

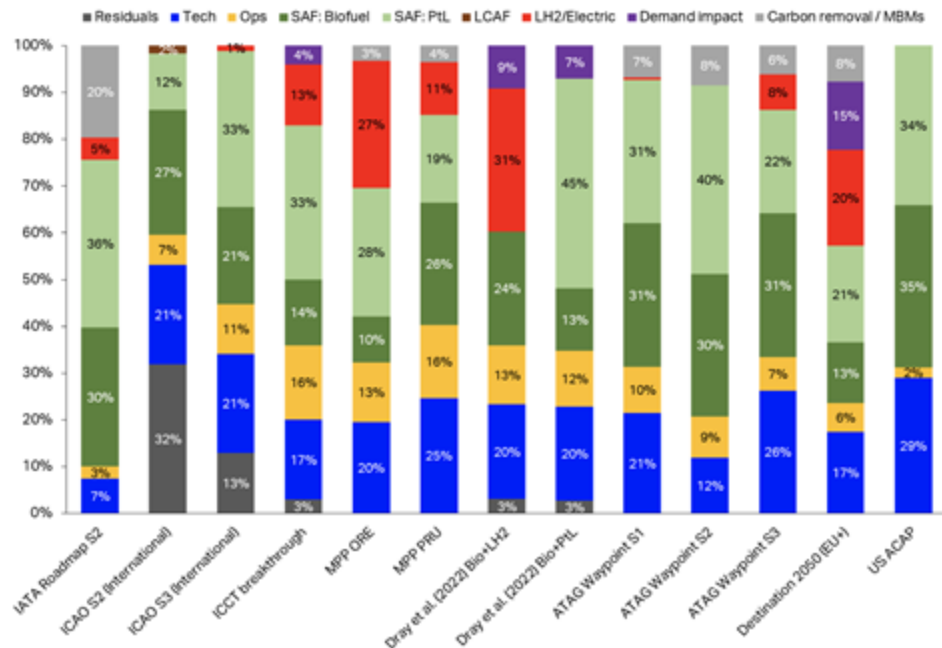
Aviation Vision 2050 Update: The Potential for Climate Neutral Growth through Non-CO₂ Control

ICCT Aviation Team

28 October 2025

Net-zero CO₂ goal: how it started and how it is going

- Agreed by industry and codified by ICAO in 2022
- Consensus on the critical role of SAF, expected to be responsible for about half (24% to 70%) of CO₂ reductions
- Fuel efficiency (airframe + load factor + traffic) ~30% of the CO₂ reductions
- Zero-emission planes, demand response, and carbon removal make modest contributions

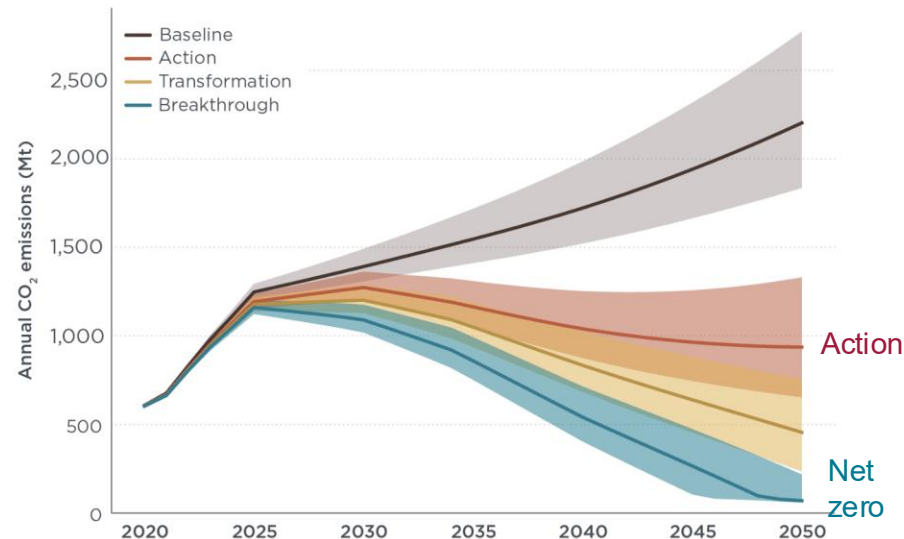


<https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/nz-roadmaps.pdf>

Net-zero CO₂ goal: how it started and how it is going

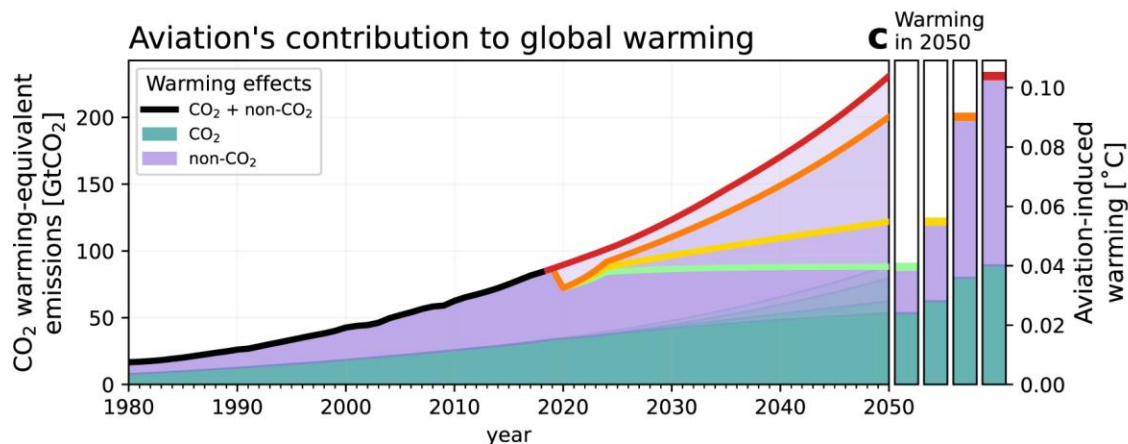
- However, progress towards the net-zero goal has been slow.
- Rate of SAF adoption, as well as other mitigation levers, is closer to our Action Scenario, **with only modest CO₂ reductions in 2050 compared to 2025.**

Metric	Measure	Vision 2050 scenario			
		BAU	Action	Transform	Breakthrough
Fuel carbon intensity (gCO ₂ /MJ)	Sustainable aviation fuel		✓		
	Zero emission planes		✓		
Aircraft energy intensity (MJ/RPK)	Fuel efficiency		✓		
Activity (RPK)	Traffic growth	✓			
	Carbon pricing		✓		



The growing importance of non-CO₂

- Greenhouse gases (GHGs): CO₂, CH₄, N₂O
 - Lifetimes of tens to thousands of years
 - Impact driven by **accumulation** in the atmosphere
- Short-lived climate pollutants (SLCP): Contrails, NO_x, nvPM, water vapor, and sulfate aerosols
 - Lifetimes of hours to days
 - Impact driven by **continuing pulses** of emissions



Klöwer et al. (2021) Quantifying aviation's contribution to global warming. Environmental Research Letters, 16(10)

