Roadmap to True Zero.

A path-breaking approach to bring down aviation's total climate impact.

Roland Berger

The aerospace and aviation industry has been the lifeblood of global trade, tourism, and connectivity for decades, contributing enormously to globalisation and economic growth. However, these benefits have come at an environmental cost. Aviation currently represents ~3% of global anthropogenic CO_2 emissions and its share is expected to increase over time given the relative maturity of decarbonisation solutions across other industries.

Moreover, aviation's climate footprint extends beyond just CO_2. Considering non-CO_2 effects such as contrails and nitrous oxides, aviation's total footprint may be 2–4x as much as CO_2 alone. The Roland Berger Roadmap to True Zero tackles this set of problems head on. We show that by 2030 aviation can reduce its total impact by ~30% from coordinating efforts to minimise fuel burn through better operations and air traffic control, and by accelerating contrail mitigation. By 2050, either a revolution in sustainable fuels, or a revolution in aircraft technology (e.g., with hydrogen aircraft), can bring the total impact down by ~75% — and achieving both at once can enable a reduction of ~85%.

Our study demonstrates that it is possible for the aerospace and aviation industry to continue growing, whilst still bringing its total climate impact down. Not only is mitigation possible, but the time is ripe for the industry to embark on its Roadmap to True Zero.

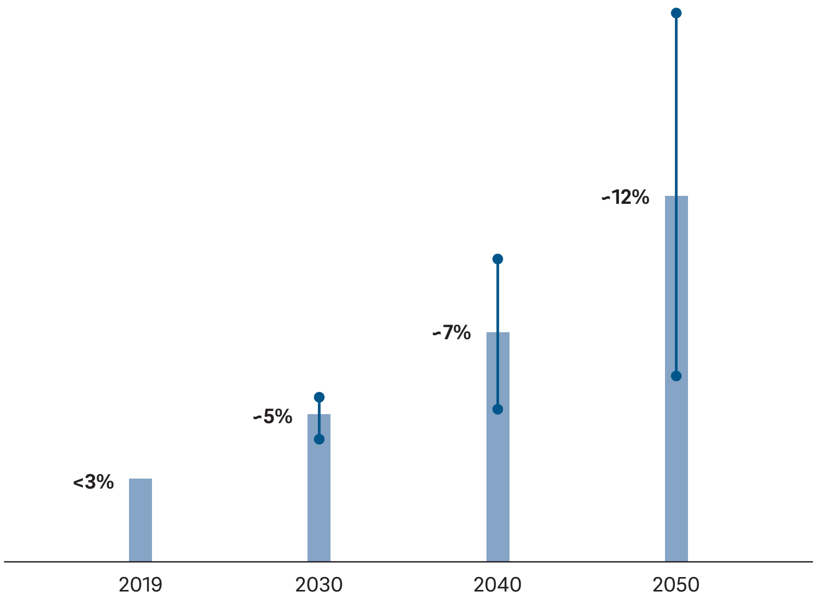
The Challenge

Aviation is hard to abate: whilst many major industries have relatively mature technologies to reduce CO_2, aviation does not. Aviation's 3% share of global CO_2 is liable to grow to ~12–18% by 2050. Compounding the matter are non-CO_2 emissions — nitrous oxides, particulates, and contrails. Indeed, aviation's total impact on climate change may be 2–4x the impact of CO_2 alone (though scientific uncertainty remains). The state of zero climate impact across all these emissions is known as True Zero.

