Dedicated to innovation in aerospace

CO_2 reduction targets for Amsterdam Airport Schiphol based on remaining IPCC CO_2 budgets up to 2050

January 2024

Stringent reductions in CO_2 emissions – and demand – required for Schiphol to meet Paris goal of 1.5˚C global warming

- Current in-sector decarbonisation measures, excluding offsetting, are not enough to meet IPCC derived carbon budgets compatible with 1.5˚C global warming for Amsterdam Airport Schiphol.
- Significant demand management measures, to be implemented by 2030 at the latest, seem the only viable way out. Demand in flights beyond a certain distance could be targeted in particular.

-32% up to -66% v. 2019
required CO_2 reduction
current goal Duurzame Luchtvaarttafel: -9% v. 2019
current measures: -20% v. 2019

Net-zero with carbon removals

2023 — 2030 — 2040 — 2050

Current measures
- ✓ Fleet renewal
- ✓ Operational improvements
- ✓ SAF (up to 10%)
- ✓ Continued efficiency improvements
- ✓ Increased use of SAF (ReFuelEU Aviation)

Additional measures
- ➢ Significant demand management measures from 2025

  Potentially by reduction of long-distance, high emission flights from 2025

Current measures in line with Destination 2050; 2030 SAF based on Clean Skies for Tomorrow (10%), above ReFuelEU (6%)

CO_2 reduction targets for Amsterdam Airport Schiphol based on remaining IPCC CO_2 budgets up to 2050

CLASSIFICATION
Public

DATE
January 2024

KNOWLEDGE AREAS
Air transport emissions
Sustainable aerospace operations
Third party risk and policy support

KEYWORDS
CO_2 emissions
Carbon budget
Paris Agreement

This report has been discussed with various experts from CE Delft, in particular to define the input assumptions and methodology. The authors are grateful for their useful suggestions and additions. Ownership and responsibility of the analysis presented lies with NLR.

How much aviation fits in a Paris-compatible CO_2 budget?

A study commissioned by Royal Schiphol Group, to inform decision making about a 2030 emissions target

In 2015, the world committed to limit global warming through the Paris Agreement

> (a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

Since this commitment, the IPCC has stressed the relevance of cumulative emissions and has determined global CO_2 budgets: how much more emissions can we have in order not to surpass the Paris-targets?

Although international aviation is not part of Nationally Determined Contributions, its emissions do count towards these budgets, as these encompass all man-made CO_2. Hence, it also has to contribute in reducing emissions.

Crucially, net-zero roadmaps do not address this, as these look at emissions in a particular year – and not at the 'area below the curve'.

This research first determines possible CO_2 budgets for flights departing from Amsterdam Airport Schiphol in the period 2020 – 2050, based on various temperature scenarios and budget shares allocated to aviation.

Then, this work explores 'how much aviation activity' fits within these budgets. This is a crucially relevant question, as activity growth has historically out-paced efficiency improvements 10 to 1 (Annex III.A).

Ultimately, implications for 2030 emission levels are derived.

Definitions

- Emissions
  Unless indicated otherwise, all emissions are tank-to-wake. Life cycle emissions reductions of SAF are taken into account using the ICAO CORSIA methodology, in which life cycle savings are evenly distributed over well-to-tank and tank-to-wake quantities. An emission index of 3.16 kg CO_2 per kg of fuel is used.
- Net in-sector emissions
  Net emissions by the aviation sector, including net emissions reduction by the use of SAF, but excluding out-of-sector carbon removal (offsetting, compensation, …)
- SAF
  Sustainable aviation fuel, spanning both bio-based as well as synthetic fuels

The IPCC has set CO_2 budgets, which specify how much CO_2 we can emit in order to limit warming to various temperature scenarios

Limiting global warming to a certain **temperature** with a certain **likelihood** yields a **global carbon budget**. For 2020 – 2050, IPCC has determined these to be the following.

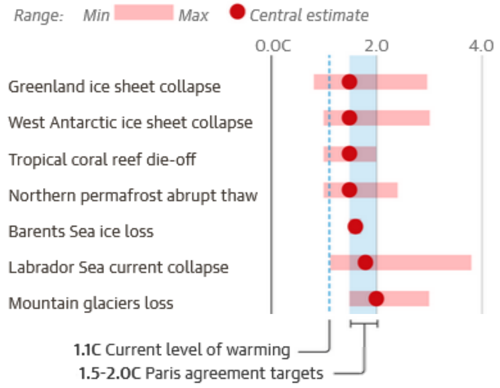
ºC	Likelihood		
	50%	66%	83%
1.5	**500 Gt**	400 Gt	300 Gt
1.7	850 Gt	**700 Gt**	550 Gt
2	1350 Gt	1150 Gt	900 Gt

This research zooms in the two bold-printed budgets for **50%/1.5˚C** and **66%/1.7˚C**. The first budget is also largely in line with 83%/ 1.7˚C.

Scenarios with 2˚C warming and 1.7˚C warming with a likelihood of 50% are not explored, as

- the Paris Agreement stipulates warming “well below 2˚C”
- the risk of reaching dangerous tipping points increases at higher levels of global warming (e.g. Lenton *et al.*, 2023; Armstrong McKay *et al.*, 2022)
- the consequences if targets are overshot, and likelihood of this happening (e.g. Beevor & Alexander, 2022)

The graph below (based on Armstrong McKay *et al.*, 2022 and Carrington, 2022) shows the “estimated range of global heating needed to pass tipping point temperature”. It illustrates the marked differences between 1.5˚C, 1.7˚C and 2˚C.



From global CO_2 budgets, CO_2 budgets for aviation in general and CO_2 budgets for flights departing from Schiphol are derived

Various sources provide a **share of the budget allocated to aviation**. Van den Berg *et al.*, (2020) show various ways to address that allocation problem, based on different equity principles. This is a fundamental societal and political choice.

This research explores two principles:

1. If the **current share** of emissions is maintained, the budget for all aviation would be **2.4%** (ICCT, 2020).
2. If one takes into account that aviation is hard / costly to abate, a larger share could be justified. In the **IEA Net Zero scenario** (2021), the aviation budget is **3.9%**.

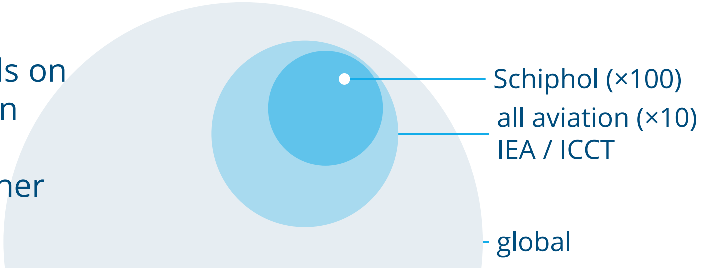
The **share of the budget for aviation at Schiphol** depends on the share of aviation activity in the Netherlands (vs. global). Currently, this is 1.16%. As other regions will see higher traffic growth, this share will reduce over time (in line with a reducing share of Europe).

Anticipated future share 1.05%

The share of the budget for Schiphol depends on the share of traffic at Schiphol compared to the Netherlands.

Share of Schiphol vs. NL 96%

Multiplying these, the **share used in analysis** is **1.01%**



The illustration above shows the global, aviation and Schiphol CO_2 budgets – the latter two magnified 10 and 100 times to be visible. It also captures the substantial difference between a 2.4% (ICCT) or 3.9% (IEA) share for aviation.

If global aviation today would be responsible for 3.9% of global CO_2 emissions, flights departing from the Netherlands would emit more than 10% of the rest of the Dutch economy.

The used share of 1.01% in this analysis is conservatively taken to determine the total cumulative budget instead of differentiating from 1.11% in 2019 to 1.01% in 2050.

In-sector emissions between 2020 and 2050 are calculated, modelled and estimated based on suitable data and methods

2020 | 2023 | 2030 | 2040 | 2050

calculated from fuel bunkers

Known

modelled, based on

- planned fleet renewal, including upgauging depending on plans
- operational improvements
- SAF usage

Lower uncertainty

estimated, based on

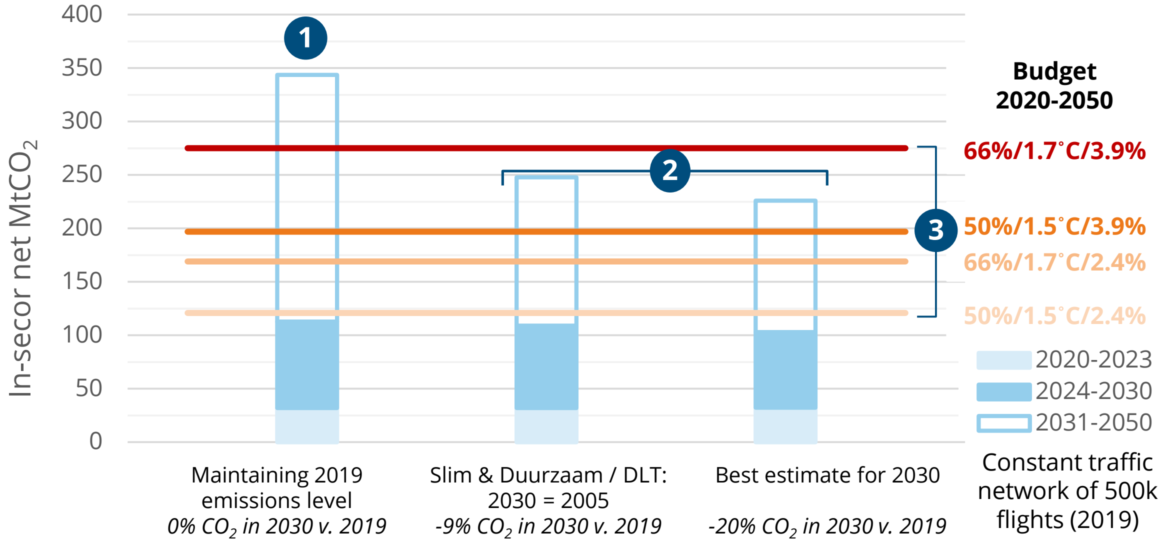
- Mandated SAF uptake (ReFuelEU Aviation, increased to 10% SAF in 2030 following Clean Skies for Tomorrow), expected emissions reduction factor (Destination 2050: 72% in 2025, linearly increasing to 95% by 2050)
- Literature-derived figures for efficiency improvement (1.3 – 1.7% p.a., in line with historical average or maximum attainable improvement), delivered by improvements in aircraft and engine technology and improvements in operation

Greater uncertainty

Key observation: 2030 emissions level is the key determinant for cumulative emissions over the 2020 – 2050 period. Period up to 2030 already includes anticipated decarbonisation actions. In-sector net emissions reduce rather quickly from 2031 thanks to ReFuelEU Aviation, but limited by efficiency improvement (1.3 – 1.7% p.a.).