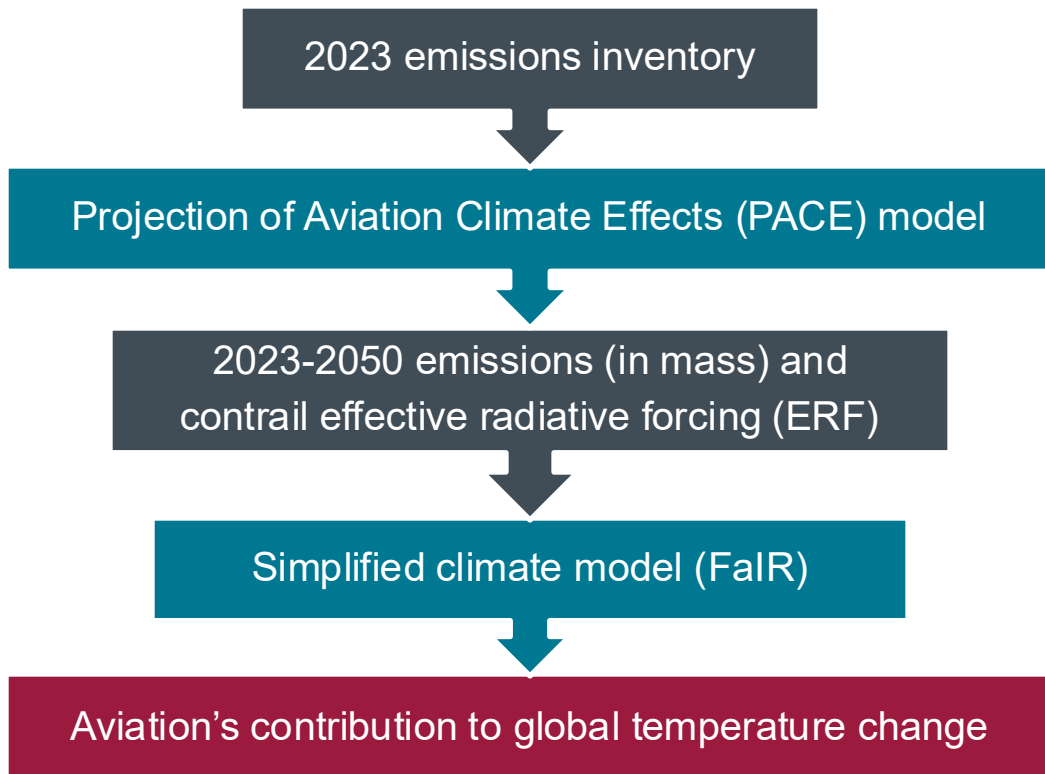
New research question

How can cuts to short-lived climate pollutants from global commercial aviation contribute to the Paris Agreement?

Methods

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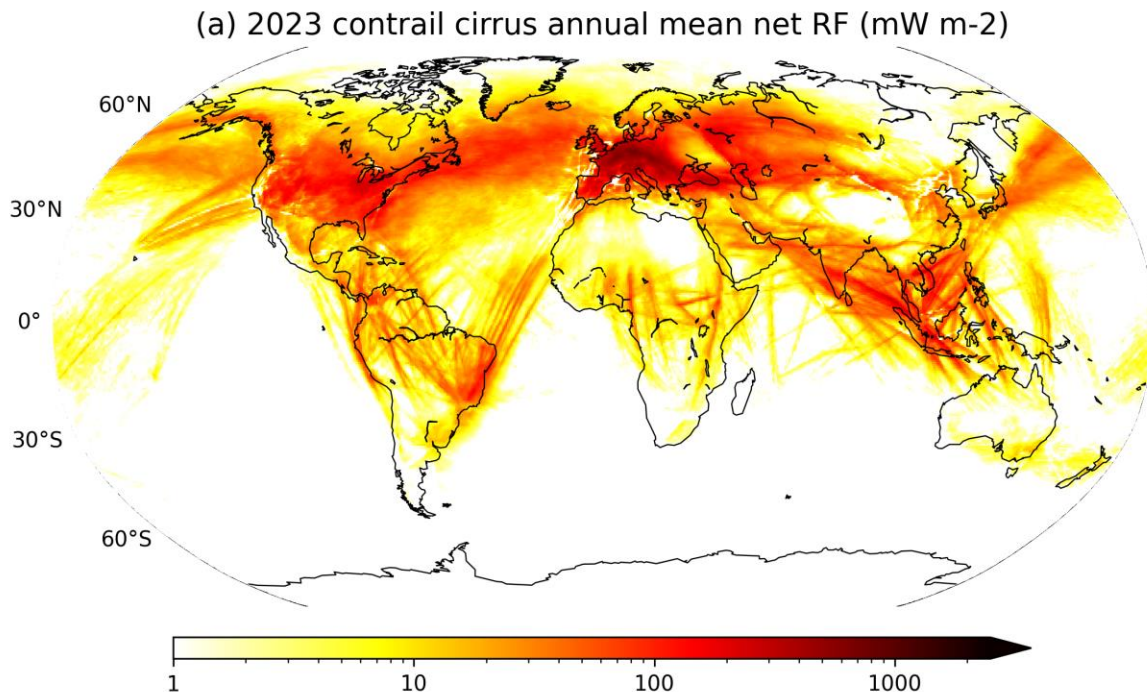
High-level Design



Trajectory-Based 2023 Inventory

Key datasets and models

- Spire ADS-B trajectories
- OAG flight schedule
- Various load factor datasets
- BADA3 aircraft performance model
- Contrail Cirrus Prediction Model (CoCiP)
- ICAO Aircraft Engine Emissions Databank (EEDB)
- Boeing FFM2 (for NO_x) and T4/T2 method (for nvPM)



Mitigation Scenarios

Scenario Name	Definition
Historical Trends	Counterfactual
Current Commitments	Announced policies and industry goals
GHG Forward	Maximum GHG reduction only
SLCP Forward	Maximum mitigation of NO _x , nvPM, and contrails
Full Breakthrough	Maximum mitigation of both short and long-lived climate pollutants

Key mitigation levers

GHG

- Aircraft fuel efficiency
- Payload and traffic efficiency
- Sustainable aviation fuels (SAFs)
- Zero emission planes (ZEPs)

SLCP

- Low-NOx/nvPM engines
- Contrail avoidance
- Hydrotreating fossil Jet A*
- Sustainable aviation fuels (SAFs)*

*Lower aromatics -> lower nvPM emission
-> lower ice particle number -> reduced
likelihood of persistent contrail formation