If no further action is taken, aviation's share of global CO_2 could rise dramatically, with global scrutiny set to increase

Forecast of aviation's share of CO_2 emissions, 2019–2050

What aviation's emissions actually are today ... and where they may be headed

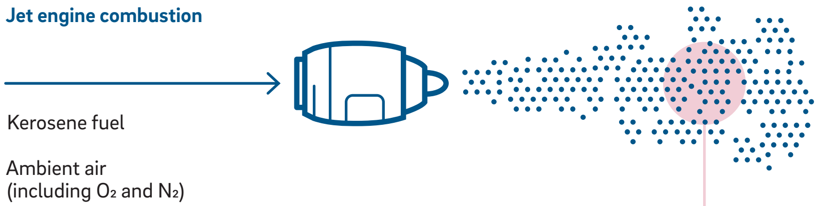


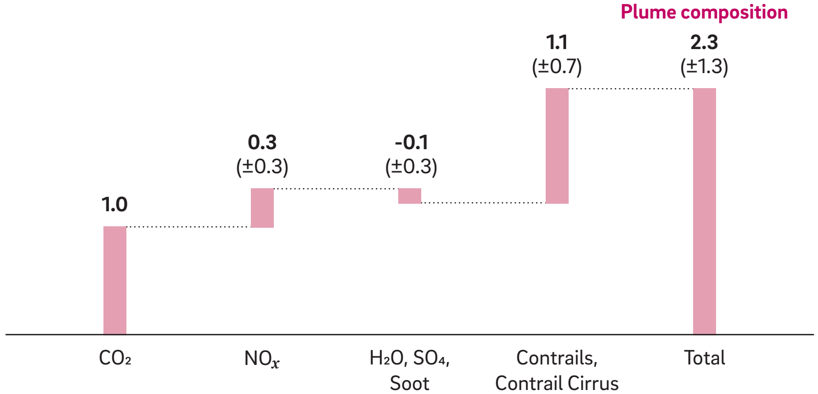
What the surveyed public believe aviation's emissions are ... and how they may perceive them in the future

Source: Global Carbon Project, IEA, Roland Berger

Aviation's challenge to climate neutrality goes far beyond the direct impact of CO_2

Aviation's radiative forcing[1] contributions — indexed to impact of CO_2 [GWP50[2]]





1 Radiative Forcing (RF) measures the balance of energy moving into vs. out of the Earth's atmosphere (i.e., the instantaneous impact on global warming); 2 Global Warming Potential, as a proportion of the impact of CO_2 alone, over a 50 year timeframe

Source: Lee et al 2020, IPCC, Roland Berger

The Roadmap to True Zero explores how the industry can concurrently approach net-zero CO_2 and zero non-CO_2 effects

{True Zero}

/truː ˈzɪə.rəʊ/

1. A state in which all net climate effects, including both CO_2 and non-CO_2 factors are reduced to zero
2. Distinct from net-zero, which refers only to CO_2
3. Compatible with net-zero, with carbon removals playing a role in Power-to-Liquid (PtL) fuel production and in the removal of residual climate effects in 2050 (targeting total carbon equivalent impact)

Source: Roland Berger

The Art of the Probable

Fortunately, as we expand the size of the problem, the set of available solutions expands too. We considered over 20 levers, categorised into six buckets from better operations to new aircraft and new fuels. Applying these levers in a realistic “business-as-usual” way, we find that aviation’s total climate impact does eventually come down, reaching just below 2019 levels by 2050, even when assuming overall traffic growth. But this does not get us to True Zero.

The aviation industry has seven distinct groups of levers to tackle CO_2 and non-CO_2 emissions

Overview of levers, in order of application — **Impact 2050**

1. **Flight operations** ●●○○○○○○
Modify in-flight operations through initiatives such as improved aircraft weight management and engine wash technology inclusion to reduce overall fuel burn and exhaust emissions

2. **Ground operations** ●○○○○○○○
Modify on-ground operations, maintenance, and turnaround procedures through initiatives such as APU usage reduction (transition to GPU) and taxi fuel consumption reduction (including transfer to single engine taxiing and electric towing) to avoid functionally non-essential emissions

3. **ATC efficiency improvements** ●●●○○○○○
Minimise in-flight routing inefficiencies, flight time, and fuel burn through improved ATC coordination and synchronisation of aircraft through route optimisation (including optimisation for turbulence avoidance), wait time reduction, and airspace unification (e.g., SESAR)