- Resulting cumulative emission values are then **compared to IPCC-derived CO_2 budgets** for aviation at Schiphol
- Remaining net in-sector **emissions in 2050** are compared to anticipated share of out-of-sector carbon removal in Destination 2050

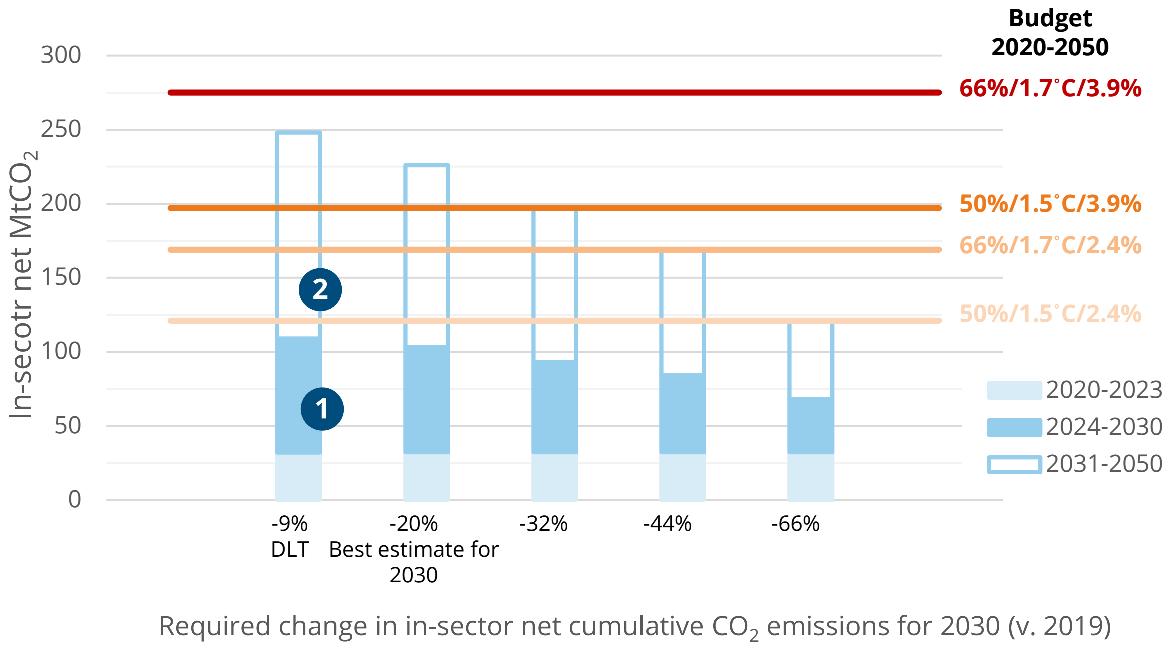
In-sector action between now and 2030 reduces cumulative CO_2 emissions but overshoots majority of airport carbon budgets



1. Maintaining emissions at 2019 level (11.5 $MtCO_2$) overshoots all budgets
2. Best-estimate for 2030 CO_2 emissions, including fleet renewal, operational improvements and SAF uptake is below current DLT-target (2030 = 2005).
3. All airport specific carbon budgets are overshot between 2030 and 2050 except those derived for 66% likelihood of 1.7˚C with 3.9% share.

Maintaining 2019 emissions level: 0% CO_2 reduction with respect to 2019: recovery to 2019 CO_2 (11.5 Mt) in 2024, maintained until 2050. // All others include SAF from 2025 (ReFuelEU Aviation, increased to 10% in 2030), 1.3% p.a. efficiency improvement between 2031 and 2050. // Slim & Duurzaam / DLT 2030 = 2005: Recovery to 2019-level of emissions (11.5 Mt) in 2024, linearly reduced to 2005-level (10.5 Mt) in 2030. // Best estimate for 2030: Traffic recovery to 2019-level in 2024, emissions modelled based on best estimate of pathway for 2020 – 2030 (fleet renewal, operational improvements, 10% SAF) // Fit for 55 and Destination 2050 scenarios are most comparable to 'best estimate for 2030' (Destination 2050 anticipates -12% CO_2 in 2030 v. 2019).

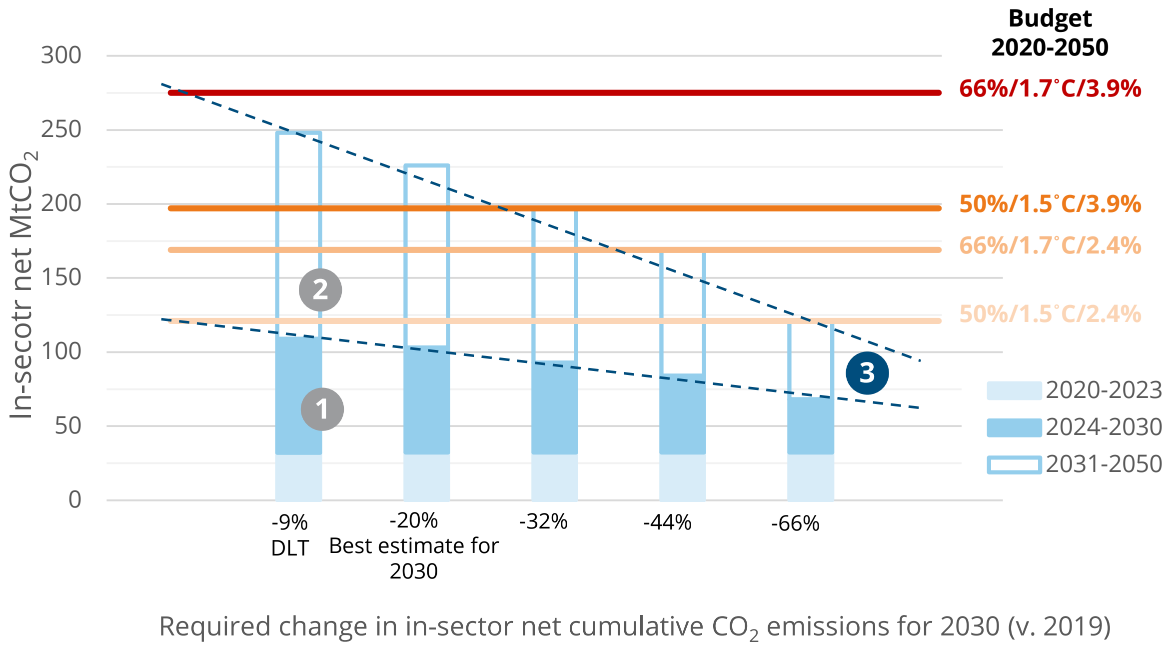
CO_2 emissions in 2030 have to reduce by 32%, 44% and 66% compared to 2019 to meet more ambitious airport carbon budgets



1. Cumulative emissions 2020 to 2030 are governed by fleet renewal, operational improvements, SAF blending and network.
2. Cumulative emissions 2031 to 2050 are governed by ReFuelEU Aviation, annual efficiency improvement and 2030 emissions level ('starting point'). Network is assumed constant from 2030 onwards.

Cumulative emissions between 2020 and 2023 are constant across all scenarios. // Best estimate for 2030: best estimate of pathway for 2020 – 2030; SAF from 2025 (ReFuelEU Aviation, 10% in 2030); 1.3% p.a. efficiency improvement 2031 – 2050.

The level of CO_2 emissions in 2030 is the key determinant for cumulative emissions over the 2020 – 2050 period



1. Cumulative emissions 2020 to 2030 are governed by fleet renewal, operational improvements, SAF blending and network.
2. Cumulative emissions 2031 to 2050 are governed by ReFuelEU Aviation, annual efficiency improvement and 2030 emissions level ('starting point'). Network is assumed constant from 2030 onwards.
3. Lower emission levels in 2030 yield lower cumulative emissions between 2031 and 2050

Cumulative emissions between 2020 and 2023 are constant across all scenarios. // Best estimate for 2030: best estimate of pathway for 2020 – 2030; SAF from 2025 (ReFuelEU Aviation, 10% in 2030); 1.3% p.a. efficiency improvement 2031 – 2050.

Additional SAF, better SAF or further efficiency improvement only make a limited (2–8%) impact on cumulative CO_2 for 2031 – 2050

Emissions levels in 2030 are hence of crucial importance

Additional SAF

ReFuelEU Aviation blending mandate scaled by 1.2 × from 2035 onwards

Year	Base estimate	Alternative estimate
2035	20%	24%
2040	34%	41%
2045	42%	50%
2050	70%	84%
Result	123 $MtCO_2$	113 $MtCO_2$
		– 8%

Higher quality SAF

SAF emissions reduction values (from Destination 2050) scaled by 1.2 × for 2030, and set to 100% for 2050

Year	Base estimate	Alternative estimate
2030	72%	86%
2050	95%	100%
Result	123 $MtCO_2$	120 $MtCO_2$
		– 2%

Higher efficiency improvement

Efficiency improvement of 1.7% per annum, based on Destination 2050 and ICAO LTAG IS3 ("maximum possible effort in terms of future technology rollout, operational efficiencies")

	Base estimate	Alternative estimate
	1.3% p.a.	1.7% p.a.
Result	123 $MtCO_2$	119 $MtCO_2$
		– 3%

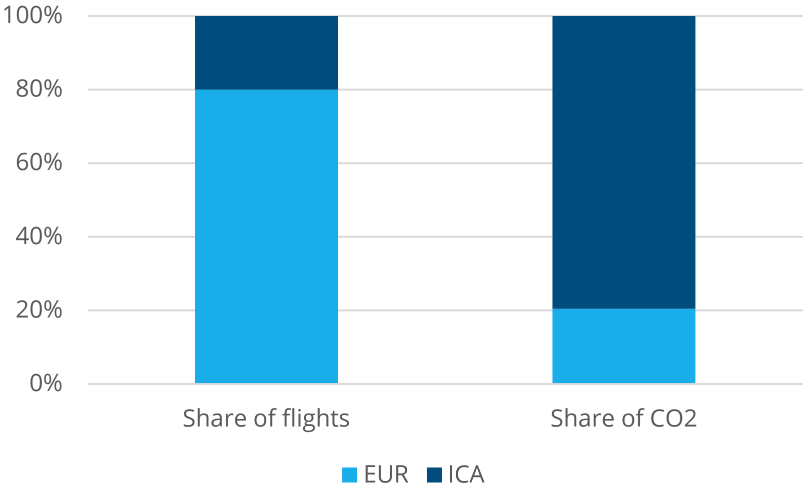
The base estimate is used throughout the analysis; the alternative estimates presented here are used to determine the impacts of additional SAF, higher quality SAF and higher efficiency improvements on the budget use.

Given no more in-sector decarbonisation opportunities, demand management remains as only option to reduce 2030 CO_2 levels v. 2019

Various compatible scenarios exist, based on vastly different emissions impacts of various flights

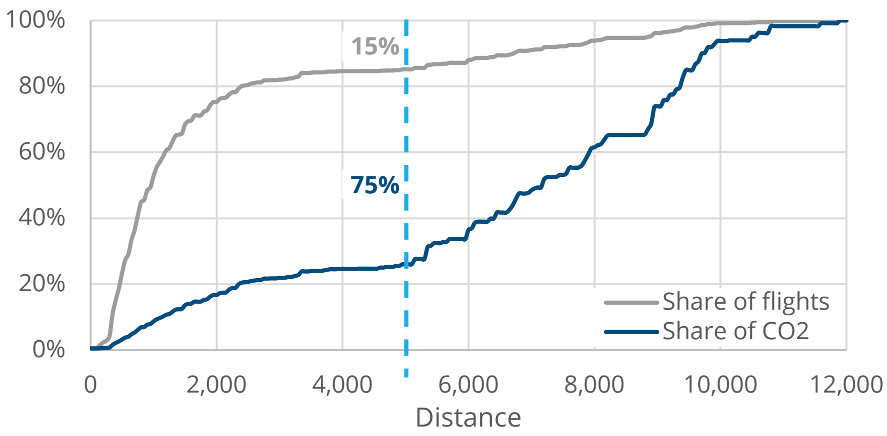
80% of flights are intra-EU and contribute about 20% of CO_2

As such: demand management measures in ICA prevent more CO_2 emissions than measures in EUR



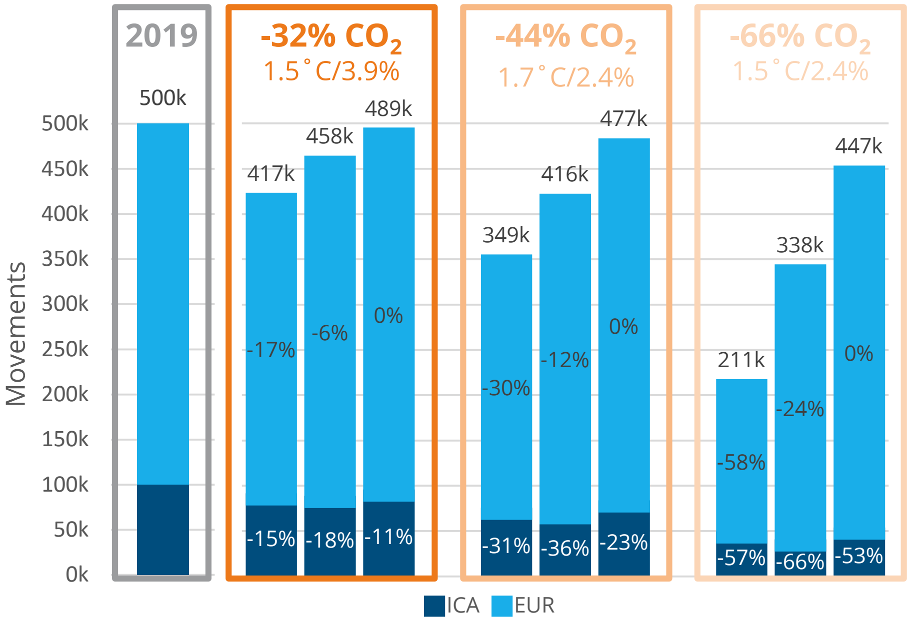
About 15% longest distance flights (> 5000 km) contribute some 75% of CO_2

