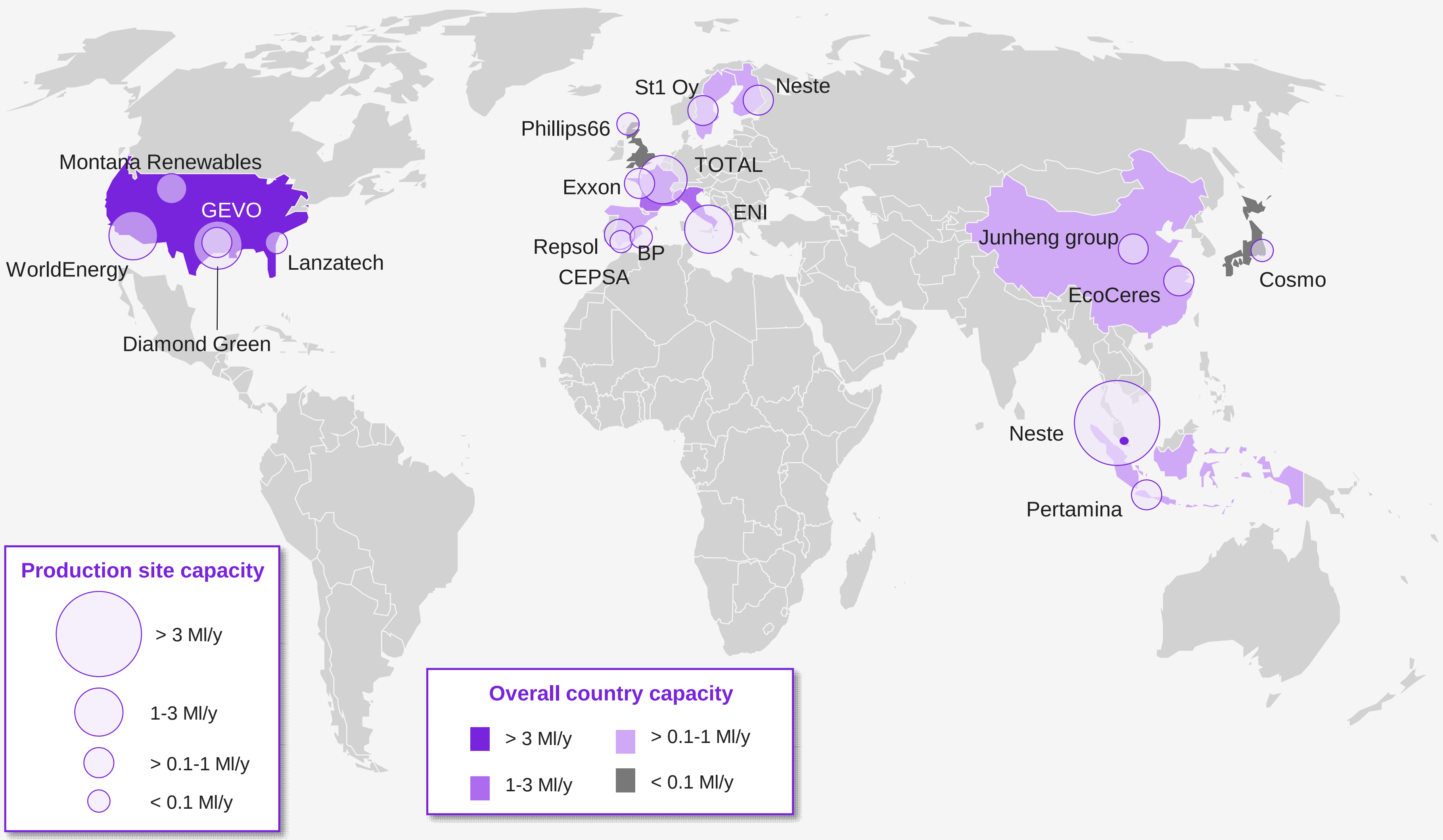
Non-exhaustive

Neste Oil is the largest SAF producer with two facilities, followed by Diamond Green and WorldEnergy, with only one large facility each. ENI and TotalEnergies trail closely behind with three and four smaller plants respectively.

2.3 SAF production

Global SAF production

Currently producing, by country and company, million liters (Ml), 2025



Sources: ICAO, 2025, ICA tracker of SAF facilities; Kearney Energy Transition Institute analysis

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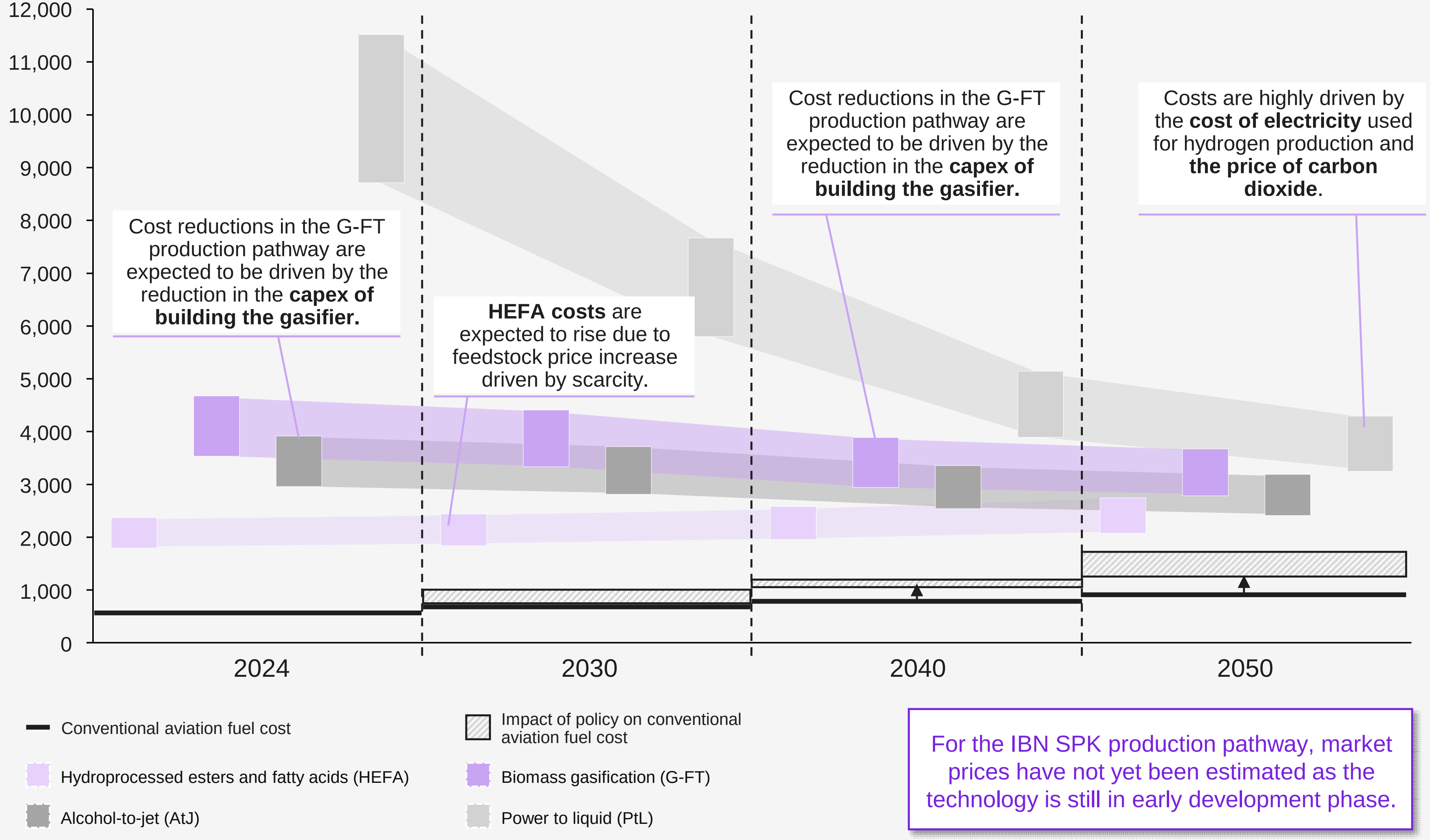
SAF needs financial backing to achieve cost competitiveness with conventional jet fuel

HEFA-produced SAF will continue to be the most cost-effective option until other production pathways achieve significant technical and commercial maturity and scalability.

2.4 SAF costs

Cost overview of various SAF types and conventional aviation fuel with carbon pricing

EUR/t, 2024–2050



For the IBN SPK production pathway, market prices have not yet been estimated as the technology is still in early development phase.

Sources: EASA, 2025, 2024 Aviation Fuels Reference Prices for ReFuelEU Aviation; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

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Today, SAF is used in blends up to 50% as aromatics in traditional jet fuel have a sealing role on aircraft fuel systems

Property	Description / relevance	Jet A-1
Specific energy (MJ/kg)	Enables fuel efficiency by lowering takeoff weight, critical for mass-limited missions	>42.8
Density @15°C (kg/m^3)	Used in calculating fuel tank volumes	775 – 840
Flash point (°C)	Safe handling	>38
Freeze point (°C)	Inhibits freezing of the fuel in flight at an altitude	<-47
Sulfur content by mass (%)	Characterizes SOx emissions and limits engine and environmental impact	<0.3
Aromatics by volume (%)	Maintains seal integrity and ensures compatibility with existing aircraft engines and fuel systems	8 – 25

ASTM International sets aviation fuel standards, requiring SAF to meet ASTM D7566 for non-petroleum fuels.[1] **A critical parameter is aromatic content**: today's commercially available **SAF is aromatic-free**, making it incompatible in its pure form with aircraft and the current fuel infrastructure.

More specifically:
- **Conventional jet fuels contain 8–25% aromatics by volume**, essential for maintaining elastomeric seal integrity in aircraft fuel systems. **SAFs typically have no aromatic content, which can lead to seal shrinkage and potential fuel leaks.**
- Aromatics have a higher density but lower energy content than other hydrocarbons. **The lower aromatic content in SAFs can result in a lower overall energy density**, potentially affecting aircraft range and performance.
- **The reduced aromatic content in SAFs can lead to lower lubricity**, affecting the performance and longevity of fuel system components.
- **The molecular structure of SAFs**, often rich in n- and iso-alkanes, **can influence the fuel's freezing point**, requiring compliance with aviation standards for safe high-altitude operations.

Therefore, **pure SAF needs to be blended with conventional jet fuel** to ensure compatibility with aircraft and existing infrastructure. However, fuel standard committees are working to facilitate the use of 100% SAF, aiming for approval by 2030.

	HEFA[2]	G-FT[3]	AtJ[4]	PtL[5]	IBN SPK[6]
Max. blending ratio to date (%)	<50	<50	<50	<50	<50

[1] ASTM is a standards organization that develops and publishes voluntary consensus technical international standards; [2] Hydroprocessed esters and fatty acids; [3] Gasification Fischer–Tropsch; [4] Alcohol-to-jet; [5] Power to liquid; 6 Isobutene synthetic paraffinic kerosene.
Sources: Global Bioenergies, 2023, A growing player of the environmental transition; Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences; CE Delft, 2022, Potential for reducing aviation non-CO_2 emission through cleaner jet fuel; Airports Council Internation and Aerospace Technology Institute, 2022, Integration of Sustainable Aviation Fuels into the air transport system; U.S. DOE, 2020, Sustainable Aviation Fuels: Review of Technical Pathways; Kearney Energy Transition Institute analysis

Selecting the right technology depends on scalability and cost, influenced by regional factors like energy prices and feedstock availability

2.6 SAF advantages and disadvantages

Higher / Lower

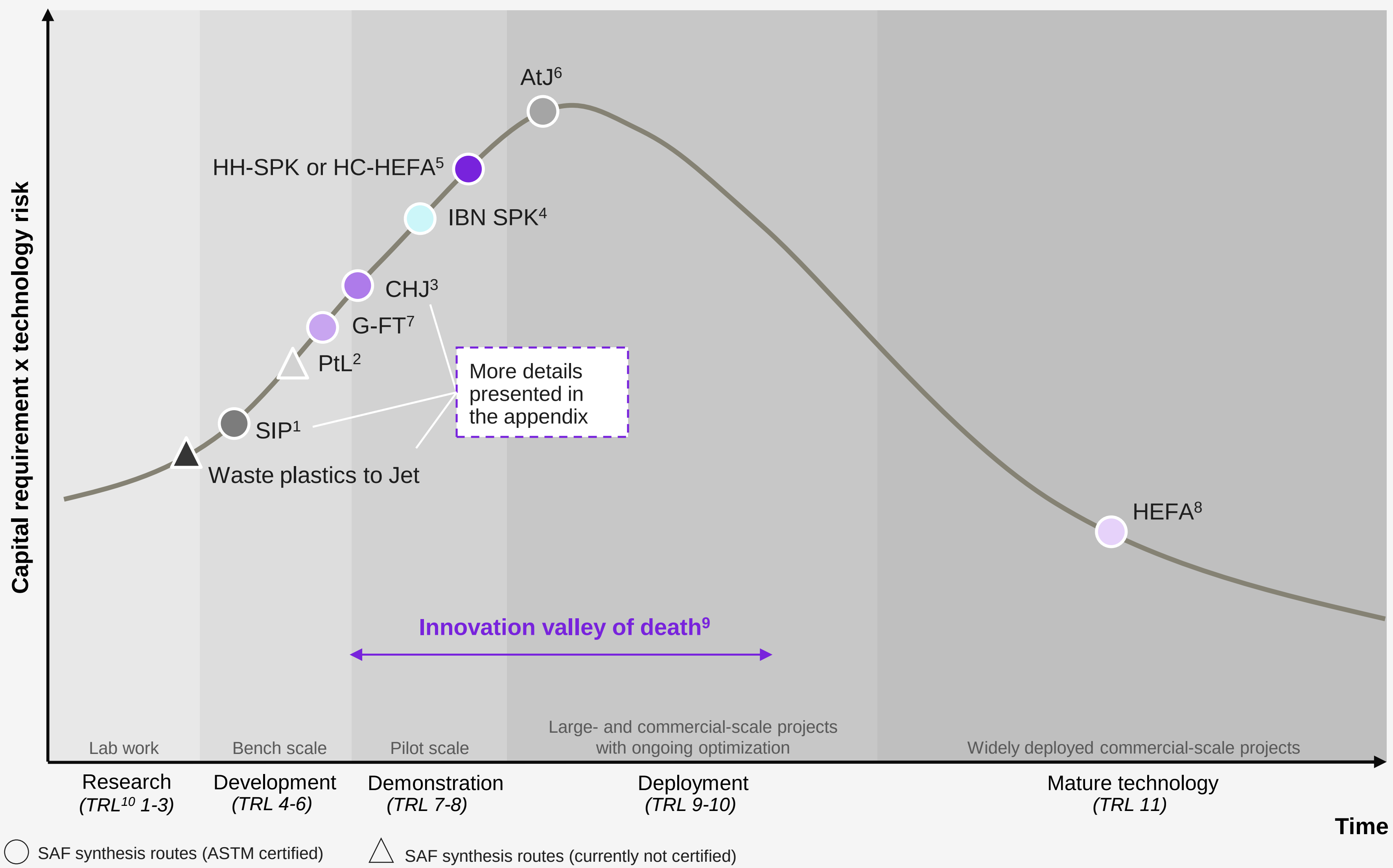
	Advantages	Disadvantages	Cost reduction potential
HEFA	– Increased **cost efficiency** – **Mature technology** with the largest production plants announced – **Feedstock cost can be reduced** via regional feedstock collection and processing	– Restricted waste oil volume, various proportions of **bio-gasoline and bio-diesel produced** – **Low flexibility / low selectivity to SAF** (can only use oils as feedstock) – Increasing feedstock scarcity will likely lead to increased feedstock cost, making **cost improvements hard to realize**	
G-FT	– Versatile technology that can use **various types of feedstock** and be inserted in **different types of processes** (e.g., PtL) – Proven technology at smaller scale with some **cost-down potentials through scaling** – **MSW is available at low cost** in urban areas and offers other additional benefits (e.g., reduced landfill)[1]	– **High opex and capex** costs for gasification processes – Feedstock cost largely depends on collection radius and location with **minimal cost-down potential** – **Feedstock might get more expensive over time** as recycling improves and biowaste content decreases	
AtJ	– **Feedstock flexibility** (wood, corn, sugar cane, waste) – High technology **maturity as individual processes** – High blending levels – Local processing of biomass to ethanol and transport to **larger production hubs enables cost savings**	– Mature individual AtJ **processes weren't tested together as one full process** on a large-scale basis – Various proportions of **bio-gasoline and bio-diesel produced**, **low selectivity to SAF** – Processing technologies already used industrially–large **long-term cost improvements only via new approaches**	
PtL	– **Not dependent on feedstock availability** – New technologies may **offer significant savings in 2030+** – Build-up of **H_2 and direct air capture (DAC) installations is a no regret move** enabling decarbonization of other sectors as well	– **Most expensive method** – Depends on water and electricity supplies – H_2 and CO_2 production largely **depends on energy costs** that change significantly by region	
IBN SPK	– **ASTM-certified for blending up to 50%** with conventional jet fuel, matching HEFA's performance without requiring engine modifications; high selectivity to SAF (>97%); no light or heavy cuts – **Can use non-food agricultural residues** (e.g., wheat straw, wood chips), avoiding **competition with food crops**	– Despite ASTM certification, **IBN-SPK does not have any commercial-scale SAF plants operational yet** – **Currently expensive method**	

[1] MSW is municipal solid waste.
Sources: Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Most SAF synthesis technologies are at pilot or commercial deployment scale, with only HEFA widely deployed currently

Non-exhaustive

Maturity curve for SAF synthesis technologies



[1] Synthesized iso-paraffin; [2] Power to liquid; [3] Catalytic hydrothermolysis jet fuel; [4] Isobutene synthetic paraffinic kerosene; [5] Hydroprocessed hydrocarbons; [6] Alcohol-to-jet; [7] Gasification Fischer–Tropsch; [8] Hydroprocessed esters and fatty acids; [9] Refers to a critical phase in new technology development where the initial momentum and early-stage funding have subsided, but the technology has not yet reached commercialization; [10] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide

Sources: Kearney Energy Transition Institute analysis

2.7 Maturity curve

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3. Aviation technology solutions

Technology to date has focused on minor adjustments to airframe and engine design; new propulsion systems offer a pathway for greater GHG reduction

3.0 Chapter summary

Broad innovation	**Improvements in aircraft design have focused on the airframe and engine concepts, both of which continue to develop,** complemented by new propulsion systems that offer greater potential for reducing GHG emissions.
Airframe design	**To date, airframe design improvements have been concentrated around winglets and lightweight composites,** achieving single-digit fuel efficiency improvements**.**
Engine concepts	**The next generation of engines aims to improve efficiency via ultra-high bypass ratios;** larger companies, such as Rolls-Royce and CFM, lead the way (UltraFan turbofan and RISE open-rotor architecture, respectively).
Electric propulsion	**Battery electric propulsion offers potential to decarbonize shorter haul and lower payload aviation;** however, larger aircraft demand higher energy densities and power-to-weight ratios. Hydrogen electric propulsion faces analogous challenges, primarily concerning the volume and weight of onboard fuel storage and fuel cell systems.
Hydrogen propulsion	**As with hydrogen electric propulsion, the size and certifiability of storage tanks** hinder hydrogen combustion aviation, necessitating re-evaluation of aircraft design and limiting hydrogen-fueled aviation to short- to medium-range flights.

Sources: Kearney Energy Transition Institute analysis

A range of technologies are being developed to deliver gains in energy efficiency

Non-exhaustive; illustrative

Existing improvements are measures/technologies which have been already deployed and are mature whereas **next-gen improvements** are still in conceptual or demonstration phase.

	A Airframe design	B Engine concepts	C New propulsion systems
Description	Developments in aircraft structure to improve aerodynamics and lift, reduce weight, and increase efficiency	Developments in combustion engine architecture	Using an alternative energy carrier in place of jet fuel for aircraft propulsion
Existing improvements	– Composites – 3D printing – Lightweight cabin interiors – Winglets – Adaptive flaps – Riblets	– Ultra high bypass ratio – High pressure ratio core – Modern turboprop – Geared turbofan	None
Next-gen improvements	– Double bubble fuselage – Laminar flow control – Next generation wings	– Boundary layer ingestion – Open rotor – UltraFan	– Hybrid – Electric – Hydrogen

Sources: ATAG, 2021, Waypoint 2050 (2nd edition); Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

Electric propulsion is the only technology solution that almost completely avoids emissions due to fuel burn; others achieve notable reductions relative to business-as-usual

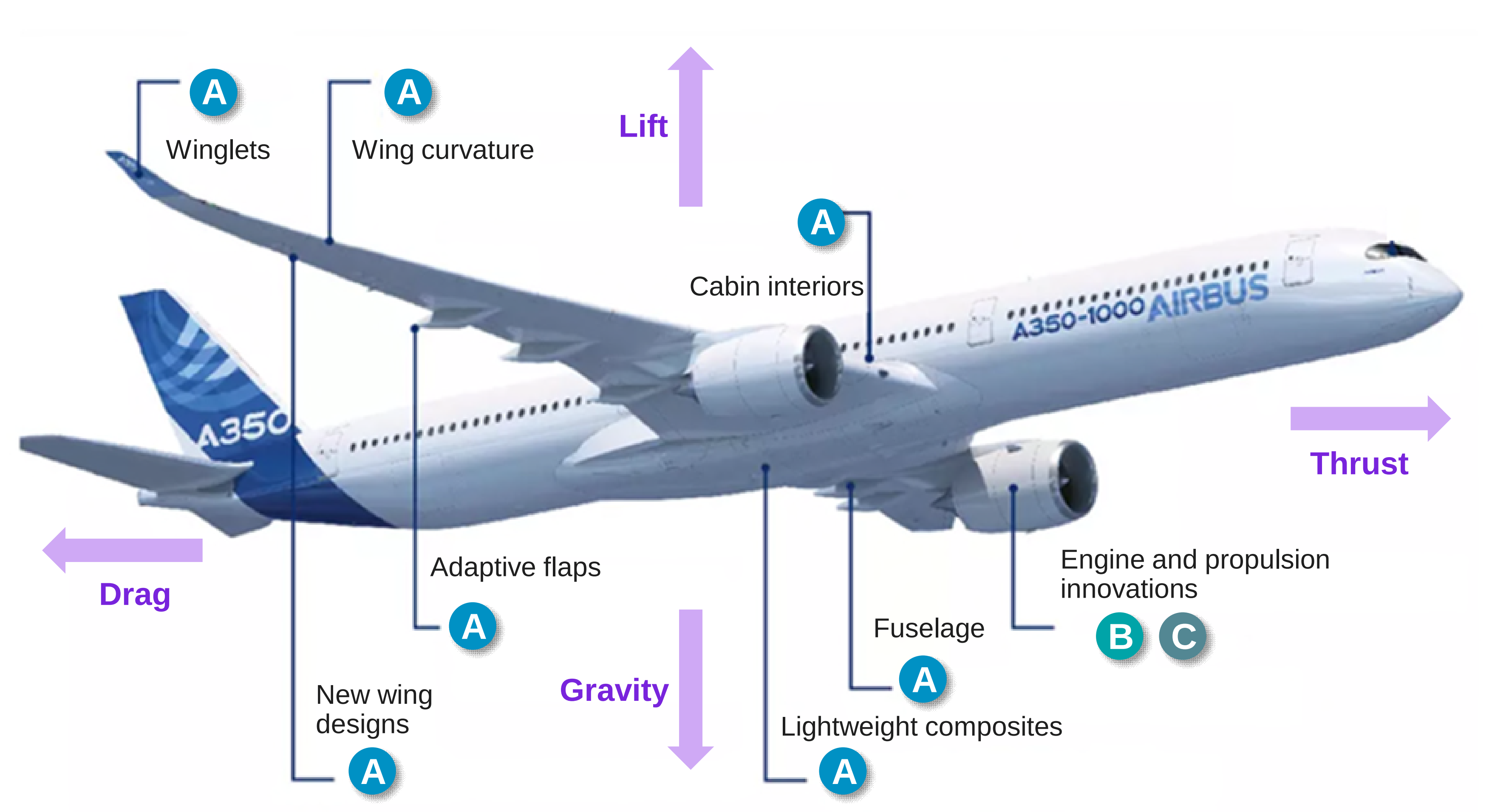
[1] Change in emissions volume per molecule relative to business-as-usual aviation; [2] Considering jet fuel carbon intensity of 89 gCO_2e/MJ and fuel efficiency improvement range expected per solution; [3] Assuming lowest carbon-intensive power sources;
Source: Kearney Energy Transition Institute analysis

Solution	Emitted species[1]					GHG reduction[2] Fuel efficiency improvement	Commentary
	CO_2	Contrail	NO_x	Soot	H_2O		
Airframe design	↓	↓	↓	↓	↓	**0.9-4.5 gCO_2e/MJ** 1-5%	Improved aerodynamics reduce fuel burn for decreased CO_2, NO_x, soot, and H_2O (hence fewer contrails)
Engine concepts	↓	↓	↓	↓	↓	**2.7-4.5 gCO_2e/MJ** 3-5%	More efficient designs reduce fuel burn (hence lesser CO_2 and non-CO_2 emissions), but a trade-off exists between CO_2 and NO_x due to higher combustion temperatures.
Electric propulsion	↓↓	↓↓	↓↓	↓↓	↓↓	**80-85 gCO_2e/MJ** 90-95%[3]	Zero emissions during flight; full impact realized by ensuring clean electricity generation upstream
H_2 propulsion	↓↓	*Ongoing research*	↓	↓	↑	**62-71 gCO_2e/MJ** 70-80%	No CO_2 or soot; no NO_x in fuel cell but present during combustion; increased H_2O can form contrails, i.e., potentially larger ice crystals, impact of which is under research
Hybrid propulsion	↓	↓	↓	↓	~	**22-31 gCO_2e/MJ** 25-35%	Reduced fuel burn for decreased CO_2, NO_x, soot, and H_2O (hence fewer contrails), although H_2O rises if H_2 used in hybrid setup

Legend: ↓↓ Complete removal ↓ Decrease ~ Uncertain impact ↑ Increase

The primary objectives of aircraft design improvements are to minimize drag, enhance lift, and increase fuel efficiency

Visualization of airplane design improvements



A Airframe design B Engine concepts C New propulsion systems

Sources: Airbus, 2018, Approche pour une aviation durable; Kearney Energy Transition Institute analysis

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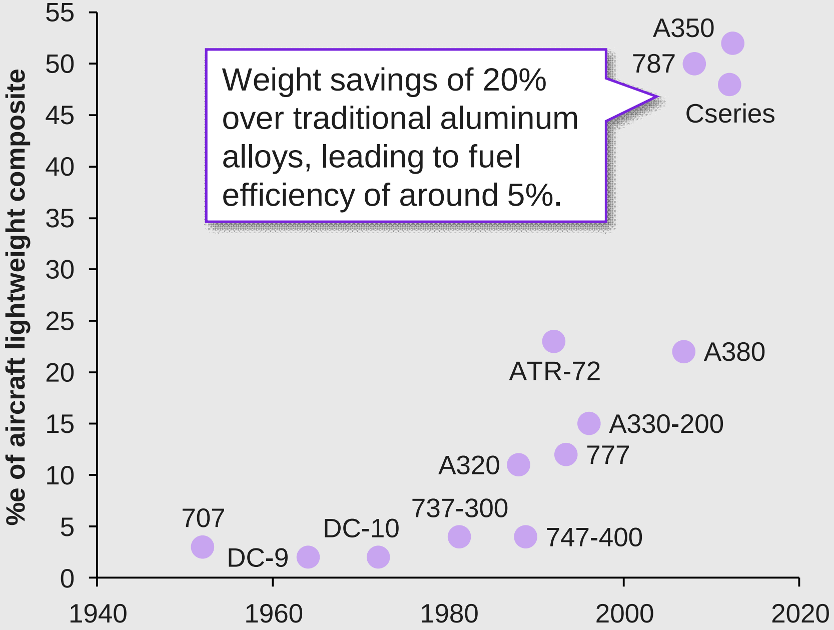
3.2 Airplane design improvements

Improvements have been achieved in the past by modifying wing designs and using composites

Lightweight composites adoption in aircraft design

Share of composite in aircraft (%), 1940–2020

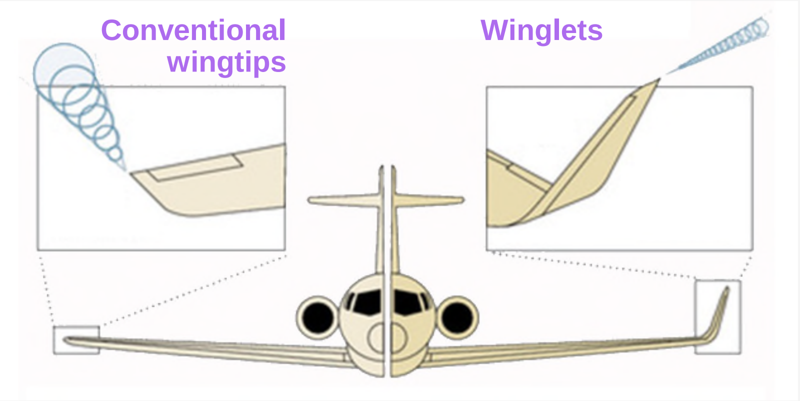


Lightweight composites for wings and fuselage

- Long-term trend is of increasing the use of composite materials that are lighter than the metals.
- Aircraft made from composite materials, however, **take longer to be built and offer lower recyclability** compared to metallic ones. Hence, enabling high-rate composite parts production is important to shorten manufacturing time.
- **Wing of Tomorrow** project led by Airbus is an example of a future composite wing demonstrator.