4. **Switch to next generation aircraft (excluding supersonic)** ●●●●●●○○
Transition from existing Legacy and Current Engine Option (CEO) aircraft to the latest, best-in-class, New Engine Option (NEO) aircraft to reduce emissions through improvements in fuel efficiency and aerodynamics (including sharkskin paint, engine wash, winglet retrofit)

5. **Contrail avoidance** ●●●●●●○○
Optimise overall aircraft trajectory (path and altitude) and implement scheduling modifications to minimise the formation of persistent and/or warming contrails

6. **New fuels** ●●●●●●○○
Transition from traditional fossil fuels to Sustainable Aviation Fuels (SAF; including synthetic and bio-based) and Low Carbon Aviation Fuels (LCAF) to reduce CO_2 and non-CO_2 emissions and overall carbon impact

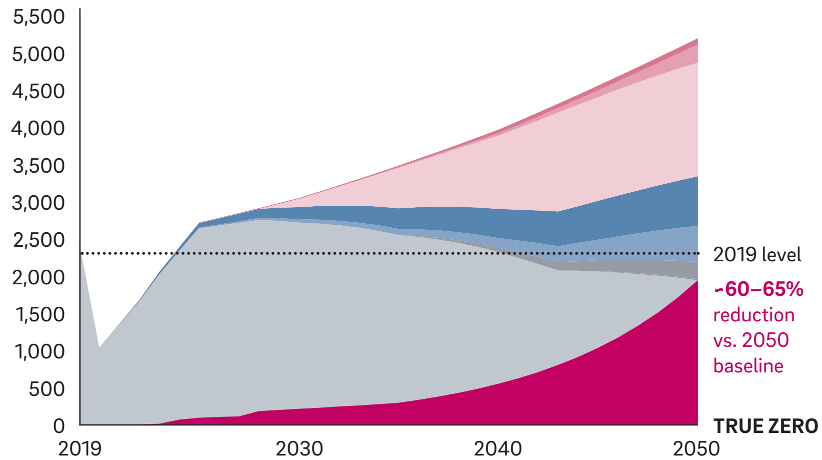
7. **Hyper-Efficient Conventional Aircraft (HECA) and revolutionary aircraft (including hydrogen, hybrid-electric concepts, etc.)** ●●●○○○○○
Transition from existing Legacy, CEOs, and NEOs to next generation HECA and revolutionary hydrogen/hybrid-electric aircrafts

●●●●●●●● High impact ●○○○○○○○ Low impact

Source: Roland Berger

In the "Art of the Probable" — or realistic — case, residual emissions are expected only to decline after 2030, reducing to just under 2019 levels by 2050

Aviation emissions reduction by lever [Mt CO_2e, GWP50]



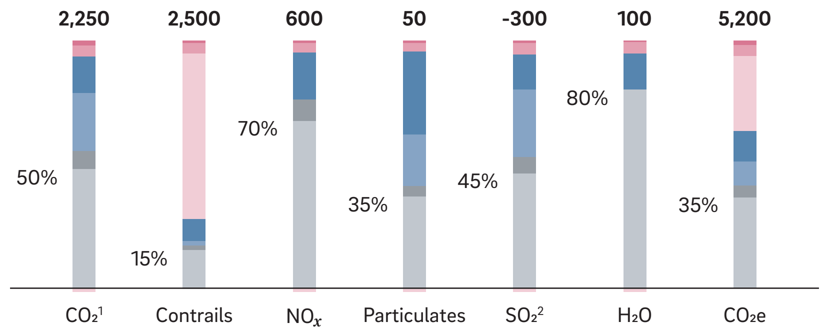
Flight operations · ATC improvements · Contrail avoidance · Nextgen aircraft · New fuels · HECA and revolutionary aircraft · Residual emissions · Carbon removals[1]

1 In-line with CORSIA targets from 2021–2035 (updated based on 41st ICAO Assembly); assuming continuation of high quality reliable carbon removals from 2035–2050, ramping up to achieve net-zero

Source: Roland Berger

A complete analysis has been done for each emissions species underlying the CO_2e — contrail mitigation is a key requirement to achieve this significant reduction