As such: demand management measures targeting long distance flights are more effective than measures reducing total demand



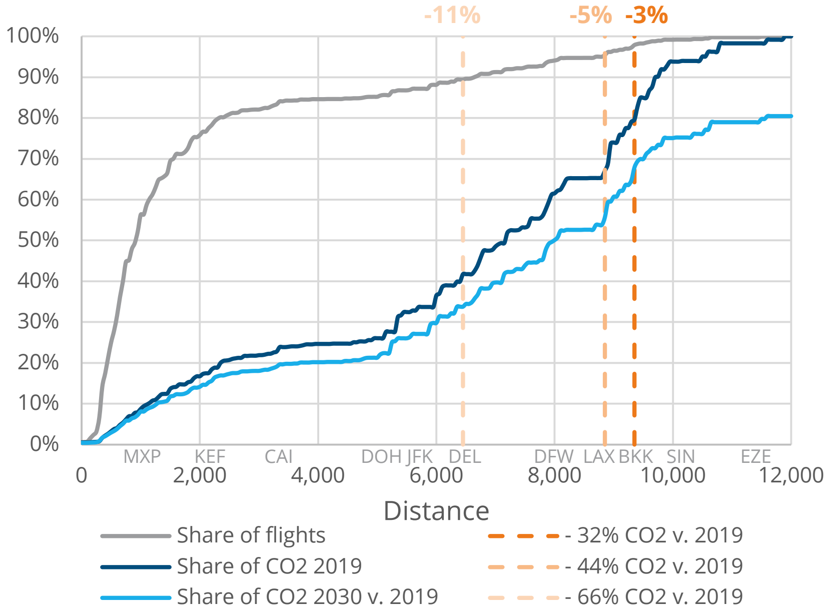
Demand management can be achieved by more generic capacity reductions or specifically targeting the longest flights

Capacity reductions



Differences shown are with respect to 2019. Scenarios assume as-equal-as-possible demand reductions for all flights (left), or differences between EUR or ICA segments (middle) with equal demand induced network reductions across each segment, or targeted reduction of long-distance flights (right). Modelling does not consider network effects nor CO_2 leakage to other areas. Capacity reductions modelled from 2025 onwards.

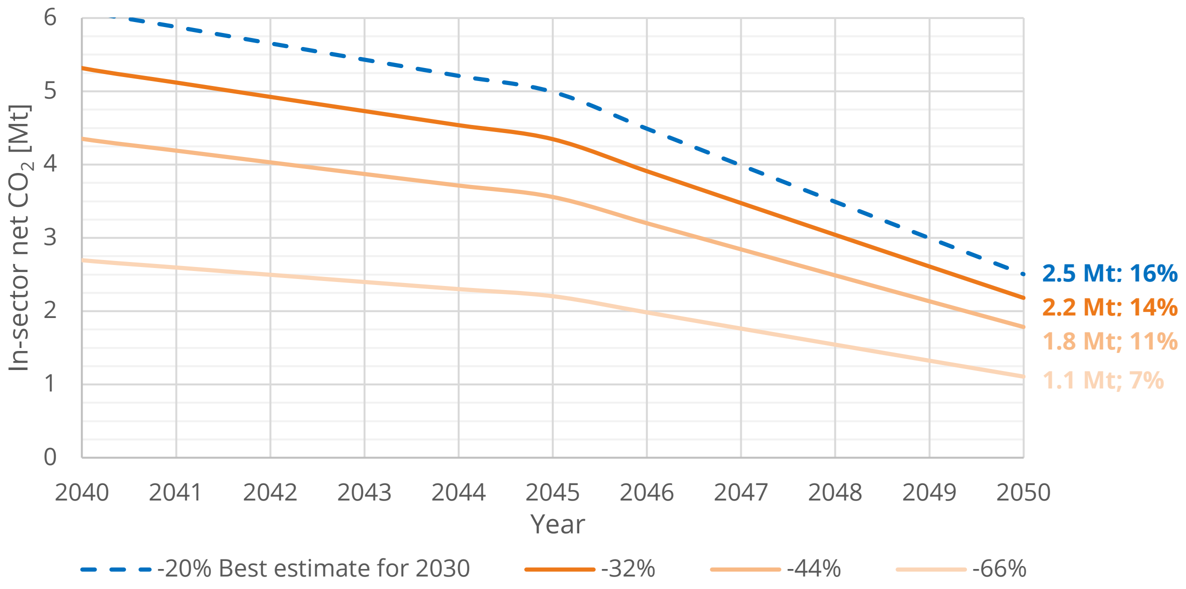
Flight distance restrictions



CO_2 budgets for 2030 can be respected by limiting maximum flight distance – reducing flights by 3%, 5% or 11%, respectively. The modelling assumes these long-distance flights are not replaced by shorter flights. Also, it must be noted that by reducing long-haul flights, CO_2 emissions may be transferred to other geographic locations and respective budgets.

In the least ambitious scenario, twice as much carbon removal is required by 2050 as in the most ambitious scenario

Achieving net-zero CO_2 emissions required additional out-of-sector carbon removal



Non-linear behaviour caused by non-linearly increasing ReFuelEU Aviation SAF blending mandate (2040: 34% // 2040: 42% // 2050: 70%).

Destination 2050 anticipates 8% contribution by carbon removal in the year 2050, compared to the ‘hypothetical no-action growth’ scenario.

For flights departing from Schiphol, 2050 emissions in this ‘hypothetical no-action growth’ equal 16.2 $MtCO_2$.

Remaining emissions exceed the 8% figure in two out of three budget-compatible cases. There, more out-of-sector carbon removal is required to meet net-zero goal.

Alternatively, 2030 emissions could be reduced beyond indicated percentages.

In the least ambitious scenario, the share of energy required for aviation grows from 4.2% to 6.0% of the primary Dutch supply

- Bio-SAF at 55% process efficiency (Van der Sman *et al.*, 2021) and synthetic SAF at 45% process efficiency (Van der Sman *et al.*, 2022) are assumed to be used in equal ratio.
- CO_2 can be removed out-of-sector for which 9.97 PJ/MtCO_2 is required (Beuttler *et al.*, 2019; Keith *et al.*, 2018; Sustainable Aviation UK, 2023).
- Total primary energy supply in the Netherlands in 2050 (den Ouden *et al.*, 2020). In 2015, the total energy share of aviation of the primary energy supply was 4.2% (CBS, 2023).

Scenario	SAF in 2050	Carbon removal in 2050	Total primary energy required in 2050 SAF, carbon removal	Total energy share of aviation of primary energy supply in 2050 SAF, carbon removal, fossil fuel
50% 1.5˚C 2.4%	0.7 Mt 61 PJ	1.1 Mt 11 PJ	72 PJ	2.7% *(– 36% v. 2015)*
50% 1.5˚C 3.9%	1.4 Mt 120 PJ	2.2 Mt 22 PJ	142 PJ	5.2% *(+ 24% v. 2015)*
66% 1.7˚C 2.4%	1.1 Mt 98 PJ	1.8 Mt 18 PJ	116 PJ	4.3% *(+ 2% v. 2015)*
66% 1.7˚C 3.9%	1.6 Mt 142 PJ	2.5 Mt 25 PJ	167 PJ	6.0% *(+ 43% v. 2015)*

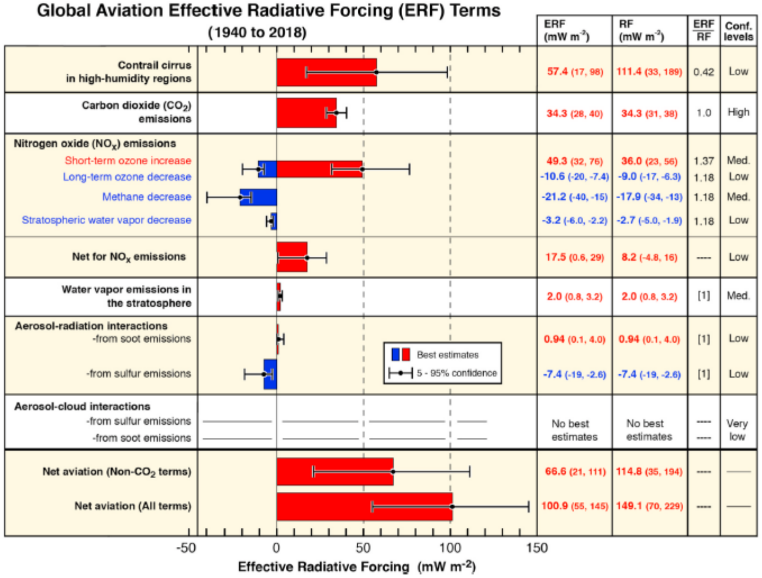
Figures for primary energy supply (i.e., including process losses, including imports) in the Netherlands by den Ouden *et al.* include non-energy uses, to which energy for maritime bunkers (including production of synthetic fuels and associated energy required for direct air capture) and aviation energy (SAF, carbon removal and fossil fuel) has been added. Domestic and maritime energy supply figures are an average over different scenarios explored by den Ouden *et al.* including some maritime activity growth (+19% v. 2015).

Smaller airport carbon budgets require larger CO_2 reductions and less flights in 2030

Warming	Budget share for aviation	Required CO_2 reduction in 2030	Indicative number of annual flights compatible with required CO_2 reduction (2025-2050)		
			EUR:ICA reduced 1:1 (current)	EUR:ICA reduced 1:3 (less ICA)	Distance limit
50% likelihood of 1.5˚C (500 Gt)	**2.4%**	**–66% v. 2019** –62% v. 2005	210k	340k	450k (6450 km)
	3.9%	**–32% v. 2019** –25% v. 2005	420k	460k	490k (9300 km)
66% likelihood of 1.7˚C (700 Gt)	**2.4%**	**–44% v. 2019** –39% v. 2005	350k	420k	480k (8850 km)
	3.9%	**Not required**	500k No flight distance restriction		

Notwithstanding the conclusions drawn, additional and dedicated measures are required to tackle non-CO_2 impact of aviation

- In determining the CO_2 budgets, IPCC (2022) has taken into account non-CO_2 emissions, such as methane emissions from the agricultural sector. These non-CO_2 emissions impact the CO_2 budget (Annex I.A).
- It is unclear if aviation-specific non-CO_2 climate effects (NO_X interactions with methane and ozone, persistent contrails and cirrus, ...) are also explicitly taken into account by IPCC.
- If non-CO_2 climate effects of aviation are accounted for, the current study is rightfully limited to CO_2 emissions only. To align to IPCC modelling and assumptions, it is in this case required to reduce non-CO_2 climate effects of aviation in line with CO_2 emissions. This requires additional and dedicated measures.
- If non-CO_2 climate effects of aviation are not accounted for, they should be 'paid for' from the carbon budgets. However, in that case it also seems fair that the share allocated to aviation is increased. As non-CO_2 climate effects will then appear 'on both sides of the equation', the conclusions presented here remain valid.