Cross-cutting

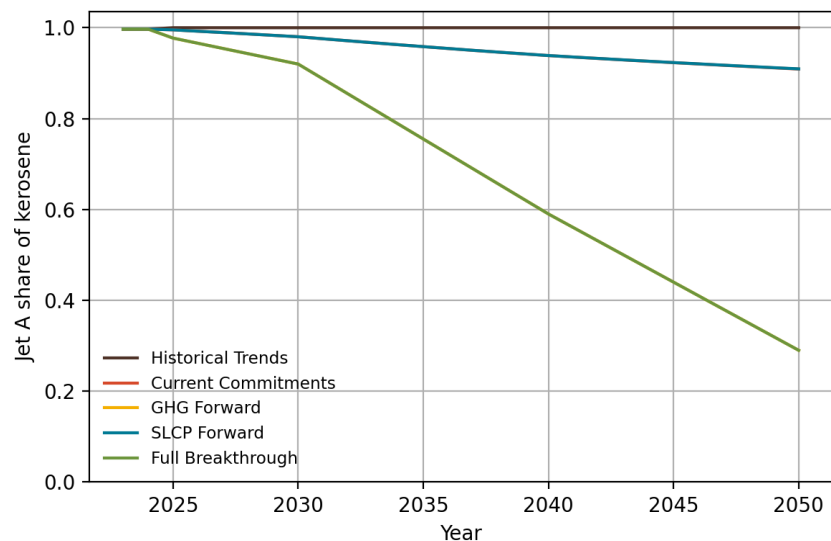
- Demand response to carbon pricing

Results

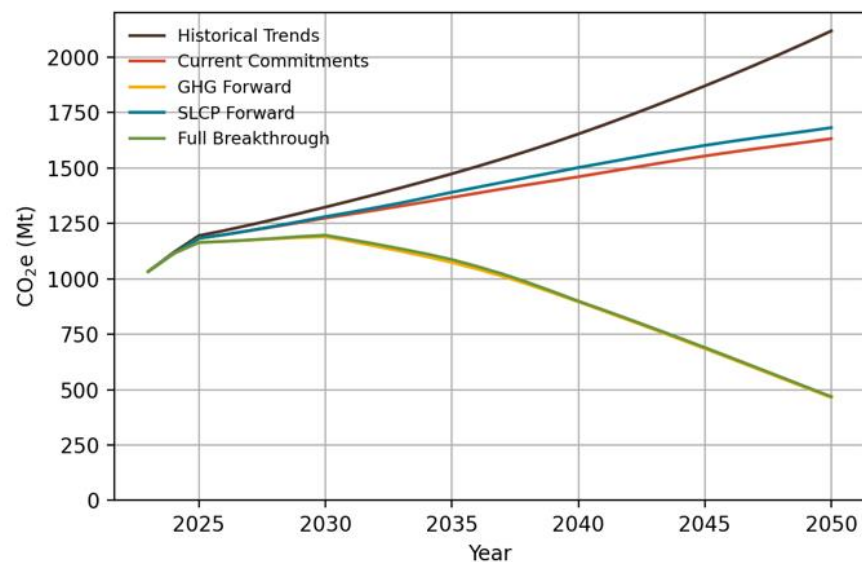
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SAF Blending and GHG Emissions

Jet A Share of Kerosene

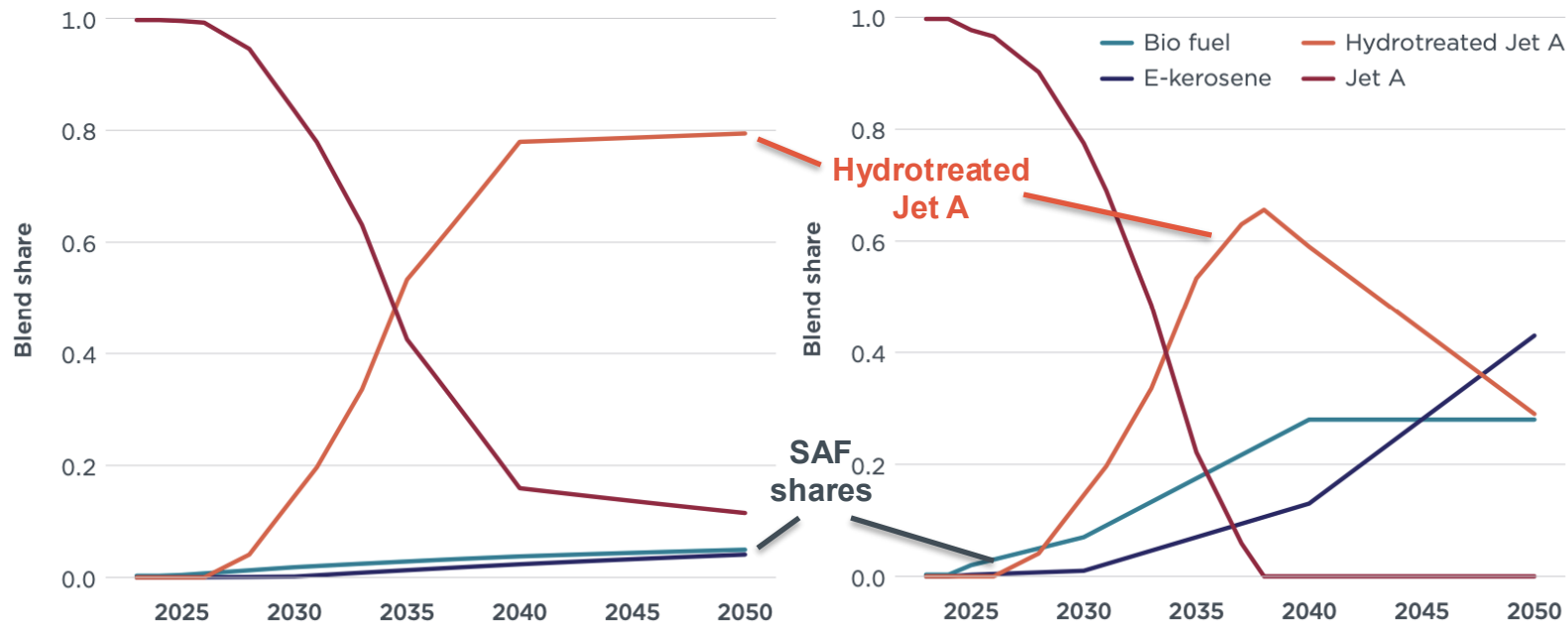


Annual GHG Emissions



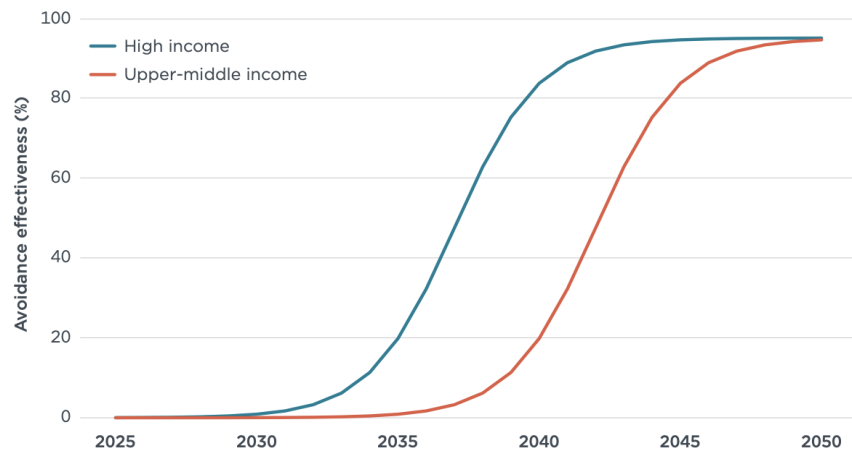
SLCP mitigation: hydrotreating fossil Jet A

Share of kerosene feedstock in SLCP Forward (left) and Full Breakthrough (right) scenarios