2050 emissions species reduction by lever [Mt CO_2e, GWP50]



Flight operations · ATC improvements · Contrail avoidance · Nextgen aircraft · New fuels · HECA and revolutionary aircraft · Residual emissions

1 Contrail avoidance produces a negligible increase of CO_2 emissions (c. 0%); 2 Cooling effect

Source: Roland Berger

The Art of the Possible

Several barriers impede a more rapid reduction — from technology development to industrialisation, to coordination and regulatory action. Thus, we considered scenarios in which these barriers are lowered or lifted. In a bullish and optimistic case for the climate, we found that we can reduce aviation's impact by ~85–90% against the 2050 baseline, or a reduction of ~60–70% vs. 2019. With the residual carbon equivalent being addressed through reliable and transparent carbon removals we can achieve True Zero.

Currently, five main types of barriers are impeding large-scale application of levers, delaying the industry's climate neutrality efforts

	Flight operations	ATC improvements	Fleet renewal (nextgen a/c)	Fleet renewal (revolutionary)	New fuels	Contrail avoidance
1 Technological and scientific → Unavailability of key technology bricks leading to slow-down of new developments → Lack of understanding of a phenomenon resulting in limitations to measure the impact of actions	Moderate impact	Limited impact	Limited impact	High impact	Moderate impact	Moderate impact
2 Certification → Complex certification process resulting in long time-to-market	Limited impact	Limited impact	High impact	High impact	Moderate impact	Limited impact
3 Industrial → Slow production ramp-up limiting product adoption	Limited impact	Limited impact	High impact	Moderate impact	High impact	Limited impact
4 Coordination → Lack of alignment among relevant stakeholders resulting in delays in implementation → Presence of significant policy hurdles (e.g., with SESAR)	High impact	High impact	Moderate impact	Moderate impact	Moderate impact	High impact
5 Markets and incentives → Supply and demand uncertainties leading to slow uptake → Lack of incentives for sustainable technology creating a market imbalance	Moderate impact	Moderate impact	High impact	Moderate impact	High impact	High impact

● High impact ● Moderate impact ○ Limited impact

Source: Roland Berger

As we adjust the pace of implementation for the levers and relax barrier constraints, six additional scenarios for the industry emerge

ART OF THE PROBABLE

0
→ General progress broadly in line with aviation industry stakeholders' currently stated ambitions

ART OF THE POSSIBLE

1 Fuel Revolution
→ Production ramp-up of SAF allows new fuels to achieve c. 70–90% market share by 2050
→ Technical breakthrough in 2030 makes synthetic fuels commercially viable and fast production ramp-up allows PtL fuels to have c. 65% market share (of total SAF) by 2050

2 Fleet Revolution
→ Industry push and incentives reduce entry into service (EIS) of all new aircraft by five years relative to the "Art of the Probable", and retirement age reduces to ~17–18 years
– Accelerated EIS of new aircraft types (HECA, hydrogen and hybrid concepts), with EIS dates brought forward by five years relative to "Art of the Probable" (e.g., hydrogen narrowbody EIS in 2035)
– Annual retirement rate increases from 3% to 5%, reducing average retirement age from ~25 to ~17–18 years, allowing faster aircraft replacement
– Lean burn (low soot) and significant NO_x reduction is incorporated as a part of the transition to HECA and hydrogen combustion aircrafts

3 NEO Acceleration
→ NEO aircraft production ramp-up and government incentives (subsidies for fleet renewal, etc.) enable an 80% NEO global fleet in 2030
→ This acceleration does not impact the development of HECA and revolutionary aircraft, nor delays their expected EIS from mid-2030 (Art of the Probable)
→ However, there is a slower uptake of HECA and revolutionary aircraft due to the younger overall fleet when they enter service

4 Coordinated Skies
→ Airlines and ATC, supported by Government subsidies, optimise flight operations (including in-the-air, on-the-ground, contrail avoidance) by 2030
→ Global airspace unification starts in 2030 and is progressively achieved by 2050
→ Contrail mitigation efforts are accelerated and are highly targeted and successful, delivering up to 80% mitigation at a global level by the early 2030s