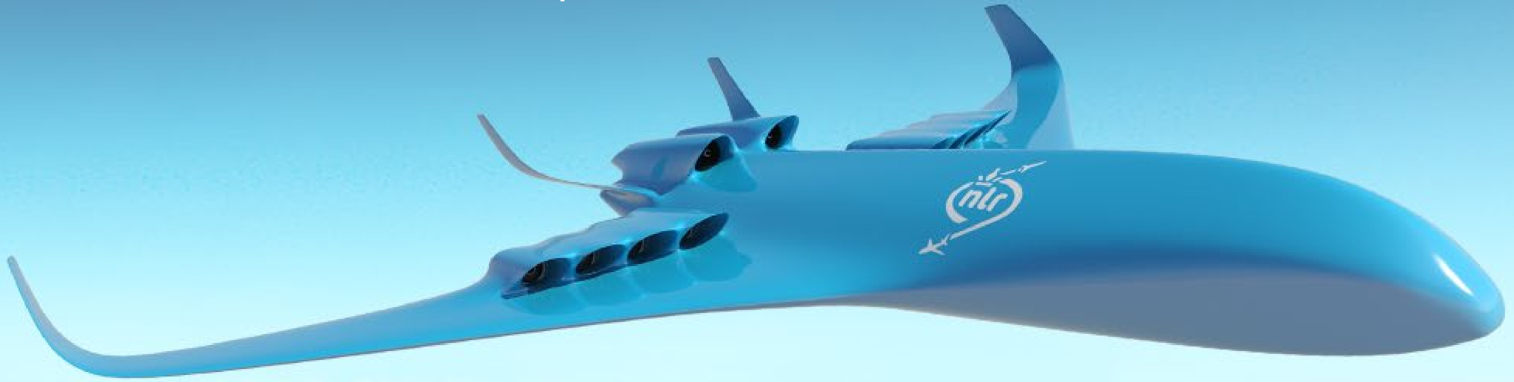


This figure, from Lee *et al*. (2021), shows non-CO_2 effects are estimated to have been responsible for two-thirds of the total aviation climate effect between 1940 and 2018. Although this ratio might be different over other periods, the non-CO_2 climate impact is nonnegligible. Additional and dedicated measures will be required to address these non-CO_2 effects.

Dedicated to innovation in aerospace

Fully engaged

NLR - Netherlands Aerospace Centre



Anthony Fokkerweg 2
1059 CM Amsterdam
The Netherlands

p) +31 88 511 31 13
e) info@nlr.nl i) www.nlr.org

Voorsterweg 31
8316 PR Marknesse
The Netherlands

p) +31 88 511 44 44
e) info@nlr.nl i) www.nlr.org

Annexes

I. Background information
  - A. IPCC global carbon budgets
  - B. Aviation growth, CO_2 intensity and cumulative CO_2 emissions
  - C. Science Based Targets initiative (SBTi)

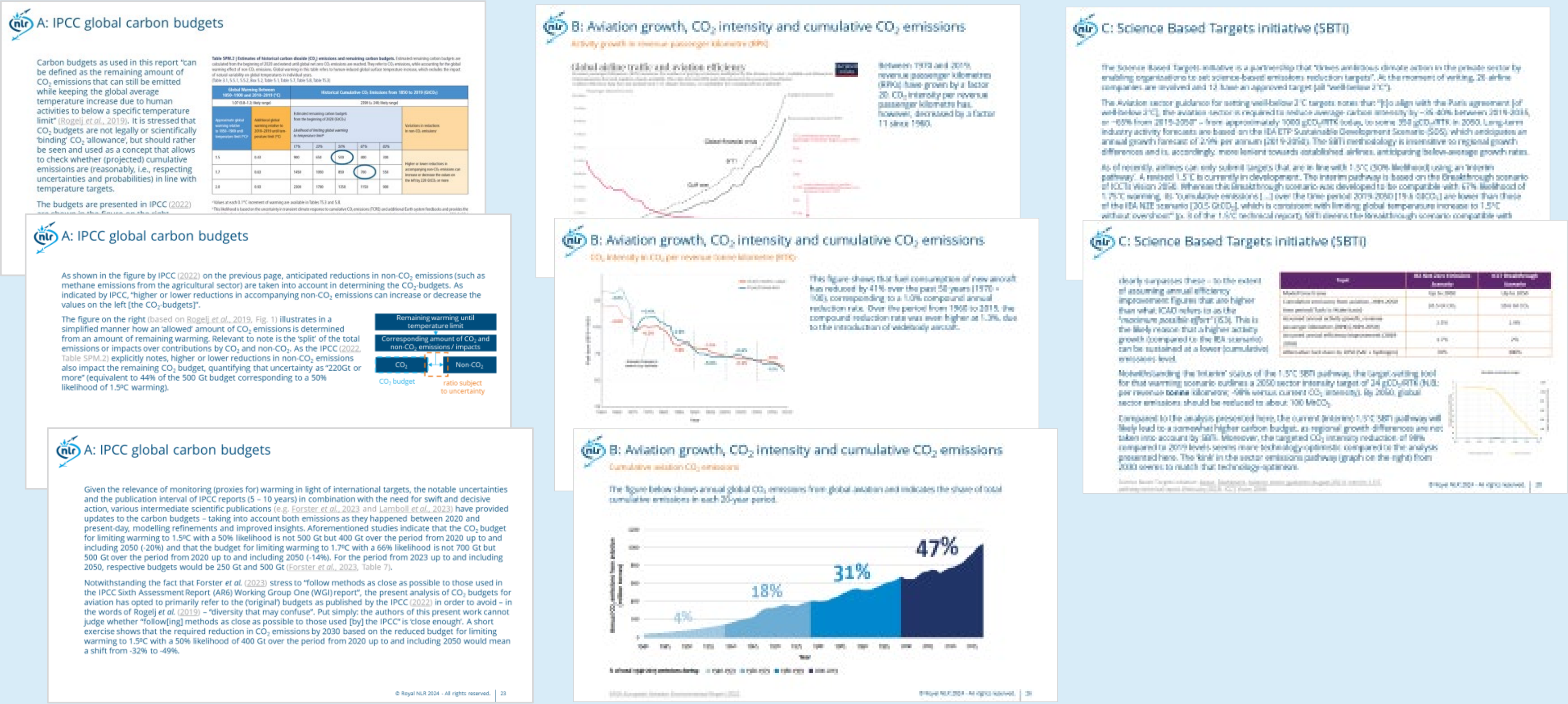
II. Carbon budgets and comparison to aviation decarbonisations pathways
  - A. Comparison of ICAO decarbonisation pathways to carbon budgets
  - B. Carbon budgets for aviation in the Netherlands and Schiphol

III. Supplementary methods and results
  - A. Approaches to emission shares
  - B. Relevance of economic measures and accounting principles adhered to
  - C. Decarbonisation modelling
  - D. Summarised results for net CO_2 emissions for 2020 – 2030
  - E. Required CO_2 emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement
  - F. Required reduction in net in-sector CO_2 emissions in 2030 for temperature targets depends on SAF

IV. Detailed results
  - A. Best estimate for 2030, compared to 1.5˚C/3.9% and 1.7˚C/3.9%
  - B. -32% CO_2 emissions in 2030 v. 2019; in line with 1.5˚C/3.9%
  - C. -44% CO_2 emissions in 2030 v. 2019; in line with 1.7˚C/2.4%
  - D. -66% CO_2 emissions in 2030 v. 2019; in line with 1.5˚C/2.4%

V. References

I: Background information



A: IPCC global carbon budgets

Carbon budgets as used in this report "can be defined as the remaining amount of CO_2 emissions that can still be emitted while keeping the global average temperature increase due to human activities to below a specific temperature limit" (Rogelj *et al.*, 2019). It is stressed that CO_2 budgets are not legally or scientifically 'binding' CO_2 'allowance', but should rather be seen and used as a concept that allows to check whether (projected) cumulative emissions are (reasonably, i.e., respecting uncertainties and probabilities) in line with temperature targets.

The budgets are presented in IPCC (2022) are shown in the figure on the right. Budgets used in this work are outlined.

Table SPM.2 | Estimates of historical carbon dioxide (CO_2) emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions, while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years.
{Table 3.1, 5.5.1, 5.5.2, Box 5.2, Table 5.1, Table 5.7, Table 5.8, Table TS.3}

Global Warming Between 1850–1900 and 2010–2019 (°C)		Historical Cumulative CO_2 Emissions from 1850 to 2019 ($GtCO_2$)					
1.07 (0.8–1.3; likely range)		2390 (± 240; likely range)					
Approximate global warming relative to 1850–1900 until temperature limit (°C)[a]	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) *Likelihood of limiting global warming to temperature limit*[b]					Variations in reductions in non-CO_2 emissions[c]
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

[a] Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

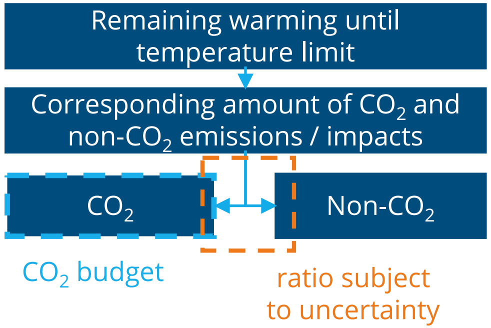
[b] This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420 $GtCO_2$) are separate.

[c] Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

A: IPCC global carbon budgets

As shown in the figure by IPCC (2022) on the previous page, anticipated reductions in non-CO_2 emissions (such as methane emissions from the agricultural sector) are taken into account in determining the CO_2-budgets. As indicated by IPCC, “higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left [the CO_2-budgets]”.

The figure on the right (based on Rogelj *et al.*, 2019, Fig. 1) illustrates in a simplified manner how an ‘allowed’ amount of CO_2 emissions is determined from an amount of remaining warming. Relevant to note is the ‘split’ of the total emissions or impacts over contributions by CO_2 and non-CO_2. As the IPCC (2022, Table SPM.2) explicitly notes, higher or lower reductions in non-CO_2 emissions also impact the remaining CO_2 budget, quantifying that uncertainty as “220Gt or more” (equivalent to 44% of the 500 Gt budget corresponding to a 50% likelihood of 1.5ºC warming).



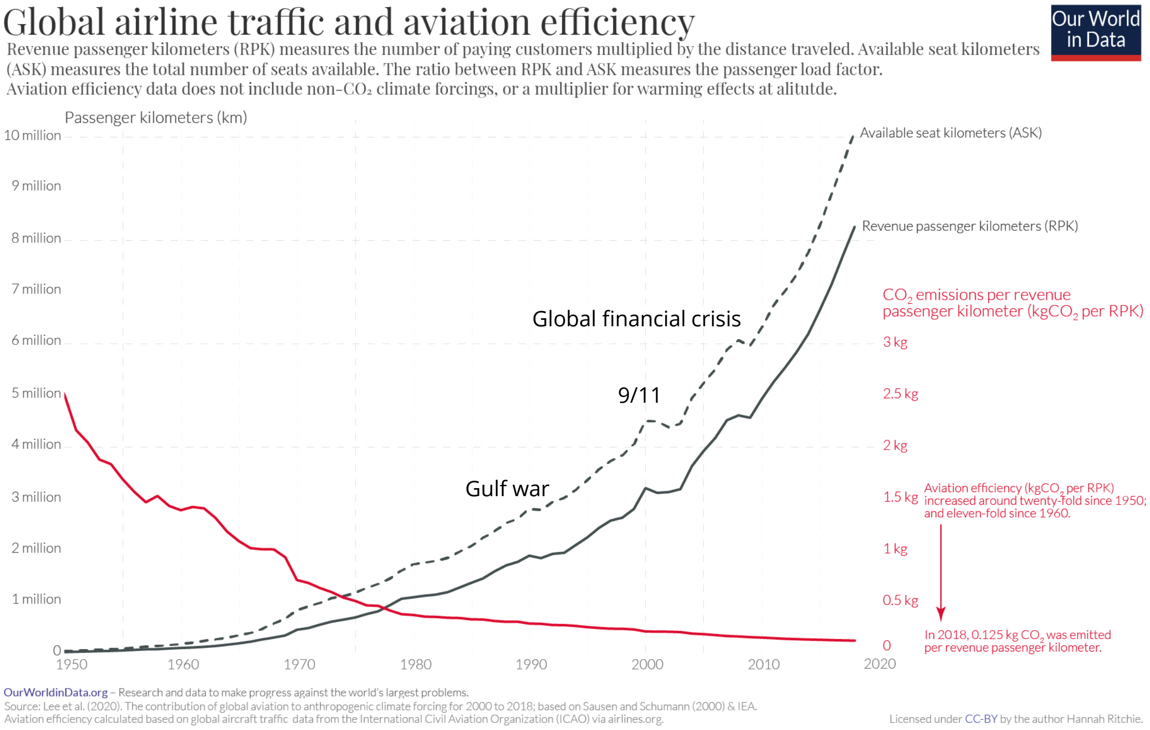
A: IPCC global carbon budgets

Given the relevance of monitoring (proxies for) warming in light of international targets, the notable uncertainties and the publication interval of IPCC reports (5 – 10 years) in combination with the need for swift and decisive action, various intermediate scientific publications (e.g. Forster *et al.*, 2023 and Lamboll *et al.*, 2023) have provided updates to the carbon budgets – taking into account both emissions as they happened between 2020 and present-day, modelling refinements and improved insights. Aforementioned studies indicate that the CO_2 budget for limiting warming to 1.5ºC with a 50% likelihood is not 500 Gt but 400 Gt over the period from 2020 up to and including 2050 (-20%) and that the budget for limiting warming to 1.7ºC with a 66% likelihood is not 700 Gt but 500 Gt over the period from 2020 up to and including 2050 (-14%). For the period from 2023 up to and including 2050, respective budgets would be 250 Gt and 500 Gt (Forster *et al.*, 2023, Table 7).