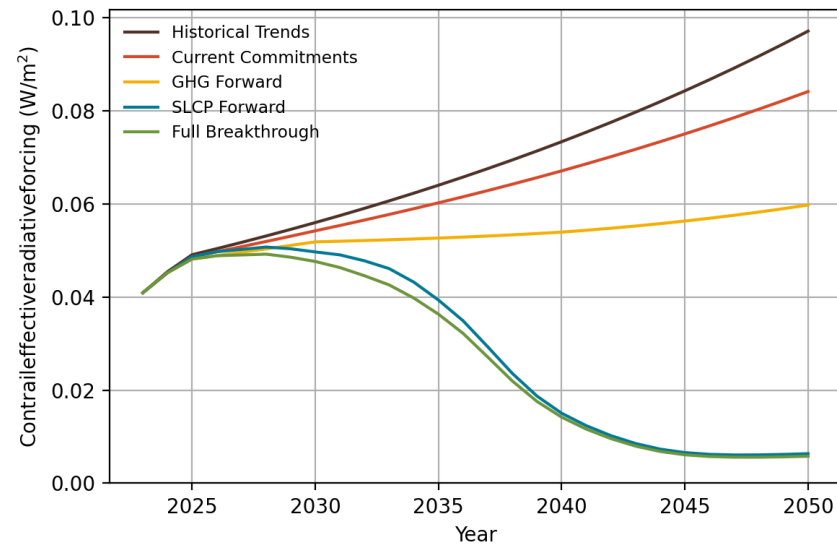


SLCP mitigation: contrail ERF

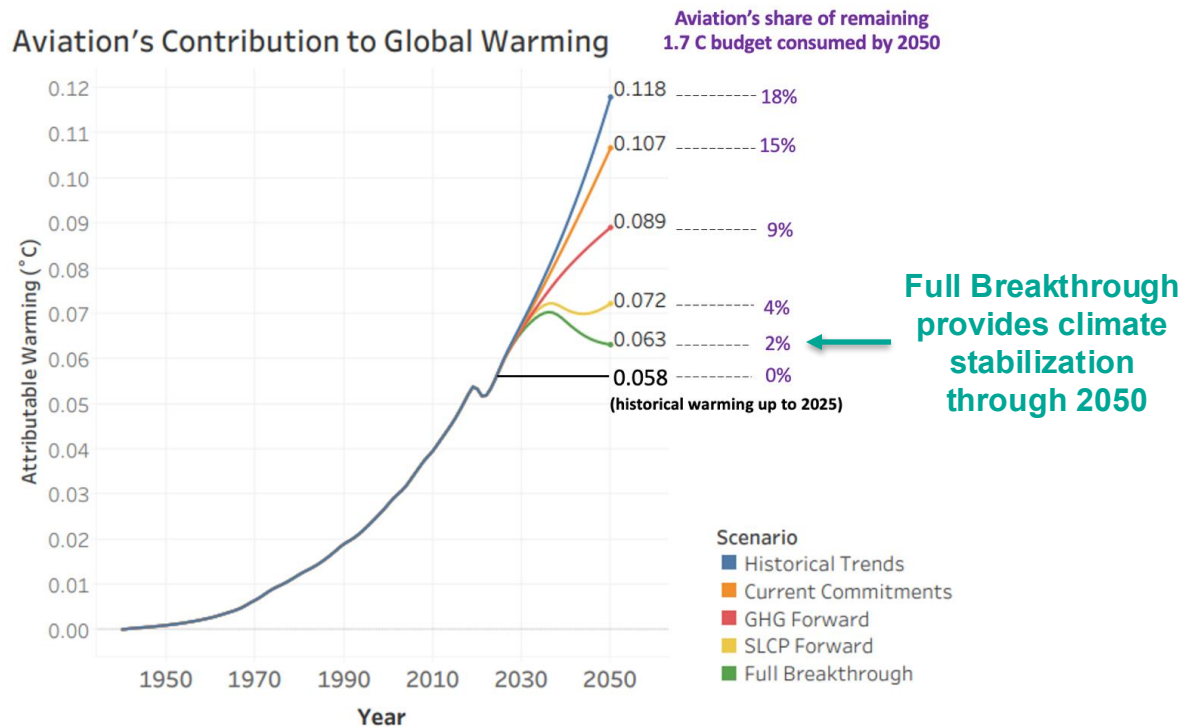
Scale-up of contrail avoidance



Contrail effective radiative forcing by scenario



Temperature response by scenario



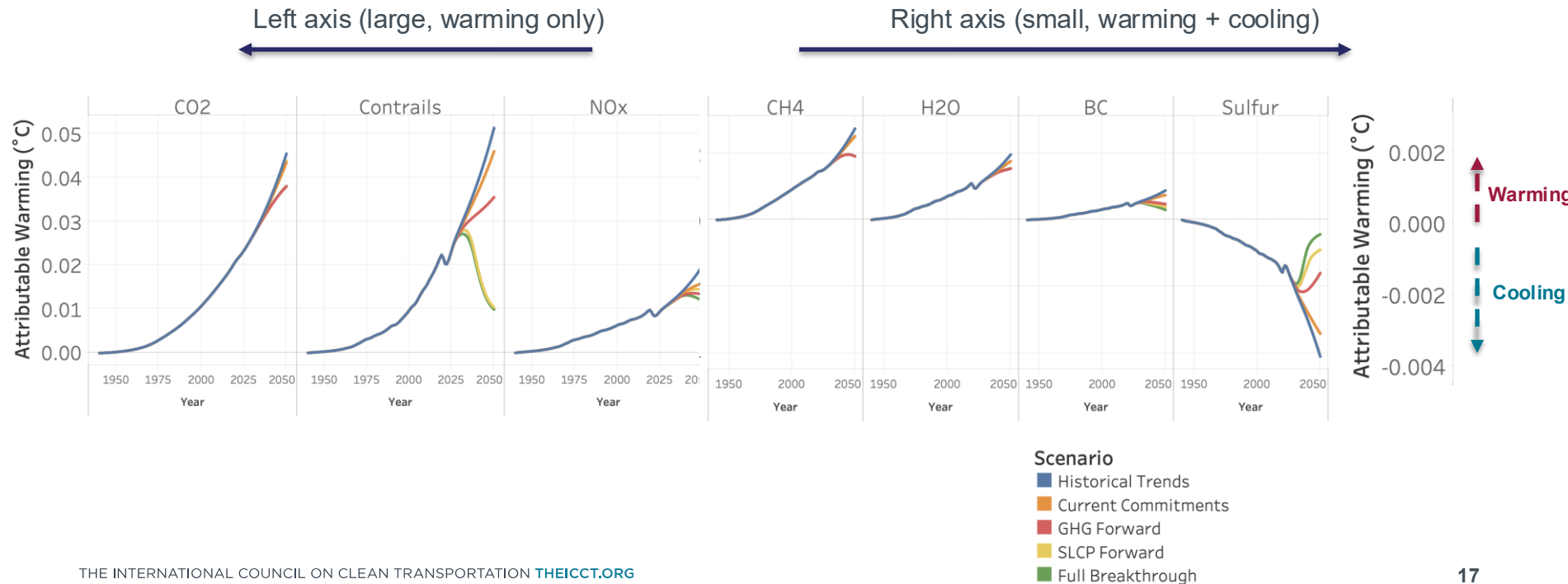
Alignment with climate budgets

Scenario	Total warming 1940–2050 (°C)	Additional warming 2025–2050 (°C)	% of remaining budget		
			1.5 °C (0.14 °C)	1.7 °C (0.34 °C)	2 °C (0.64 °C)
Historical Trends	0.118	0.0603	43%	18%	9%
Current Commitments	0.107	0.0493	35%	15%	8%
GHG Forward	0.089	0.0313	22%	9%	5%
SLCP Forward	0.072	0.0143	10%	4%	2%
Full Breakthrough	0.063	0.0053	4%	2%	1%