Sources: ATAG, 2021, Waypoint 2050 (2nd edition); Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

Winglets



- Wake vortices are generated at the wingtips due to pressure difference between lower and upper surfaces of the wing. Air from the higher-pressure region beneath the wing flows around the tip toward the lower-pressure region above, producing counter-rotating swirling airflows that trail beneath the aircraft.
- Wingtip devices are designed to mitigate the strength and size of wake vortices by reducing pressure differential at the wing tips, reducing lift-induced drag without significant increase in horizontal span.
- Modifying wingtips/adding winglets tilted upward in new aircraft or in retrofits delivers **3–5% fuel burn reduction** depending on flight length and aircraft.
- Improved models are continually being developed:
  - Airbus introduced **"sharklets"** in 2013 to A320 series and its new carbon fiber reinforced plastic-based winglets offer **about 10–20%** weight reductions.
  - Boeing's 737 MAX AT Winglet is a unique design incorporating features from blended, split-scimitar and raked winglets.

A B C

3.3 Airframe design

New airframe designs can bring emissions reductions beyond an evolution of the “tube and wing” standard configuration

Next-generation improvements

Indicative

Canard wing

Already used in military airplanes, canard-wing planes—with the main wing being set further back behind small forewings — create low drag.

Expected fuel efficiency of these new designs is around **25–30%.**

Blended wing

Wide airfoil-shaped bodies and efficient high-lift wings enable significant lift-to-drag ratio improvements compared with conventional aircraft. High fuel savings are generated as the entire plane is designed to generate lift.

Double bubble fuselage

Conceptualized by NASA, the wide flattened fuselage body generates additional lift, allowing the wings to be smaller and lighter, resulting in a significant reduction in fuel burn. Expected fuel efficiency of **20%.**

Strut-braced wing

Leverages an external support strut to enable a longer, thinner wing (with a far higher aspect ratio) without a significant weight penalty, thus reducing drag and fuel consumption.

Box wing

Improves aerodynamic efficiency by reducing induced drag via a closed-wing configuration that minimizes wingtip vortices and optimizes lift distribution.

Laminar flow control

Optimizing the air flow over the aircraft surface through suitable shaping of aircraft surface (natural) or boundary-layer suction (hybrid). Expected fuel efficiency of **4.6%.**

Sources: ATAG, 2021, Waypoint 2050 (2nd edition); Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

The new generation of engines aims to improve propulsive efficiency by increasing fan size and bypass ratio

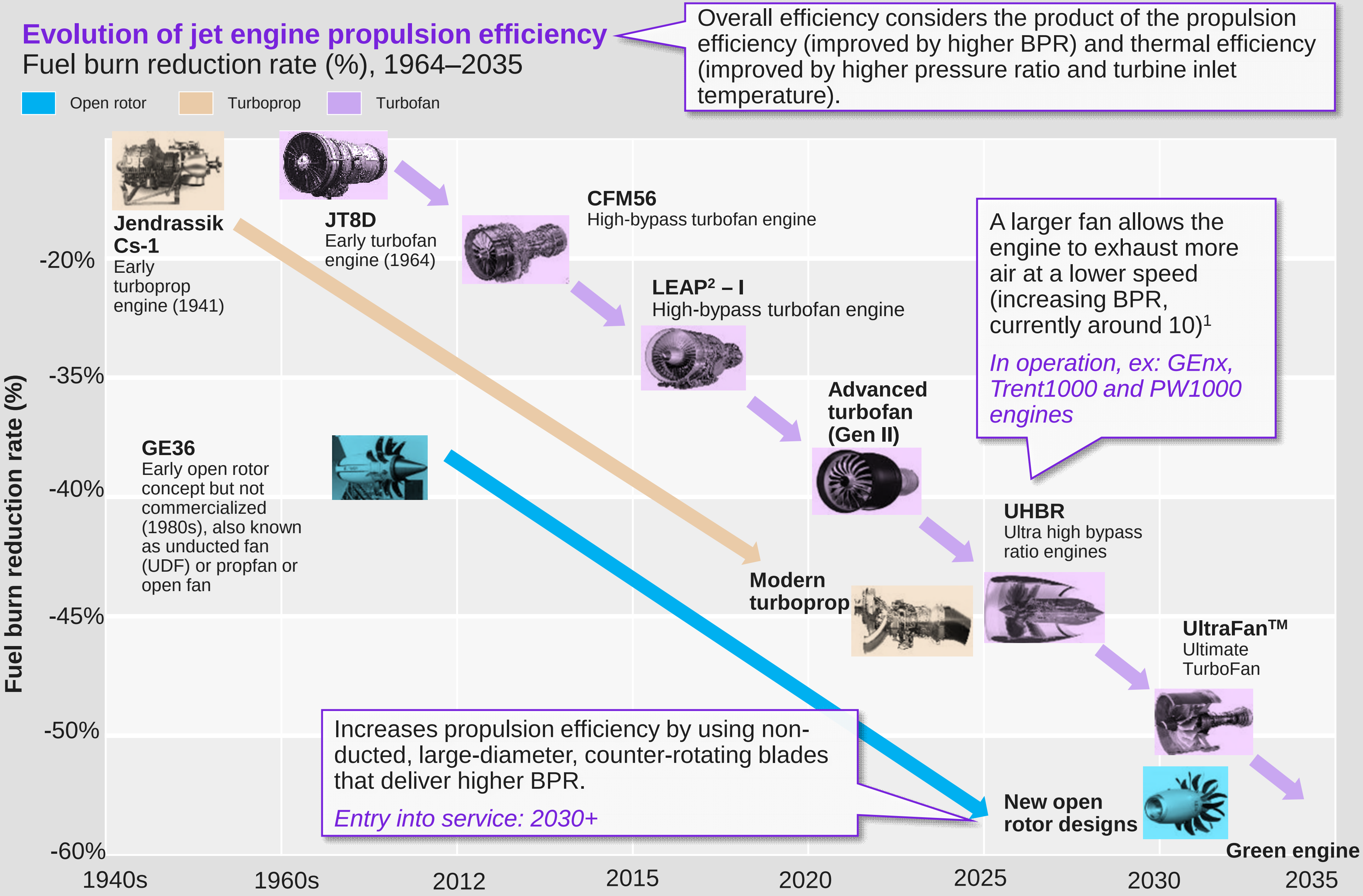
Non-exhaustive

Turboprop engines appeared in the 1940s before the arrival of turbofan engines in the 1960s. Turboprop engines are mainly used for **low-speed and short-haul routes**, especially among regional aircraft and cargo planes, due to **25–40% lower fuel consumption** compared to turbofan engines.

A B C

3.4 Engine concepts

Evolution of jet engine propulsion efficiency
Fuel burn reduction rate (%), 1964–2035



[1] The bypass ratio (BPR) of a turbofan engine is the ratio between the mass flow rate of the bypass stream to the mass flow rate entering the core. A 10:1 bypass ratio, for example, means that 10 kg of air passes through the bypass duct for every 1 kg of air passing through the core.
[2] LEAP is leading edge aviation propulsion.
Sources: Airbus, 2018, Approche pour une aviation durable; Kearney Energy Transition Institute analysis

Significant advances in engine design and installation are under way

Non-exhaustive

A B C

3.4 Engine concepts

Existing improvements

Technology/description

Geared turbofan engines

- Inserts a gearbox between fan and compressor which each rotate at most efficient speed.
- **Status:** In operation on A320neo, A220, Embraer E-Jets (Pratt & Whitney GTF™ engine family - PW1500G, PW1100G-JM, PW1900G)

High pressure ratio core engines

- Engines that operate at higher pressure, reducing engine weight and improving thermal efficiency.
- **Status:** In operation on Boeing 777X (GE9X engine supplied by GE Aviation)

Next-generation improvements

UltraFan™

UltraFan™ is the world's largest aero engine technology demonstrator by Rolls Royce:

- A new turbofan engine core architecture with carbon/titanium fan blades (140 inches in diameter) and a composite casing
- **25%** more fuel efficient than the original Trent 700 and **10%** more efficient than Trent XWB
- **40%** improvement in NO_x, **35%** lower noise

Open rotor

Although the open rotor concept is several decades old, its development was initially hindered by high noise levels, which has since been resolved. The new generation of advanced open fan architecture will be capable of flying at the same speed as current single-aisle aircraft (up to Mach 0.8).

Status: Safran, through CFM JV with GE, is running an open rotor demonstration program as part of EU research program CleanSky2. The RISE (Revolutionary Innovation for Sustainable Engines) open fan architecture proposes a **BPR of 70+** and **reducing fuel consumption and CO_2 emissions by 20%.**[1]

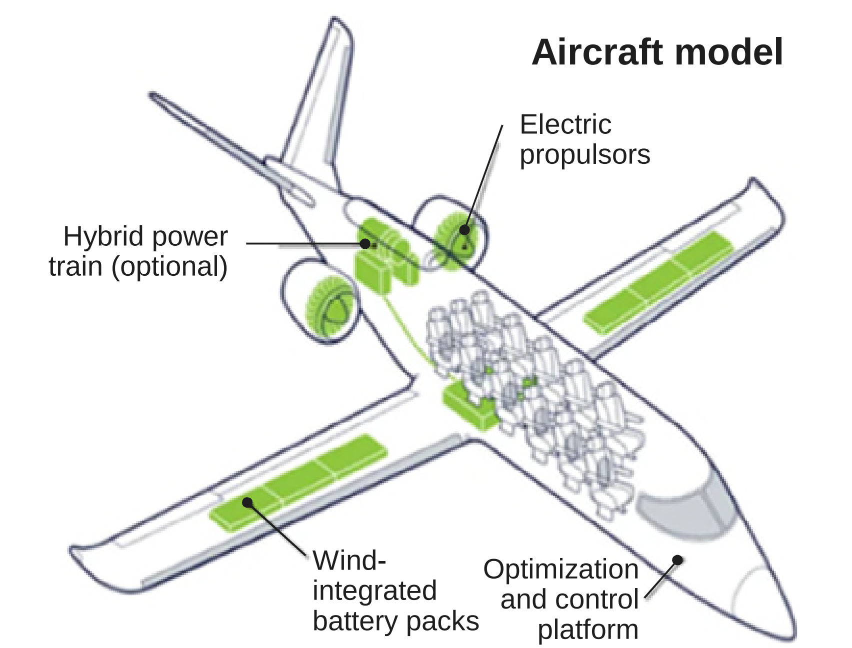
Boundary layer ingestion

Airplane's engines are located near the rear of the aircraft so that air flowing over the aircraft body becomes part of the mix of air going into the engine and is then accelerated out the back. NASA's STARC-ABL project guides toward potential energy savings of **11–15%.**[2]

[1] Compared to the most efficient commercial aircraft engines in service today
[2] The results quantify the power savings from boundary layer ingestion compared to a conventional propulsion system in terms of the power saving coefficient.
Sources: ATAG, 2021, Waypoint 2050 (2nd edition); CFM, 2021, CFM RISE PROGRAM; Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

Battery electric aviation can decarbonize short-haul and low payload urban air traffic, but larger aircraft require higher energy densities and power-to-weight ratios

Electric aviation: batteries



Technology readiness

Under development

– Technology under development for urban air mobility, small propeller, commuter, and regional aircraft
– Large-scale aircraft technologically not possible at this stage

Challenges –

Technical limitations

– **Specific energy density** of current batteries is lower compared to jet fuel (~250–300 Wh/kg vs. 12,000 Wh/kg).
– **Power density** for jet engines is typically 5–10 kW/kg, while for current li-ion batteries it is about 1–2 kW/kg, requiring larger and heavier battery packs to meet the peak power requirements.
– **Weight** of batteries reduces the available payload capacity and requires new approaches to aircraft design; unlike fuel, battery weight remains the same along the flight.

Safety and reliability

– Li-ion batteries are associated with **thermal runaway** risks, posing challenges that can lead to explosion or fires.
– **Supply and environmental impact challenged by resource availability and sovereignty,** as well as recyclability.
– **The wide range of temperatures** to which the aircraft is exposed during flight impacts battery's **thermal stability.**
– The **frequent cycling between high and low power states** accelerates battery aging.
– **Reduced air pressure and low temperatures at altitude** decrease battery efficiency and lifespan.

Opportunities +

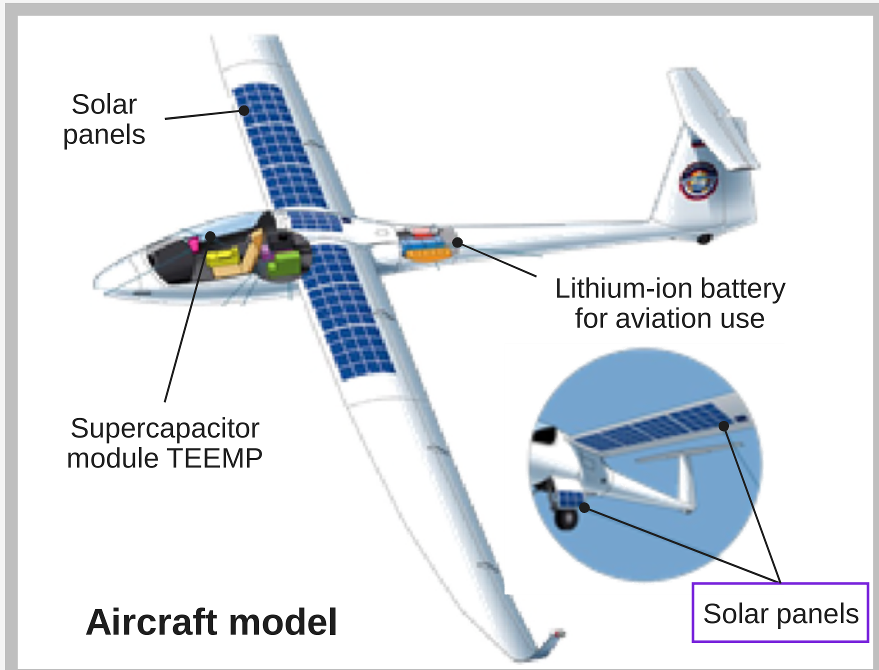
GHG emissions	– **Reduce in-flight emissions;** no NO_x emission effects as well as contrails/water vapor
Hybrid-electric	– Can **work with other power sources (gas turbines and fuel cells)** to provide additional power, potentially utilizing different battery technologies such as solid-state

Sources: Suárez, M.Z. et al., 2023, Battery Technologies to Electrify Aviation: Key Concepts, Technologies, and Figures, International Journal of Aviation Science and Technology; Pattanayak, T. and Mavris, D., 2024, Battery Technology in Aviation: Current State and Future Prospects, Georgia Institute of Technology; Kearney Energy Transition Institute analysis

A solar-powered aircraft is theoretically possible but realistically does not have a future in commercial transport as PV panels fail to fulfill energy requirements

Solar-powered aviation is ultimately an anecdote; challenges are too significant for the technology to be viable vs. sustainable alternatives

Electric aviation: solar-powered



Aircraft model

Challenges –

Energy capture and storage limitations
- Solar panels operate at **10–20% efficiency.**
- **There are weight limitations related to batteries,** which are required for nighttime operation.

Aerodynamic and structural vulnerabilities
- **Ultra-wide wingspans** would maximize solar panel area but increase **vulnerability to turbulence and wind shear.**
- **Lightweight carbon fiber composites** would reduce weight but are prone to **damage during ground handling or extreme weather.**

Weather and operational constraints
- **Solar aircraft require cloudless skies** and are designed to operate in the stratosphere, typically above 20 km, where they can access sunlight above cloud cover.
- Vertical wind shear would threatens stability, requiring advanced route optimization.

Economic barriers
- **The high cost of advanced materials** for solar panels and batteries hinders scalability.

Technology readiness

Research
- First demonstrators of the technology have been developed by multiple companies
- Commercialization still outstanding

Opportunities +

GHG emissions	– **No direct in-flight emissions**
Hybrid-electric	– Solar aircraft excel in **long-endurance missions due to continuous energy from solar power or batteries,** exemplified by Airbus' Zephyr, which can fly for months

Sources: Kearney Energy Transition Institute analysis

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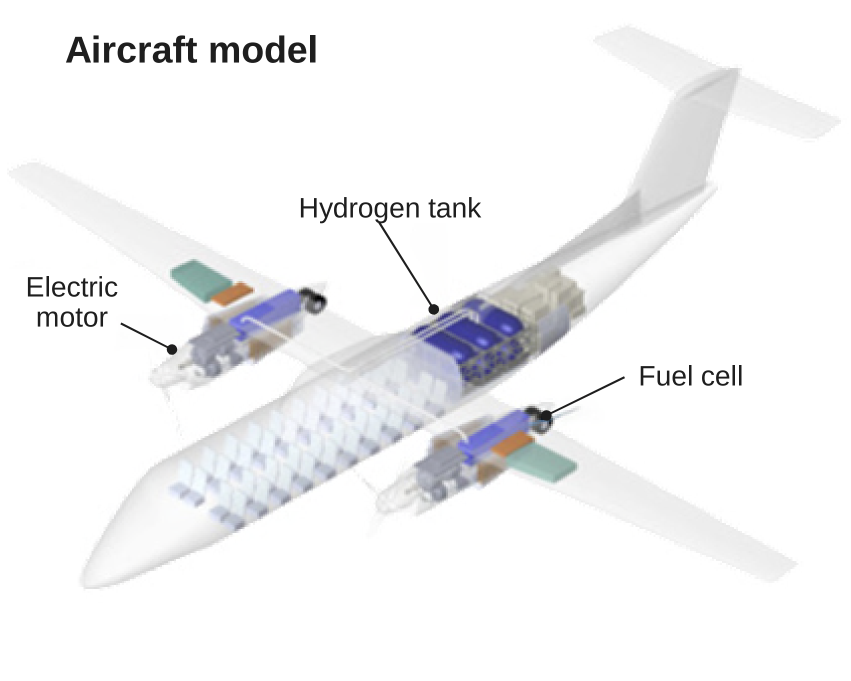
Hydrogen fuel cell can decarbonize short-haul and regional air travel, but current low energy density limits it to very small prototypes

Electric aviation: hydrogen fuel cell

Aircraft model



Challenges

Liquid or gaseous H_2?
– **Liquid provides a storage advantage,** achieving energy density comparable to gas but requires pressure of up to 350 bar, introducing significant safety and structural challenges.

Liquid H_2 volumetric and gravimetric energy density
– **Despite higher gravimetric energy density vs. Jet A** (~120 MJ/kg vs. ~43 MJ/kg, respectively), liquid H_2 exhibits far lower volumetric energy density (~8.5 MJ/kg vs. ~35 MJ/kg, respectively).

Liquid H_2 storage
– **Requires cryogenic storage** and distribution system to maintain fuel below its boiling point (−253 °C), introducing a significant mass and volume penalty due to insulation, structural containment, and management equipment required.

Aircraft and engine redesign
– **Requires redesign** to modify propulsion, expand fuel storage, and **structurally overhaul for fuel cell integration.**

H_2 production line
– **Generates no direct emissions but requires feedstock H_2O and renewable electricity** for electrolysis; its climate benefit is dependent on availability and sustainability of these upstream resources.

Infrastructure
– Development of **fuel delivery to airports** and **airport refueling infrastructure**

Cost
– **Green H_2 is costlier than kerosene per kWh** with **multiple energy conversions** from electricity to H_2 and back to electricity via fuel cells, **reducing its overall efficiency.**

Environmental footprint
– **Increased water vapor emissions** have an unclear impact on **contrails cloud formation.**

Technology readiness

Research
– First demonstrations developed by multiple companies
– Certification still required
– Commercialization still outstanding

Opportunities

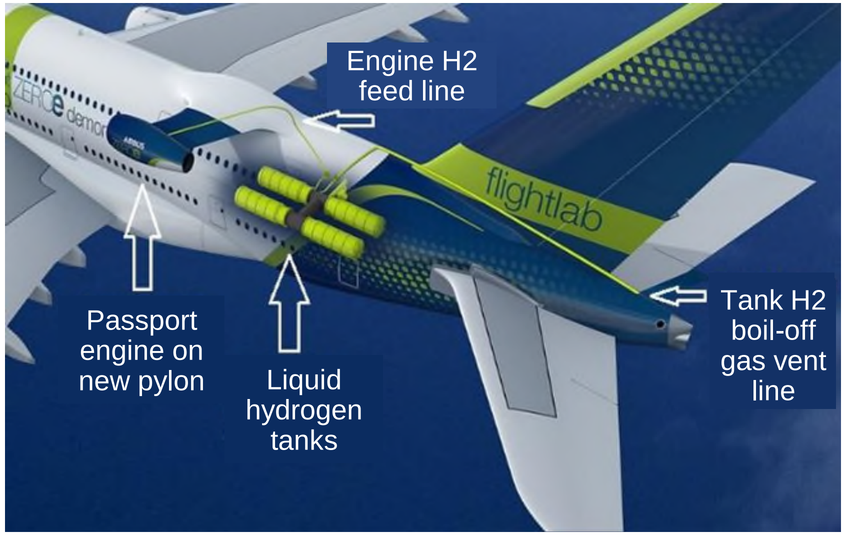
GHG emissions	– **Minimal environmental impact** – zero CO_2 ,CO, NO_x, SO_x, and hydrocarbon emissions
Hybrid-electric	– Compatible with electric propulsion, with potential to benefit from distributed propulsion[1]

[1] Distributed propulsion features the novel approach of utilizing electrically driven propulsors which are only connected electrically to energy sources or power-generating devices.
Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; International Council on Clean Transportation, 2022, Performance Analysis of Evolutionary Hydrogen-Powered Aircraft; Yusaf, T. et al., 2024, Sustainable hydrogen energy in aviation – A narrative review, International Journal of Hydrogen Energy; Kearney Energy Transition Institute analysis

Hydrogen-fueled aircraft are compatible with small propeller to short- and medium-ranges but require storage tanks four times larger than jet-fueled aircraft, impacting aircraft design

H_2 Hydrogen aviation

Aircraft model



Challenges

Aircraft and engine redesign
- **Use of liquid H_2 required accommodation of larger storage tanks,** reducing available space for payload and systems, and altering mass distribution, given the tanks cannot be integrated within wings, placed in fuselage or aft

Liquid H_2 storage
- **Requires cryogenic storage** and distribution system to maintain fuel below its boiling point (−253 °C), introducing a significant mass and volume penalty due to insulation, structural containment, and management equipment required.

H_2 production line
- **Generates no direct emissions but requires feedstock H_2O and renewable electricity** for electrolysis; its climate benefit is dependent on availability and sustainability of these upstream resources.

Infrastructure
- Development of **fuel delivery to airports** and **airport refueling infrastructure**

Cost
- **Large-scale development of electrolyzers is constrained by high capital cost,** limited stack lifetime, and maintenance demands; improving membrane durability, catalyst utilization, and system efficiency are among research and industrial priorities for cost-competitive green H_2.

Environmental footprint
- **Still produces NO_x emissions** and can potentially have negative warming impact through **leaks.**[1]
- **Increased water vapor emissions** have an unclear impact on **contrails cloud formation.**

Technology readiness

Research
- First demonstrators of the technology have been developed by multiple companies
- Certification still required
- Commercialization still outstanding

Opportunities

GHG emissions	– **Reduced environmental impact** – zero CO_2 ,CO, SO_x, and hydrocarbon emissions
Propulsion system	– Similar propulsion system to conventional aircraft
Supply chain	– **More compatible with current aerospace supply chain** than other technologies

[1] It is to be noted that hydrogen suffers from leakage and is an indirect greenhouse gas. A recent multi-model study found the Global Warming Potential over a 100-year time horizon (GWP-100) for hydrogen to be 11.6 ±2.8. As a gas with a shorter atmospheric lifetime (~2 years), its GWP-20 value is ~3x higher than GWP-100 value.