Notwithstanding the fact that Forster *et al.* (2023) stress to "follow methods as close as possible to those used in the IPCC Sixth Assessment Report (AR6) Working Group One (WGI) report", the present analysis of CO_2 budgets for aviation has opted to primarily refer to the ('original') budgets as published by the IPCC (2022) in order to avoid – in the words of Rogelj *et al.* (2019) – "diversity that may confuse". Put simply: the authors of this present work cannot judge whether "follow[ing] methods as close as possible to those used [by] the IPCC" is 'close enough'. A short exercise shows that the required reduction in CO_2 emissions by 2030 based on the reduced budget for limiting warming to 1.5ºC with a 50% likelihood of 400 Gt over the period from 2020 up to and including 2050 would mean a shift from -32% to -49%.

B: Aviation growth, CO_2 intensity and cumulative CO_2 emissions

Activity growth in revenue passenger kilometre (RPK)

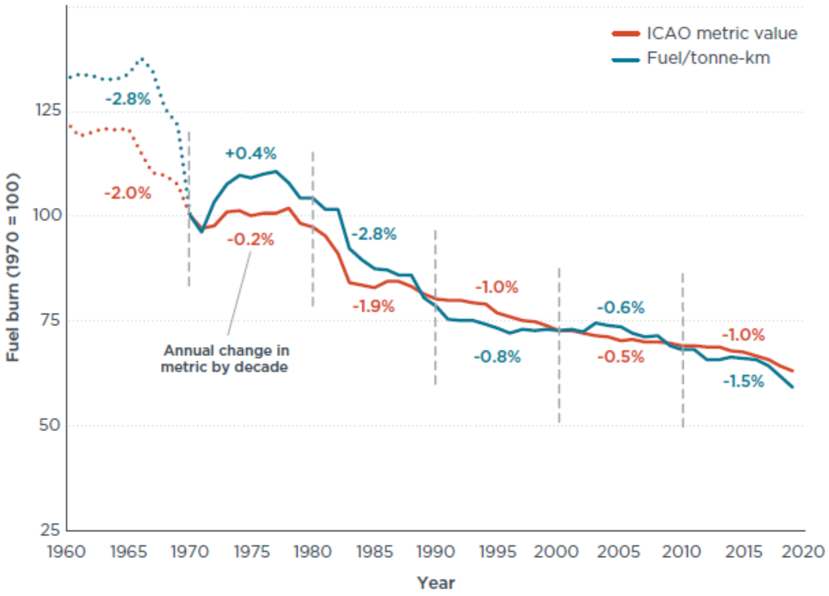


Between 1970 and 2019, revenue passenger kilometres (RPKs) have grown by a factor 20. CO_2 intensity per revenue passenger kilometre has, however, decreased by a factor 11 since 1960.

Our World in Data (2022)

B: Aviation growth, CO_2 intensity and cumulative CO_2 emissions

CO_2 intensity in CO_2 per revenue tonne kilometre (RTK)



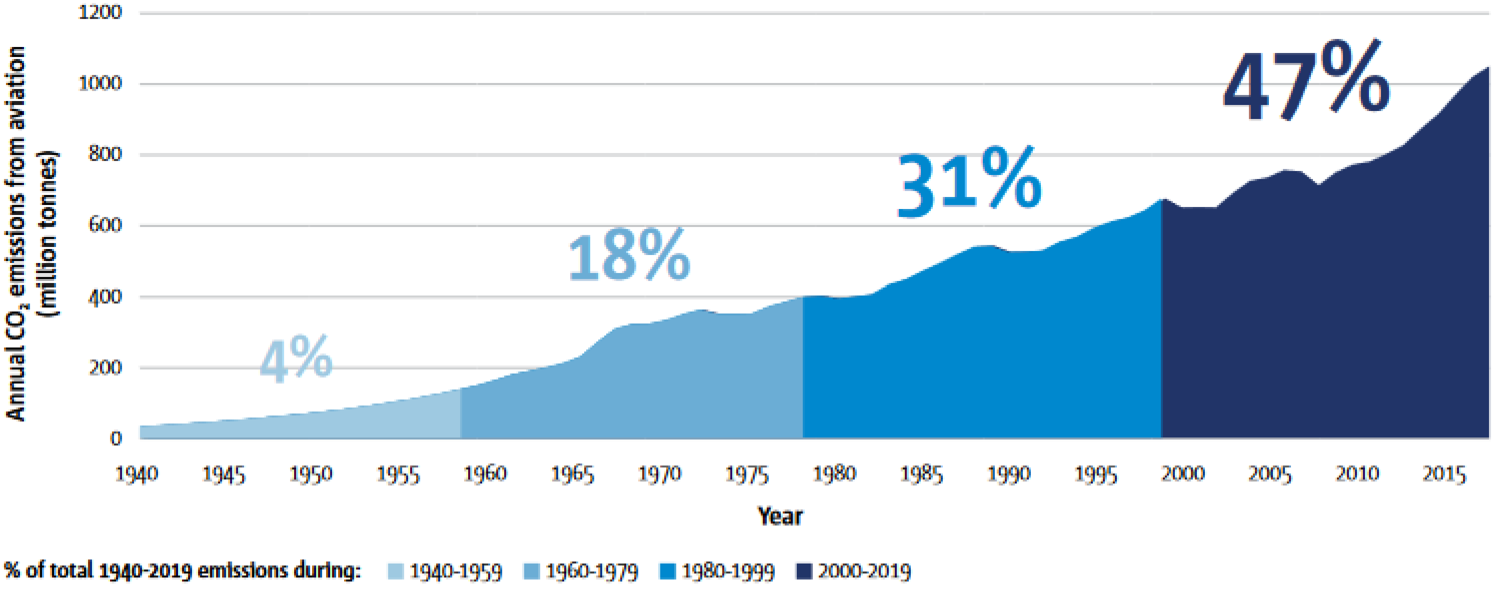
This figure shows that fuel consumption of new aircraft has reduced by 41% over the past 50 years (1970 = 100), corresponding to a 1.0% compound annual reduction rate. Over the period from 1960 to 2019, the compound reduction rate was even higher at 1.3%, due to the introduction of widebody aircraft.

Zheng & Rutherford (2020)

B: Aviation growth, CO_2 intensity and cumulative CO_2 emissions

Cumulative aviation CO_2 emissions

The figure below shows annual global CO_2 emissions from global aviation and indicates the share of total cumulative emissions in each 20-year period.



EASA European Aviation Environmental Report 2022

C: Science Based Targets initiative (SBTi)

The Science Based Targets initiative is a partnership that “drives ambitious climate action in the private sector by enabling organizations to set science-based emissions reduction targets”. At the moment of writing, 26 airline companies are involved and 12 have an approved target (all “well-below 2˚C”).

The Aviation sector guidance for setting well-below 2˚C targets notes that “[t]o align with the Paris agreement [of well-below 2˚C], the aviation sector is required to reduce average carbon intensity by ~35-40% between 2019-2035, or ~65% from 2019-2050” – from approximately 1000 gCO_2/RTK today, to some 350 gCO_2/RTK in 2050. Long-term industry activity forecasts are based on the IEA ETP Sustainable Development Scenario (SDS), which anticipates an annual growth forecast of 2.9% per annum (2019-2050). The SBTi methodology is insensitive to regional growth differences and is, accordingly, more lenient towards established airlines, anticipating below-average growth rates.

As of recently, airlines can only submit targets that are in line with 1.5˚C (50% likelihood) using an ‘interim pathway’. A revised 1.5˚C is currently in development. The interim pathway is based on the Breakthrough scenario of ICCTs Vision 2050. Whereas this Breakthrough scenario was developed to be compatible with 67% likelihood of 1.75˚C warming, its “cumulative emissions [...] over the time period 2019-2050 [19.6 $GtCO_2$] are lower than those of the IEA NZE scenario [20.5 $GtCO_2$], which is consistent with limiting global temperature increase to 1.5°C without overshoot” (p. 3 of the 1.5˚C technical report), SBTi deems the Breakthrough scenario compatible with 1.5˚C. The difference is likely caused by the different shares of carbon budget allocated to aviation (3.9% in case of IEA, 2.9% in case of ICCT, the latter including WtW emissions). Further differences between these pathways are noted in Table 1 (p. 4) of the technical report, shown on the next page. Whereas technology and alternative fuel assumptions of IEA are fairly well in line with assumptions made in this report, the ICCT Breakthrough scenario

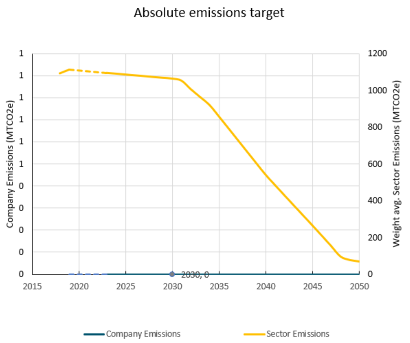
Science Based Targets initiative: About, Dashboard, Aviation sector guidance (August 2021), Interim 1.5˚C pathway technical report (February 2023). ICCT Vision 2050,

C: Science Based Targets initiative (SBTi)

clearly surpasses these – to the extent of assuming annual efficiency improvement figures that are higher than what ICAO refers to as the "*maximum possible effort*" (IS3). This is the likely reason that a higher activity growth (compared to the IEA scenario) can be sustained at a lower (cumulative) emissions level.

Topic	IEA Net-Zero Emissions Scenario	ICCT Breakthrough Scenario
Model time frame	Up to 2050	Up to 2050
Cumulative emissions from aviation, 2019-2050 time period (Tank to Wake basis)	20.5 Gt CO_2	19.6 Gt CO_2
Assumed annual activity growth, revenue passenger kilometers (RPK) (2019-2050)	2.5%	2.9%
Assumed annual efficiency improvement (2019-2050)	1.7%	2%
Alternative fuel share by 2050 (SAF + hydrogen)	70%	100%

Notwithstanding the 'interim' status of the 1.5˚C SBTi pathway, the target-setting tool for that warming scenario outlines a 2050 sector intensity target of 24 gCO_2/RTK (N.B.: per revenue **tonne** kilometre; -98% versus current CO_2 intensity). By 2050, global sector emissions should be reduced to about 100 $MtCO_2$.



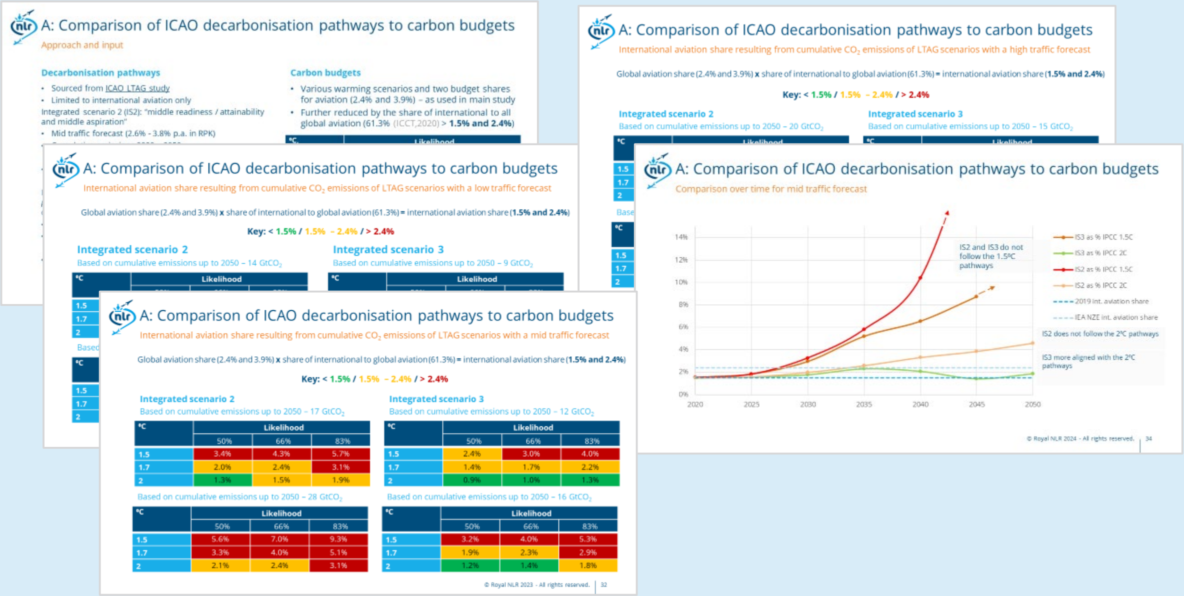
Compared to the analysis presented here, the current (interim) 1.5˚C SBTi pathway will likely lead to a somewhat higher carbon budget, as regional growth differences are not taken into account by SBTi. Moreover, the targeted CO_2 intensity reduction of 98% compared to 2019 levels seems more technology-optimistic compared to the analysis presented here. The 'kink' in the sector emissions pathway (graph on the right) from 2030 seems to match that technology-optimism.