5 Fuel Revolution + Fleet Revolution
→ Fuel Revolution and Fleet Revolution scenarios are implemented simultaneously

6 All-in: Fuel Revolution + Fleet Revolution + Coordinated Skies
→ Coordinated Skies, Fuel Revolution, and Fleet Revolution scenarios are implemented simultaneously

Source: Roland Berger

Four scenarios have high CO_2e mitigation potential, but a combination of Coordinated Skies, Fuel Revolution, and Fleet Revolution yields the best potential outcome

Comparison of scenarios' impact and feasibility

2050 baseline	**Impact 2030** Emissions reduction vs. baseline	**Impact 2050** Emissions reduction vs. baseline	**Scenario feasibility**
Art of the Probable	c. -10%	c. -60–65%	●●●●●●○○
Fuel Revolution	c. -10%	**c. -75–80%**	●●●●○○○○
Fleet Revolution	c. -10%	**c. -75–80%**	●●●○○○○○
NEO Acceleration	**c. -15%**	c. -60–65%	●●●●●○○○
Coordinated Skies	**c. -30%**	c. -60–65%	●●●●●○○○
Fuel Revolution + Fleet Revolution	c. -10%	**c. -85–90%**	●●○○○○○○
All-in: Fuel Revolution + Fleet Revolution + Coordinated Skies	**c. -30%**	**c. -85–90%**	●○○○○○○○

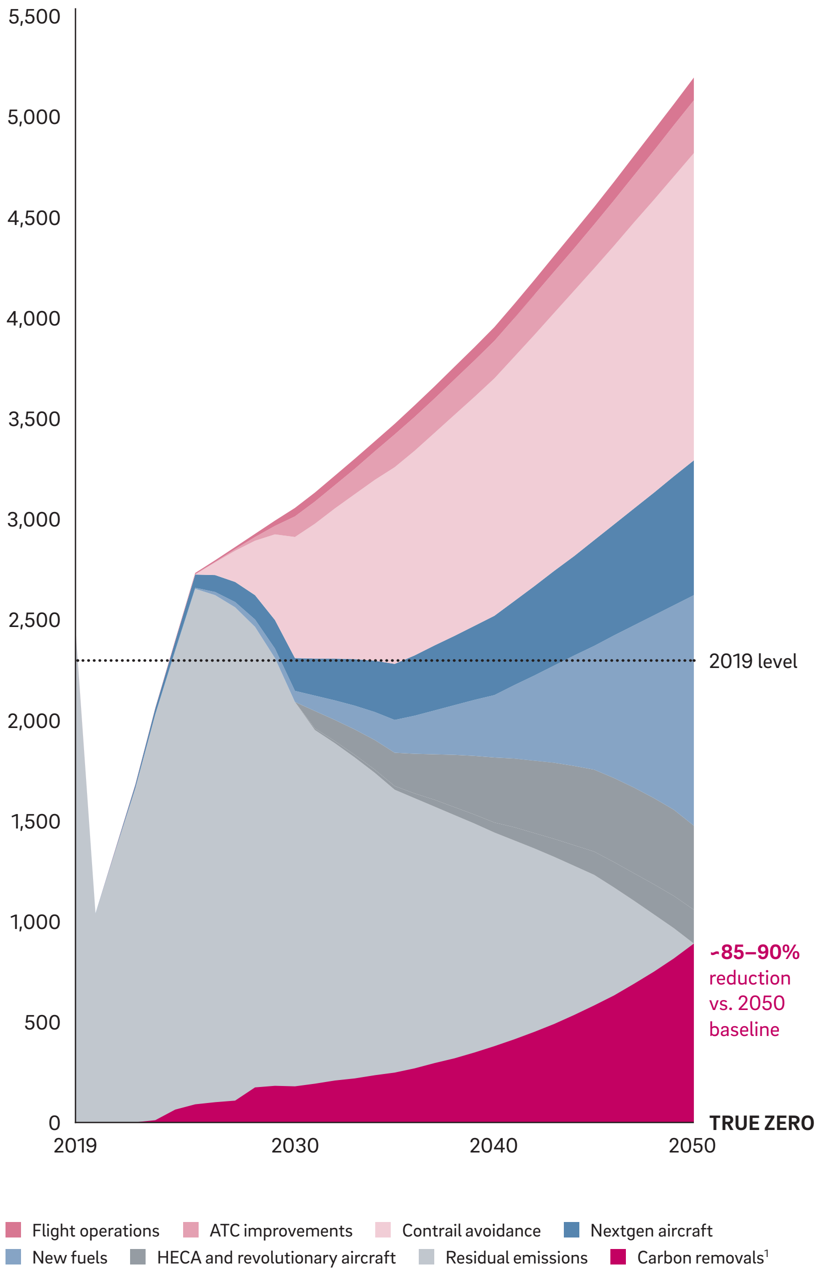
2019 baseline	**Impact 2030** Emissions reduction vs. baseline	**Impact 2050** Emissions reduction vs. baseline	**Scenario feasibility**
Art of the Probable	c. +30%	c. -10–15%	●●●●●●○○
Fuel Revolution	c. +30%	**c. -40–50%**	●●●●○○○○
Fleet Revolution	c. +30%	**c. -40–50%**	●●●○○○○○
NEO Acceleration	**c. +20%**	c. -5–10%	●●●●●○○○
Coordinated Skies	**c. 0%**	c. -10–15%	●●●●●○○○
Fuel Revolution + Fleet Revolution	c. +30%	**c. -60–70%**	●●○○○○○○
All-in: Fuel Revolution + Fleet Revolution + Coordinated Skies	**c. -5%**	**c. -60–70%**	●○○○○○○○