Sources: Yusaf, T. et al., 2024, Sustainable hydrogen energy in aviation – A narrative review, International Journal of Hydrogen Energy; Skeie et al, 2024, Sensitivity of climate effects of hydrogen to leakage size, location, and chemical background; Kearney Energy Transition Institute analysis based on desktop research

The most promising low-emission propulsion technologies focus on hydrogen fuel cells rather than batteries, though significant developments are still required

Emerging aviation technologies

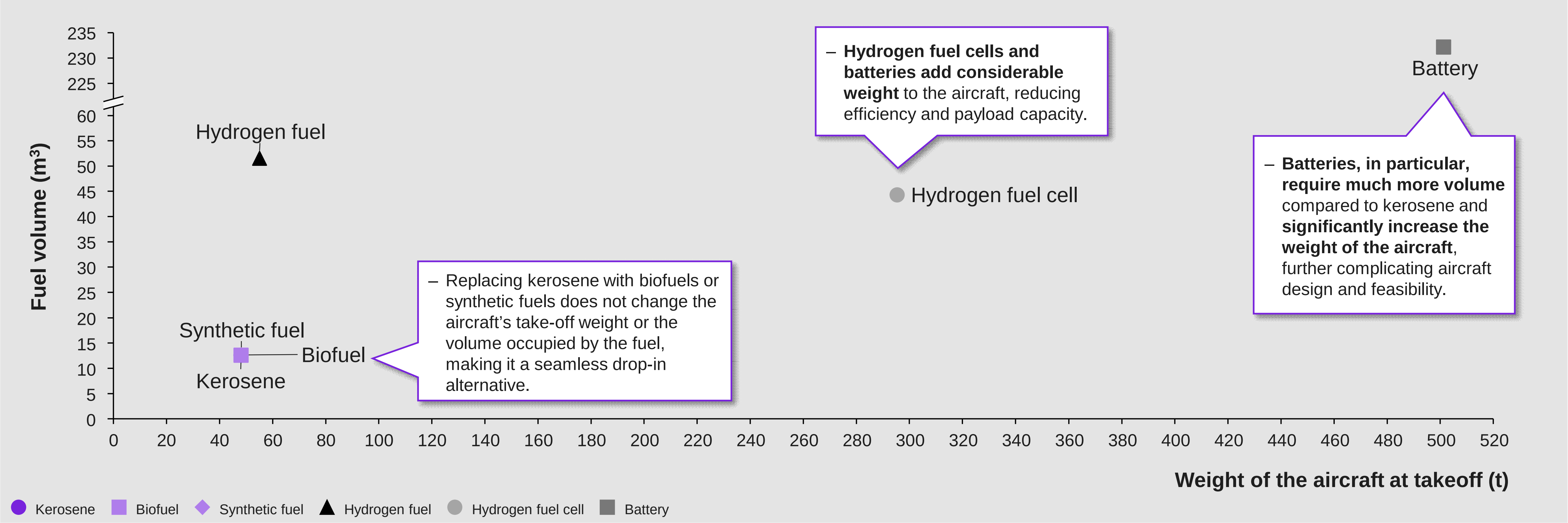
	Tech	Company	Specifications	Announced timeline	Funding	Details
Performers		AIRBUS	– 200 seats – ~3,700 km	2040–2045	Unknown	– Project ZeroE based on H_2-combustion technology – Development of 3 separate aircraft platforms – Still causes NOx and hot water vapor emissions
Performers	H_2	ZEROAVIA	– 20–200 seats – > ~6 t[1] – ~500–9,300 km	2026–2040	$150 mn	– Based on H_2 fuel cell, first used to transform a Dornier-228 – Step-wise upscaling of aircraft toward 2040 – Capital and company growth challenging
Visionaries	H_2	H2FLY	– 40–80 seats – ~1,500–1,900 km	2025	~ $10 mn	– Demonstrated longest fuel-cell-powered flight in 2020 – Focused on converting conventional aircraft (Dornier 328) – Additionally targets small passenger aircraft short-term
Visionaries		Wright	– 100–186 seats – < ~1,300 km	2026–2030	~ $3 mn	– Wright is focusing primarily on advanced battery technology – Targeting single-aisle aircraft globally – Still require substantial amounts of capital to scale up

[1] The Dornier 228 retrofitted with the ZA600 powertrain has a maximum takeoff weight of ~5,650 kg.
Sources: Airbus, 2017, Approche pour une aviation durable; ZeroAvia, 2024, Scaling Hydrogen-Electric Propulsion for Large Aircraft; Kearney Energy Transition Institute analysis

Currently, replacing kerosene with alternative fuel is the only option that does not change aircraft weight or design

Aircraft propulsion system impact by volume and mass

for a 200-passenger aircraft traveling a distance of 2,000 km



Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Yusaf, T. et al., 2024, Sustainable hydrogen energy in aviation – A narrative review, International Journal of Hydrogen Energy; Kearney Energy Transition Institute analysis

Technology solutions are spread across the maturity curve

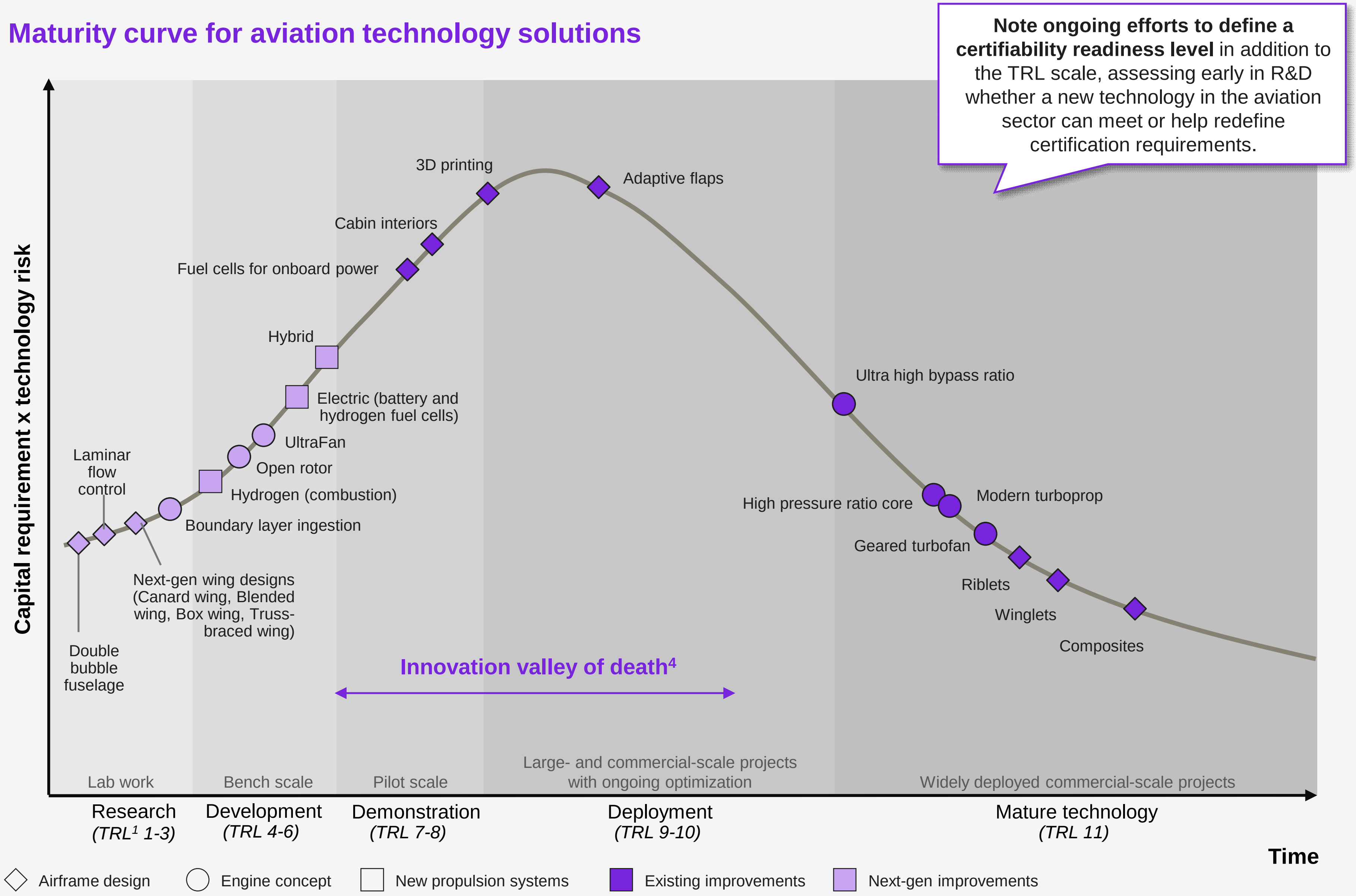
Non-exhaustive

Some technologies under airframe design and engine concepts are already mature and widely deployed.

However, alternative propulsion systems are mostly in the development stage.

3.6 Maturity curve

Maturity curve for aviation technology solutions



[1] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide
Sources: ATAG, 2021, Waypoint 2050 (2nd edition); Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

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4. Operational improvements

Improving operations can help reduce CO_2 emissions

A broad scope	Key net zero levers are based on optimizing **airspace configurations, in-flight operations, ground operations, and infrastructure.**
Collaboration effectiveness	A number of actors work together to ensure the safety and improve efficiency of air transport operations, which **directly influences the environmental footprints.**
Traffic and airspace management	Air traffic and airspace measures aim to achieve efficiency gains through airspace capacity management but have **limits imposed on them due to safety requirements.**
Airplane trajectories	Airline routes can be modified to align with **minimum-fuel trajectory,** which is not always identical to minimum cost flight path. It is also a potentially effective solution to **avoid contrails** as the recent trials and projects have demonstrated.
Ground operations	Ground operations have the potential to reduce emissions with **taxiing optimization** being the main lever.
Best practices	**Best operating practices are focused on reducing aircraft weight,** including fuel and water volumes, and more frequent aircraft **and engine cleaning,** including removal of built-up contaminants on wings, fuselage, and engine.
Readiness	Certain solutions, such as optimal aircraft taxiing, have reached **wider deployment**, but many are still in development.

Sources: Kearney Energy Transition Institute analysis

Key levers for achieving operational improvements in aviation

Non-exhaustive

	A Traffic and airspace optimization	B Flight and trajectory optimization	C Ground operation optimization	C Operations and operating practices
Description	Better utilization of the airspace in which airlines operate	Improving how aircraft are used in-flight by airlines	Addressing emissions produced between the gate and the runway	Enhancements in operations, equipment selection, and maintenance
Improvements	– Trajectory based operations – Advanced navigation – SES/SESAR[1] – Continuous decent/climb – Flexible use of military airspace – Collaborative decision-making – Space based navigation	– Wake energy retrieval – Flight planning – Optimized trajectories	– Electric/hydrogen taxiing – Stationary power and ventilation – Reduced engine use during taxiing	– Cabin and equipment weight optimization – Fuel and water usage – Interior and cargo cleanliness

[1] Single European Sky ATM Research Project is the technological pillar of the EU's single sky initiative.

Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Operational solutions successfully reduce the volume of emitted species across the board, but fall short of removing any entirely

[1] Change in emissions volume per molecule relative to business-as-usual aviation; [2] Ice-supersaturated regions
Source: Kearney Energy Transition Institute analysis

Solution	Emitted species[1]					GHG reduction Fuel efficiency improvement	Commentary
	CO_2	Contrail	NO_x	Soot	H_2O		
Traffic and airspace optimization	Decrease	Decrease	Decrease	Decrease	Decrease	**0.9-4.5 gCO_2e/MJ** 1-5%	Reduced fuel consumption via greater operational efficiency achieves emissions reduction for most aircraft types in nearly all flight phases; solutions targeting improvement on the ground or far from the crossing of ISSR during the cruise phase have little to no impact on contrail formation.[2]
Flight and trajectory optimization	Decrease	Decrease	Decrease	Decrease	Decrease	**2.7-4.5 gCO_2e/MJ** 3-5%	
Ground operations	Decrease	~	Decrease	Decrease	Decrease	**0.9-2.7 gCO_2e/MJ** 1-3%	
Improved operations / practices	Decrease	~	Decrease	Decrease	Decrease	**~0.5 gCO_2e/MJ** ~1%	

Legend: Complete removal; Decrease; ~ No impact; Increase

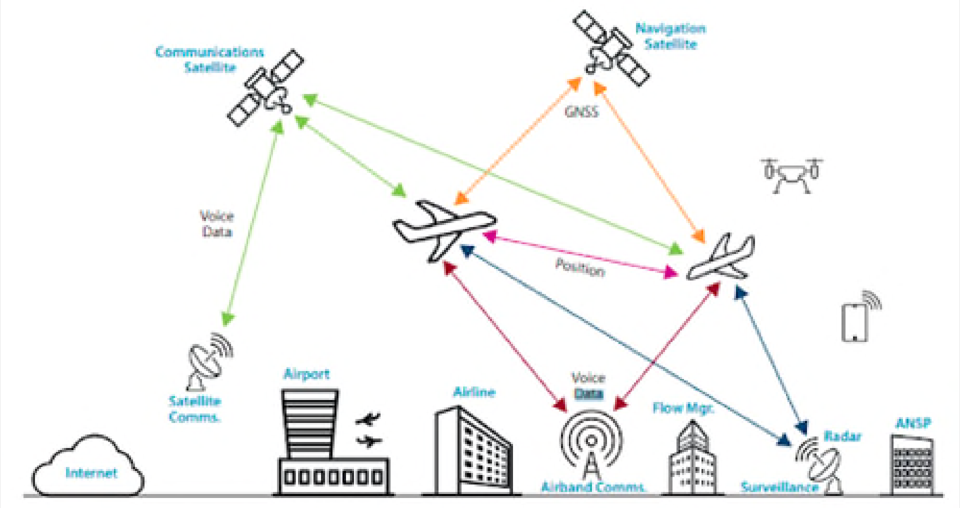
Air traffic and airspace management aims to ensure safe and efficient flights, while managing airspace capacity

ATM improvements are inherently limited because it is not possible to eliminate all inefficiencies considering safety requirements and capacity constraints.

A B C D

4.2 Traffic and airspace optimization

Air traffic management schematic view



Air traffic management (ATM) corresponds to the dynamic, integrated management of air traffic and airspace.

- It ensures air traffic services, airspace management, and air traffic flow management in a safe, economic, and efficient manner.
- ATM requires close collaboration between airborne and ground-based functions.
- In a highly regulated and complex air transport operating environment that is often organized locally, different stakeholders collaborate with one another, including airlines, ANSP, airports, ground handling agents, and aircraft and system manufacturers.

Key measures to reduce carbon emissions

Expanded in the next slide

Measure	Description
Collaborative decision-making	Beyond data sharing, redefines how air traffic flow management decisions are made, considering all stakeholder needs and optimizing airport and airspace capacity
Continuous descent/climb	Avoid tiered flight phases to optimize vertical flights paths and reduce fuel consumption
Flexible use of military airspace	Using military airspace to optimize trajectories
Single European Sky SES/SESAR	Harmonizing practices and systems in European airspace

Measure	Description
Next-gen project	Optimizing air traffic management through satellite and real-time route data (SESAR equivalent in the US)
Advanced navigation	Performance-based navigation (PBN): using satellite technology for landing and airways
	Reinforcing PBN by adopting the Required Navigation Performance (RNP) specifications
4D trajectory-based operations	Integration of a time element into the 3D aircraft trajectory

Air Navigation Service Provider

Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Single European Sky (SES) is an ambitious initiative to reform the architecture of European ATM

A B C D

4.2 Traffic and airspace optimization

Description

The Single European Sky ATM Research (SESAR) project was launched in 2004 as the technological pillar of the Single European Sky (SES).

– Established in 2007 as a public–private partnership, the SESAR Joint Undertaking (SESAR JU) is responsible for the modernization of the European air traffic management system by coordinating and concentrating all ATM relevant research and innovation efforts in the EU.

Intra EU+
Main scope of SES/SESAR research program

Outside EU+
These destinations will benefit less as only a part of their flight happens through European airspace

North Atlantic corridor
The reduction potential is additional to the non-European ATM efficiency gains due to easing of pre-defined tracks

Potential emissions reduction (% per flight, to and from Europe)

Measure	2030	2040	2050	Remarks
SES1/ SESAR intra EU	3.9	5.7	5.7	Intra EU + flights
SES/SESAR extra EU + including non-European ATM efficiency improvements	2.7	3.9	3.9	Departure flights to outside EU+
Improved North Atlantic flight-efficiency	1.3	1.3	1.3	Flights from Europe to North America

Sources: SESAR Joint Undertaking, 2025; Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Objectives and goals

Key objectives of the SES:

– To restructure European airspace in accordance with air traffic flows
– To create additional capacity
– To increase the overall efficiency of the air traffic management system

To fulfill these objectives, the European Commission has set the following high-level goals:

– Enable a **3-fold increase** in capacity which will also reduce delays both on the ground and in the air
– Improve safety by a **factor of 10**
– Enable a **10% reduction** in the effects flights have on the environment
– Provide ATM services to the airspace users at 50% (or more) discount **than the current cost**

As of 2024, **191 SESAR solutions** have been developed/are in development out of which **68 (around 36%)** are focused on reducing fuel consumption and emissions.

Optimizing aircraft trajectories can improve fuel consumption and reduce the distance flown

4.3 Flight and trajectory optimization

Flight planning

Airlines typically plan their flights to minimize the costs but the cost-optimal trajectory **is not always** identical to the minimum-fuel (and CO_2 emission) trajectory

– By reducing the nominal speed to long range cruise (LRC) speed, fuel burn and CO_2 emissions can be reduced by **0.3%**, while the costs stay nearly constant.

– Using advanced flight planning software is estimated to enable fuel savings of **2.6–3%**.

Potential emissions reduction (% per year)

Measure	2030	2040	2050
Improved flight planning	1.2	1.2	1.2
Reduced cruise speeds	0.3	0.3	0.3
Flight management control updates	0.5	1.0	1.0

Optimized trajectories

Implementing collaborative decision-making approaches based on improved air-ground communication allows pilots to request and obtain clearance to divert from planned route or change flight level.

In 2021, a straight-line flight by Air France from Paris to Toulouse reduced CO_2 emissions by **7–8%**.

Wake energy retrieval

In 2018, Boeing demonstrated 10% fuel burn benefit in 777 freighter tests.
In 2021, Airbus flight tests with two A350 aircraft showed **5–10%** reduction in fuel burn for the follower aircraft.

Concept in which aircraft (not more than 2) fly in an extended formation which leads to benefits in fuel consumption of the follower aircraft.

– SESAR project GEESE will assess the feasibility
– The implementation is **expected to start in 2030** on North Atlantic routes because of the predominantly bi-directional traffic flow.

Potential emissions reduction (% per year)

Measure	2030	2040	2050	Remarks
Wake energy retrieval	0.0	1.0	2.0	Flights from Europe to North America
	0.0	0.08	0.38	Other flights

Space-based navigation

Communicating with satellites or ground stations to pass the data to air traffic control, allowing for precise positions in isolated areas/oceans. Benefits include:

– reduction of safety margins
– optimization of routes
– reduction of fuel consumption

Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Flight trajectory adjustments are under research as a means to avoid contrail formation

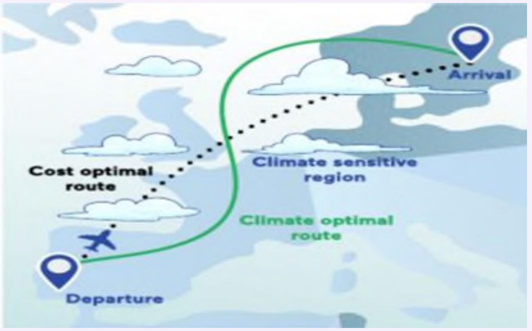
Non-exhaustive

ISSRs can extend for **several hundreds of kilometers but are usually <1 km thick;** in principle, avoiding them is similar to avoiding storms or turbulent areas of the atmosphere.

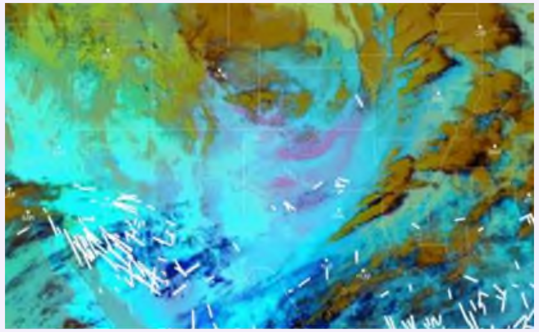
4.3 Flight and trajectory optimization

Main approaches toward flight path deviation

1 Using weather forecasting models	2 Using real-time satellite observations
Weather data is analyzed to estimate ISSRs locations using a **contrail formation numerical model** and then the filed flight plan is reviewed to predict whether the contrail will be formed. Accordingly, an alternative flight path is then filed which deviates the flight away from that region usually by vertical changes to the original route.	A contrail management system has been devised that **uses satellite data analysis to differentiate contrails from natural cirrus clouds, combined with weather prediction models** to detect contrail via AI and machine learning. The aim is to help pilots adjust cruise altitude to avoid contrail formation.



Flying on climate-optimized trajectories vs. cost-optimal flight paths



Contrails detected over the US using AI and GOES-16 satellite imagery

Based on simulations and flight tests, contrail avoidance can increase fuel burn, estimated between **0.01% and 0.3%** at a fleet level. In practice, due to airspace constraints, it could be higher. However, it is estimated that the reduction in contrail warming is **20x** greater than the additional CO_2 from fuel burned.

Sources: IATA, 2024, Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions; Transport & Environment, 2024, Contrail avoidance: aviation's climate opportunity of the decade; Kearney Energy Transition Institute analysis

Projects/trials/initiatives

Air France – Météo France 1

In 2023, in collaboration with Météo France, Air France experimented with a contrail avoidance process on four European and intercontinental flights.

Google's "Project Contrails" 2

Partnered with American Airlines to monitor 70 test flights over six months using satellite data and AI-based predictions registering **54%** decline in contrail formations.

Expanded in more detail on next page

Etihad – SATAVIA 1

In 2023, Etihad Airways signed a multi-year agreement with SATAVIA to scale its contrail management platform, DECISIONX:NETZERO within day-to-day flight operations.

MIT – GOES-16 2

Current methods mostly estimate the horizontal location of the contrail. MIT has proposed a technique, based on satellite images and trained on data from 3,214 contrails, to also estimate their height.

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Contrail avoidance trials in commercial aviation have shown promising results in combining satellite-based contrail detection with predictive modeling

Contrail avoidance maneuvering

- For the selected routes, contrail formation zones were predicted using CoCiP (a physics-based simulation model) and a machine learning (ML) model trained on a database of automatically detected contrails.
- This approach aims to improve upon the limitations of an approach based on the weather forecast data.
- Pilots made altitude adjustments based on these forecasts in rerouted flights.
- Contrail avoidance flight legs were planned using flight management system software developed by PACE, integrated with the ML contrail forecasts.

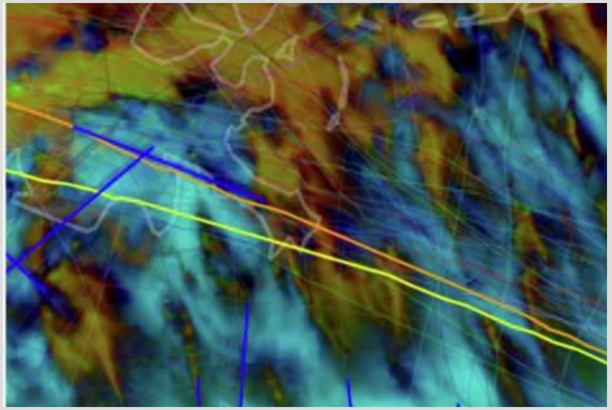
American Airlines' trial (2023)

Ten senior pilots flew **44 flights** with half being rerouted to demonstrate the feasibility of contrail avoidance on a per-flight basis.

Panel of PACE software
The pilot originally planned to fly at FL360 (36,000 feet), the level of the gray line. By staying at FL320 (32,000 feet) for part of the flight, the CLZ was avoided and no detectable contrails were created.

Post-flight verification using satellites and trained algorithms

- Satellite imagery was used to observe the actual contrail formation post-flight, enabling a direct assessment of the effectiveness of the avoidance strategy.
- An example of one frame of the GOES-16 satellite imagery sequence over the Gulf Coast area for American Airlines flight 189 is highlighted below.



Yellow: *The flight path, which was obtained from Automatic Dependent Surveillance Broadcast data licensed from FlightAware*
Orange: *The wind-advected flight trajectory over time*
Blue lines: *contrails detected by an automated computer vision system*

The advected flight path and the observed contrail are aligned, hence ***the flight led to contrail formation.***

- Without satellite observation, it would be extremely difficult to objectively assess whether the rerouting efforts led to a reduction in contrails over wide geographic regions and at fine temporal scales

The trial represented a **54.4%** reduction in detectable contrails per flight kilometer in the contrail avoidance flights. Fuel usage was tracked and the modified flights used an average of **2% more fuel** per adjusted flight, corresponding to an additional **0.26 kg of CO_2 emissions per kilometer** per flight.

[1] CLZ is contrail likely zone (predicted).
Sources: Elkin et al., 2024, Feasibility test of per-flight contrail avoidance in commercial aviation; Kearney Energy Transition Institute analysis

Airlines can reduce their emissions through comprehensive ground operations strategies

Ground operations have the potential to reduce emissions during operations by ~7%.

Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Sustainable Taxiing Taskforce, 2024, Sustainable Taxi Operations: Concept of Operations & Industry Guidance; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation ; Tabernier, L et al., 2021, Fuel Tankering: Economic Benefits and Environmental Impact for Flights Up to 1500 NM (Full Tankering) and 2500 NM (Partial Tankering), Aerospace; Kearney Energy Transition Institute analysis

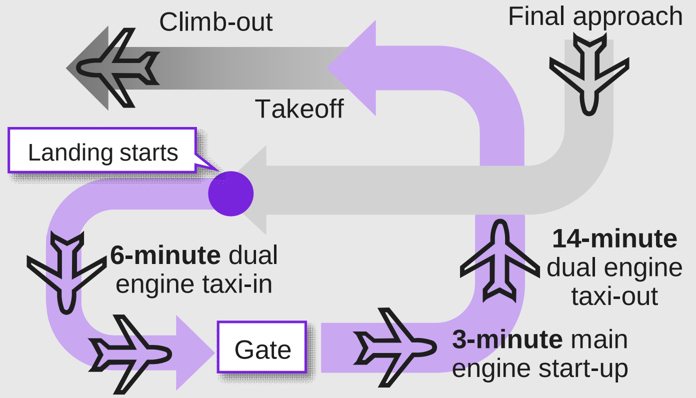
4.4 Ground operations optimization

Main levers of emissions reduction in ground operations

Lever		Practice	Readiness	CO_2 reduction potential (%)[1]
Ground operation optimization	Engine and taxiing optimization	Reduced engine use during taxiing	Can currently be deployed	0.03–0.42% / flight
		Electric or hydrogen taxiing via operational towing	Long-term development and/or deployment	0.05–0.96% / flight
	Stationary energy management	Stationary power and ventilation	Long-term development and/or deployment	0.3% / flight

Long-term development and/or deployment · Medium-term development and/or retrofit · Can currently be deployed

Engine and taxiing optimization



Main engine taxiing   **Times** (minutes) are indicative

- **Single-engine taxiing** saves fuel by using only **one engine for thrust**, while **multi-engine aircraft use fewer active engines.**
- **Using electric or hydrogen tugs for towing aircraft** over long distances eliminates fuel consumption during taxiing.

Stationary energy management

1. **Electricity** provided by **airport power supply**, instead of the APU.
2. **Pre-conditioned air** delivered to aircraft, through a ground-based pre-conditioned air system.

- The **auxiliary power unit (APU)** onboard provides **electricity for onboard systems** and compressed air for **air conditioning** when main engines are off.
- **Reduce reliance on the APU when ground power is available** to minimize unnecessary fuel consumption and emissions while the aircraft is stationary at the terminal.

Major airports made net-zero carbon one of their top priorities, introducing net-zero targets by 2030–2050

Preliminary; non-exhaustive

In 2021, **Airports Council International** adopted a **goal for member airports** worldwide to achieve **net zero carbon by 2050**.

A B C D

4.4 Ground operations optimization

Objectives and strategies of international airports

Amsterdam Schiphol (AMS)
- Net-zero emissions target: **2030**
- Key levers to reach target include electrification of ground operations, use of renewable energy sources and create surplus, waste-reduction initiatives
- **100% electrification of GSE objective by 2030**[1]

Schiphol

Delhi International Airport (DEL)
- Net-zero emissions target: **2030**
- Key levers used include operation on **100% renewable energy,** 90% airside vehicles replaced with EV, installation of high-voltage and fast-charging stations, use of TaxiBot to reduce aircraft fuel consumption during taxi
- **Obligation to use minimum 50% electric GSE to participate in airport tenders**

DELHI INDIRA GANDHI INTERNATIONAL AIRPORT

Los Angeles International Airport (LAX)
- Net-zero emissions target: **2045**
- **Levers:** Aiming for **100% renewable electricity**, zero potable water usage, waste diversion
- **100% EV fleet expected by 2031**

LAX

Dubai International Airport (DXB)
- Net-zero emissions target: **2050**
- **Levers: renewable energy** use (15,000-panel solar energy system), **energy-efficient lighting**, and reduction in **landfill waste** (2,000 tons of food waste annually), **electric GSE**

DXB

Changi Airport Group (SIN)
- Net-zero emissions target : **2050** (zero carbon growth by **2030**, benchmarked against 2018 emissions)
- **Levers:** building energy efficiency, renewable energy use, **support partner decarbonization** (sustainable aviation fuel, **GSE electrification)**

CHANGI airport singapore

[1] GSE is ground support equipment.
Sources: Kearney Energy Transition Institute analysis

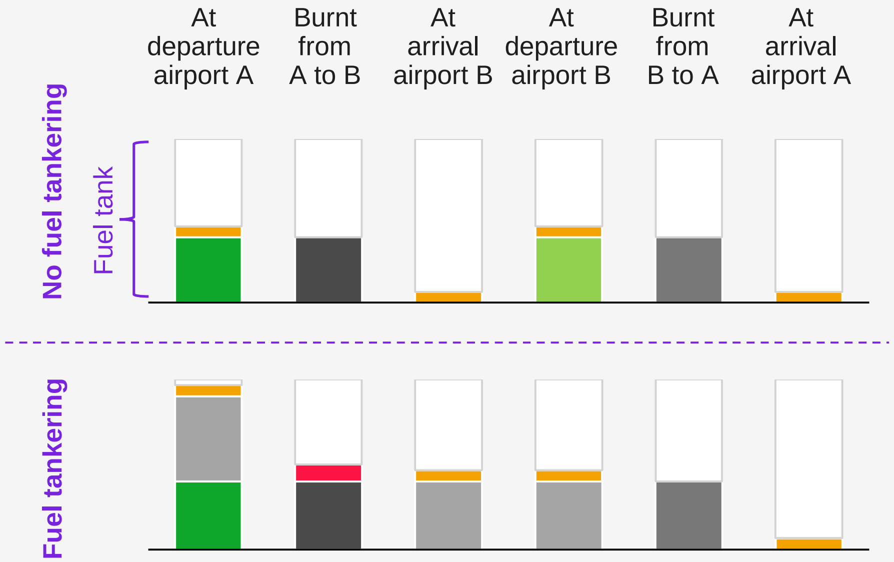
Minimizing tankering practices can help airlines reduce emissions

Main levers of emissions reduction in operating practices

Lever		Practice	Readiness	CO_2 reduction potential (%)[1]
Improved operations and operating practices	Weight and load optimization	Adjust fuel and water supply use		0.56–0.71% / flight
		Cabin and equipment weight optimization		0.41% / flight
	Aircraft condition and maintenance	Optimizing surface and engine maintenance, ensuring interior and cargo cleanliness		0.53–1.05% / flight

Long-term development and/or deployment · Medium-term development and/or retrofit · Can currently be deployed

Adjust fuel and water supply



- **Tankering, the practice of carrying excess fuel motivated by** operational or economic reasons, increases aircraft weight, fuel consumption, and CO_2 emissions.
- **Carrying extra fuel increases fuel burn by 2.5 to 4.5% of its weight**, per hour of flight, depending on the characteristics of the aircraft.