Aviation activity (1940-2025) is responsible for about 4% of anthropogenic global warming since pre-industrial levels

SLCP warming mitigation dominates because of short residence times in the atmosphere relative to CO₂

Aviation's historical and projected contribution to global warming by pollutant and scenario, 1940 to 2050



Share of avoidable warming by mitigation lever under the Full Breakthrough scenario

Mitigation lever	Avoided warming (mC)			% of total
	GHGs	SLCPs	Total	
Contrail avoidance	0.07	-23.4	-23.3	42.5%
SAF	-5.90	-5.68	-11.6	21.1%
Hydrotreating	0.05	-6.35	-6.30	11.5%
Operational efficiency	-1.37	-4.58	-5.95	10.8%
Low NOx/nvPM engines	0.00	-4.39	-4.39	8.0%
Technical efficiency	-0.84	-1.80	-2.62	4.8%
Demand response	-0.12	-0.30	-0.42	0.8%
Modal shift	-0.07	-0.17	-0.25	0.5%
ZEP	-0.02	-0.02	-0.05	0.1%
Total	-8.20	-46.6	-54.9	100%
% of total	15%	85%	100%	

Findings and Conclusions



Conclusions

- Aviation is on track to nearly double (+85%) its contribution to global warming by 2050 and to consume 15% of a Paris compatible climate budget.
- Maximum GHG controls can halve additional aviation warming in 2050, but aviation would still double (to 8%) its share of a Paris compatible climate budget, with additional warming afterwards.
- SLCP controls, notably contrail avoidance, can complement GHG mitigation with large near-term reductions via available technology.
- Concerted action on GHGs and SLCPs can cut additional warming from aviation by more than 90% and put aviation on a path to “climate neutrality” after 2035.
- Four mitigation levers—contrail avoidance, SAFs, hydrotreating, and operational efficiency—account for nearly 90% of avoidable warming in 2050.
- To achieve mid-term climate stabilization, policymakers should adopt SLCP controls while continuing to develop long-term GHG-reduction technologies.

Questions?



Supplemental materials follow

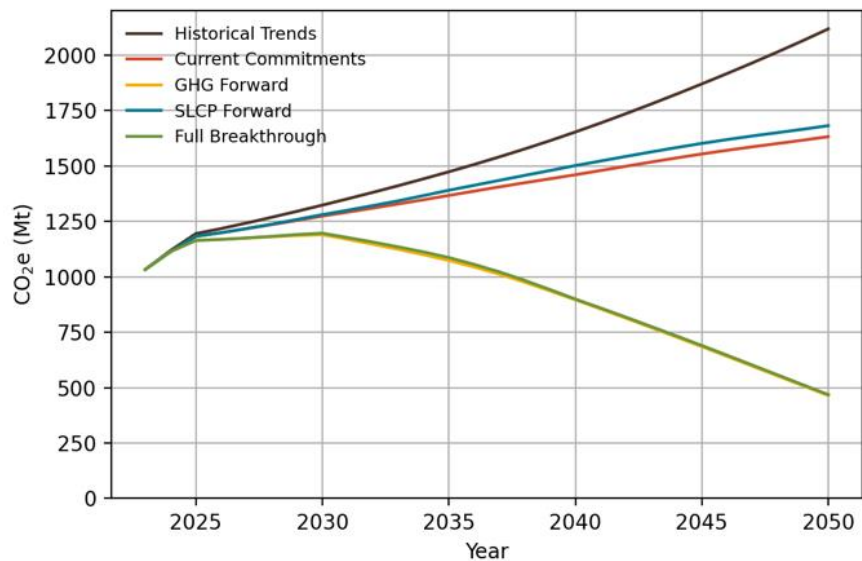


Scenario assumptions

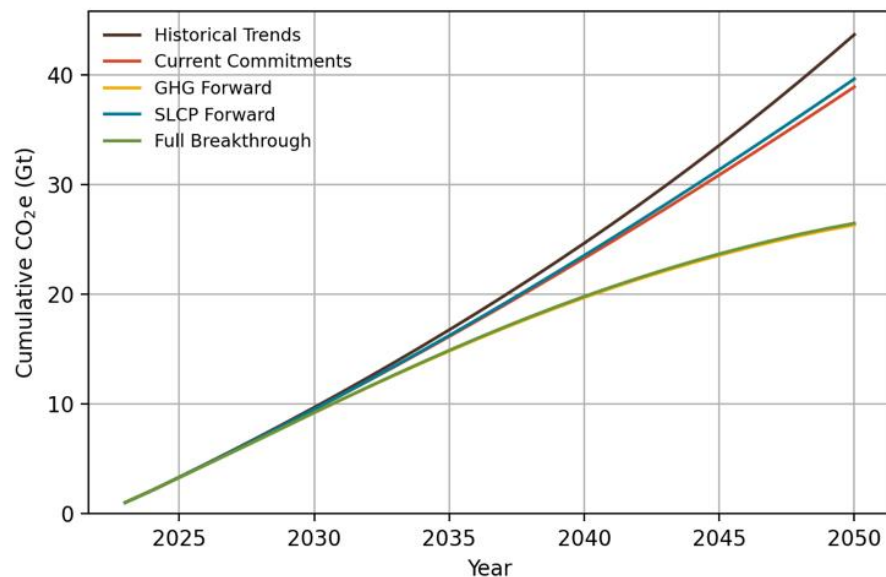
		Historical Trends	Current Commitments	GHG Forward	SLCP Forward	Full Breakthrough
Technical efficiency (MJ/RTK)	2023–2050 (improvement per year)	-0.8%	-1.1%	-1.5%	-1.1%	-1.5%
Operational efficiency (MJ/RTK)	2023–2050 (improvement per year)	-0.2%	-0.5%	-0.8%	-0.5%	-0.8%
Global sustainable aviation fuel share (%)	2030	–	2%	8%	2%	8%
	2050	–	9%	71%	9%	71%
ZEPs entry into service	Electric commuter	–	2030			
	Hydrogen regional	–	2035			
	Hydrogen narrowbody	–	–	2045	–	2045
Advanced engines entry into service	Regional jets/narrowbody	–	2035			
	Widebody	–	2040	2035	2040	2035
	Freighters	–	2045	2040	2045	2040
Avoided contrail radiative forcing (global)	2035	–	–	–	15%	
	2050	–	–	–	90%	
Share of hydrotreated kerosene	2027	–	–	–	5%	
	2035	–	–	–	100%	