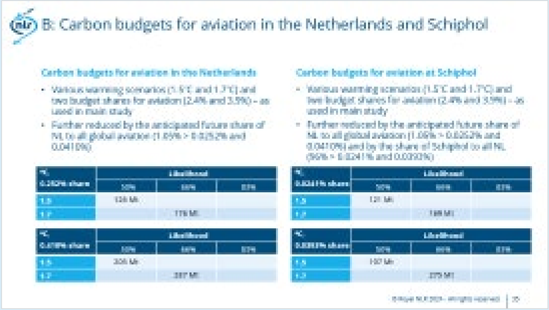
Science Based Targets initiative: About, Dashboard, Aviation sector guidance (August 2021), Interim 1.5˚C pathway technical report (February 2023). ICCT Vision 2050,

II: Carbon budgets and comparison to aviation decarbonisations pathways

A. Global aviation:
comparison of ICAO decarbonisation pathways to carbon budgets

B. Dutch aviation:
Carbon budgets for aviation in the Netherlands and Schiphol





A: Comparison of ICAO decarbonisation pathways to carbon budgets

Approach and input

Decarbonisation pathways

- Sourced from ICAO LTAG study
- Limited to international aviation only

Integrated scenario 2 (IS2): "middle readiness / attainability and middle aspiration"

- Mid traffic forecast (2.6% - 3.8% p.a. in RPK)
- Cumulative emissions 2020 – 2050:
  - 17 $GtCO_2$ (range 14 - 20 $GtCO_2$)
- Cumulative emissions 2020 – 2070:
  - 28 $GtCO_2$ (range 23 - 34 $GtCO_2$)

Integrated scenario 3 (IS3): "represents the *maximum possible effort* in terms of future technology rollout, operational efficiencies, and fuel availability"

- Mid traffic forecast (2.6% - 3.8% p.a. in RPK)
- Cumulative emissions 2020 – 2050:
  - 12 $GtCO_2$ (range 9 - 15 $GtCO_2$)
- Cumulative emissions 2020 – 2070:
  - 16 $GtCO_2$ (range 12 - 20 $GtCO_2$)

Carbon budgets

- Various warming scenarios and two budget shares for aviation (2.4% and 3.9%) – as used in main study
- Further reduced by the share of international to all global aviation (61.3% (ICCT,2020) > **1.5% and 2.4%**)

⁰C, 1.5% share	**Likelihood**		
	50%	66%	83%
1.5	7.4 Gt	5.9 Gt	4.4 Gt
1.7	12.5 Gt	10.3 Gt	8.1 Gt
2	19.9 Gt	16.9 Gt	13.2 Gt

⁰C, 2.4% share	**Likelihood**		
	50%	66%	83%
1.5	12.0 Gt	9.6 Gt	7.2 Gt
1.7	20.3 Gt	16.7 Gt	13.1 Gt
2	32.3 Gt	27.5 Gt	21.5 Gt

A: Comparison of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO_2 emissions of LTAG scenarios with a low traffic forecast

Global aviation share (2.4% and 3.9%) **x** share of international to global aviation (61.3%) **=** international aviation share (**1.5% and 2.4%**)

Key: < 1.5% / 1.5% – 2.4% / > 2.4%

Integrated scenario 2

Based on cumulative emissions up to 2050 – 14 $GtCO_2$

⁰C	Likelihood		
	50%	66%	83%
1.5	2.8%	3.5%	4.7%
1.7	1.6%	2.0%	2.5%
2	1.0%	1.2%	1.6%

Based on cumulative emissions up to 2070 – 23 $GtCO_2$

⁰C	Likelihood		
	50%	66%	83%
1.5	4.6%	5.8%	7.7%
1.7	2.7%	3.3%	4.2%
2	1.7%	2.0%	2.6%

Integrated scenario 3

Based on cumulative emissions up to 2050 – 9 $GtCO_2$

⁰C	Likelihood		
	50%	66%	83%
1.5	1.8%	2.3%	3.0%
1.7	1.1%	1.3%	1.6%
2	0.7%	0.8%	1.0%

Based on cumulative emissions up to 2070 – 12 $GtCO_2$

⁰C	Likelihood		
	50%	66%	83%
1.5	2.4%	3.0%	4.0%
1.7	1.4%	1.7%	2.2%
2	0.9%	1.0%	1.3%

A: Comparison of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO_2 emissions of LTAG scenarios with a mid traffic forecast

Global aviation share (2.4% and 3.9%) **x** share of international to global aviation (61.3%) **=** international aviation share (**1.5% and 2.4%**)

Key: < 1.5% / 1.5% – 2.4% / > 2.4%

Integrated scenario 2

Based on cumulative emissions up to 2050 – 17 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	3.4%	4.3%	5.7%
1.7	2.0%	2.4%	3.1%
2	1.3%	1.5%	1.9%

Based on cumulative emissions up to 2070 – 28 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	5.6%	7.0%	9.3%
1.7	3.3%	4.0%	5.1%
2	2.1%	2.4%	3.1%

Integrated scenario 3

Based on cumulative emissions up to 2050 – 12 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	2.4%	3.0%	4.0%
1.7	1.4%	1.7%	2.2%
2	0.9%	1.0%	1.3%

Based on cumulative emissions up to 2070 – 16 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	3.2%	4.0%	5.3%
1.7	1.9%	2.3%	2.9%
2	1.2%	1.4%	1.8%

A: Comparison of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO_2 emissions of LTAG scenarios with a high traffic forecast

Global aviation share (2.4% and 3.9%) **x** share of international to global aviation (61.3%) **=** international aviation share (**1.5% and 2.4%**)

Key: < 1.5% / 1.5% – 2.4% / > 2.4%

Integrated scenario 2

Based on cumulative emissions up to 2050 – 20 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	4.0%	5.0%	6.7%
1.7	2.4%	2.9%	3.6%
2	1.5%	1.7%	2.2%

Based on cumulative emissions up to 2070 – 34 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	6.8%	8.5%	11.3%
1.7	4.0%	4.9%	6.2%
2	2.5%	3.0%	3.8%

Integrated scenario 3

Based on cumulative emissions up to 2050 – 15 $GtCO_2$

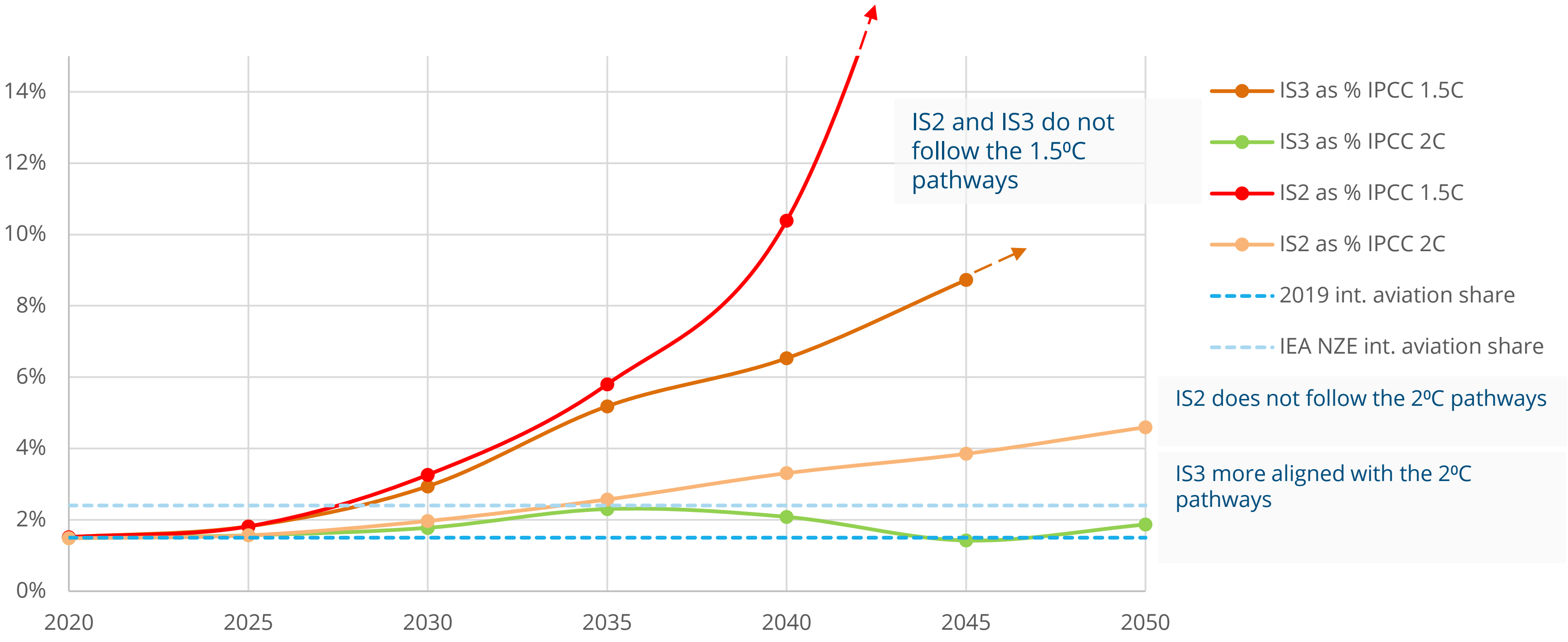
ºC	Likelihood		
	50%	66%	83%
1.5	3.0%	3.8%	5.0%
1.7	1.8%	2.1%	2.7%
2	1.1%	1.3%	1.7%

Based on cumulative emissions up to 2070 – 20 $GtCO_2$

ºC	Likelihood		
	50%	66%	83%
1.5	4.0%	5.0%	6.7%
1.7	2.4%	2.9%	3.6%
2	1.5%	1.7%	2.2%

A: Comparison of ICAO decarbonisation pathways to carbon budgets

Comparison over time for mid traffic forecast



B: Carbon budgets for aviation in the Netherlands and Schiphol

Carbon budgets for aviation in the Netherlands

- Various warming scenarios (1.5˚C and 1.7˚C) and two budget shares for aviation (2.4% and 3.9%) – as used in main study
- Further reduced by the anticipated future share of NL to all global aviation (1.05% > 0.0252% and 0.0410%)