A B C D

4.5 Improved operations and operating practices

Sources: Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Sustainable Taxiing Taskforce, 2024, Sustainable Taxi Operations: Concept of Operations & Industry Guidance; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Tabernier, L et al., 2021, Fuel Tankering: Economic Benefits and Environmental Impact for Flights Up to 1500 NM (Full Tankering) and 2500 NM (Partial Tankering), Aerospace; Kearney Energy Transition Institute analysis

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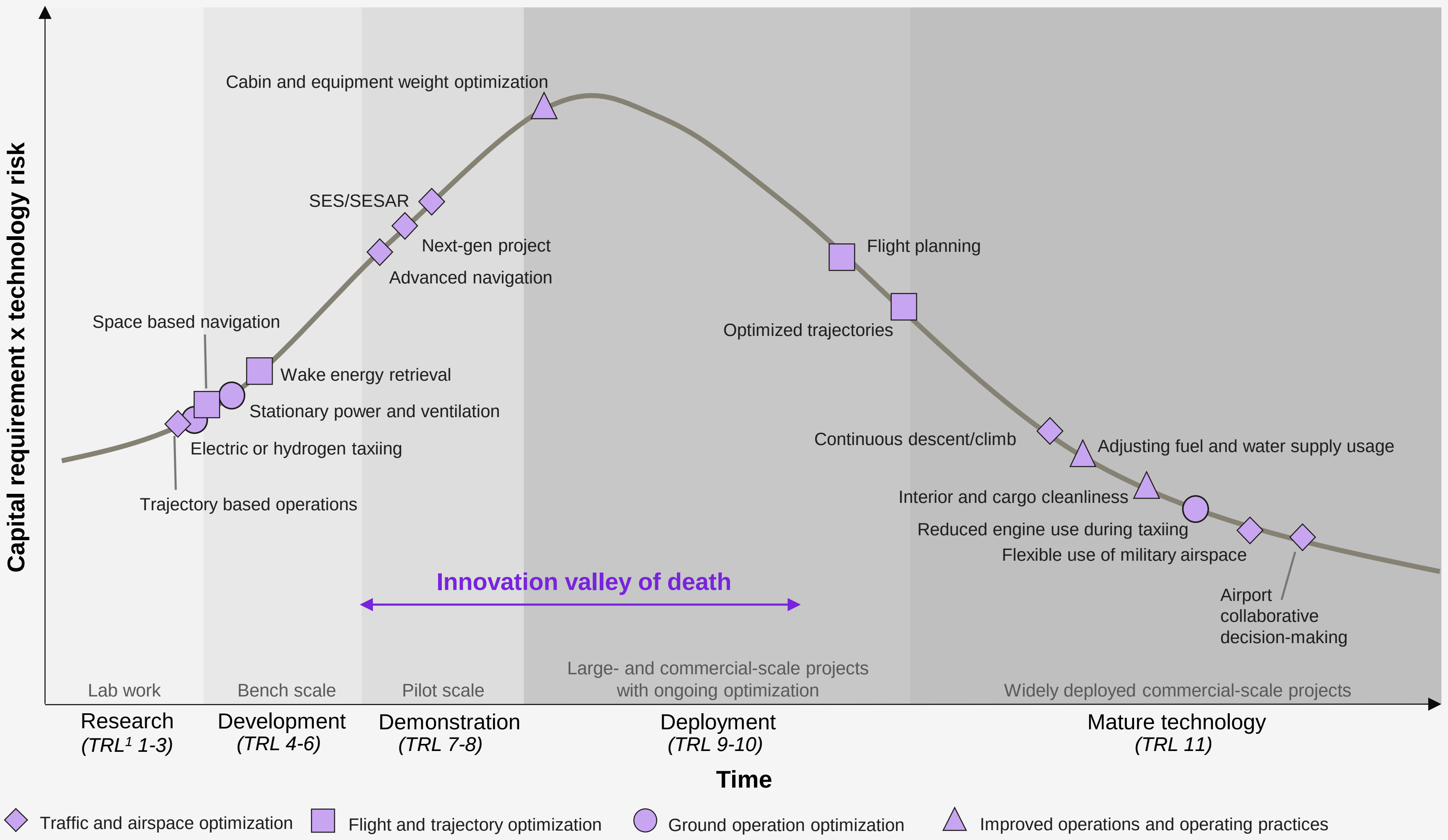
Certain solutions, such as optimal aircraft taxiing and interior cleaning, have reached wider deployment, but many are still in development

Non-exhaustive

Maturity curve for other climate impact mitigation levers



[1] TRL (technology readiness level) scale adapted from IEA (2020), Assessing technology readiness: The ETP Clean Energy Technology Guide
Sources: Sustainable Taxiing Taskforce, 2024, Sustainable Taxi Operations: Concept of Operations & Industry Guidance; Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

4.6 Maturity curve

5. Policy and regulation

Aviation industry aims to reach net-zero carbon emissions by 2050 through international collaboration and use of various regulatory tools

Regulatory landscape	The aviation regulatory landscape consists of **multiple stakeholders** working closely with industry players to enable technological and operational solutions for species-wide emissions reduction
Net-zero goals	**IATA (International Air Transport Association) and ICAO (International Civil Aviation Organization)** have committed to achieving **net-zero carbon emissions from aviation by 2050.**
Use of carbon offsets	**CORSIA** is an international offsetting scheme from ICAO which will become **globally binding by 2027.**
SAF mandates	Ambitious **SAF mandates** have been adopted in **Europe** to accelerate its development and deployment. Many countries in **Asia Pacific** have formulated or are in the process of formulating **SAF targets.**
EU ETS	Aviation was included in the **EU ETS** in 2012 with an aim of **phasing out free allowances by 2027.**
New technologies in the US	**The US** had numerous initiatives to accelerate emissions reductions through scaling **SAF** and pioneering **improved aircraft technologies.**
Non-CO_2 policy measures	Measures to mitigate non-CO_2 emissions, **especially contrails**, are globally limited. Regulations for NOx have been in place for more than a decade.

Sources: Kearney Energy Transition Institute analysis

5.0 Chapter summary

Policy and regulation in major countries and regions serve as enablers of technological and operational solutions to realize species-wide emissions reduction

Solution	Emitted species[1]					Commentary
	CO_2	Contrail	NO_x	Soot	H_2O	
Emissions cap	Decrease	~	Decrease	Decrease	Decrease	Reduced fuel burn to limit CO_2 emissions under the cap creates knock-on decrease in NO_x, soot, and H_2O; otherwise, policy measures targeted at contrails are limited presently.
SAF mandates	Decrease	Decrease	~	Decrease	~	Decreased CO_2 emissions depending on the blend ratio and sustainability of sourcing/production; reduced soot formation in turn reduces contrail formation; minimal change in NO_x and H_2O.
Financing	Decrease	Decrease	Decrease	Decrease	Decrease	Financing allows other solutions to scale and realize species-wide emissions reductions by a variety of measures.
Engine standards	Decrease	Decrease	Decrease	Decrease	Decrease	Species-wide emissions reduction realized via higher-efficiency engines.

[1] Change in emissions volume per molecule relative to business-as-usual aviation; Source: Kearney Energy Transition Institute analysis

Complete removal | Decrease | ~ No change | Increase

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The aviation regulatory landscape consists of multiple stakeholders which work closely with industry players to accompany the sector

Non-exhaustive

Regulatory bodies

ICAO
Established in 1947, it's a UN agency that coordinates the principles and techniques of international air navigation.

National or regional agencies
Government bodies which regulate the aviation sector across various dimensions including operations, safety, and environment.

Financing institutions
Public or public–private entities which provide grants or loans for development of aviation projects, research and innovation, etc.

Industry bodies

IATA
Trade association for the world's airlines

ACI World
Association of world's airports

CANSO
Air traffic management industry group

ATAG
Association of players from aviation value chain

GAMA
General Aviation Manufacturers Association

ASD
Aerospace, Security and Defence group in Europe

Certifying bodies

ASTM
Jet fuel and aerospace materials

ASD-STAN
European aerospace standards

Carbon registries
Carbon offsets projects

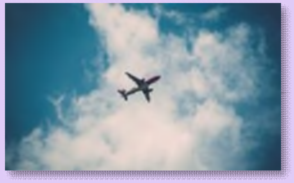
RTCA
Communication, navigation, surveillance, and air traffic management

Laws, mandates, incentives, penalties, financing, etc.

Standards, certification, guidelines, etc.

Aviation industry

Aviation fuel suppliers
Suppliers must gradually increase the share of SAF blended with conventional aviation fuel.



Aircraft operators
Operators must cut emissions and move toward lower emission aviation pathways.

Airports
Airports must facilitate access to the necessary infrastructure to deliver, store, and refuel aircraft with SAF.

OEMs
OEMs must upgrade their technology and products to support industry's net zero efforts including engines that can run on SAF.

Source: Kearney Energy Transition Institute analysis

The global aviation sector aims to achieve net-zero carbon emissions by 2050

Non-exhaustive

Various **policy tools and measures**, such as SAF mandates or offsets, are adopted to achieve these goals.

5.3 Net zero objectives

Net zero targets

Type	Organization	Scope	Description
Binding targets	ICAO	Global	85% of 2019 emissions as CORSIA's baseline from 2024 until the end of the scheme in 2035
	EU	Local	EU ETS and free allocation in the aviation sector fully phased out by 2026
	UK	Local	UK has committed to achieve net-zero aviation emissions by 2050 with all domestic flights and airports; in England this net-zero target is more ambitious, expected to be achieved in 2040
Aspirational targets[1]	ICAO	Global	ICAO Member States adopted a collective long-term global aspirational goal (LTAG) of net-zero carbon emissions by 2050
	IATA	Global	The 77th IATA AGM in Boston approved a resolution for the global air transport industry to achieve net-zero carbon emissions by 2050
	DESTINATION 2050[2]	Local	Net-zero carbon aviation in Europe by 2050
	US	Local	The US aviation sector aims to achieve net-zero greenhouse gas emissions by 2050

[1] By industry bodies and countries/regions. Additionally, individual industry players have also announced their own net-zero goals.
[2] Road map developed by Royal Netherlands Aerospace Centre (NLR) and SEO Amsterdam Economics and commissioned by A4E, ACI EUROPE, ASD, CANSO Europe and ERA
Sources: Kearney Energy Transition Institute analysis

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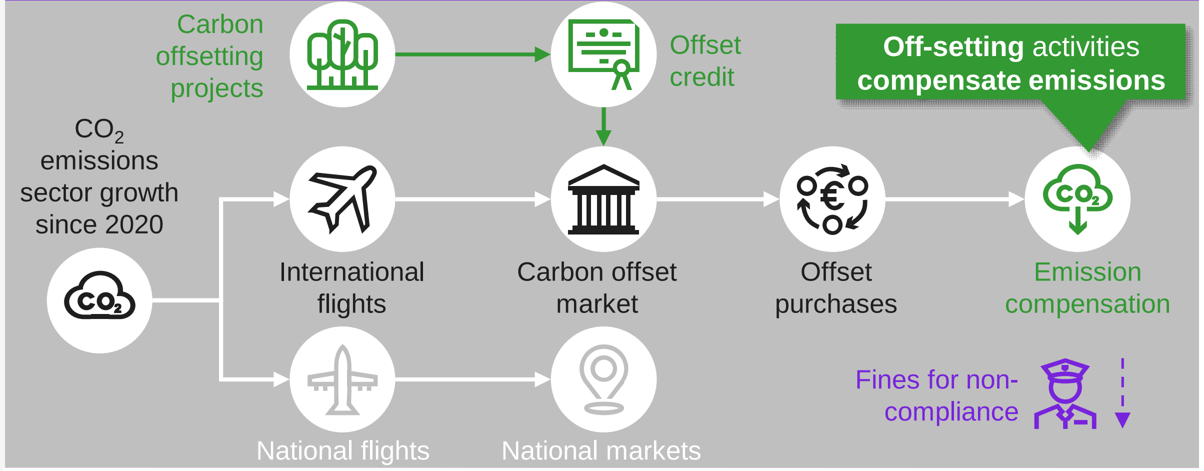
CORSIA is an international offsetting scheme from ICAO aiming to stabilize CO_2 emissions from international aviation and will become globally binding by 2027

Carbon offsets trading scheme

Indicative



Context

- **CORSIA** is an **offsetting mechanism** developed by the ICAO.[1,2]
- Adopted in **2016** and applied since **January 1 2019** when all airlines were required to report their CO_2 emissions on an annual basis.
- Offsetting is **not intended to replace** sector's efforts to decarbonize its operations.

Highlights

Currently in **phase I**	**129** states participation
99% of total 2023 CO_2 international aviation emissions	**670** airplane operators from 131 states[3]
6 eligible emissions units programs[4]	**56** verification bodies accredited in 34 states

CORSIA implementation phases

Pilot	Phase I	Phase II
2021–2023 – Designed to serve as a testing ground for the scheme – Started with 88 voluntary states' participation	**2024–2026** – Scheme expands with more states choosing to participate voluntarily – The baseline during this phase is set at 85% of 2019 emissions	**2027 onward** – Participation becomes mandatory for all ICAO Contracting States[5] – The inclusion criteria are based on 2018 revenue tonne kilometer (RTK)

Details

- **CORSIA Emissions Unit Eligibility Criteria** consists of a set of principles by which the programs are assessed on eligibility to supply emissions units, approved by the **ICAO Council**. Eligible CORSIA credits can be bought/traded from IATA's Aviation Carbon Exchange (ACE), online marketplaces, brokers, and other platforms.
- Scheme allows aircraft operators to **reduce** offsetting requirements via CORSIA eligible fuels, including **CORSIA sustainable aviation fuels** and **CORSIA lower-carbon aviation fuels.**

[1] CORSIA is Carbon Off-setting and Reduction Scheme for International Aviation; [2] ICAO is International Civil Aviation Organization, a United Nations agency that manages and regulates international air travel; [3] Additional airlines participating even though countries are not enrolled; [4] Programs supplying CORSIA eligible emissions units; [5] Exemptions: least developed countries, small island and landlocked, developing countries, states with <0.5% share international air traffic.
Sources: ICAO; Kearney Energy Transition Institute analysis

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Airlines can use carbon offsets to reduce both direct and indirect emissions, complementing but not replacing technological and operational solutions

Non-exhaustive

What are carbon offsets/credits?

- Mechanism to **mitigate greenhouse gas (GHG) emissions** by **investing in projects that avoid, reduce,** or **remove** an **equivalent amount of carbon dioxide** (CO_2) or other GHG. A **certificate is granted per ton of CO_2e reduced.**
- Carbon offsets are often used to **achieve emissions reduction** beyond what an **organization can achieve** through **internal efforts alone.**
- Mainly traded on the **voluntary carbon markets** though some carbon offsets can also be used in select compliance markets/regulatory schemes such as CORSIA.
- Rules are established by **independent standards bodies** (both private and public).

Type of carbon offsets

Avoided emissions ↔ Carbon removal

Korean Air's "Korea Air Forest" initiative

Lufthansa and British Airways have partnered with Climeworks to purchase direct air capture credits.

Carbon storage potential	**No storage**	**Potential short-term storage**	**Short-term storage**	**Long-term storage**
Type of solution	Technology-based solutions	Nature-based solutions	Nature-based solutions	Technology-based solutions
Project examples	– Switching to solar energy – Energy efficiency – Landfill methane capture – Methane avoidance at dairy farms	– Avoided deforestation – Improved forest management	– Afforestation – Reforestation – Mangrove reforestation	– Direct air capture (DAC) with storage – Carbon capture and storage (CCS) – Enhanced weathering

Source: Kearney Energy Transition Institute analysis

SAF mandates have been adopted in Europe to accelerate its development and deployment

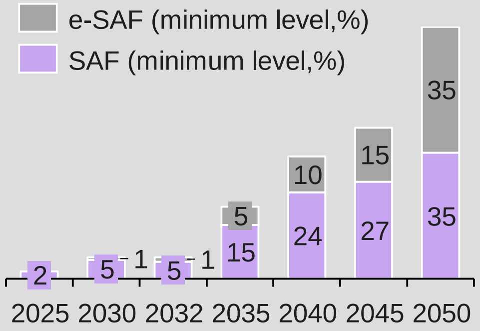
Non-exhaustive
Europe

5.6 Regional regulations

ReFuelEU Aviation

Part of **“Fit for 55” package under European Green Deal,** which aims to reduce net GHG emissions in transport by at least **55% by 2030.** It **mandates fuel suppliers to blend increasing levels of sustainable aviation fuels** for the flights originating in the EU regardless of the destination

- In force since **January 1, 2024**
- Targets for SAF and **synthetic SAF** blending
- It will increase demand, investment, and infrastructure for SAF
- It **prohibits** member states from having national SAF measures of any kind



Both minimum shares can be met with **hydrogen as a fuel** in aircraft (renewable and non-fossil low-carbon hydrogen), along with **synthetic low-carbon aviation fuels** (produced from non-fossil low-carbon hydrogen).

Additional measures to support SAF

- Establishing **The Renewable and Low-Carbon Fuels Value Chain Industrial Alliance** to enhance the cooperation in the SAF value chain.
- **Financing** to de-risk SAF production at all stages of technology maturity, notably through funding instruments like Horizon Europe, Innovation Fund, and InvestEU.
- Accelerating and facilitating qualification of **new SAF pathways** through establishment of the EU SAF Clearing House.

[1] The power-to-liquid obligation will be introduced from 2028 at 0.2% of total jet fuel demand.
Sources: European Union; GOV.UK; Kearney Energy Transition Institute analysis

EU Renewable Energy Directive

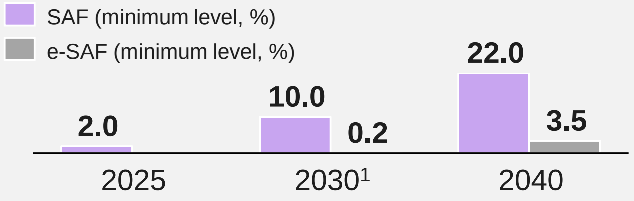
The Renewable Energy Directive (RED III, 2023 revision) establishes targets for increased renewable use in the EU. For the **transport sector**, following targets are set:

- **14.5% greenhouse gas intensity reduction** in transport thanks to the use of renewables by 2030; or
- at least **29% of renewables** within the final consumption of energy in the transport sector by 2030.

SAF, to be eligible for ReFuelEU, must be **compliant with the RED II sustainability criteria.**

United Kingdom mandate

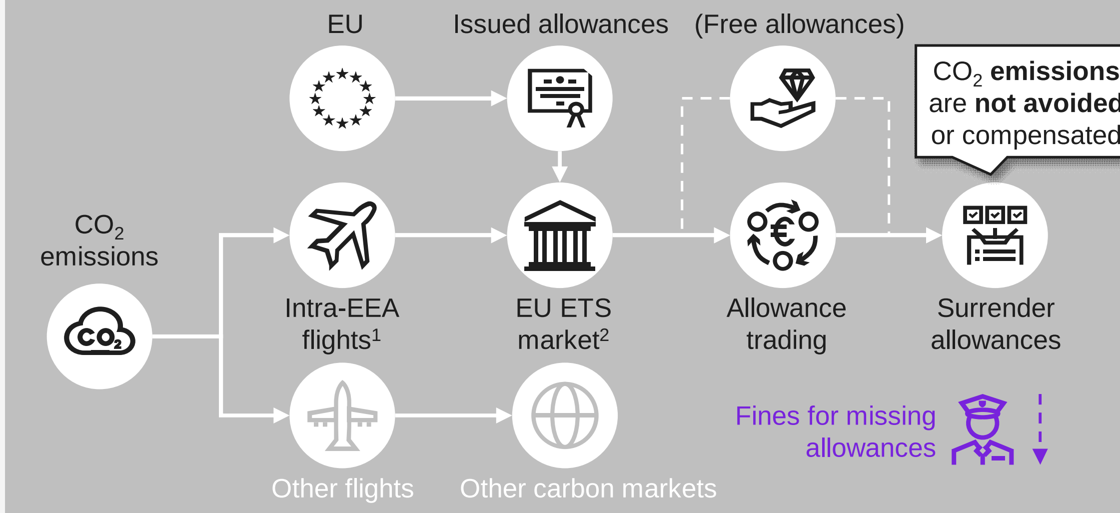
Sustainable Aviation Fuel mandate: From 2025, a legal obligation is set on fuel suppliers in the UK to supply an increasing proportion of SAF over time.



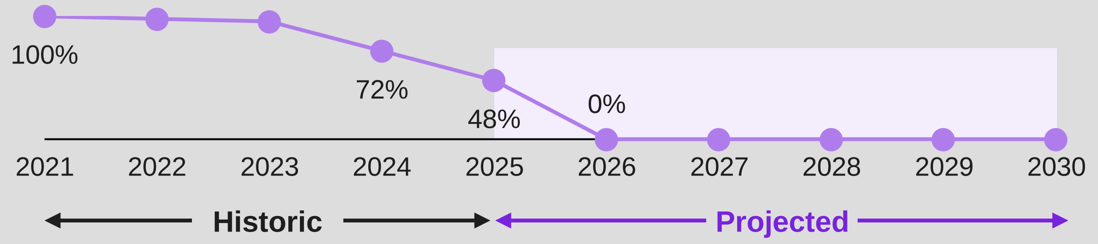
Air Passenger Duty: A tax charged on passengers flying from the United Kingdom. Its rates vary by destination and travel class.

Aviation was included in the EU ETS in 2012; reduction of allowances along with phasing out of free allowances by 2027 will result in higher CO_2 costs for conventional jet fuel under this scheme

Allowance trading scheme



Free allocated emissions reduction during Phase IV of the EU ETS relative to 2021



Details

Emissions cap reduction during EU ETS Phase IV (2021–2030)

- **2.2%** annual decrease from **2021–2023**
- **4.3%** from **2024–2027**
- **4.4%** from **2028**

From January 2025, EU ETS introduces the monitoring and report of non-CO_2 effects of aviation emissions.

Free allocation reduction timeline

- **2023 and prior:** 82% of aviation allowances allocated for free
- **2024:** free allocation reduced by 25%
- **2025:** free allocation reduced by 50%
- **2026:** 0% free allocation – full auctioning begins

Activities covered and exceptions

- Applies to all commercial aircraft operators (EEA-based and foreign carriers) for flights within the EEA, Switzerland, and the UK under the EU-UK Trade Agreement.
- 3% of allowances reserved for new entrants and fast-growing airlines.
- **From 2024–2030, 20 million allowances from the aviation cap** are reserved to subsidize eligible **sustainable aviation fuels (SAF).**

Fit for 55 reforms – CORSIA alignment

- **Exemption of intra-EEA, UK, and Swiss flights from CORSIA obligations.** For extra-EEA routes, EU carriers must comply with CORSIA, specifically for flights to participating countries.
- These changes position the **EU ETS as a more stringent alternative to the global CORSIA scheme**, which covers only emissions above 2019 baselines (higher than for baseline for EU ETS in 2021) and relies on low-cost offsets.

[1] EEA is European Economic Area; [2] ETS is Emissions Trading System
Sources: European Commission, 2025, Climate Action: Reducing emissions from aviation; Kearney Energy Transition Institute analysis based on desktop research

By the end of 2024, the US had several initiatives in place to accelerate emissions reductions by scaling SAF and pioneering improved aircraft technologies, but progress across the board is variable

Category	Policy	Key features and targets	Progress to date
SAF[1]	**SAF Grand Challenge** (DOT, DOE, USDA)[2,3,4]	– **≥50% life cycle GHG emissions reduction** vs. conventional jet fuel by scaling SAF production and use – **3 billion gallons/year production** by 2030 – **35 billion gallons/year** production by 2050	**Production <16 million gallons/year;** 2030 goal appears feasible with clear road map but 2050 remains highly challenged by feedstock and logistics constraints.
	IRA SAF tax credits (IRS, DOE)[5,6]	– Incentivize SAF Grand Challenge targets via **Clean Fuel production Credit up to $1.75/gallon (base $1.25 plus bonus)**	**Credits spurred investment;** pipeline projects underway (e.g., Pine Bend, Gevo), but risk of potential repeal
	FAST grant program (FAA)[7,8]	– **Funding for infrastructure development,** including production, blending, storage, etc. to support SAF Grand Challenge target – **$245 million total allocated**	**Grants currently being awarded;** progress modest relative to scale needed
	Renewable fuel standard (EPA)[9]	– **Obligated parties must blend renewable fuels to meet annual volume mandates** of 0.11 billion gallons/year in 2022 rising to 3 billion gallons/year in 2030	**Volumes climbed ~130 million gallons/year in 2024** but will fall short of mandate trajectory in 2030.
Aircraft technology	**CLEEN program** (FAA)[10]	– **FAA-industry partnership to reduce fuel burn and noise** – **25% CO_2 reduction** per aircraft target	**Early-phase prototypes delivered as Phase IV underway;** likely achieve incremental baseline targets but full fleet benefits likely to lag
	SFNP (NASA, FAA)[11]	– **NASA-led public-private partnership** demonstrating advanced airframe and propulsion technologies – **Up to 30% fuel burn reduction vs. current state by early 2030s**	**Project on schedule;** first flight expected in 2028
	FAA airplane fuel efficiency certification rule (FAA)	– **Implement ICAO CO_2 standards,** ensuring new aircraft meet efficiency minimum – **Mandatory compliance** for aircraft certified after 2028	**Rule finalized;** uncertainty remains around compliance technology availability but enforcement mechanism in place

[1] SAF is sustainable aviation fuel; [2] DOT is Department of Transportation; [3] DOE is Department of Energy; [4] USDA is United States Department of Agriculture; [5] IRA is Inflation Reduction Act; [6] IRS is Internal Revenue Service; [7] FAST is Fuel Aviation's Sustainable Transition; [8] FAA is Federal Aviation Administration; [9] EPA is Environmental Protection Agency; [10] CLEEN is Continuous Lower Energy, Emissions, and Noise; [11] SFNP is Sustainable Flight National Partnership

Sources: US Environmental Protection Agency, 2024, United States 2024: Aviation Climate Action Plan; Context Network, 2024, Global Agricultural Carbon: Get Smart, Stay Smart; Kearney Energy Transition Institute analysis

US policies complement technology advancements by optimizing operational efficiency, upgrading airport infrastructure, and leveraging carbon markets to achieve net-zero emissions by 2050

Category	Policy	Key features and targets	Progress to date
Operational efficiency and airport infrastructure	**NextGen Airspace Modernization** (FAA)[1]	– **Satellite-based navigation**, trajectory-based operations, data communications – **Estimated cumulative savings of more than 900 million gallons of fuels from 2010–2023** aiming for 2.8 billion by 2030	**Fuel savings on track;** accrued $2.2 billion in 2024 to reach $12.4 billion total
	VALE program (FAA)[2]	– **Grants** for airport emission reduction projects as **gate electrification and electric ground support equipment**	**Funding awarded to 141 projects at 58 airports**
	ZEV program (FAA)[3]	– **Grants** airports for funding for replacing/converting vehicles to **electric or hydrogen fuel cell vehicles**	**Initial grants awarded and early electrification projects completed**
	Energy efficiency program (FAA)	– Funding energy assessments and implementation of **energy efficiency measures** at airports **(e.g., LED lighting upgrades, solar arrays)**	**Hundreds of assessments completed** with measured site savings of 10-15% energy use
	Sustainability pilot program (FAA)	– **Supports airports** integrating sustainability into master plans; includes **energy-efficiency measures and renewable energy projects**	**Majority of large-hub airports adopted sustainability plans**
Carbon markets and offsets	**Voluntary Carbon Markets Joint Policy Statement and Principles** (USDT)[4]	– **Carbon credits should meet credible atmospheric integrity standards** and represent real decarbonization – **Credit-generating activities should avoid environmental and social harm** and should support co-benefits and transparent and inclusive benefits sharing – **Corporate buyers** that use credits should **prioritize emissions reductions** within their own value chains – Credit users should **publicly disclose nature of purchased and retired credits** – **Policymakers and market participants** should facilitate **efficient market participation**, lower transaction costs, and **improve market integrity**	**Federal agencies aligned on guidance in May 2024;** private standards bodies (ICVCM, VCMI) are updating frameworks to improve market integrity but voluntary uptake and real-world offset supply remain challenged.