Annual and cumulative GHG Emissions

annual

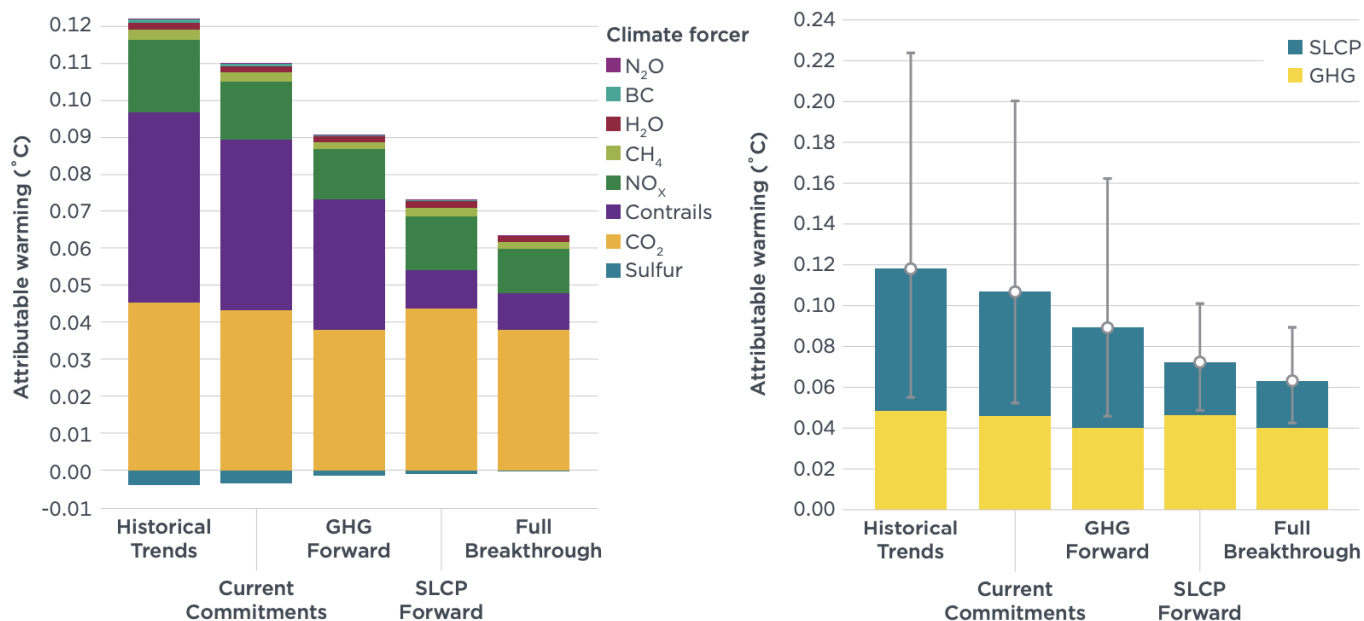


cumulative



Warming by pollutant

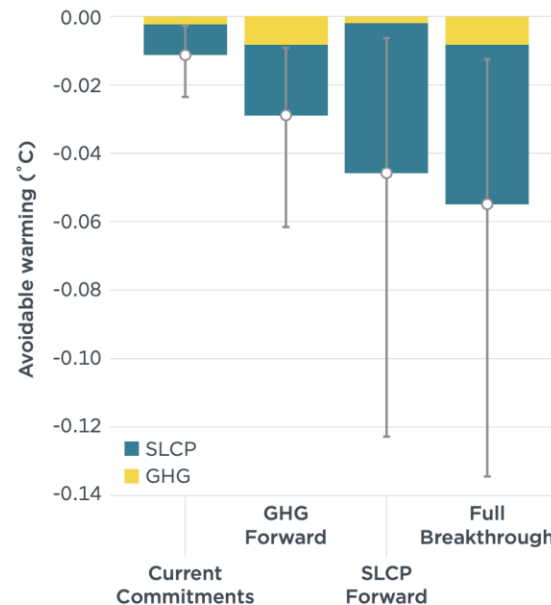
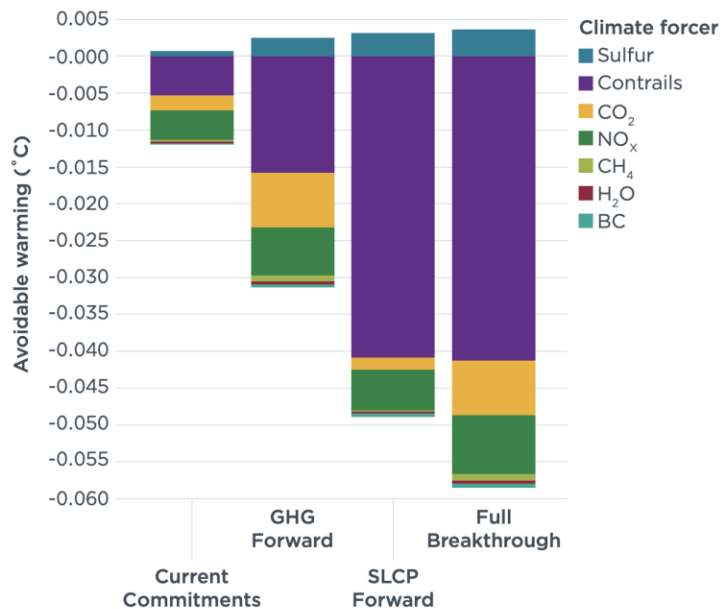
Total warming by pollutant from 1940 to 2050 (left) and GHG versus SLCP warming in 2050 (right)



Note: Lines on the right represent the 95% confidence interval for the SLCP temperature response.

Avoidable warming by pollutant species

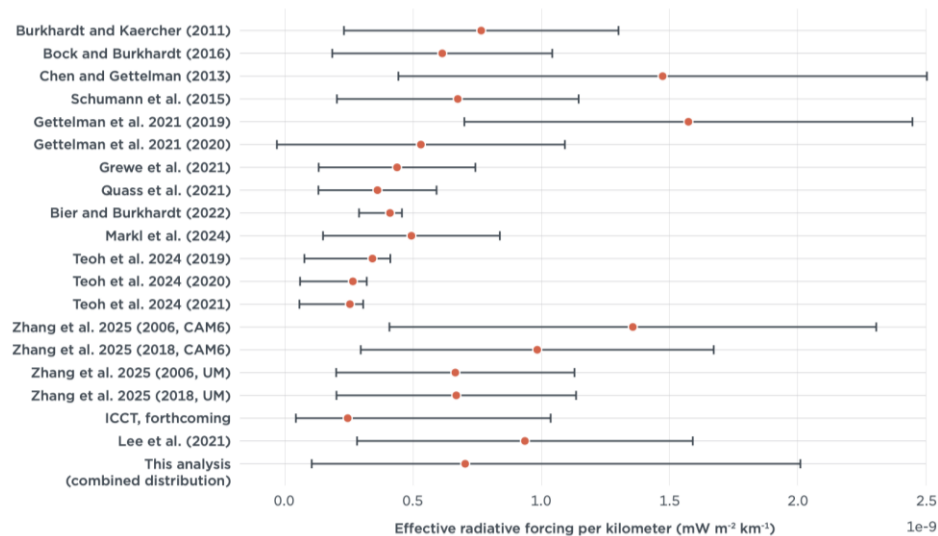
Avoidable 2050 global warming by pollutant and scenario and aggregated by GHGs versus SLCPs groups



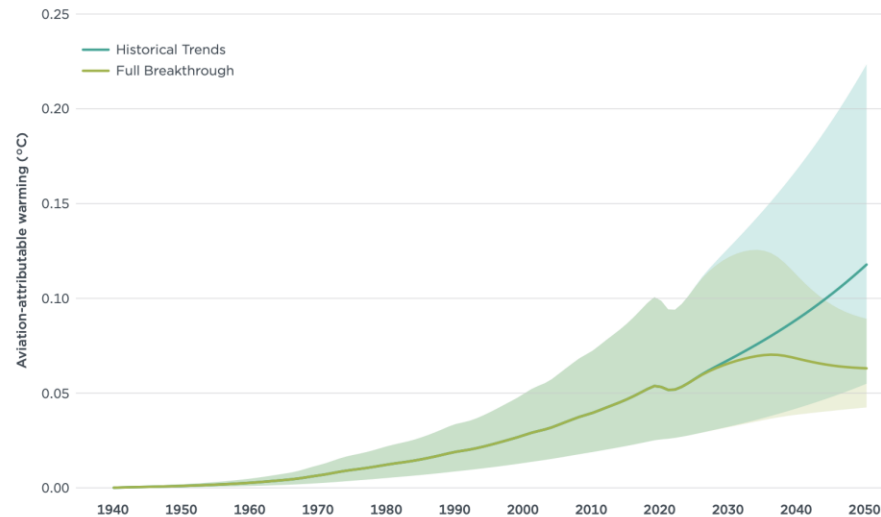
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION [THEICCT.ORG](https://theicct.org)

Contrail uncertainty quantification

Central estimate and uncertainty intervals used for this meta-analysis



Temperature response for the Historical Trends and the Full Breakthrough scenarios



Note: The shaded area representing the range of possible responses due to uncertainty in the climate impact of SLCPs.