ºC, 0.252% share	Likelihood		
	50%	66%	83%
1.5	126 Mt		
1.7		176 Mt	

ºC, 0.410% share	Likelihood		
	50%	66%	83%
1.5	205 Mt		
1.7		287 Mt	

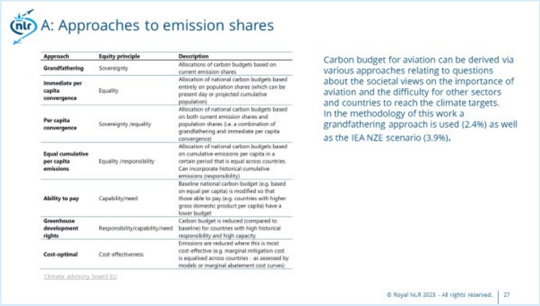
Carbon budgets for aviation at Schiphol

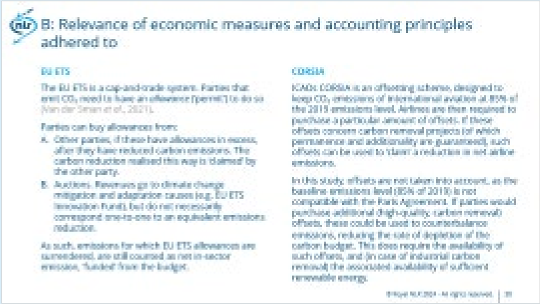
- Various warming scenarios (1.5˚C and 1.7˚C) and two budget shares for aviation (2.4% and 3.9%) – as used in main study
- Further reduced by the anticipated future share of NL to all global aviation (1.05% > 0.0252% and 0.0410%) and by the share of Schiphol to all NL (96% > 0.0241% and 0.0393%)

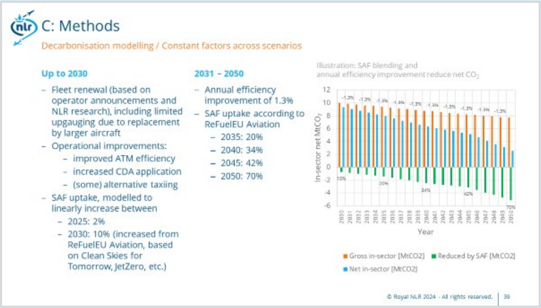
ºC, 0.0241% share	Likelihood		
	50%	66%	83%
1.5	121 Mt		
1.7		169 Mt	

ºC, 0.0393% share	Likelihood		
	50%	66%	83%
1.5	197 Mt		
1.7		275 Mt	

III: Supplementary methods and results







A: Approaches to emission shares

Approach	Equity principle	Description
Grandfathering	Sovereignty	Allocations of carbon budgets based on current emission shares
Immediate per capita convergence	Equality	Allocation of national carbon budgets based entirely on population shares (which can be present day or projected cumulative population)
Per capita convergence	Sovereignty /equality	Allocation of national carbon budgets based on both current emission shares and population shares (i.e. a combination of grandfathering and immediate per capita convergence)
Equal cumulative per capita emissions	Equality /responsibility	Allocation of national carbon budgets based on cumulative emissions per capita in a certain period that is equal across countries. Can incorporate historical cumulative emissions (responsibility)
Ability to pay	Capability/need	Baseline national carbon budget (e.g. based on equal per capita) is modified so that those able to pay (e.g. countries with higher gross domestic product per capita) have a lower budget
Greenhouse development rights	Responsibility/capability/need	Carbon budget is reduced (compared to baseline) for countries with high historical responsibility and high capacity
Cost-optimal	Cost-effectiveness	Emissions are reduced where this is most cost-effective (e.g. marginal mitigation cost is equalised across countries - as assessed by models or marginal abatement cost curves)

The carbon budget for aviation can be derived via various approaches relating to questions about the societal views on the importance of aviation and the difficulty for other sectors and countries to reach the climate targets.

The 2.4% share for aviation used in this analysis is an example of the **Grandfathering**-approach. The 3.9% share for aviation, based on the IEA Net Zero Emissions scenario, can be considered in line with the **Cost-optimal** approach.

Climate advisory board EU, based on Van den Berg *et al.* (2020)

B: Relevance of economic measures and accounting principles adhered to

EU ETS

The EU ETS is a cap-and-trade system. Parties that emit CO_2 need to have an *allowance* (‘permit’) to do so (Van der Sman *et al*., 2021).

Parties can buy allowances from:

A. Other parties, if these have allowances in excess, after they have reduced carbon emissions. The carbon reduction realised this way is ‘claimed’ by the other party.
B. Auctions. Revenues go to climate change mitigation and adaptation causes (e.g. EU ETS Innovation Fund), but do not necessarily correspond one-to-one to an equivalent emissions reduction.

As such, emissions for which EU ETS allowances are surrendered, are still counted as net in-sector emission, ‘funded’ from the budget.

CORSIA

ICAOs CORSIA is an offsetting scheme, designed to keep CO_2 emissions of international aviation at 85% of the 2019 emissions level. Airlines are then required to purchase a particular amount of offsets. If these offsets concern carbon removal projects (of which permanence and additionality are guaranteed), such offsets can be used to ‘claim’ a reduction in net airline emissions.

In this study, offsets are not taken into account, as the baseline emissions level (85% of 2019) is not compatible with the Paris Agreement. If parties would purchase additional (high-quality, carbon removal) offsets, these could be used to counterbalance emissions, reducing the rate of depletion of the carbon budget. This does require the availability of such offsets, and (in case of industrial carbon removal) the associated availability of sufficient renewable energy.

C: Methods

Decarbonisation modelling / Constant factors across scenarios

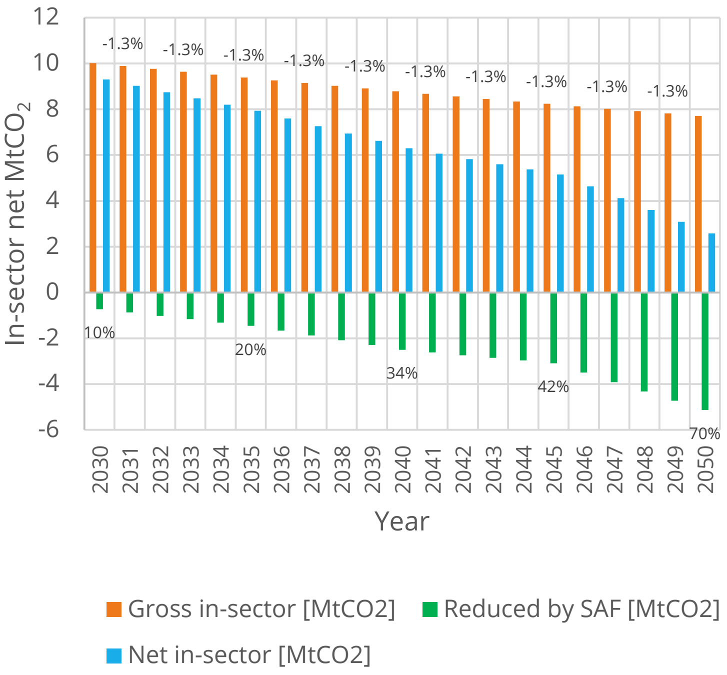
Up to 2030

- Fleet renewal (based on operator announcements and NLR research), including limited upgauging due to planned replacement by larger aircraft
- Operational improvements:
  - improved ATM efficiency
  - increased CDA application
  - (some) alternative taxiing
- SAF uptake, modelled to linearly increase between
  - 2025: 2%
  - 2030: 10% (increased from ReFuelEU Aviation, based on Clean Skies for Tomorrow, JetZero, etc.)

2031 – 2050

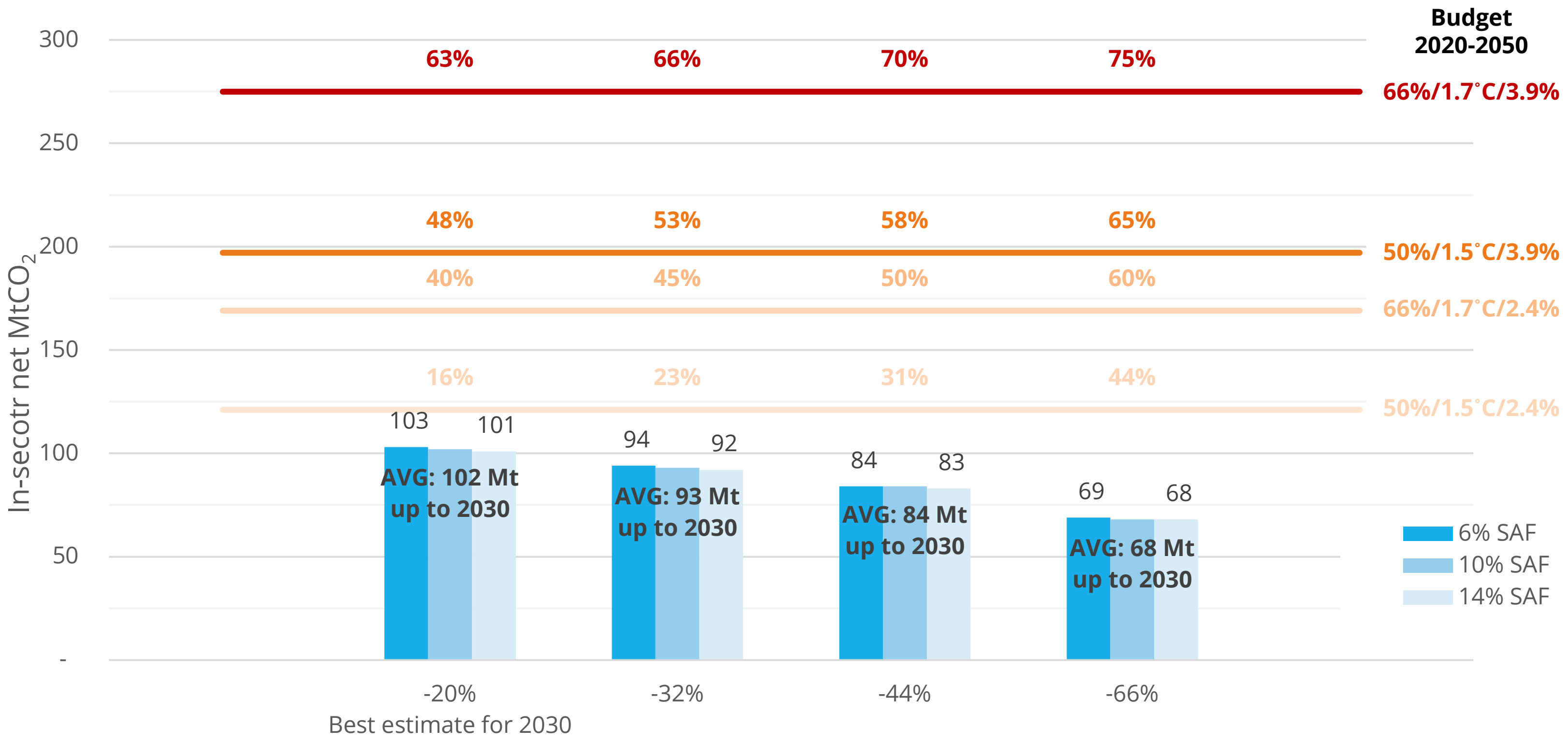
- Annual efficiency improvement of 1.3%
- SAF uptake according to ReFuelEU Aviation
  - 2035: 20%
  - 2040: 34%
  - 2045: 42%
  - 2050: 70%