[1] FAA is Federal Aviation Administration; [2] VALE is Voluntary Airport Low Emissions; [3] ZEV is Zero Emission Vehicle; [4] USDT is US Department of the Treasury
Sources: US Environmental Protection Agency, 2024, United States 2024: Aviation Climate Action Plan; Kearney Energy Transition Institute analysis

In alignment with the global trend, many countries in Asia Pacific have formulated or are in the process of formulating SAF targets

Non-exhaustive
Asia Pacific

5.6 Regional regulations

Overview of various SAF mandates and goals
By country

Singapore

First in southeast Asia to set SAF mandate:
- 1% by 2026
- 3–5% by 2030, depending on SAF availability and market conditions

China

Blending targets for flights operated by Chinese airlines, both domestic and international:
- 2% SAF blend by 2025
- 15% SAF blend by 2030

India

Indicative blending percentages for international flights:
- 1% SAF target in 2027
- 2% SAF target in 2028
- 5% SAF target by 2030

Japan

Indicative blending target:
- 10% SAF by 2030

South Korea

SAF blending percentages for international flights:
- 1% SAF target in 2027

Indonesia

Blending mandate for international flights:
- 1% in 2027
- 2.5% in 2030
- 12.5% in 2040
- 30% in 2050
- 50% in 2060

Malaysia

National Energy Transition Roadmap, published in 2023, proposed establishing a SAF blending mandate:
- 1% in 2026
- 47% by 2050

Thailand

SAF blending targets:
- 1% in 2026
- Goal of gradually increasing it to 8% by 2036

ANZ

In process of finalizing targets:
- Australia: currently undertaking an impact analysis process to inform a decision on an SAF mandate
- New Zealand: 2.5% mandate in 2025 which increases to 50% in 2050 (under consideration)

Sources: Kearney Energy Transition Institute analysis

Measures to mitigate non-CO_2 emissions, especially contrails, are gaining traction globally with Europe taking the lead

Non-exhaustive

Research indicates that **SAF can reduce the mass and number of soot particles emitted**, which in turn could potentially decrease the lifetime of contrail cirrus clouds. Hence, **SAF mandates** are also effective in reducing contrails.

5.7 Non-CO_2 regulations and initiatives

European Union

Europe has started to focus on non-CO_2 effects by incorporating **monitoring, reporting, and verification** requirements as a part of its **EU ETS** mechanism:

– Starting January 1, 2025, every aircraft operator should monitor and report the non-CO_2 effects from each aircraft operating on the routes within the EEA (as well as departing to Switzerland or to the UK). From January 2027, the monitoring and reporting requirement will be mandatory for all inbound and outbound flights to the EEA. The European Commission will provide yearly information on reported non-CO_2 emissions, followed by a final report by 2027. If appropriate, a legislative proposal for mitigating non-CO_2 aviation emissions will be crafted.

This is complemented by financial support from the EU ETS **Innovation Fund** to mitigate the non-CO_2 impacts, as well as the **Horizon Europe** research program.

EU research initiatives on contrails	
AEROPLANE[1]	Focuses on contrail formation and the contrails' impact on cirrus clouds' heat-trapping capacity.
E-CONTRAIL[2]	Using artificial intelligence to help air traffic managers predict and prevent contrails.
CICONIA[3]	Aims to describe, measure, and forecast the climate impacts of aviation, including contrails.
CONCERTO[4]	Building digital solution which piggybacks on current air traffic management infrastructure, using decision-making algorithms and cutting-edge climate science to minimize non-CO_2 pollutants, such as engine particles (nitrogen oxides) and persistent contrails.

[1] Full name = Advancing mEasures to Reduce aviatiOn imPact on cLimate and enhAnce resilieNce to climate-change
[2] Full name = Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness
[3] Full name = Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment
[4] Full name = dynamiC cOllaboration to geNeralize eCo-friEndly tRajecTOries
Sources: SESAR Joint Undertaking, 2025, European ATM masterplan; FAA, 2025, Contrails research roadmap; GOV.UK, 2022, Jet Zero Strategy; Kearney Energy Transition Institute analysis

The United States

In January 2025, a **national contrails research program** was unveiled to study how contrails form, persist, and impact the environment:

– **Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration (NOAA)** have partnered to lead this initiative.
– It also includes research organizations, aircraft and engine manufacturers, airlines and operators, and associated customers and shareholders.

The United Kingdom

The UK's **Jet Zero strategy,** formulated in 2022, aims to reach net zero emissions from aviation by 2050 and includes a pillar to address non-CO_2 emissions. Key plans include:

– Exploring whether and how non-CO_2 impacts could be included in the scope of the **UK ETS**
– Collaborating with scientists and industry via the Jet Zero Council SAF Delivery Group to advance understanding of **SAF blend flights' non-CO_2 impacts**
– Determining at what point **contrail avoidance trials** in the UK can be run

NO_x emissions standards for aircraft engines have been made more stringent over time

Recent studies have attributed global temperature increase of **~0.05°C in 2023-24** to International Maritime Organization's 2020 regulation which mandates lower sulphur limits in the fuel oil leading to **lower sulphur emissions from the shipping sector.**

Similarly, reduction in **NO_x** could potentially lead to global temperature increase as its **cooling effects**, often underestimated, are diminished.[2]

5.7 Non-CO_2 regulations and initiatives

Reducing nitrogen oxides (NO_x) emissions

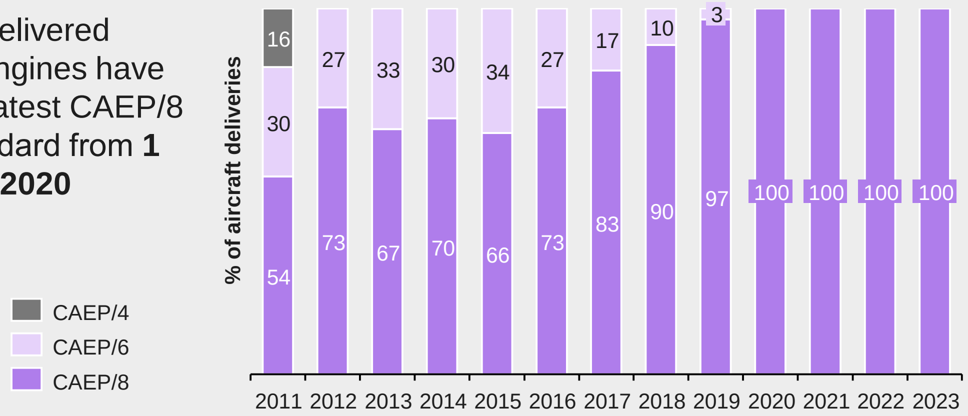
ICAO, through its Committee on Aviation Environmental Protection **(CAEP)**, has developed a series of NO_x emission standards for **aircraft engines**[1]:

- **CAEP/2 to CAEP/8:** The NO_x standards for aircraft engines became more stringent between 1992 and 2010 and are typically referred to by the CAEP meeting in which they were agreed (CAEP/2, CAEP/4, CAEP/6, and CAEP/8, which was the last update published in 2010).
- NO_x limits are defined as the mass (Dp) of NO_x emitted during the **LTO (landing and takeoff) test cycle** and divided by the rated thrust of the engine, expressed in grams of NO_x per kiloNewton of thrust (g/kN).
- **Engine efficiency**: The standards account for thermodynamic efficiency as development of more fuel-efficient engines is leading to higher overall pressure ratio (OPR), which in turn tends to increase NO_x emissions. Hence, **the higher the OPR, the higher the regulatory limit.**

Share of delivered aircraft that meet CAEP NO_x standards

(%, within the European fleet)

All new delivered aircraft engines have met the latest CAEP/8 NO_x standard from **1 January 2020 onward**



[1] ICAO Annex 16 Volume II contains international aircraft engine emissions standards [2] Analysis is subject to scientific uncertainties as other factors contributing to warming have to be considered
Sources: ICAO, 2025, Environmental Report; EASA, 2025, Aircraft engine environmental standards; Clean Air Fund, 2025, The science behind cutting shipping emissions and short-term global warming; Kearney Energy Transition Institute analysis

Future developments

Tackling NO_x emissions in a cruise mode:

- Current regulations are based on LTO cycle but there's growing understanding that cruise-phase NO_x emissions significantly impact global air quality and climate.
- Historically, it has been accepted that controlling LTO NO_x would control cruise/climb NO_x to a high degree.
- However, in the CAEP/13 cycle, analysis considering new technology combustors and the several stages of the cruise phase showed that cruise/climb emissions can depend differently on the engine power points compared to LTO cycle.
- This could result in a scenario where two of the most modern engines could have similar values in the LTO NO_x metric, while they might have very different cruise NO_x performance.
- As a result, ICAO, at CAEP/13 meeting (February 2025), decided to develop **complementary cruise NO_x metrics.**

6. Aviation market evolution and projections

Kearney18/M

All segments are expected to register strong growth in the future with SAF emerging as a key net zero lever

Emission reduction potential	Airlines are upgrading fleets to new-generation aircraft that cut **CO_2 emissions by 25%** and significantly **reduce NOx** compared to older models.
Passenger segment market	Passenger traffic demand is set to **grow rapidly until 2027** before stabilizing at pre-COVID levels in the long run.
Cargo segment market	World freighter fleet in service will increase **more than 50% by 2043** as air cargo traffic continues to increase.
Business segment market	Business fleet replacement and expansion plans aim to **replace 19% of today's fleet within five years.**
Military segment market	Pilot SAF projects have been introduced but **widespread adoption in militaries remains challenging** due to the focus on maintaining capability, preparedness, or interoperability.
SAF	Most airlines plan to ramp up SAF consumption in their operations from **less than 1% currently** to **10% by 2030** and an average of **41% by 2050.**
Fleet renewal	**Slower aircraft deliveries**, due to ongoing supply chain bottlenecks, are delaying fleet renewal benefits to airlines.

Sources: Kearney Energy Transition Institute analysis

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Market cargo players are taking steps across different levers to decarbonize their operations

Net zero targets and initiatives
For top air cargo players

Non-exhaustive

Company	FedEx	UPS	Qatar Airways Cargo	DHL	Cargolux	Lufthansa Cargo
Overall goal	Carbon neutral by 2040	Carbon neutral by 2050	Carbon neutral by 2050	Net zero by 2050	Carbon neutral by 2050	Carbon neutral by 2050
Technology improvements	Retiring entire MD-11 fleet by the end of FY28 to shift to Boeing, ATR, and Cessna SkyCourier	Retiring current fleet of MD-11 and introducing new planes such as Boeing 767-300F Testing electric vertical takeoff and landing (eVTOL) aircraft in UAE	Transitioning to Boeing 777-8F fleet First to use GE's new engine wash tech (360 Foam Wash system) to increase fuel efficiency	Phased deployment of new Boeing 777F and B777-200LR Ordered up to 12 all-electric Alice cargo aircraft (from Eviation) to be in operation from 2027	Replacing its aging 747-400 freighters with 777-8F aircraft First to reach 1 million hours on GE's engine, Genx; remains a leader in total operating hours on this engine	Replacing four-engine aircraft types with more efficient twin-engine long-haul jets AeroSHARK technology, a special coating reducing the frictional resistance by 1%
Sustainable aviation fuels	30% SAF by 2030	30% SAF by 2035	10% SAF by 2030	30% SAF by 2030 Leader in SAF with 14% share of all SAF used globally in 2023	Agreement to purchase SAF from Norsk e-fuel and has indicated recently a plan to move into SAF production and distribution	One of the world's largest SAF consumers
Operation and route efficiency	Programs for taxiing and lightweight cargo containers Testing flight trajectory optimization	Its fuel conservation efforts include computer-optimized flight routes, aircraft taxi time management, etc.	Implemented over 80 projects as part of Fuel Optimisation Programme, including enhancing flight paths and continuous descent approaches	Washing the engines before the flight to improve aerodynamics Optimizing the routes through technology	Implemented a digital platform to streamline operations, from landing to takeoff, for real-time monitoring and optimization	AI tool OPSD (Operations Decision Support Suite) helps select the most efficient aircraft for a route
Policy and regulations	Not buying carbon offsets currently but plans to in the latter half of the next decade	Currently buys carbon offsets	Currently buys carbon offsets	Currently buys carbon offsets	No mention of buying carbon offsets	Currently buys carbon offsets

Sources: Kearney Energy Transition Institute analysis

Kearney18/MET.0000186.01/NL/ll/01

SAF leads decarbonization strategies, with most airline companies currently using less than 1% SAF in their operations, targeting 10% by 2030 and an average of 41% by 2050

Illustrative; non-exhaustive

Airline	SAF 2030	SAF 2050	Air traffic management and flight operations	Sustainable ground operations	Fleet optimization and retrofit	Aircraft operational efficiency	Hydrogen propulsion development	Batteries propulsion development
American Airlines[1]	10%	NZE[2]	✓	✓	✓	✓	✓	✓
Delta Airlines[1]	10%	>95%	✓	✓	✓	✓	✓	✓
United Airlines[1]	5%	NZE	✓	✓	✓	✓	✓	✓
Air France/KLM[1]	10%	70%[3]	✓	✓	✓	✓	✓	✓
Lufthansa[1]	6%[3]	70%[3]	✓	✓	✓	✓	✓	✓
IAG	10%	NZE			✓	✓		
Ryanair[1]	12.5%	NZE		✓	✓	✓		
Singapore Airlines	5%	NZE	✓	✓	✓	✓		
ANA	10%	NZE	✓	✓	✓	✓		
Qantas Airlines	10%	60%	✓	✓	✓	✓		
Turkish Airlines	6%[3]	70%[3]	✓	✓	✓	✓		
Qatar Airways	10%	NZE	✓	✓	✓	✓		
Emirates	1%[4]	NZE	✓	✓	✓	✓		
LATAM Airlines	5%	Carbon-neutral	✓	✓	✓	✓		
Gol Linhas Aéreas	5%	NZE			✓	✓		

Hydrogen propulsion systems **await scalability breakthroughs**, while batteries propulsion development remains limited due to technological constraints and range limitations.

Beyond SAF development, airlines **prioritize operational efficiency improvements.**

[1] SBTi committed; [2] Net-zero emissions commitments, therefore high SAF adoption rates expected; [3] EU mandates; [4] Goal to reach at least 1% of total fuel supplied at UAE airports for UAE airlines by 2031, sourced from SAF.
Sources: Kearney Energy Transition Institute analysis

Passenger traffic demand is set to grow rapidly until 2027 before stabilizing at pre-COVID levels in the long run

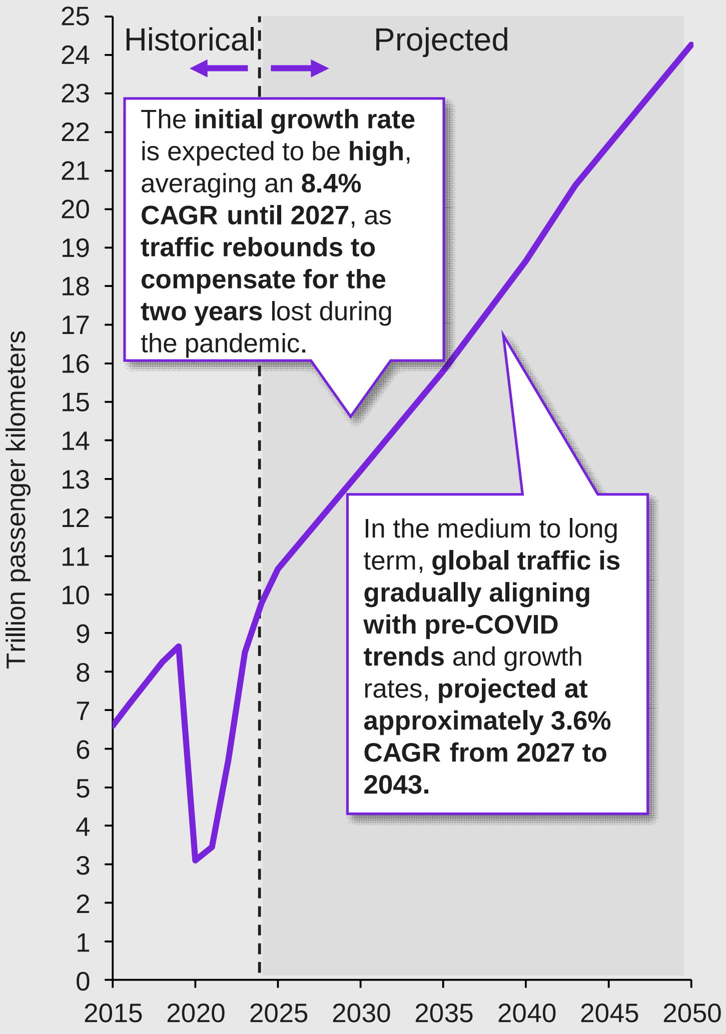
Illustrative

Passenger kilometers is the total distance traveled by all the passengers. **Revenue passenger kilometers** is a measure of the volume of passengers carried by an airline and is calculated by multiplying the number of revenue passengers by the distance traveled.

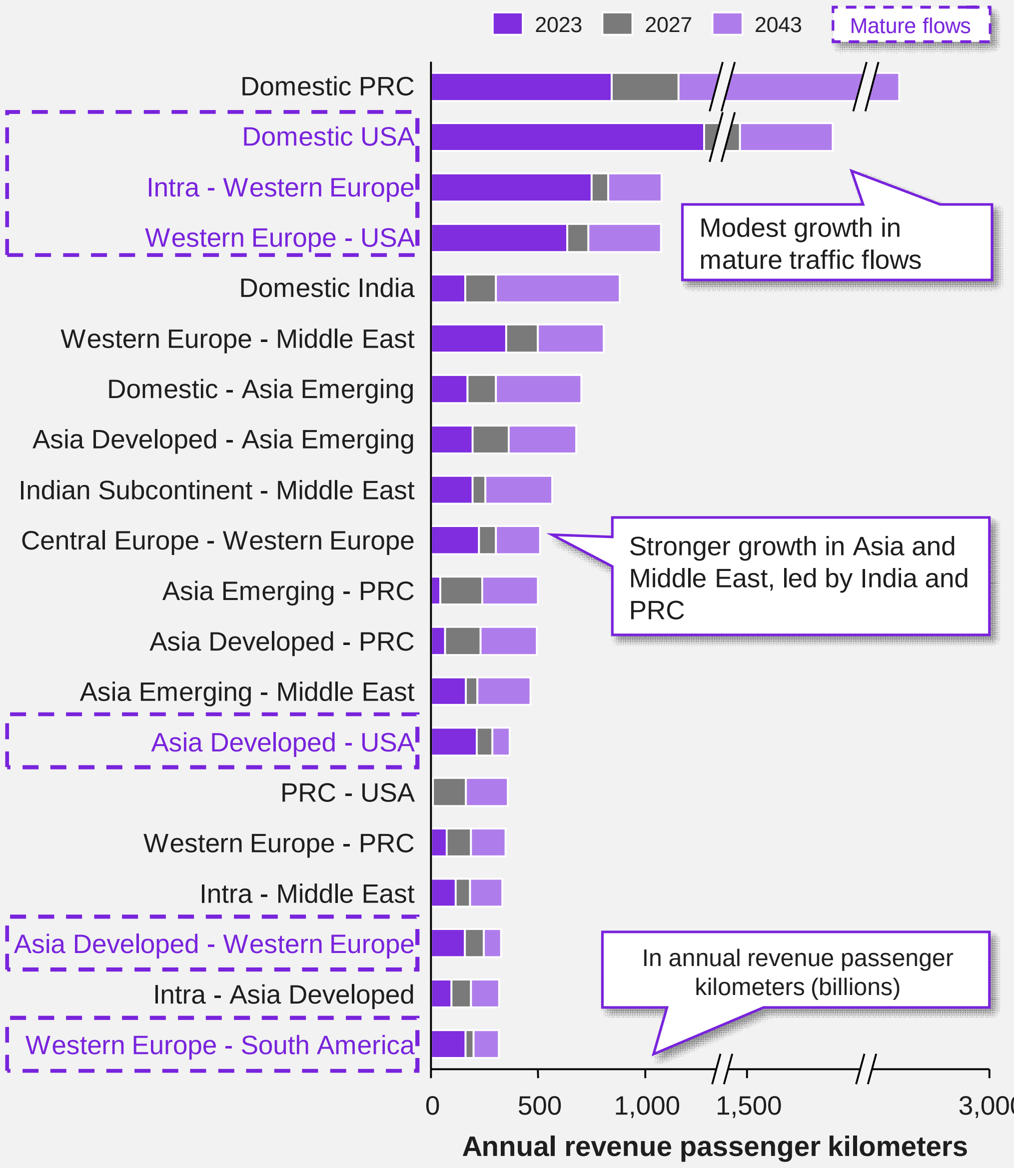
6.2 Passenger traffic

Global passenger traffic demand

Trillion passenger kilometers, 2015–2050



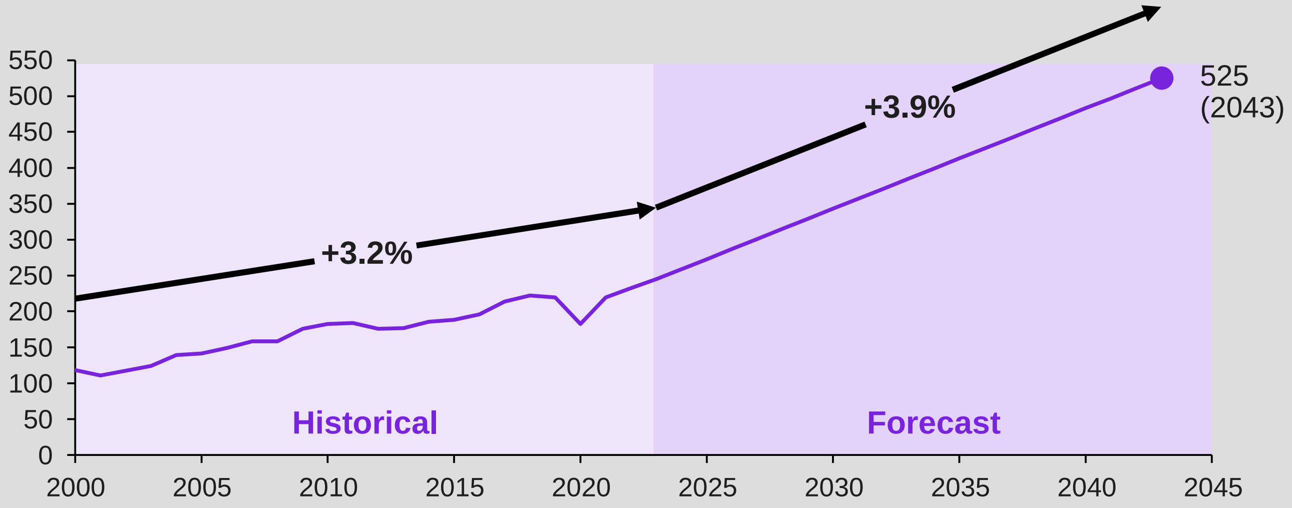
Top 20 traffic flows



Sources: Airbus, 2024, Global Market Forecast 2024; BNEF, 2022, Decarbonizing Aviation: A Climate Technology White Paper; Kearney Energy Transition Institute analysis

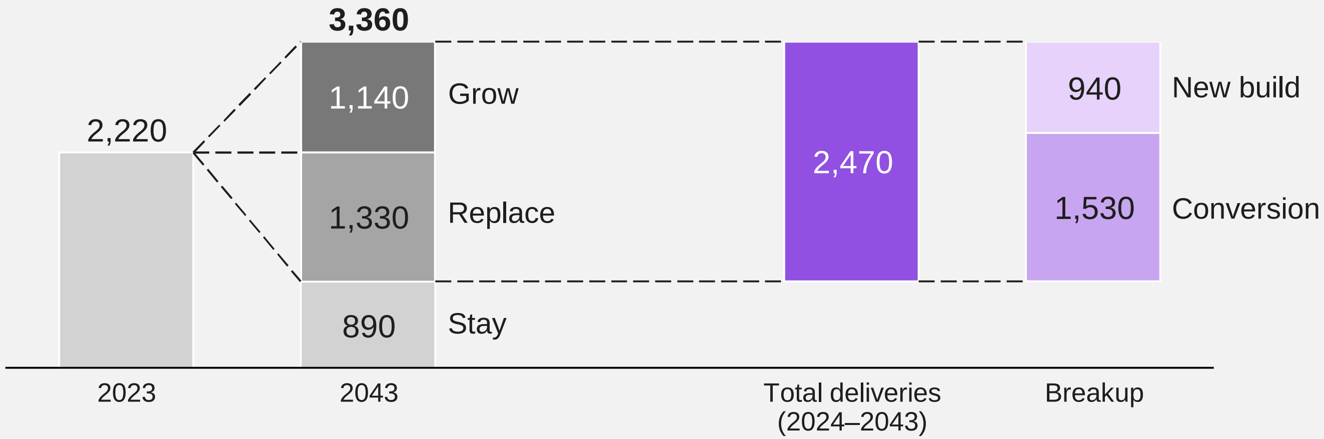
Propelled by a strong growth trend in air cargo traffic, world freighter fleet in service will increase more than 50% by 2043

World air cargo traffic
Billion freight tonne kilometers



- Express air cargo growth will outpace general air cargo over the forecast period.
- **East Asia – North America corridor** will continue to dominate the air cargo traffic

World cargo fleet
# of aircraft, 2023 and 2043



The expected global demand of **2,470** aircraft will consist of:

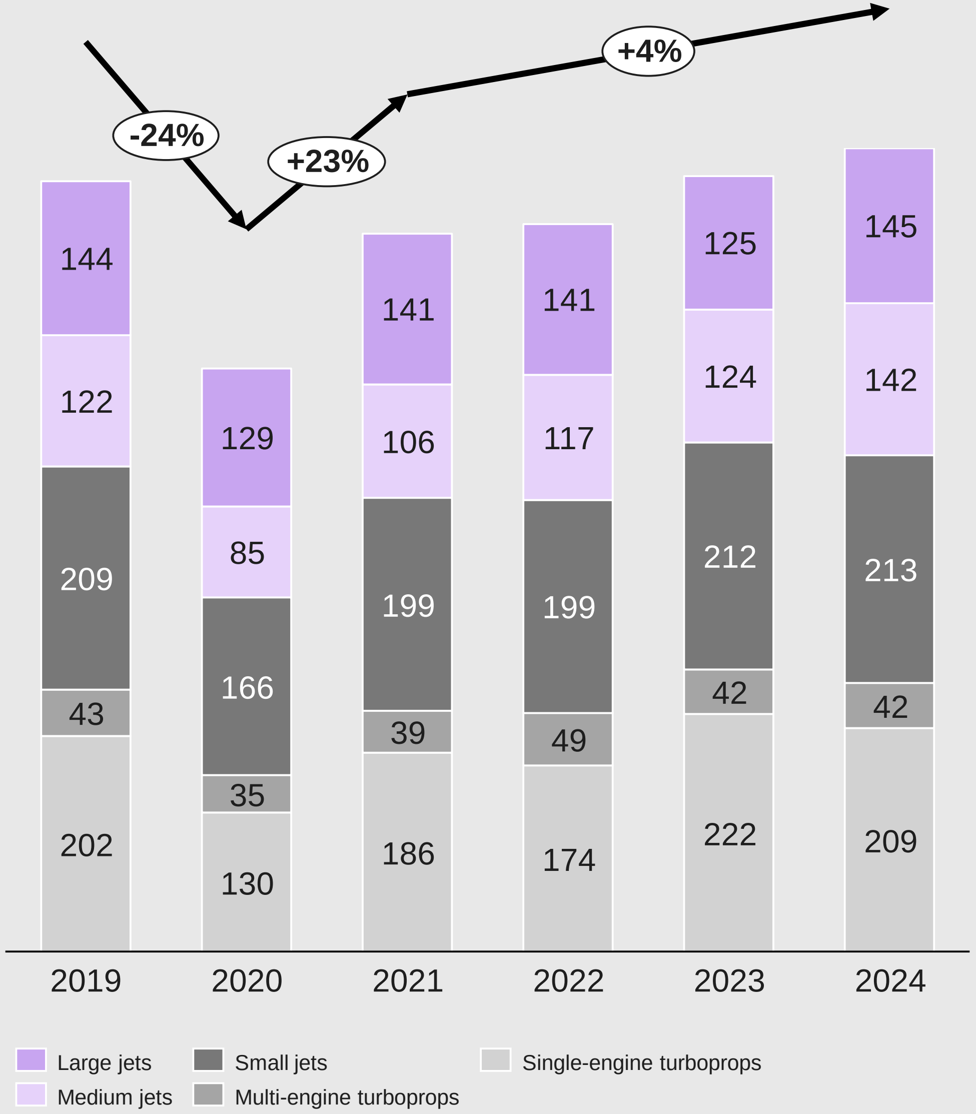
- **970** single-aisle (10t–40t) aircraft
- **880** mid-size wide-body (40t–80t) aircraft
- **620** large wide-body (> 80t) aircraft

6.3 Cargo traffic

Sources: World Bank, 2025, World Development Indicators - Air transport freight; Airbus, 2024, Global Market Forecast; Boeing, 2024, World air cargo forecast; Kearney Energy Transition Institute analysis

The business jet market has recovered rapidly, surpassing 2019 levels, and is expected to stabilize around 900 new aircraft deliveries per year by 2030

Business jet deliveries by aircraft category
Units, 2020–2024



- **The business jet market saw a major downturn in 2020**, with flights dropping significantly **due to global lockdowns.**
- However, **private aviation rebounded quickly** as travel restrictions eased, **with concerned individuals and corporations turning to business jets** for safety, flexibility, and reliability.
- **New aircraft deliveries reached 725 in 2023,** surpassing 2019 levels. **Across the five major business jet OEMs,** they forecast delivery growth of **11% in 2025 compared with 2024.**[1]
- Fleet replacement and expansion plans indicate that **19% of today's fleet will be replaced within five years.**
- **Toward 2030,** the market is expected to stabilize at a high delivery baseline, reaching approximately **850–900 new aircraft deliveries** per year.