Two-thirds of contrail warming attributable to flights leaving Europe and North America

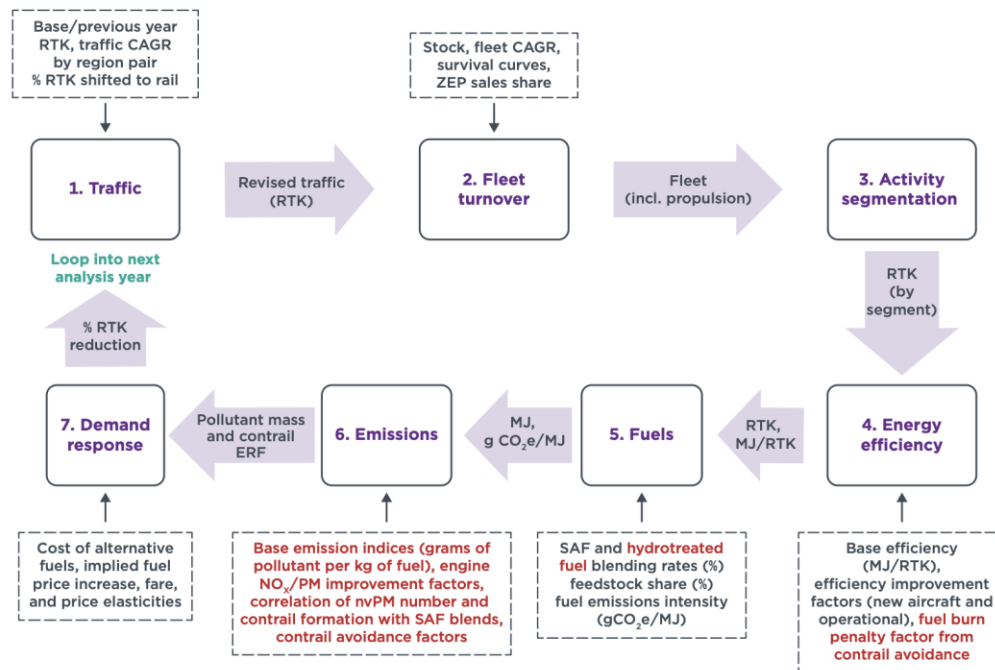
Share of revenue tonne-kilometers and contrail effective radiative forcing by ICAO departure region, 2023

ICAO departure region	RTK		Contrail ERF	
	Value (billions)	Share of total	Value (mW/m ²)	Share of total
Europe	267	25%	15.6	38%
North America	262	24%	10.7	26%
Pacific-Southeast Asia	105	10%	3.2	8%
China	145	13%	2.7	7%
North Asia	66	6%	2.2	5%
Middle East	81	8%	1.9	5%
South America	41	4%	1.2	3%
Central America	34	3%	1.2	3%
Southwest Asia	46	4%	1.1	3%
Africa	30	3%	1.0	2%
Global	1,077	100%	39.9 [6.9, 114.4] ^a	100%

^a Bracketed values denote upper and lower bound of 95% confidence interval, respectively.

PACE model flow

PACE 2.0 model flow



Note: Red text denotes newly added modeling capabilities; CAGR = compound annual growth rate.

Traffic assumptions used for modeling

Traffic type	Metric	Year	Case		
			Low	Central	High
Passenger	Annual increase	2025-2050	+2.8%	+3.4%	+3.7%
	Trillion RPK	2025	9.78		
		2050	19.5	22.6	24.3
		2050/2025	1.99	2.31	2.48
Freight	Annual increase	2025-2050	+3.1%	+3.6%	+3.9%
	Billion FTK	2025	291		
		2050	624	705	758
		2050/2025	2.15	2.42	2.60