■ Significant impact by 2030 ■ Significant impact by 2050

Source: Roland Berger

Our 'all-in' scenario combining Coordinated Skies, Fleet Revolution, and Fuel Revolution shows considerable reductions achieving ~85–90% reductions by 2050

Aviation emissions reduction by lever [Mt CO_2e, GWP50]



1 In-line with CORSIA targets from 2021–2035 (updated based on 41st ICAO Assembly); assuming continuation of high quality reliable carbon removals from 2035–2050, ramping up to achieve net-zero

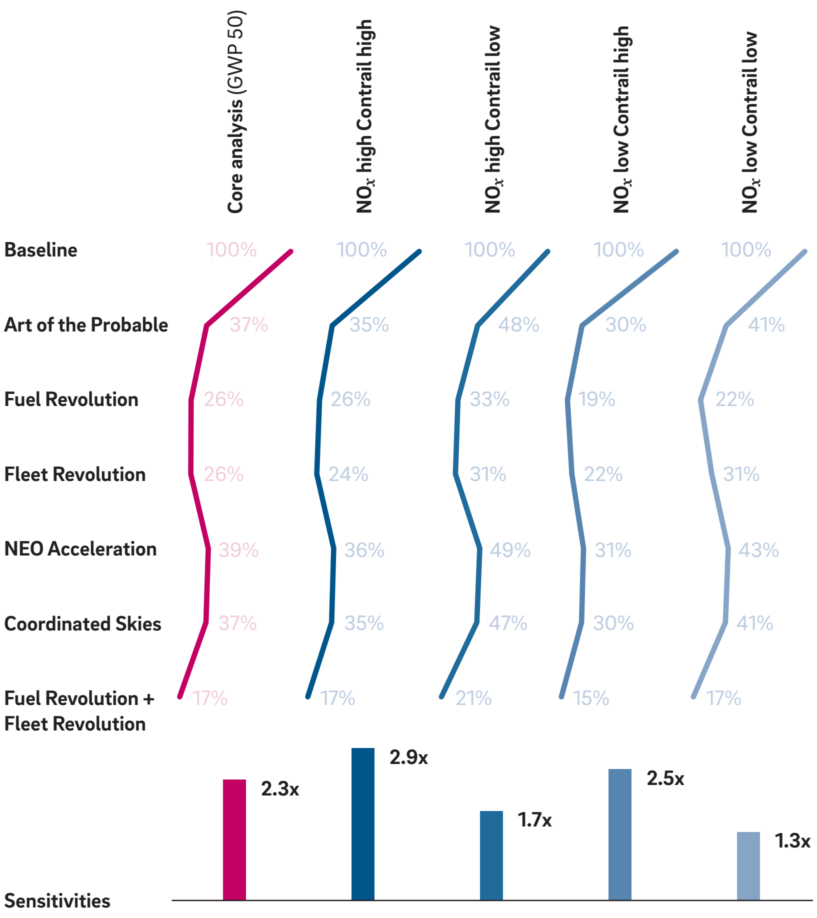
Source: Roland Berger

The Urgency of Now

But what about the scientific uncertainty? Is it not risky to act now before the science is "settled"? We ran a rigorous sensitivity analysis, testing our Roadmap against extremes of the current scientific uncertainty, considering over 30 different outcomes in the relative scale of CO_2 and non-CO_2 effects. In each, our final recommendations remained consistent, and the optimal Roadmap was always the same. Thus, we should strive forward on non-CO_2 and focus on mitigation, with four key recommendations to implement.

The relative impact of each scenario is unchanged regardless of the sensitivity and chosen metric — and thus, the recommendations are unchanged as well

Sensitivity analysis by scenario, 2050 outlook — 2050 baseline



Source: Roland Berger

Four clear recommendations emerge from the Roadmap to True Zero

The industry should agree that non-CO_2 emissions are a major part of aviation's climate footprint, and:
- → Align on a standardised approach to track and measure non-CO_2 emissions, whilst continuing to invest in advancing the underlying science
- → Invest in developing mitigations for non-CO_2 emissions, whilst continuing to emphasise CO_2 reduction

The industry should focus on achieving Coordinated Skies by 2030 through no-regret operational improvements and contrail mitigation:
- → Improved routing
- → Reduction of waiting times
- → Airspace unification (e.g., SESAR)
- → Mitigating contrails through trajectory optimisation

The estimated impact of this package of improvements is ~6–8% in CO_2 reduction, ~80% in contrail reduction, whilst simultaneously reducing costs.

The incremental benefit of a fleet revolution in addition to a fuel revolution — or vice versa — is marginal (~10% CO_2e by 2050). Doing both may not be the optimal solution for society.
- → The industry should either:
  - — Let the "invisible hand of the market" reign, or
  - — Discuss benefits of collectively selecting a strategy — fuel, fleet, or both
- → The decision must consider:
  - — Capital requirements
  - — Ticket costs
  - — Political/regulatory implications
  - — Speed of implementation
  - — Likelihood of success
  - — Incentives to innovate

We must act now: our sensitivity analysis demonstrates that the above recommendations do not change regardless of the scientific uncertainty.

Source: Roland Berger

Your aerospace experts

Manfred Hader
Senior Partner
manfred.hader@rolandberger.com

Robert Thomson
Partner
robert.thomson@rolandberger.com

Nikhil Sachdeva
Principal, Centre for Aerospace & Aviation Sustainability
nikhil.sachdeva@rolandberger.com

Your aviation experts

Didier Bréchemier
Senior Partner
didier.brechemier@rolandberger.com

Florian Dehne
Partner
florian.dehne@rolandberger.com

Gabriel Schillaci
Partner
gabriel.schillaci@rolandberger.com

Your sustainability experts

Yvonne Ruf
Senior Partner, Sustainability & Climate Action Co-Lead
yvonne.ruf@rolandberger.com

Dan Gabaldon
Senior Partner
dan.gabaldon@rolandberger.com

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Publisher

Roland Berger Ltd
55 Baker Street
London W1U 8EW
United Kingdom
+44 20 3075 1100

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