[1] The five major business jet OEMs are: Bombardier Aerospace, Gulfstream Aerospace, Dassault Aviation, Textron Aviation (Cessna), and Embraer
Sources: Aviation Week Network, 2025, Commercial Aviation Fleet & MRO Forecast; Honeywell, 2023, Business Aviation Outlook Report; Kearney Energy Transition Institute analysis

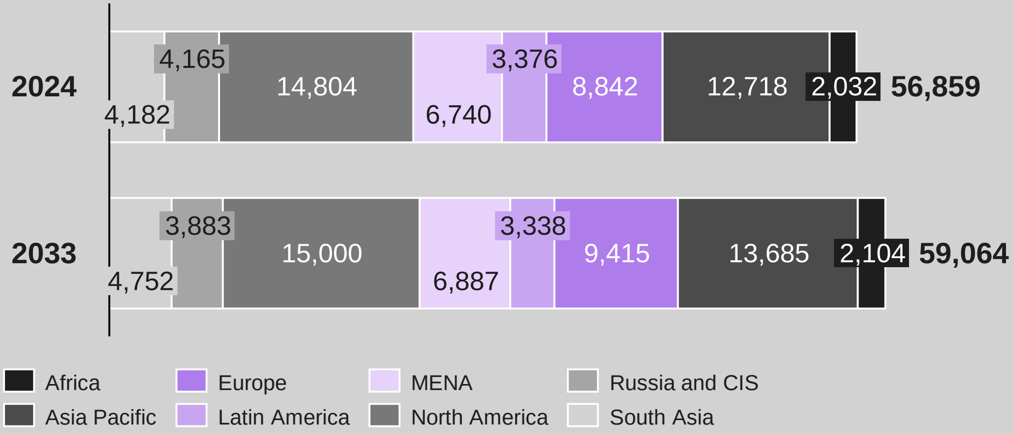
6.4 Business jet traffic

Sustainable aviation fuel can help militaries reduce dependency on imported fossil fuels, mitigate supply chain risks, and improve environmental footprints

However, widespread adoption of SAF in the military remains challenging due to the focus on military capability, preparedness, and interoperability.

Military aircraft in service

By region, 2024–2033



Key insights

- The US Air Force (USAF) is a significant user of aviation fuel, consuming **about 10% of the entire domestic supply.**
- The global fleet of military aircraft is projected to grow by **3.9% over the next 10 years**, although these numbers might increase with current geopolitical tensions.
- Growth is chiefly driven by **Asia** where the region's expanding economies are able to support expansion of air military power capabilities.
- **The North American fleet** is the largest but is expected to log only a small increase over the forecast period.

Sustainable aviation fuels initiatives

Select examples

US Air Force

- In 2021, the USAF invested in Twelve, a chemical transformation company of the fossil-free jet fuel from CO_2 called E-jet.
- The Department of Defense inked a USD 65 million deal with SAF start-up Air Company in 2023.

Royal Air Force

- In 2022, the Royal Air Force (RAF) and industry partners carried out a world first 100% sustainable aviation fuel flight using RAF Voyager—the military variant of an Airbus A330, a military transport plane.

Royal Australian Air Force

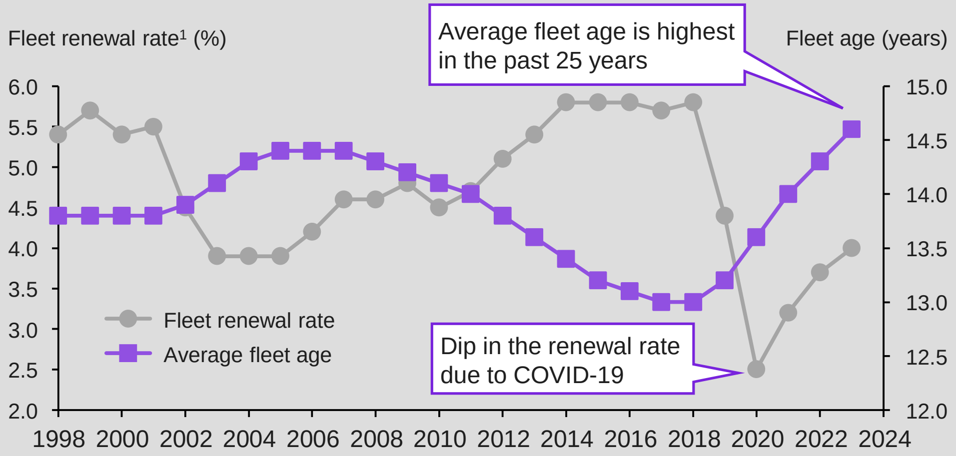
- A 12-month pilot program using sustainable aviation fuel has recently commenced at its military base in Victoria, Base East Sale (2025).

Sources: Aviation Week, 2025, 2024 Market summary report (Military); Kearney Energy Transition Institute analysis

Slower aircraft deliveries, due to ongoing supply chain constraints, are delaying fleet renewal benefits to airlines

World fleet renewal rate and average fleet age

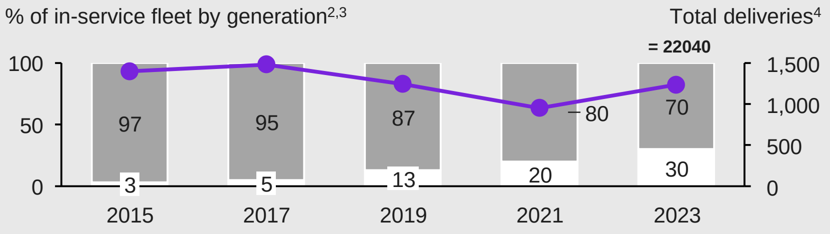
1998–2023



- Airlines modernize their fleets for lower fuel consumption and the associated carbon emissions reduction as a new generation aircraft can realize **25%** CO_2 savings compared to the previous generation.
- However, the pace of new aircraft deliveries plummeted, firstly during the COVID-19 pandemic (by **50%** in 2020 compared to the peak seen in 2018) and since then, because of supply chain challenges.
- The drop in deliveries comes in the background of burgeoning global backlog, which climbed to **17,000 aircraft in 2023.**
- As a result, the average age of the global fleet increased by over 18 months over the past 5 years, from just over **13 years in 2018 to 14.6 years in 2023.**

In-service fleet split and deliveries

2015–2023

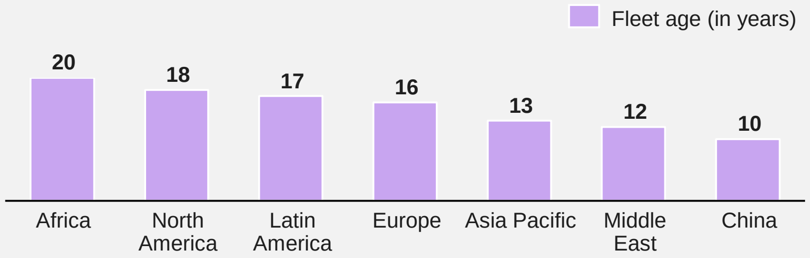


Considering the recent delivery volumes, it might take ~**10–16 years** to replace the old generation aircraft from the current in-service. fleet

Aircraft deliveries | Old generation | New generation

Average age varies by region

2024



- **Asia Pacific and the Middle East** have the youngest fleets while Africa's fleet is the **oldest.**
- Recently, most of the new aircraft went to Asia Pacific, the Middle East, and Latin America.
- Regional fleet sizes as well as demand for new aircraft usually correspond to their respective traffic levels.

[1] Renewal rate refers the value of number of delivered aircraft divided by the total number of fleet at the beginning of applicable calendar year; [2] For passenger aircraft above 100 seats; [3] New generation aircraft: A220, A320neo family, A330neo, A350, 737Max, 777X, 787; [4] Total deliveries from Airbus and Boeing
Sources: Airbus, 2024, Global market forecast; Cirium, 2025, Shaking out the Airbus and Boeing 2024 delivery numbers; Volgina, N. and Kidun, E., 2021, Global Civil Aircraft Industry: Modern Trends; IATA, 2024, Chart of the Week (May 10); Aviation Week, 2024, Fleet discovery; Kearney Energy Transition Institute analysis

6.6 Fleet renewal

7. Environmental and social impacts

The aviation sector faces various environmental challenges and increasing social scrutiny

Carbon footprint per various modes of transport	**Flights** emit similar direct CO_2 as other transport modes but **have double the climate impact due to radiative forcing.**
Aviation emissions by flight range	**Short- and medium-haul domestic flights** are the largest contributors to global aviation emissions, **accounting for approximately 63% of total CO_2 emissions.**
Aviation infrastructure land footprint	**Aviation and road infrastructure** require similar land areas, both of which are **less than what rail infrastructure needs.**
SAF feedstock land requirements	**An increased SAF demand could shift crops from food to fuel**, with **HEFA**, for example, potentially **requiring up to 76%** of the **global soybean harvest area** in 2030.
Noise pollution	**Noise peaks during takeoff at 90–110 dBA**, posing significant nuisance to local populations, but is decreasing thanks to **improved engine designs and new propulsion systems.**
Local air quality	Aviation emissions impact local air quality, **particularly in and around airports**
Social benefits and challenges	**Aviation** supported around **86 million jobs** and **contributed 4.1 trillion USD to GDP** globally in 2023, but the sector **faces increasing social scrutiny.**

Sources: Kearney Energy Transition Institute analysis

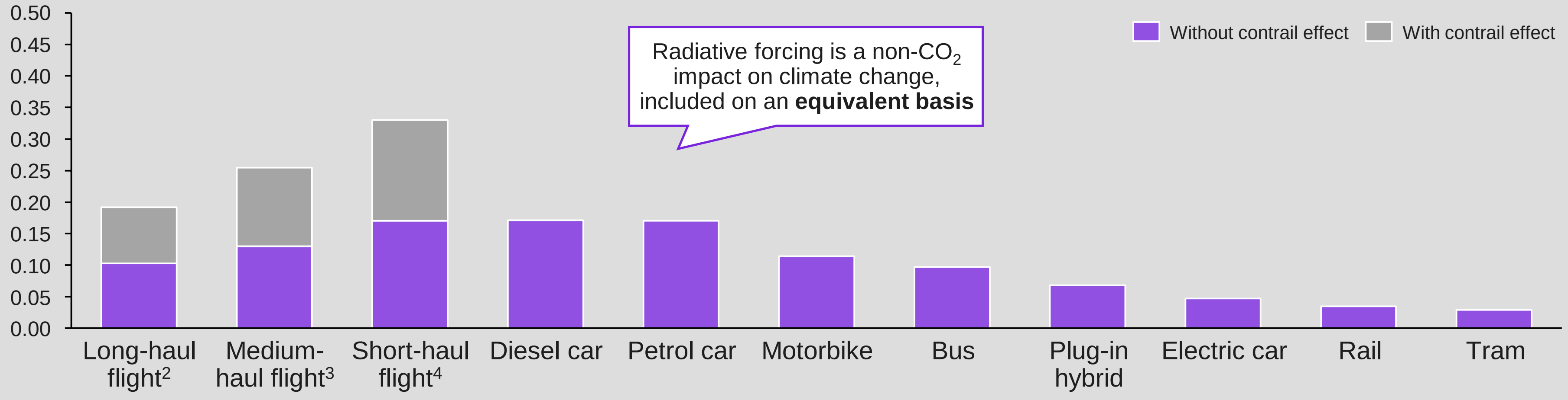
7.0 Chapter summary

Flight emissions are comparable to other modes of transportation considering direct CO_2 emissions alone, but overall climate impact is about two times greater accounting for contrail effect

Illustrative

Carbon footprint per passenger-kilometer traveled for selected modes of transport[1]

$kgCO_2e/pkm$, 2022



Calculation methodology for aircraft emissions

– Aviation emissions are commonly measured on a standardized per passenger-kilometer basis for **ease of comparison between flight routes, aircraft types, ticket classes, airlines, and against other transport modes.**

– Calculated as follows:

Emissions for first-class ticket is ~1.7x greater in long-haul flights due to larger seats and additional services provided.

$$\text{Emissions per passenger kilometer} = \frac{\begin{bmatrix}(\text{Fuel consumption} \times \text{Emissions factor}) + (\text{Passenger load} \times \text{Emissions per passenger}) \\ +(\text{Cargo load} \times \text{Emissions per unit cargo}) + \text{Contrail effect}\end{bmatrix}}{\text{Total passenger distance}}$$

Note: Emissions [$kgCO_2e/km$], Fuel consumption [kg_{Fuel}], Emissions factor [$kgCO_2e/kg_{Fuel}$], Passenger load [Absolute number], Emissions per passenger [$kgCO_2e$/Passenger], Cargo load [kg_{Cargo}], Emissions per unit cargo [$kgCO_2e/kg_{Cargo}$]; Contrail effect [$kgCO_2e$]; Total passenger distance [km]

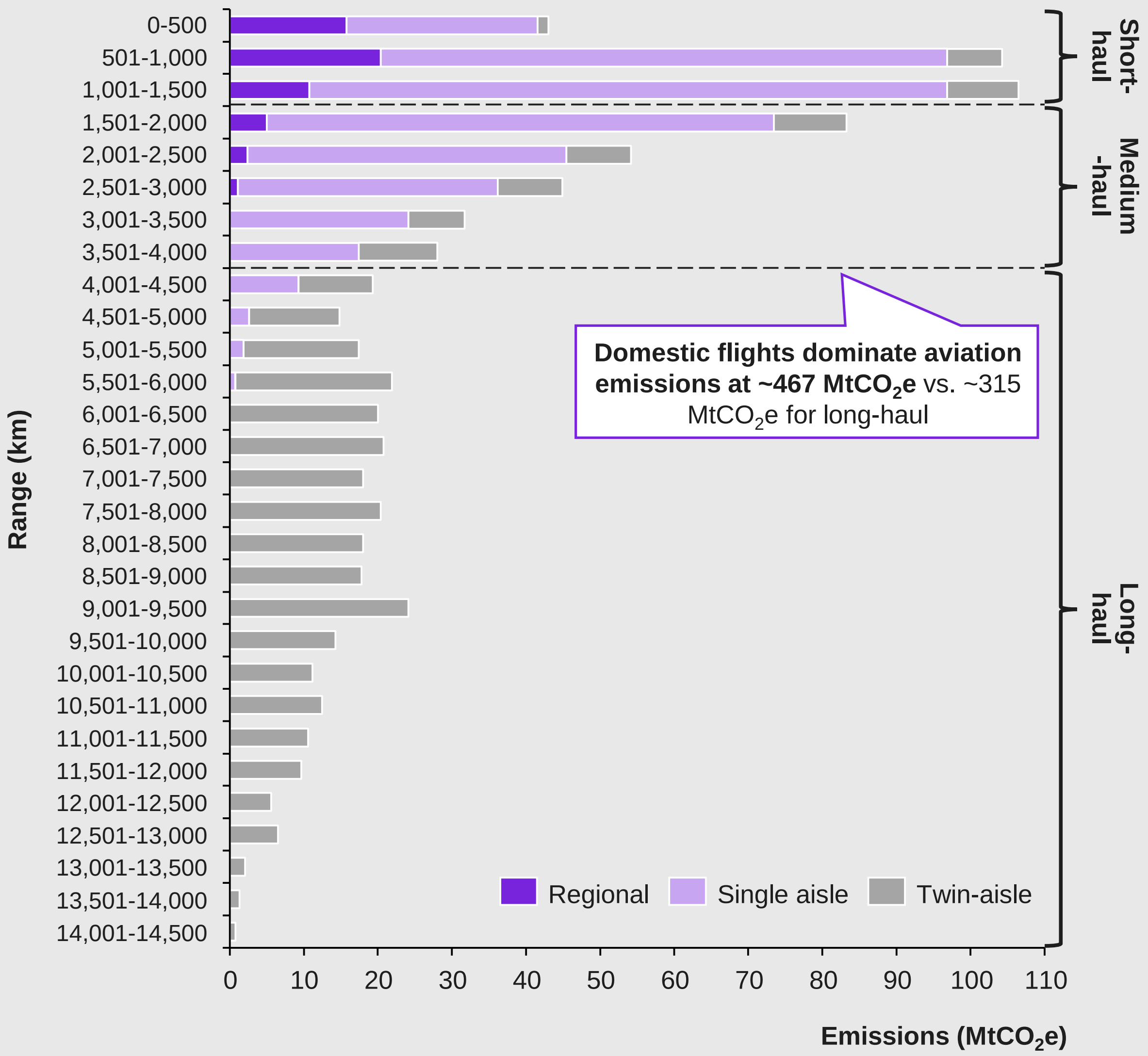
[1] These are average values; individual case values can differ significantly on a case-by-case basis.; [2] Considering economy return flight outside Europe; [3] Considering economy return flight in UK; [4] Considering economy return flight in Europe

Sources: GOV.UK, 2022, Greenhouse gas reporting; NASA, 2022, The Contrail Education Project; ADEME, 2022, Elaboration de scenarios de transition écologique du secteur aérien; SkootEco, 2025, Understanding the Air Travel Carbon Footprint: The True CO_2 Emissions from Flying; Kearney Energy Transition Institute analysis

Short- and medium-haul flights account for around 63% of global aviation emissions

Global aviation emissions by flight range and aircraft

$MtCO_2e$ and km, 2019



Sources: Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

Drivers for greater emissions per passenger kilometer in short- and medium-haul flights

- **Takeoff and landing fuel consumption:** A large portion of fuel is burned during takeoff and landing stages, which constitute a larger portion of domestic flights on a distance traveled basis compared to short- or long-haul.
- **Aircraft type:** Domestic flights use smaller aircraft with lower fuel efficiency per seat compared to larger long-haul flights.
- **Passenger load factor:** Longer flights have higher occupancy rates and better weight-to-passenger ratio.
- **Taxiing and ground operations:** Shorter flights spend more time taxiing and waiting on runways, increasing fuel consumption.

The ground surface requirement for aviation infrastructure is comparable to road, both of which fall below rail

Example

7.2 Land footprint

France example: Land area requirement for proposed HSR Great South-West railway project (Bordeaux to Toulouse) vs. existing transport modes[1]
Km², 2021

Train ~40.3 km²

– Great South-West Railway Project
– Link Bordeaux to Toulouse via rail
– 12.3 km² agricultural land
– 28.5 km² silvicultural land

Note upside potential in train and railway given estimates do not account for local road infrastructure required

Airplane ~11 km²

– Existing airport infrastructure
– 6.5 km² Bordeaux airport
– 4.5 km² Toulouse airport

Road ~3.8 km²

– Existing road infrastructure
– A62 Bordeaux to Toulouse
– 284 km length and assumed average width of 13.5 m

[1] HSR is high-speed rail; [2] Land designated for track and infrastructure
Sources: Global Clean Energy, 2023, Global Clean Energy Reports Largest Camelina Acreage Worldwide; Institut Montaigne, 2022, Decarbonizing Aviation; Kearney Energy Transition Institute analysis

Key insights

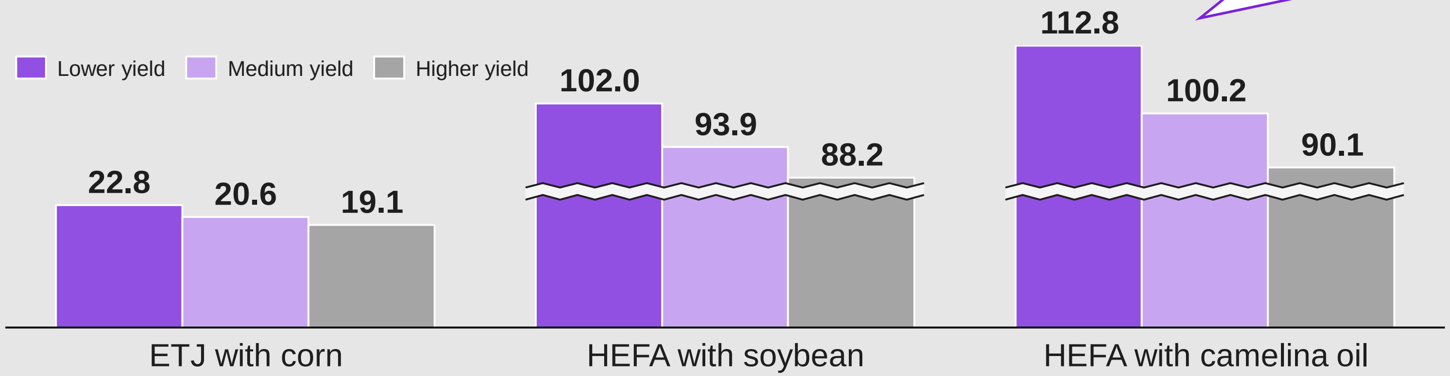
– HSR Great South-West railway project started construction in 2024 to **connect Paris to Toulouse via Bordeaux** with a total cost of ~€14.3 billion.
– **Aside from emissions,** the choice of transport mode determines the ground surface area requirement.
– The Great South-West railway project will require around **3.5 times more land area than the equivalent journey via air or road,** driven by:
  – Wide path curvature to ensure carriage alignment, stability, and passenger comfort.
  – Wider ride of way to accommodate buffer zones around the track for safety, maintenance access, drainage systems, etc.[2]
  – Multiple tracks for bidirectional traffic, varying train speeds, and service types.

Rising SAF demand to 2030 risks diverting crops from food to fuel; HEFA alone would require up to 76% of global soybean harvested area

Global feedstock land requirement per SAF production pathway

Million acres, 2030

Considering global SAF demand of **6.3 billion US gallons** in 2030



Equivalent to **9–11% of global corn harvested area planted** in 2024

Equivalent to **66–76% of global soybean harvested area planted** in 2024

Global total harvested area planted unavailable; key player, **Global Clean Energy, reported 65,000 acres in 2023**

SAF yield range and unit land requirement per production pathway

Production pathway	Metric	Case		
		Lower	Medium	Higher
ETJ with corn	Yield (gallon/acre)	268.1	329.5	391.0
	Land requirement (million acre/billion gallon)	**3.7**	**3.0**	**2.6**
HEFA with soybean	Yield (gallon/acre)	60.0	72.4	84.8
	Land requirement (million acre/billion gallon)	**16.7**	**13.8**	**11.8**
HEFA with camelina oil	Yield (gallon/acre)	56.0	63.0	70.0
	Land requirement (million acre/billion gallon)	**17.9**	**15.9**	**14.3**

Sources: FAO, 2024, FAOSTAT Land Use; Kearney Energy Transition Institute analysis

7.2 Land footprint

Aviation noise is a notable nuisance; however, noise levels are decreasing due to improved engine designs

Example

Aircraft noise pollution corresponds to unwanted sound generated by aviation activities. **During takeoff, noise peaks at 90–110 dBA,** while **ground operations**, such as APU usage and taxiing, produce lower noise levels, **ranging from 65 to 80 dBA.**[1]

Noise pollution health and societal impacts

1. **Physiological consequences**
   - Cardiovascular strain
   - Metabolic disruption
   - Sensory overload
2. **Psychological and cognitive effects**
   - Sleep disruption
   - Mental health exacerbation
   - Cognitive performance
3. **Community-level impacts**
   - Economic burdens (cost of home insulation programs)
   - Land use constraints (housing development)

7.3 Noise

Noise zoning around Liège airport

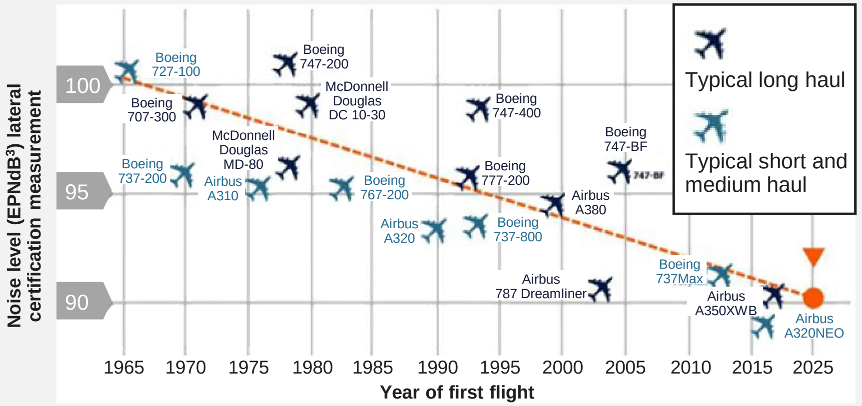
In Europe, **measurable health consequences** are observed at exposures above **45 dB Lden[2].**

Noise limits for the zones around Liège airport and location of noise monitors

1. Lden ≥ 70 dBA
2. 66 dBA ≤ Lden ≤ 70 dBA
3. 61 dBA ≤ Lden ≤ 66 dBA
4. 56 dBA ≤ Lden ≤ 61 dBA

X Location of noise monitors around Liège

Aircraft are getting quieter



- The **noise level** of aircraft engines is **decreasing**.
- **Noise level** has decreased to around **90** dB for **Airbus A350, Boeing 787, Airbus A320neo, and Boeing 737 MAX aircraft.**
- **Hydrogen-electric systems** should present significant reduction of engine noise.

[1] A-weighted decibels are used when human hearing is affected.; [2] Lden is the noise level in decibel of day, evening, and night.; [3] Effective perceived noise in decibels

Sources: IATA, 2025, Improving the local environment – noise & air quality ; ALG, 2024: Noise Around Airports: Regulation and Mitigation; ENVISA, 2023, Mitigating and Managing Noise from Airport Practices; ZeroAvia, 2024, Scaling Hydrogen-Electric Propulsion for Large Aircraft; ENVISA, 2021, Impact of aircraft noise pollution on residents of large cities; Kearney Energy Transition Institute analysis

Aviation emissions impact local air quality, particularly in and around airports during the landing and takeoff cycle[1]

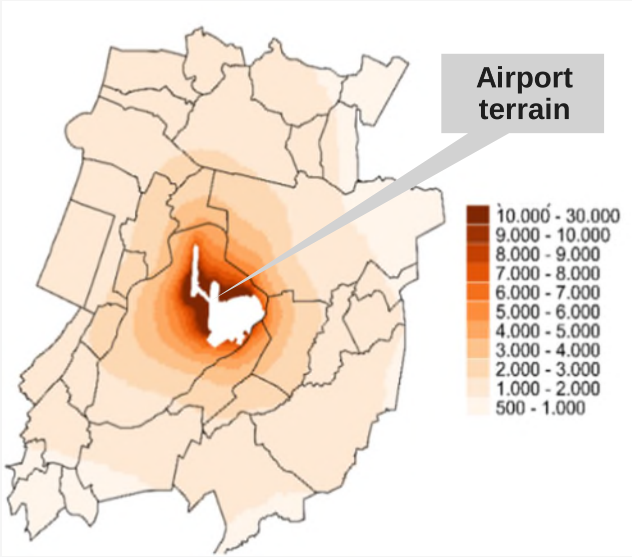
Non-exhaustive

Impact of key pollutants on air quality

The impact of aviation's emissions on air quality and human health is substantial. One of the key pollutants from jet engines is **particulate matter (PM)**, a broad term that encompasses various particles.