GHG mitigation: fuel efficiency

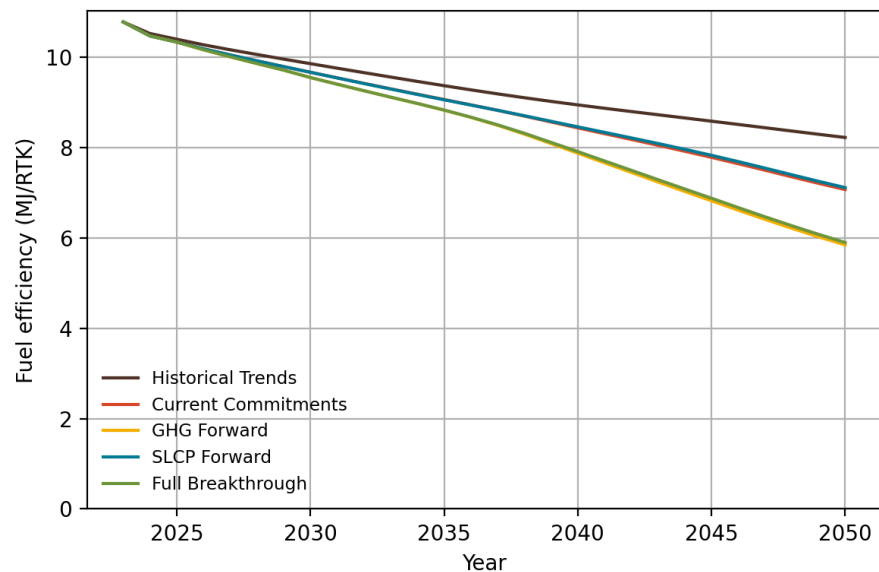
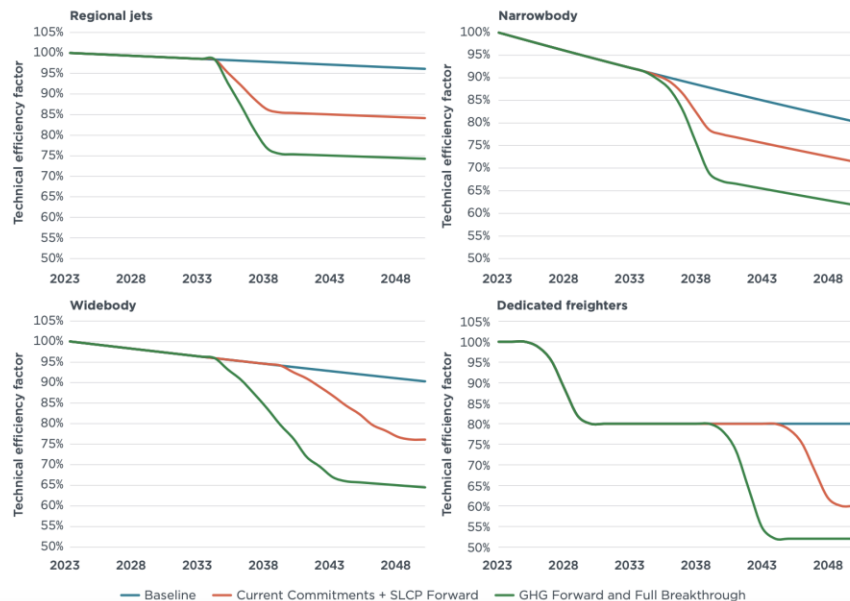
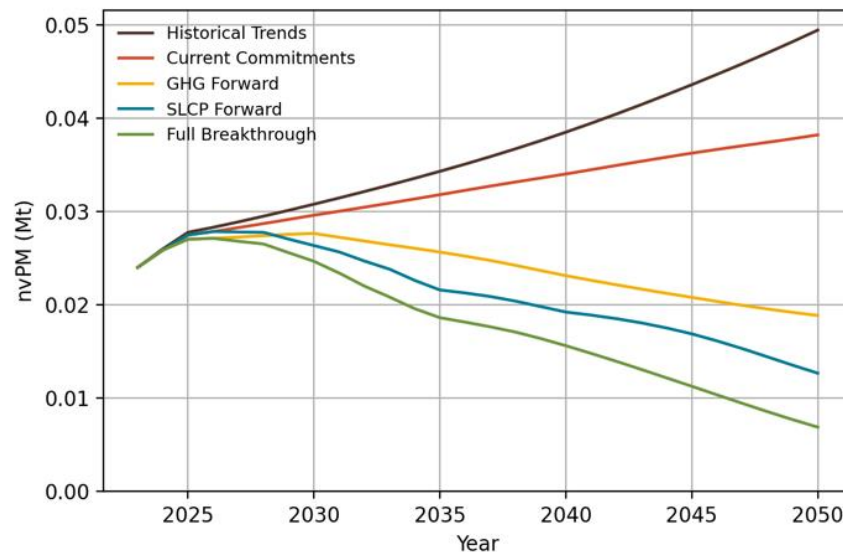
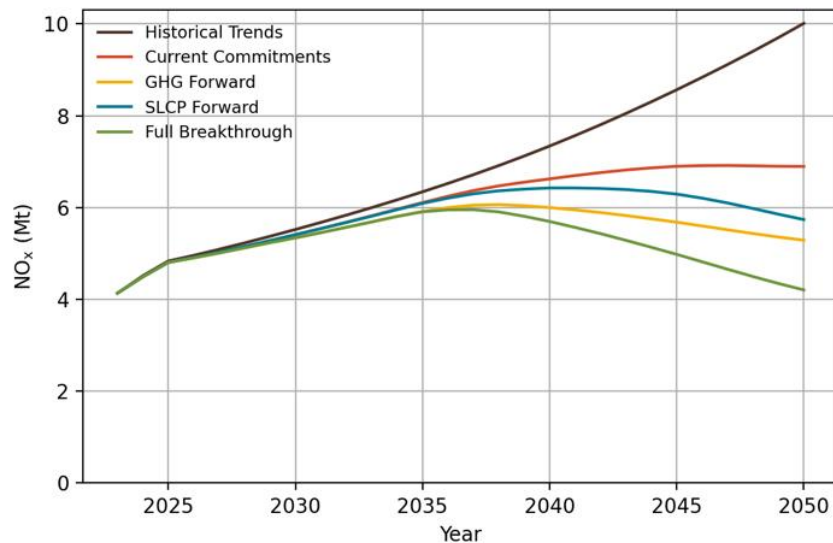


Figure 3
Technical efficiency assumptions by scenario for regional, narrowbody, widebody, and freighter aircraft



NOx and nvPM trends

NOx and nvPM emissions by scenario, 2023 to 2050



NO_x/nvPM engine emission assumptions

Table 9

**Cruise-phase NO_x emission indices by aircraft class and scenario for new deliveries
(g NO_x/kg fuel)**

Aircraft class	Scenario				
	Historical Trends	Current Commitments	GHG Forward	SLCP Forward	Full Breakthrough
Regional jet	13.96	10.41			8.71
Narrowbody	15.81	10.12			7.1
Widebody	17.68	12.80	12.41		8.66

Table 10

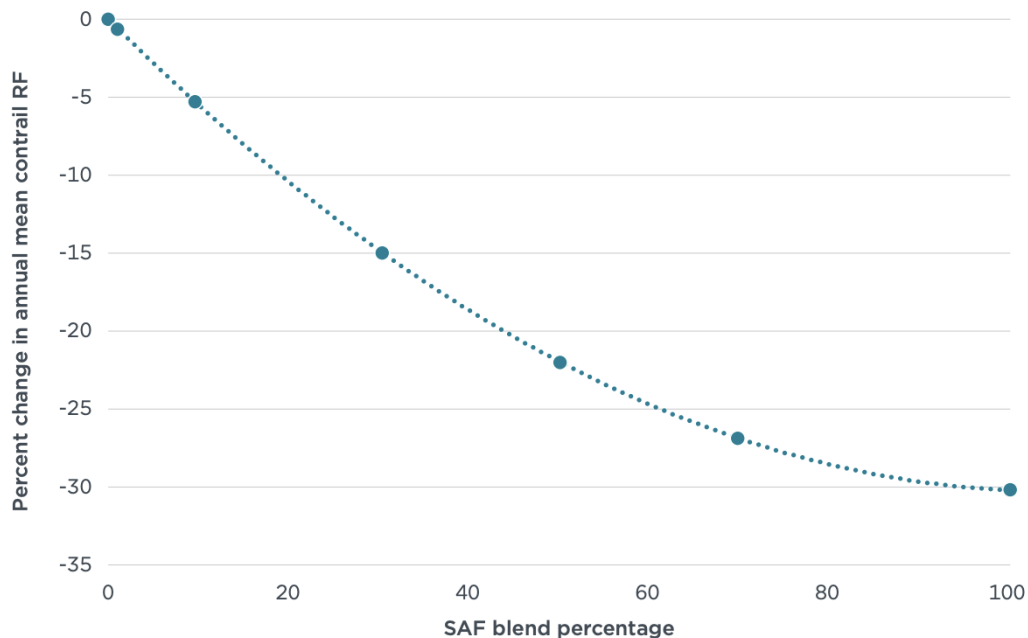
**nvPM number emission indices by aircraft class and scenario for new deliveries
(# of particles/kg fuel)**

Aircraft class	Scenario				
	Historical Trends	Current Commitments	GHG Forward	SLCP Forward	Full Breakthrough
Regional jet			9.79 × 10 ¹⁴		
Narrowbody		9.28 × 10 ¹⁴			2.81 × 10 ¹⁰
Widebody		9.71 × 10 ¹⁴			1.06 × 10 ¹¹

Impact of SAF blending on contrail ERF

Figure 4

SAF blend percentage versus percent change in annual net mean radiative forcing



Contrail ERF by region

Figure 13

Annual ERF for flights departing each region in the Full Breakthrough scenario