Pollutants	Health effects	Emission factor (kg/LTO)
NO_x	– Ground-level impacts are due to formation of NO_2 which leads to chronic respiratory diseases, especially in children. – High-altitude emissions are a dominant source of surface-level ozone and fine particulate matter.	16.29
CO	– Emitted during the LTO cycle, particularly during idling and taxiing phases. – Can reduce the blood's ability to carry oxygen, affecting the heart and brain.	9.14
Sulfur oxides	– Irritates the respiratory system and contributes to the formation of fine particulate matter (PM2.5).	1.4
Ultrafine particles (UFPs)	– They can penetrate deep into the lungs and enter the bloodstream, potentially causing respiratory symptoms, cardiovascular issues, elevated blood pressure, and even long-term effects like increased mortality and neurological diseases.	~0.53
Soot	– Damages the lungs and cardiovascular system but also transports toxic substances throughout the body.	0.26
Lead	– Small aircraft using leaded aviation gasoline (avgas) are a major source of airborne lead in the US. – Can adversely affect the nervous system, kidney function, immune systems.	NA

Emission concentration near airports is highest



UFP concentrations around Schiphol Airport, averaged from 2006 until 2019, particles/cm³

Areas in close proximity to airports experience **disproportionately higher concentrations.**

UFPs from aircraft can extend to unexpectedly large areas near airports, especially **downwind and along flight paths.**

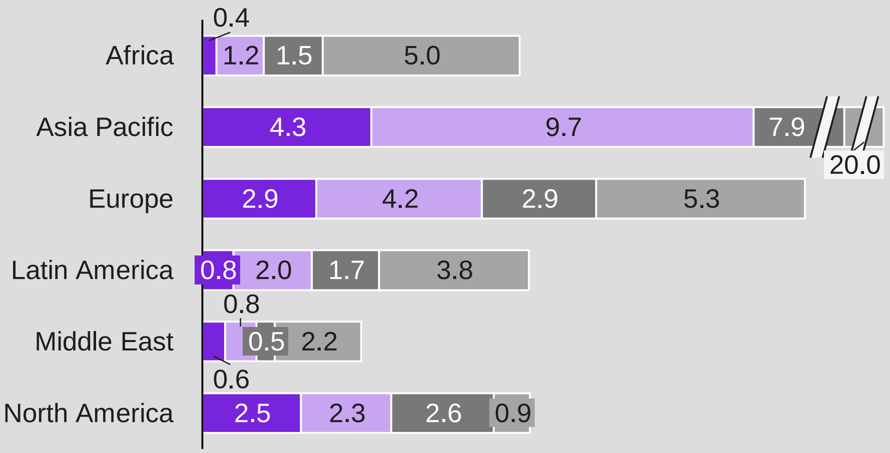
Airport emissions can interact with **existing urban pollution**, potentially worsening overall air quality and contributing to secondary pollutant formation like ozone.

[1] Other sources of pollutants from aviation (especially in and around airports) are ground support equipment, airport vehicles, auxiliary power units, fuel storage and handling, maintenance activities, on-site Power and heating and re-suspension of particulates by aircraft and ground vehicles
Sources: Seters D., Grebe S. and Faber J., 2024, Health Impacts of Aviation UFP Emissions in Europe; Kearney Energy Transition Institute analysis

Aviation supported around 86 million jobs and contributed USD 4.1 trillion to GDP globally in 2023, but the sector faces increasing social scrutiny

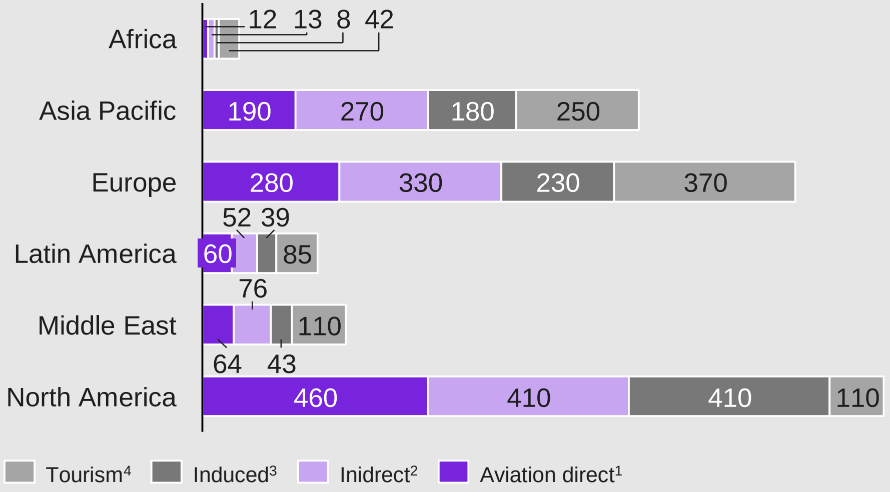
Jobs generated by aviation per region

Million jobs, 2023



GDP generated by aviation per region

Billion USD, 2023



[1] Aviation direct channel incudes the operational spending that airlines, airports, civil aircraft manufacturers, airport operators, and air navigation service providers undertake to generate profits and employ people at their operational sites; [2] Indirect channel consists of the aviation sector's procurement of inputs of goods and services from other businesses in the economy; [3] Induced channel comprises wage payments to staff in the aviation sector and the supply chain. Some or all of those wages are subsequently spent in the consumer economy, which supports further economic activity and jobs in retail and leisure outlets and their supply chains; [4] Tourism explores the economic impact arising from tourists who arrive by air and spend money on goods and services.
Sources: ATAG, 2024, Aviation Benefits Beyond Borders; Kearney Energy Transition Institute analysis

Examples of social scrutiny in aviation

Noise and community resistance

- Significant challenges around Amsterdam's Schiphol Airport, where Dutch government proposed reducing flights from 500,000 to 460,000 due to noise concerns.
- Similar capacity reductions implemented or considered in Brussels, Mexico City, Rio de Janeiro, and Dublin due to community complaints.

Environmental performance gaps

- Despite industry efforts, SAF constituted around 0.2% total fuel used in 2023, highlighting substantial gap between sustainability ambitions and implementation.
- Consumer skepticism concerning environmental taxes, often perceived as government "greenwashing" rather than effective action.

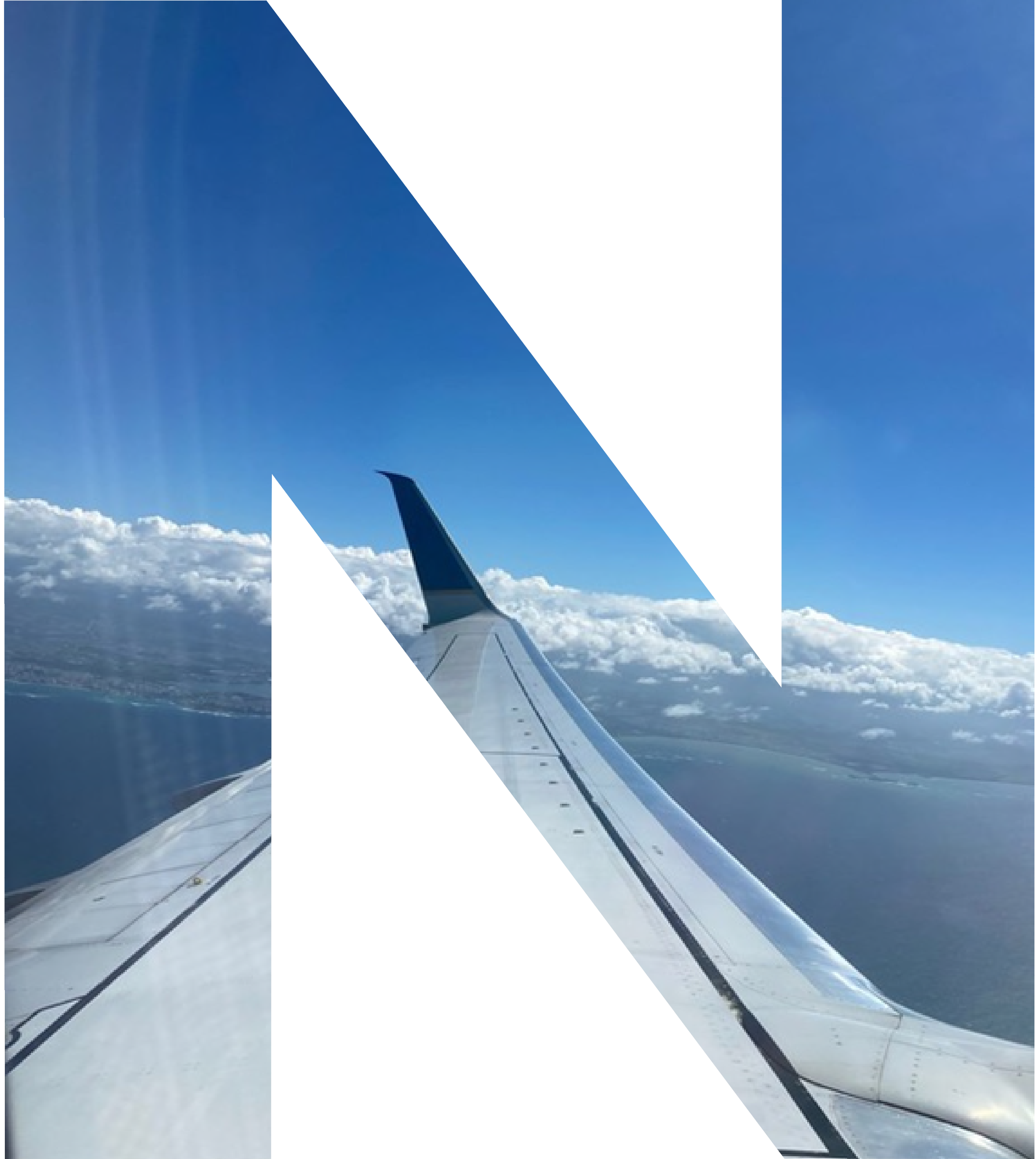
Data privacy

- Growing concerns about passenger data privacy and security with increased digitalization.
- Uneven global implementation of regulations affecting passenger rights, creating inconsistencies in cross-border transfer of passenger data.

Social movements like flight shame

- Youth-led initiatives such as the "flight shame" (flygskam) movement are significantly influencing travel behaviors, pushing for societal shifts toward eco-friendly travel practices.

8. Solutions' feasibility and scalability



Technology solutions must overcome challenges pertaining to attaining scale, speed to market, and costs

Non-exhaustive

Technology-based solutions detailed in the following slides

Achieving net zero aviation

- **Technology-based solutions are projected to account for ~90% of the emissions** reduction for the aviation sector by 2050, according to ICAO.

Sustainable aviation fuel | Technology improvements | Operation and routes efficiency | Policy and regulations

- However, **adoption hurdles create a net zero gap** between the sector's net-zero goals and current implementation.
- **Low-carbon technologies and solutions are costly, immature, and face uncertainty in scaling** quickly enough to meet climate targets.

Solution	Key challenges	Description
Sustainable aviation fuel	Feedstock availability	– Competition from other uses/industries for biomass-based SAF – Infrastructure gap for PtL pathway
	High production costs	– Feedstock scarcity inflating input costs – High capex – Immature technology (PtL)
Air traffic management	Technical limit, integration issues	– Technical incompatibilities between systems – Lack of global harmonization
Ground operations	Insufficient infrastructure	– Lack of electric charging and hydrogen handling infrastructure at the airports
Fleet renewal	Demand–supply mismatch	– Delays in production due to supply chain disruption
New propulsion systems	Technical limitations, uncertainty over costs	– Low energy density of hydrogen – Green hydrogen costs
Airframe and engine design	Regulatory and production delays, operational trade-offs	– New designs face lengthy approval timelines – Supply chain disruptions – Higher maintenance and recycling needs

Source: Kearney Energy Transition Institute analysis

Feedstock is theoretically available but is unlikely to be sufficiently allocated to SAF to meet current and future demand

SAF offers a high emissions reduction potential, ranging from 75% to 95%.

Current status

- **Global SAF production (2024):** 1 million tons; **SAF maximum blending ratio with jet fuel:** 50%
- **SAF conversion pathways:** 95% HEFA, 5% G-FT
- **Cropland for biofuel production:** ~7% of cropland globally; SAF making up only around 1% of it.
- **Feedstock required for SAF production (2024):** ~1.4 million tons of feedstock
- **Average installation refining capacity:** 0.1 to 1 million tons/year for HEFA, <0.1 to 0.5 million tons/year for G-FT

Evolution toward 2050

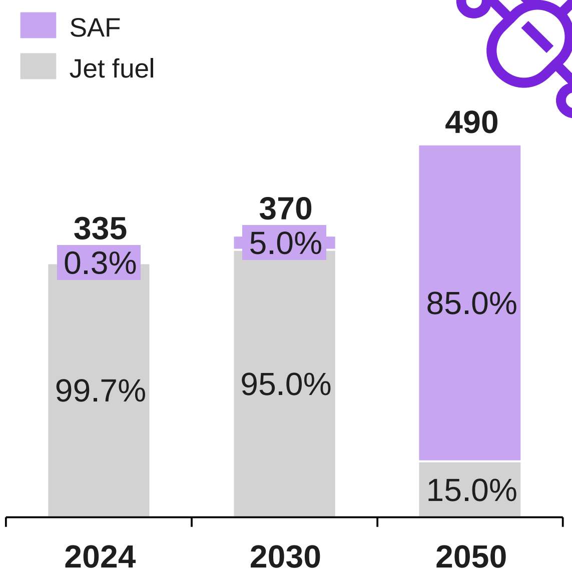
- **Feedstock needed for 100% jet fuel (~335 million tons) replacement:** ~460 million tons
- **Global SAF production (2030):** ~19 Mt, requiring **~32 Mt of feedstock, ~0.5 Mt H_2, and ~3.3 Mt CO_2**
- **Global SAF production (2050):** ~420 Mt, requiring **~960 Mt of feedstock, ~90 Mt H_2, and ~620 Mt CO_2**
- **Industrial requirements:** refining installations to increase by ~25 to 700 times, alongside the development of low-carbon H_2 and CCUS technologies

Challenges

- **Feedstock supply insufficient** to meet SAF demand—other industries competition, scarcity, and regulations
- Two unlikely ways to get necessary feedstock for SAF:
  - **increase crop production**, and
  - **redirect crops** from either food or energy/biofuels to SAF
- **PtL pathway:** current green H_2 and CO_2 capture capacities reveal a significant infrastructure gap to meet SAF supply

Targets from IATA

SAF vs. jet fuel demand in Mt, %



%

replacement of jet fuel

Note: Estimates based on a SAF mix of 75% HEFA, 10% GFT, 10% AtJ, and 5% PtL by 2030 and a mix of 14% HEFA, 24% GFT, 24% AtJ, and 38% PtL by 2050. Jet fuel demand is projected to increase by 1.25 times by 2030 and 2.5 times by 2050. Meanwhile, efficiency improvements in technology are expected to result in a 2% annual reduction in fuel consumption.
Sources: IATA Sustainability and Economics, 2024, Finance: Net Zero CO_2 Emissions Roadmap; Kearney Energy Transition Institute analysis

HEFA SAF production will face high operational costs, while other pathways will encounter high capital costs

SAF production pathways cost[1]

GFT 2025
Comparison with jet fuel: ~600 USD/ton, 2–10 times less expensive than SAF

AtJ 2050
Comparison with jet fuel: ~1,400 USD/ton, 1–1.5 times less expensive than SAF

	Technology	Cost	Impact on opex	Impact on capex
2025	HEFA	~1,200 USD/ton	Constrained feedstock	Existing renewable fuel production capacity
2025	AtJ	~2,000 USD/ton	Abundant waste-based feedstock; low value	New renewable fuel production capacity required
2025	GFT	~2,400 USD/ton	Abundant waste-based feedstock; low value	New renewable fuel production capacity required
2025	PtL	~5,800 USD/ton	Abundant carbon source needs, requires further technology maturity	New renewable fuel production capacity required
2050	HEFA	~1,400 USD/ton	Feedstock prices will increase due to limited availability and competition with other industries	Stable
2050	AtJ	~1,600 USD/ton	Relies on feedstocks, which require significant pre-processing to convert into jet fuel	Technology maturity but also the need for larger facilities
2050	GFT	~1,800 USD/ton	Extensive feedstock collection, sorting, and pre-processing	Technology maturity but also the need for larger facilities
2050	PtL	~2,200 USD/ton	Costs of green hydrogen production	Investments in electrolyzers and CO_2 capture technologies

Challenges

- **HEFA:** feedstock scarcity and competition with other biofuel markets
- **AtJ:** agricultural dependency for ethanol feedstocks and pre-processing costs
- **GFT:** complex logistics for waste collection and high capex for gasification plants
- **PtL:** immature technology with reliance on renewable electricity infrastructure

The transition for the airline industry to…

Use a **5%** SAF share in in-flight energy **by 2030** and **85% by 2050**

Could cost **~$12** billion and **~$600** billion **annually**, respectively

The SAF industry requires annually…

New SAF facilities and capex investments for
- **~25** units (**~$10 billion) in 2030**
- **~500** units (**~$300 billion) in 2050**

[1] SAF production pathways cost is equal to the minimum selling price (MSP), enabling suppliers to cover capital costs and break even when selling to airlines.; [2] The transition cost of using SAF is defined as the premium between the MSP of SAF and the unit price of jet fuel, multiplied by the amount of SAF production that would be needed in that particular year for the airline industry to stay on track to the net-zero target. Share of in-flight energy demand by SAF under the IATA road map (including conventional aviation fuel, bio SAF, SAF-PtL, and hydrogen/battery-electric): 4.7% – 2030, 16.1% – 2035, 30.1% – 2040, 55.7% – 2045, and 87.2% – 2050.
Sources: IATA, 2024, SAF Handbook; IATA Sustainability and Economics, 2024, Finance: Net Zero CO_2 Emissions Roadmap; Kearney Energy Transition Institute analysis

Pace of fleet renewal is slowed by a mismatch between supply and demand

Current status

– **New planes are more efficient:** New generation planes yield a 20–25% CO_2 savings compared to previous generation.
– **Demand:** Demand for new aircraft is strong as many airlines and cargo players have announced fleet renewal plans.
– **Supply:** Manufacturers are struggling to meet this demand. Aircraft deliveries have fallen to **1,254** (2024 estimate) from the peak of **1,813 aircraft** in 2018. As a result, retirements are being temporarily delayed, negatively impacting renewal rate and average fleet age. This has led to a record global **backlog of 17,000 planes** (2024).

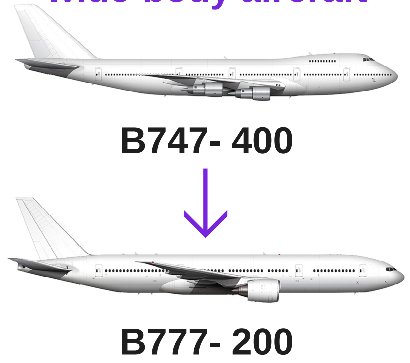
Evolution toward 2050

– **Demand:** Industry projects a demand for **45,900** aircraft worth **$3.3 trillion** over the next 20 years with nearly half of deliveries for replacement.
– **Supply:** Induced constraints in supply chain will lead to a **5%** drop in deliveries till 2027. As a result, plane delivery forecasts will be downgraded.
– **Impact on fleet renewal plans:** Airlines might have to temper their fleet renewal targets. Example: Boeing recently informed **Alaska Airlines** of extended delivery timelines for 787-9 and 737 MAX.

Challenges

– **Costs:** High capex expenditures pose a barrier for airlines even though fleet renewal reduces opex (fuel savings, maintenance, etc.).
– **Operational:** Integrating new technology, training staff on new aircraft, etc.
– **Supply chain:** Delays in aircraft production, availability of parts, labor strikes, and logistical challenges have disrupted the pace of fleet renewal.
– **Regulatory:** Different countries have varying regulations regarding aircraft certification, environmental standards, and safety requirements.

Fleet renewal for large wide-body aircraft



Fuel efficiency increase per cargo ton
+22%

Fuel cost savings per aircraft[1]
+13.4 M€ /year

CO_2 emission reduction per aircraft
-57,1 $ktCO_2$ / year

[1] Fuel cost of 3 USD per US gallon assumed.
Sources: IATA, 2024, Supply Chain Issues Continue to Negatively Impact Airline Performance into 2025; Airbus, 2024, Global Market Forecast; Cirium, 2024, Fleet Forecast; Kearney Energy Transition Institute analysis

Radical airframe and engine designs have driven efficiency gains to date, but further improvements are expected to diminish over time

Current status

- **Aerodynamic enhancements:** Sharklet wingtips (e.g., Airbus A320neo) and raked wingtips (e.g., Boeing 787) reduced fuel burn by 3–5%.
- **Composite materials:** Lighter weight materials (e.g., carbon fiber reinforced polymers) dominate narrowbody structures, cutting weight by 15–20% vs. aluminum.
- **Open fans:** Unshrouded fans achieve 20% fuel saving vs. turbofans.
- **Hybrid-electric integration:** Next-generation batteries (e.g., Airbus' 2025 prototypes) power non-propulsive systems, reducing reliance on fossil-fueled auxiliary units.

Evolution toward 2050

- **Radical airframes:** Evolution beyond standard "tube and wing" configuration expected to increase fuel efficiency by 25–30% (e.g., canard wind, blended wing).
- **H_2-ready structures:** Cryogenic fuel tanks and reinforced airframes for liquid H_2 storage, targeting entry into service in the 2030s.
- **Next-generation engines:** Scale-up of UltraFan™ and open rotor engines for fuel efficiency gains of up to 25%.

Challenges

- **Certification delays:** New designs face lengthy approval as regulators struggle to keep pace with technology innovation surge while formulating new safety standards (e.g., Boeing 787 Dreamliner increased composites to ~50% and experienced delays >3 years).
- **Production scalability:** Supply chain disruptions due to geopolitical tensions hinder timely manufacturing of new designs.
- **Operational trade-offs:** Advanced materials reduce weight but increase maintenance complexity and introduce recycling challenges.

Since the first jet-powered aircraft

Fuel burn per passenger has decreased by

~80%

With expectations for a further **~5%** reduction by 2040

Sources: Aerospace Technology Institute, 2022, Aviation Emissions – Modelling the road to Net Zero 2050; Airbus, 2025, Airbus advances key technologies for next-generation single-aisle aircraft; IATA, 2024, Aircraft Technology Net Zero Roadmap; IEA, 2025, Aviation; Kearney Energy Transition Institute analysis

New propulsion systems promise CO_2 emissions reduction by displacing fossil fuels; scale adoption is questioned by economic viability and fuel availability

Current status

- **Fossil-based propulsion:** Fossil-powered propulsion systems account for ~99% of commercial aviation; H_2 and electric/hybrid-electric constitute <1% each.
- **H_2 propulsion:** Demonstrated in modified gas turbines (e.g., Airbus' ZEROe program), achieving zero CO_2 emissions when using green H_2 (although NOx challenge remains).
- **Hybrid-electric propulsion:** Hybrid propulsion used for regional aircraft to achieve 15–20% fuel reduction (e.g., Ampaire's EEL and Heart ES-30).

Evolution toward 2050

- **H_2 propulsion:** Continued interest/support to scale H_2 propulsion systems, e.g., Airbus aims for H2-powered single-aisle aircraft by 2040–2045.
- **H_2-electric propulsion:** Fuel cell systems (e.g., ZeroAvia's 19-seat prototype) aim for regional flights by 2035, scaling to narrowbodies by 2050.
- **Electric propulsion:** Solid-state batteries could enable 500-km flights by 2035, working in hybrid set-up with fossil fuels for longer distances.

Challenges

- **Infrastructure needs:** Liquid H_2 requires storage at -253 °C, necessitating around EUR 37 billion in EU airport upgrades for cryogenic storage/refueling, 2025–2050.
- **Technical limitations:** Low energy density of H_2 (3x less than kerosene) reduces payload capacity (increasing payback period for investment); battery weight similarly restricts electric aircraft to short haul routes (<500 km).
- **Availability/cost:** Uncertain availability of green H_2 and whether cost parity will be achieved with kerosene.

Aviation total H_2 demand in 2050, considering 100 Mt H_2 required for projected SAF production and

20 Mt H_2
Projected hydrogen-fuel demand

=

1,200 TWh
Clean electricity required for green H_2 production[1]

=

4x
Electricity requirement of the UK (300 TWh)

[1] Considering production via PEM electrolyzer and accounting for requirements of compression/liquefaction and transmission losses

Sources: Aerospace Technology Institute, 2022, Aviation Emissions – Modelling the road to Net Zero 2050; Airbus, 2025, Airbus advances key technologies for next-generation single-aisle aircraft; IATA, 2024, Aircraft Technology Net Zero Roadmap; IEA, 2025, Aviation; Kearney Energy Transition Institute analysis

Air traffic management modernization efforts can play a key role in the sector's green transition but face challenges due to rapid pace of change and lack of harmonization

Current status

- Operational efficiencies, including more efficient air traffic management (ATM), have resulted in a **55%** improvement in fuel burn per passenger km since 1990.
- Various measures, such as **continuous climb/descent and flexible use of military airspace**, have already been implemented in different regions/airports and are utilized when possible.
- However, operational needs and the related improvements **vary across regions** depending on congestion, seasonal peaks, fragmentation due to airspace sovereignty, etc.

Evolution toward 2050

- Operational improvements, including ATM advancements, offer a **quicker** reduction in CO_2 emissions as the implementation timeline is shorter than the adoption of new aircraft/fuel (5.7% reduction in emissions per flight on intra-EU routes in SES).[1]
- Future traffic management will **require fewer human tactical interventions** and will allow for the free flow of information between trusted operators, which will include new types of service providers and operators.
- The future traffic management system will be an **integrated system** of traditional ATM, uncrewed traffic management (UTM), and space traffic management (STM).

Challenges

- **Integrating** traffic growth, long-haul flights, and new generation aircraft.
- ATM is a highly integrated system with **technical incompatibilities** between ATM technologies and aircraft equipage and performance requirements.
- On a single-flight basis, the **optimal trajectory** forms a limit for the absolute improvement potential. However, network effects can be realized and need to be considered.
- **Lack of harmonization** as different regions/countries may have different operating procedures potential.
- Emergence and proliferation of **other airspace users**, such as unmanned aerial vehicles.

Technological reforms are characterized by **long implementation timelines,** especially if systems have to be tested for their safety.

sesar JOINT UNDERTAKING

400 million tonnes of emissions saved by 2050

=

[1] SES is Single European Sky.
Sources: IATA, 2023, Operations Net Zero Roadmap; SESAR JU, 2025, European ATM masterplan; Kearney Energy Transition Institute analysis

Shifting to electric- or hydrogen-powered taxiing and ground operations presents infrastructure challenges

Current status

- Reduced, or single-engine taxiing is a widely implemented practice, with **40%** of all flights already performing reduced-engine taxiing.
- **Electric green taxiing systems (EGTS)** have been actively developed and promoted.
- **Semi-autonomous tow trucks (TaxiBots)** certified by EASA for Boeing 737 Classic and NG-series, and for Airbus A320 Family. In 2020, **Amsterdam Airport Schiphol** performed trials with a TaxiBot finding fuel savings of **50–65%** compared to the standard taxiing procedure.
- Several airports are replacing diesel-powered ground power units (GPUs) with **e-GPUs.**

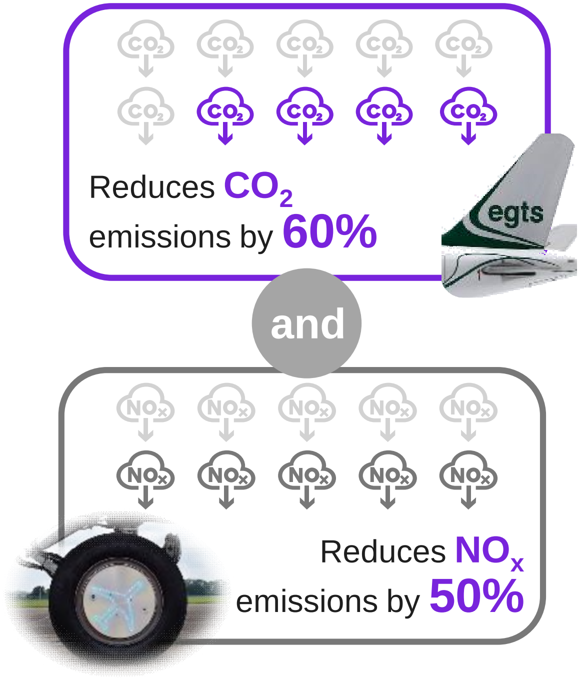
Evolution toward 2050

- **80%** of all flights are expected to perform reduced-engine taxiing by **2030.**
- Safran Landing Systems (SLS) is actively refining EGTS for **future single-aisle aircraft.**
- Current TaxiBots use hybrid electric and diesel engines; **a full electric version** is under development. The ICAO aims for 10% of flights to use electric tug towing by 2030, and 80% by 2050.
- **TULIPS project** is testing hydrogen-powered GPU and tugs at Schiphol Airport, while Frankfurt Airport aims to use only **electric drives by 2040.**

Challenges

- Deployment of **charging infrastructure** at the airport for e-GPUs and electrical tugs.
- EGTS systems **add weight to the aircraft**, which can impact fuel efficiency on longer flights.
- Hydrogen-powered aircraft taxiing faces challenges such as requiring **specialized infrastructure**, addressing safety concerns due to flammability, and managing storage and distribution logistics.

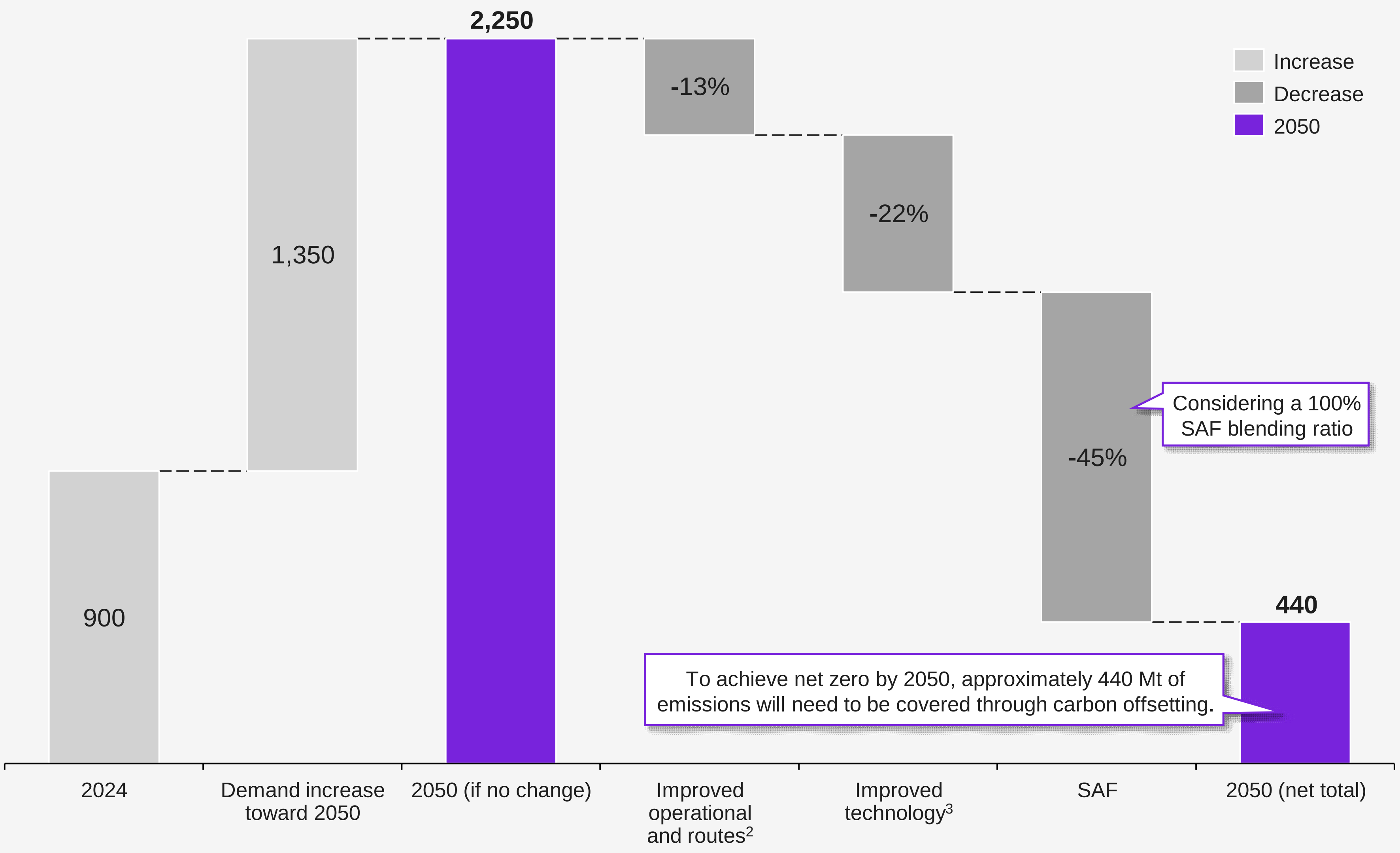
EGTS taxiing operation reduction compared to dual-engine



Sources: ATAG, Electric taxiing takes aircraft efficiency to a new level; Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation; Kearney Energy Transition Institute analysis

Mandating 100% SAF use does not achieve net-zero aviation

Global CO_2 emissions for aviation[1]
Million tons, 2024–2050



Currently, substantial CO_2 reductions depend on decreased flight activity, making demand management a key strategic lever while other measures are unlikely to deliver rapid, large-scale emission reductions in the near term.

8.8 Net zero gap

[1] The analysis is considering that aviation in only consisting of passenger aviation, which currently represents 71% of emissions.; [2] Operational and routes efficiency included optimizing airspace, routes, ground operations, loads, and maintenance practices to reduce fuel burn.; [3] Technology improvements refer to efficiency gains including aerodynamics, improved engine performance, and load factor improvements.
Sources: Kearney Energy Transition Institute analysis

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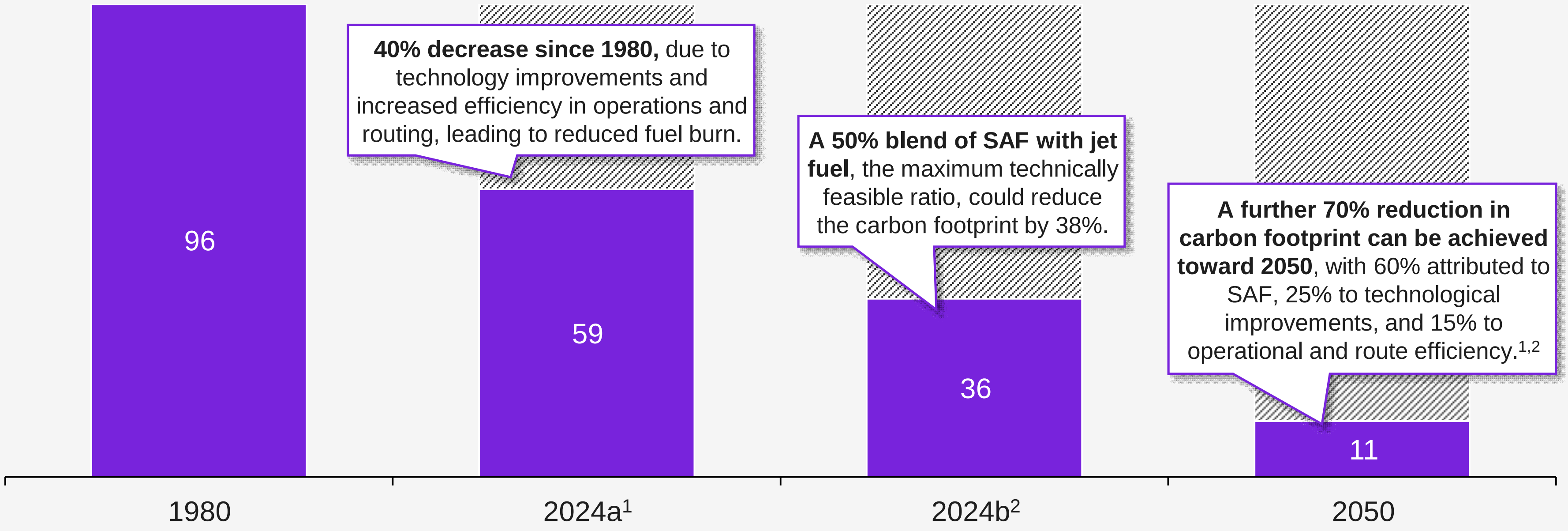
To achieve net zero aviation by 2050, all decarbonization levers must be deployed to their fullest potential

Carbon footprint per passenger-kilometer traveled for flight from Paris to New York

gCO_2 / passenger-kilometer, 1980–2050



Airbus A300B4-200	Airbus A350-900	Airbus A350-900	Hypothetical next-generation aircraft
0% **SAF blending ratio**	0.3% SAF blending ratio	50.0% SAF blending ratio	100.0% SAF blending ratio
Baseline technology efficiency	3.3% annual emissions reduction	6.5% annual emissions reduction	25.0% annual emissions reduction
Baseline operational and routes efficiency	1.3% annual emissions reduction	2.6% annual emissions reduction	13.3% annual emissions reduction

Carbon footprint per passenger-kilometer   Carbon footprint reduction

[1] Technology improvements refer to efficiency gains including aerodynamics, improved engine performance, and load factor improvements.; [2] Operational and routes efficiency included optimizing airspace, routes, ground operations, loads, and maintenance practices to reduce fuel burn.
Sources: Kearney Energy Transition Institute analysis

8.9 Carbon footprint projection

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9. Acronyms, bibliography, and photo credits

Acronyms (1/2)

AGM	Annual general meeting
ANSP	Air navigation service providers
APAC	Asia Pacific
ASD	Aerospace, Security and Defence group in Europe
ASD-STAN	European aerospace standards by ASD
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
ATJ	Alcohol-to-jet
ATM	Air traffic management
BPR	Bypass ratio
CANSO	Civil Air Navigation Services Organisation
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CH_4	Methane
CHJ	Catalytic hydrothermolysis jet fuel
CLEEN	Continuous Lower Energy, Emissions, and Noise
CO	Carbon monoxide
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOE	Department of Energy
DOT	Department of Transportation
EGTS	Electric green taxiing system
EPA	Environmental Protection Agency
ERF	Effective radiative forcing
ETS	Emission trading scheme
EU	European Union
EVTOL	Electric vertical takeoff and landing
FAA	Federal Aviation Administration
FAST	Fuel Aviation’s Sustainable Transition
GAMA	General Aviation Manufacturers Association
GDP	Gross domestic product
G-FT	Gasification Fischer-Tropsch
GHG	Greenhouse gas
GPU	Ground power units
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbons
HEFA	Hydroprocessed esters and fatty acids
HH	Hydroprocessed hydrocarbons
IATA	International Air Transport Association
IBN SPK	Isobutene synthetic paraffinic kerosene

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Acronyms (2/2)

ICAO	International Civil Aviation Organization
IRA	Inflation Reduction Act
IRS	Internal Revenue Service
LRC	Long range cruise
LWB	Large wide body
MJ	Mega Joule
Ml	Million liters
MSW	Municipal solid waste
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NOx	Nitrogen oxide
O_2	Oxygen
OEM	Original equipment manufacturer
OPEX	Operating expenditure
PBN	Performance-based navigation
PRC	People's Republic of China
PtL	Power to liquid
RAF	Royal Air Force
RED	Renewable energy directive
RIN	Renewable identification number
RNP	Required navigation performance
RTCA	Radio Technical Commission for Aeronautics
SAF	Sustainable aviation fuel
SES	Single European Sky
SESAR	Single European Sky ATM Research Project
SFNP	Sustainable Flight National Partnership
SIP	Synthesized iso-paraffin
SOx	A group of air pollutants containing sulfur and oxygen
TWh	Terawatt-hour
UAE	United Arab Emirates
UDF	Unducted fan
UHBR	Ultra high bypass ratio engines
UK	United Kingdom
UN	United Nations
US	United States
USAF	United States Air Force
USD	United States dollar
USDA	United States Department of Agriculture
USDT	United States Department of Treasury
VALE	Voluntary airport low emissions
Wh	Watt-hour
ZEV	Zero emission vehicle

9.1 Acronyms

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Bibliography (1/3)

Aerospace Technology Institute, 2022, Aviation Emissions – Modelling the road to Net Zero 2050

ADEME, 2022, Elaboration de scenarios de transition écologique du secteur aérien

Airbus, 2018, Approche pour une aviation durable

Airbus, 2024, Global market forecast

Airbus, 2025, Airbus advances key technologies for next-generation single-aisle aircraft

Airlines for Europe, Airports Council International, Aerospace, Security and Defence Industries Association of Europe, CANSO Europe, and ERA, 2025, Destination 2050: A Route to Net Zero European Aviation

ALG, 2024: Noise Around Airports: Regulation and Mitigation

ATAG, 2021, Waypoint 2050 (2nd edition)

ATAG, 2024, Aviation Benefits Beyond Borders

ATAG, Electric taxiing takes aircraft efficiency to a new level

Aviation Week Network, 2025, Commercial Aviation Fleet & MRO Forecast

Aviation week, 2024, Fleet discovery

Aviation week, 2025, 2024 Market summary report (Military)

Bergero et al., 2023, pathways to net zero emissions from aviation

BNEF, 2022, Decarbonizing Aviation: A Climate Technology White Paper

BNEF, 2024, United Airlines Is Betting Big on a Pricey Green Aviation Fuel

Boeing, 2024, World air cargo forecast

CE Delft, 2022, Potential for reducing aviation non-CO_2 emission through cleaner jet fuel

Cerulogy, 2024, Vertical Take-Off?

CFM, 2021, CFM RISE PROGRAM

Cirium, 2024, Fleet Forecast

Cirium, 2025, Shaking out the Airbus and Boeing 2024 delivery numbers

Context Network, 2024, Global Agricultural Carbon: Get Smart, Stay Smart

EASA, 2025, 2024 Aviation Fuels Reference Prices for ReFuelEU Aviation

ENVISA, 2021, Impact of aircraft noise pollution on residents of large cities

ENVISA, 2023, Mitigating and Managing Noise from Airport Practices

European Commission, Climate Action: Reducing emissions from aviation, accessed April 2025

European Commission, Joint Research Center, GHG emissions of all world countries, 2023

9.2 Bibliography

Bibliography (2/3)

FAO, 2024, FAOSTAT Land Use

FAA, 2025, Contrails research roadmap

Global Bioenergies, 2023, A growing player of the environmental transition

Global Bioenergies, 2024, From cosmetics to SAF: Fostering the environmental transition through biosciences

Global Carbon Budget, 2024

Global Clean Energy, 2023, Global Clean Energy Reports Largest Camelina Acreage Worldwide

GOV.UK, 2022, Greenhouse gas reporting

Honeywell, 2023, Business Aviation Outlook Report

IATA Sustainability and Economics, 2024, Finance: Net Zero CO_2 Emissions Roadmap

IATA, 2023, Operations Net Zero Roadmap

IATA, 2024, Aircraft Technology Net Zero Roadmap

IATA, 2024, Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions

IATA, 2024, Chart of the Week (May 10)

IATA, 2024, SAF Handbook

IATA, 2024, Supply Chain Issues Continue to Negatively Impact Airline Performance into 2025

IATA, 2025, Global Air Passenger Demand Reaches Record High in 2024

IATA, 2025, Improving the local environment – noise & air quality

ICAO, 2024, CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels

ICAO, 2024, LTAG Integrated Scenario

ICAO, 2025, ICAO, ICA tracker of SAF facilities, accessed April 2025

ICAO, LTAG Integrated Scenario 3

ICAO, 2025, SAF rules of thumb

IEA, 2025, Aviation

IEA, Transport, accessed March 2025

Institut Montaigne, 2022, Decarbonizing Aviation: All Abroad

Institute for sustainable aviation, ISAE Supaero, AeroMaps, retrieved February 2025

International Council on Clean Transportation, 2022, Performance Analysis of Evolutionary Hydrogen-Powered Aircraft

IPCC, 2018, Special report: Aviation and the global atmosphere

ISAE Supaero, Aviation et climat, 2021

Bibliography (3/3)

ISAE Supaero, Aviation et Climat, 2022

ISAE-SUPAERO, 2022, Aviation and Climate: A Literature Review

Kearney and Airports of Tomorrow, 2024, Scaling Up Sustainable Aviation Fuel Supply

Mission Possible Partnership, 2022, Making Net-Zero Aviation Possible: An industry-backed, 1.5°C-aligned transition strategy

NASA, 2022, The Contrail Education Project

Pattanayak, T. and Mavris, D., 2024, Battery Technology in Aviation: Current State and Future Prospects, Georgia Institute of Technology

RMI, 2024, Fueling Up Sustainable Aviation

RMI, 2024, Understanding Contrail Management: Opportunities, Challenges, and Insights

SESAR Joint Undertaking, accessed April 2025

SESAR JU, 2025, European ATM masterplan

Seters D., Grebe S. and Faber J., 2024, Health Impacts of Aviation UFP Emissions in Europe

Seympur, K., Held, M., Georges, G., and Boulochos, K., 2023, Future costs of power-to-liquid sustainable aviation fuels produced from hybrid solar PV-wind plants in Europe

SkootEco, 2025, Understanding the Air Travel Carbon Footprint: The True CO_2 Emissions from Flying

Suárez, M.Z. et al., 2023, Battery Technologies to Electrify Aviation: Key Concepts, Technologies, and Figures, International Journal of Aviation Science and Technology

Sustainable Taxiing Taskforce, 2024, Sustainable Taxi Operations: Concept of Operations & Industry Guidance

Tabernier, L et al., 2021, Fuel Tankering: Economic Benefits and Environmental Impact for Flights Up to 1500 NM (Full Tankering) and 2500 NM (Partial Tankering), Aerospace

U.S. DOE, 2020, Sustainable Aviation Fuels: Review of Technical Pathways

US Environmental Protection Agency, 2024, United States 2024: Aviation Climate Action Plan

Volgina, N. and Kidun, E., 2021, Global Civil Aircraft Industry: Modern Trends

World bank, 2025, World Development Indicators - Air transport freight

World Meteorological Organization, Record carbon emissions highlight urgency of Global Greenhouse Gas Watch, November 2024

Yusaf, T.et al., 2024, Sustainable hydrogen energy in aviation – A narrative review, International Journal of Hydrogen Energy

ZeroAvia, 2024, Scaling Hydrogen-Electric Propulsion for Large Aircraft

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9.3 Photo credits

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10. Appendix

Technology improvement for efficiency gain to date has focused on airframe and engine design, but the greatest potential lies in new propulsion systems

Greatest impact solution per sub-lever

Mitigation lever	Sub-lever	Solution	Fuel efficiency improvement potential	GHG reduction potential (gCO_2e/MJ)
2 Technology improvement	Airframe design	**Next-generation wings**	**10-20%**	**9.0-18**
		Double bubble fuselage	10-15%	9.0-13
		Adaptive flaps	5-15%	4.5-13
		Riblets	5-15%	4.5-13
		Composites	5-10%	4.5-9.0
		Winglets	4-6%	3.5-5.5
		Fuel cells for onboard power	1-5%	0.9-4.5
		Cabin interiors	1-5%	0.9-4.5
		3D printing	1-5%	0.9-4.5
		Laminar flow control	1-5%	0.9-4.5
	Engine concept	**UltraFan**	**20-30%**	**18-27**
		UHBR	15-20%	13-18
		High-pressure ratio core	15-20%	13-18
		Geared turbofan	15-20%	13-18
		Open rotor	15-20%	13-18
		Modern turboprop	10-15%	8.9-13
		Boundary layer ingestion	3-5%	2.5-4.5
	New propulsion systems	**Electric**	**90-100%**	**80-90**
		Hydrogen	70-80%	62-71
		Hybrid	25-35%	22-31

Source: Kearney Energy Transition Institute analysis

10.1 Aviation climate impact mitigation levers

Technology improvement for efficiency gain to date has focused on airframe and engine design, but the greatest potential lies in new propulsion systems

Greatest impact solution per sub-lever (marked by dashed outline: Space-based navigation; Stationary power and ventilation; Interior and cargo cleanliness; Advanced navigation)

Mitigation lever	Sub-lever	Solution	Fuel efficiency improvement potential	GHG reduction potential (gCO_2e/MJ)
3 Operation and routes efficiency	Flight and trajectory optimization	Space-based navigation	3-5%	2.5-4.5
		Wake energy retrieval	3-5%	2.5-4.5
		Flight planning	3-5%	2.5-4.5
		Optimized trajectories	5-10%	4.5-8.9
	Ground operation optimization	Stationary power and ventilation	1-3%	0.9-2.5
		Reduced engine use during taxiing	1-3%	0.9-2.5
		Electric or hydrogen taxiing	1-5%	0.9-4.5
	Improved operations and operating practices	Interior and cargo cleanliness	~1%	~0.5
		Cabin and equipment weight optimization	1-3%	0.9-2.5
		Adjusting fuel and water supply usage	1-3%	0.9-2.5
	Traffic and airspace optimization	Advanced navigation	1-5%	0.9-4.5
		Flexible use of military airspace	1-5%	0.9-4.5
		Collaborative decision-making	1-5%	0.9-4.5
		Continuous descent/climb	1-5%	0.9-4.5
		Trajectory-based operations	3-5%	2.5-4.5
		SES/SESAR	5-10%	4.5-8.9
		Next-generation projects	5-10%	4.5-8.9

Source: Kearney Energy Transition Institute analysis

10.1 Aviation climate impact mitigation levers

Niche early-stage SAF pathways use different feedstocks and have not yet reached commercial deployment

Non-exhaustive

[1] Synthesized IsoParaffin; [2] Catalytic Hydrothermolysis Jet fuel
Sources: AIREG, 2025, Sustainable fuels for aviation; IEA Bioenergy, 2024, Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies and policies; Ali at al, 2022, Current progress in thermochemical conversion of plastics into jet-fuel hydrocarbons and recommendations for COVID-19 waste management; Kearney Energy Transition Institute analysis

Summary of select early-stage SAF pathways

	SIP[1]	CHJ[2]	Waste plastics to jet
Process description	This route uses modified yeasts to ferment sugars into a hydrocarbon molecule. This produces a C15 hydrocarbon molecule called farnesene, which is hydroprocessed to farnesane and can be used as a blendstock in jet fuel.	Also called hydrothermal liquefaction, clean free fatty acid (FFA) oil from the processing of oils is combined with preheated feed water and then passed to the CH reactor. There, under very high temperature and pressure conditions, a single phase is formed consisting of FFA and supercritical water (SCW) wherein the FFAs are cracked, isomerized, and cyclized into paraffin, isoparaffin, cycloparaffin, and aromatic compounds.	Thermal degradation under microwave, hydrothermal liquefaction, pyrolysis, methanolysis/hydrogenation, thermal cracking/co-hydrogenation, and aqueous phase hydrodeoxygenation are possible routes for plastic to jet-fuel conversion.
Feedstocks	Carbohydrates/sugars from crops (e.g., sugar beet, sugar cane)	Fatty acids and fatty acid esters, or more generally various lipids that come from plant and animal fats, oils, and greases	Mixed plastics
ASTM certified	Yes	Yes	No
Approved blending ratio	Up to a 10% maximum level	Up to a 50% maximum level	NA
Current status	Pilot/demo stage Example: Amyris and TotalEnergies have partnered to produce biojet from SIP route.	Pilot/demo stage Example: ReadiJet SAF by Applied Research Associates Inc. and Chevron Lummus Global LLC	Ongoing research/small pilot projects; regulatory acceptance and quality consistency needed for ASTM certification approval

10.2 SAF pathways

Replacing jet fuel in aviation involves electrification, sustainable aviation fuels, and hydrogen, each suited to different ranges and payloads

Non-exhaustive

	Urban air mobility	Small propeller aircraft	Commuter	Regional	Short range	Medium range	Long range
Description	*Covers air taxis and eVTOLs primarily for short, intra-city travel*[1]	*Often used for personal, business, or short-haul charter flights*	*Small regional aircraft capacity connecting remote areas to larger hubs*	*Includes turboprop and small regional jets for feeder routes*	*Narrow-body used for short routes, single-aisle (passenger)*	*Narrow-body or small wide-body for medium routes, single-aisle (passenger)*	*Wide-body for long routes, double-aisle (passenger)*
Haul	Short haul	Short haul	Short haul	Short haul	Short haul	Medium haul	Long haul
All electric	✓	✓					
Electric and hydrogen fuel cell		✓	✓	✓			
SAF and gas turbine		✓	✓	✓	✓	✓	✓
Liquid hydrogen and gas turbine		✓	✓	✓	✓	✓	
Range (km)	<100	100-400	400-800	800-4,000	2,500-4,500	4,500-7,000	>6,000
Payload (kg)	<550	550-2,000	2,000-7,000	7,000-12,000	12,000-18,000	18,000-25,000	<250,000
Passenger (seats) *When applicable*	<10	5-20	9-50	50-100	100-150	150-250	>250

[1] Electric vertical takeoff and landing

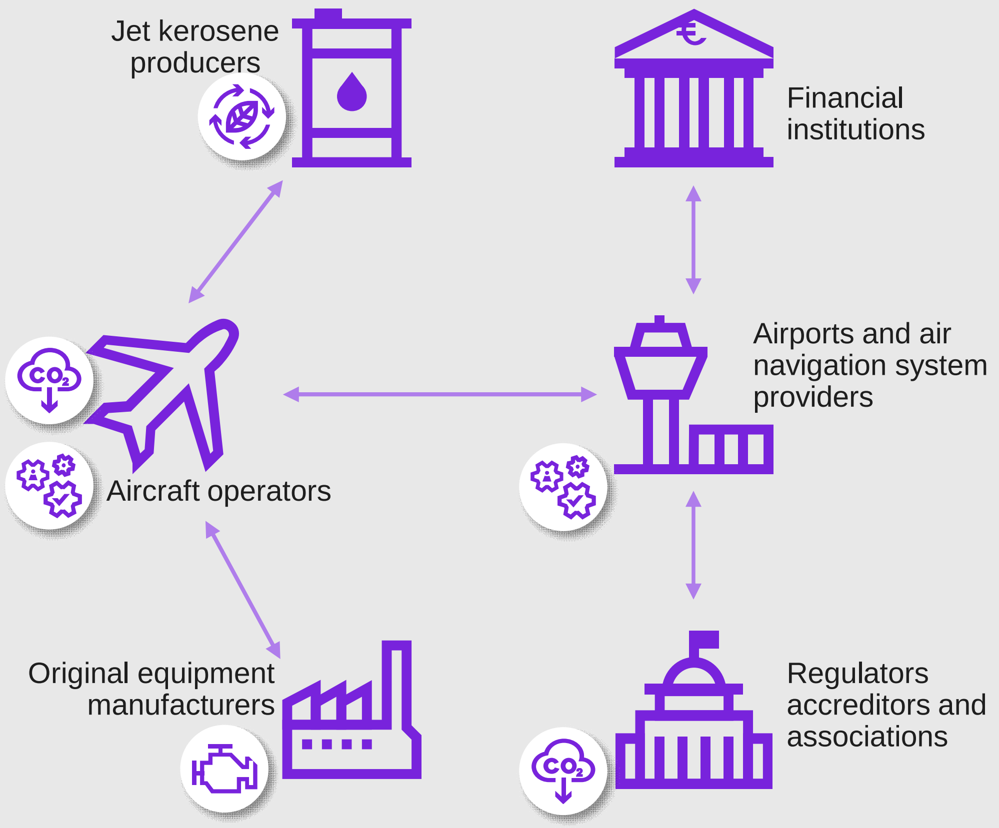
Sources: CATAPULT, 2022, The Roadmap to Zero Emission Flight Infrastructure; Sripad, S. et Viswananthan, V., 2021, The promise of energy-efficient battery-powered urban aircraft; EASA, 2021, Study on the societal acceptance of Urban Air Mobility in Europe; Ehang, 2020, The Future of Transportation: White Paper on Urban Air Mobility Systems; German Aerospace Center, 2024, The Future of Urban Air Mobility; Kearney Energy Transition Institute analysis based on desktop research.

10.3 Net zero solutions per range and load

The aviation industry relies on multiple stakeholders, each of which can influence the levers for decarbonization

Illustrative; non-exhaustive

Simplified ecosystem of the aviation industry



Original equipment manufacturers

Aircraft operators

Jet fuel producers

Airports and air navigation system providers

Regulators, accreditors and associations

Sources: Kearney and Airports of Tomorrow, Scaling Up Sustainable Aviation Fuel Supply; 2024; Kearney Energy Transition Institute