Illustration: SAF blending and annual efficiency improvement reduce net CO_2

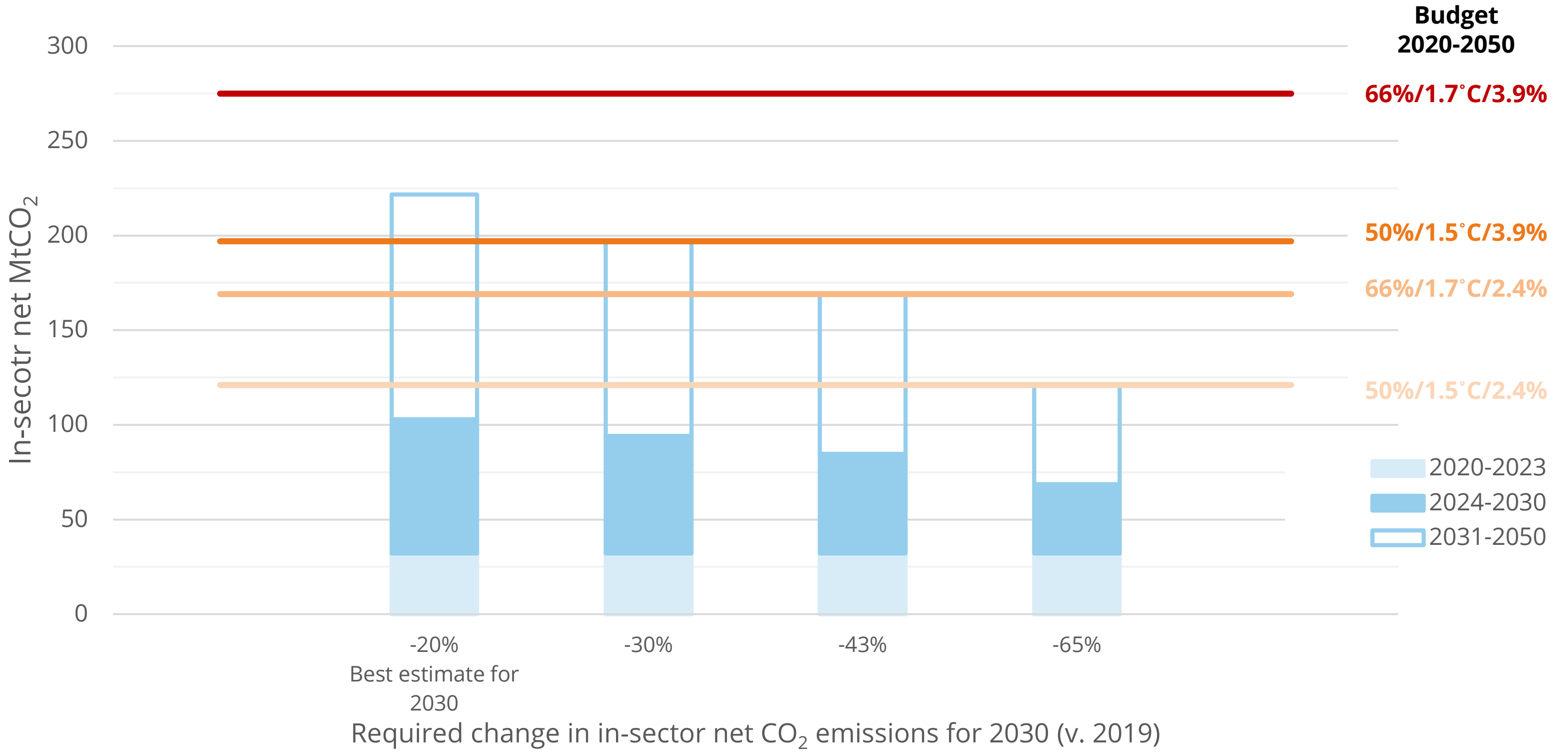


D: Summarised results for net CO_2 emissions for 2020 – 2030

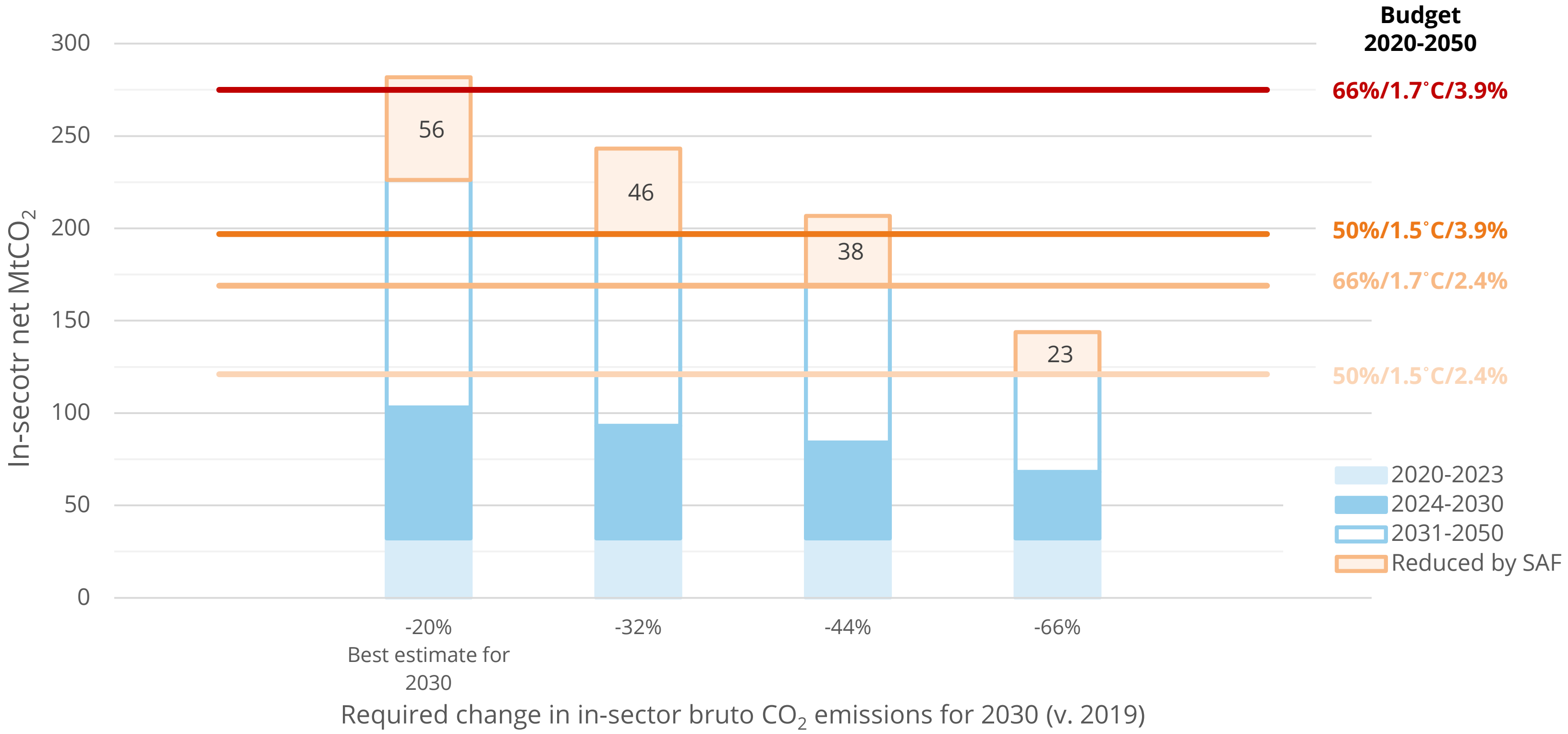
Compared to carbon budgets for 2020 – 2050, showing remaining budget shares in %



E: Required CO_2 emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement



F: Required reduction in net in-sector CO_2 emissions in 2030 for airport carbon budgets depends on SAF



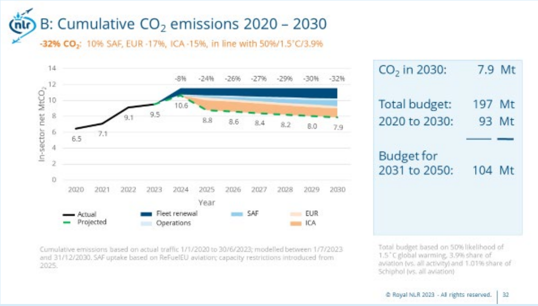
Cumulative emissions between 2020 and 2023 are constant across all scenarios. // Best estimate for 2030: best estimate of pathway for 2020 – 2030; SAF from 2025 (ReFuelEU Aviation, 10% in 2030); 1.3% p.a. efficiency improvement 2031 – 2050.

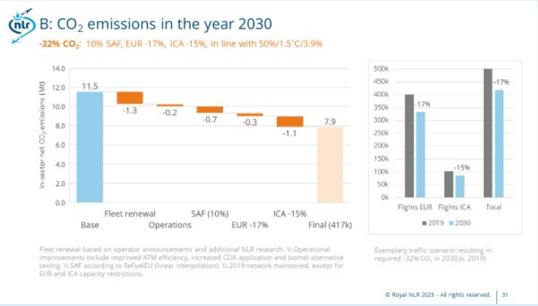
IV: Detailed results

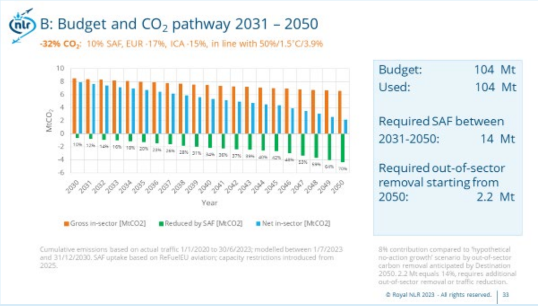
CO_2 emissions in the year 2030
Cumulative CO_2 emissions 2020 – 2030
Budget and CO_2 pathway 2031 – 2050

For scenarios:

A. Best estimate for 2030 compared to 1.5˚C/3.9% and 1.7˚C/3.9%
B. -32% CO_2 emissions in 2030 v. 2019; in line with 1.5˚C/3.9%
C. -44% CO_2 emissions in 2030 v. 2019; in line with 1.7˚C/2.4%
D. -66% CO_2 emissions in 2030 v. 2019; in line with 1.5˚C/2.4%

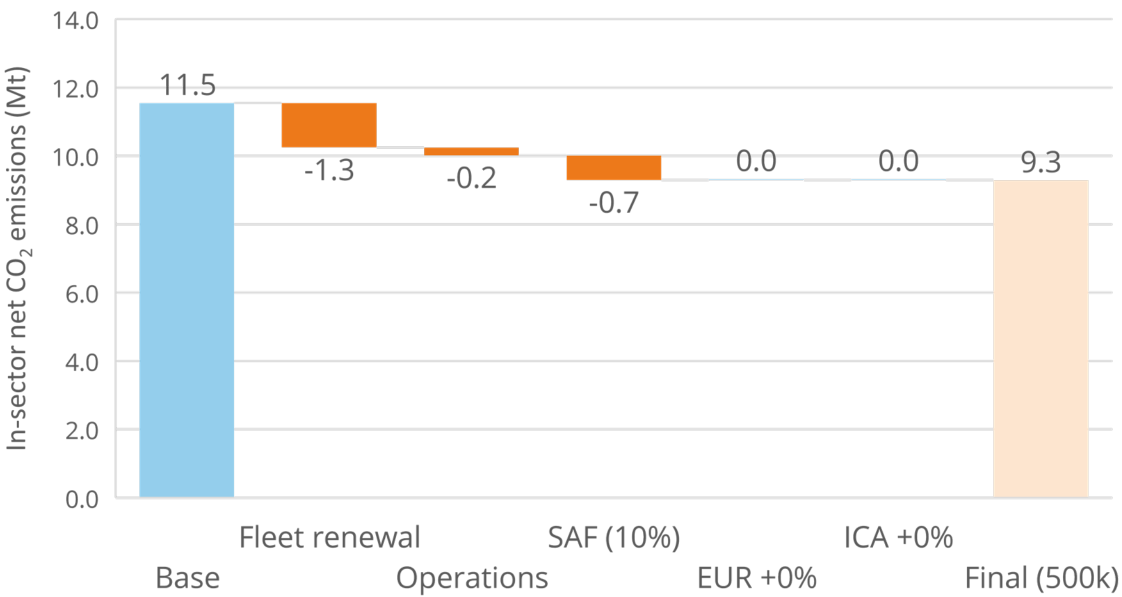


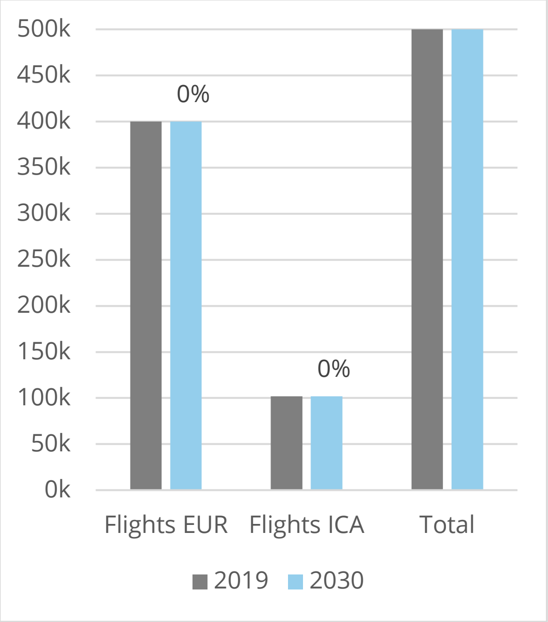




A: CO_2 emissions in the year 2030

Best estimate for 2030: 10% SAF, EUR -0%, ICA -0%, compared to 50%/1.5˚C/3.9% & 66%/1.7˚C/3.9%

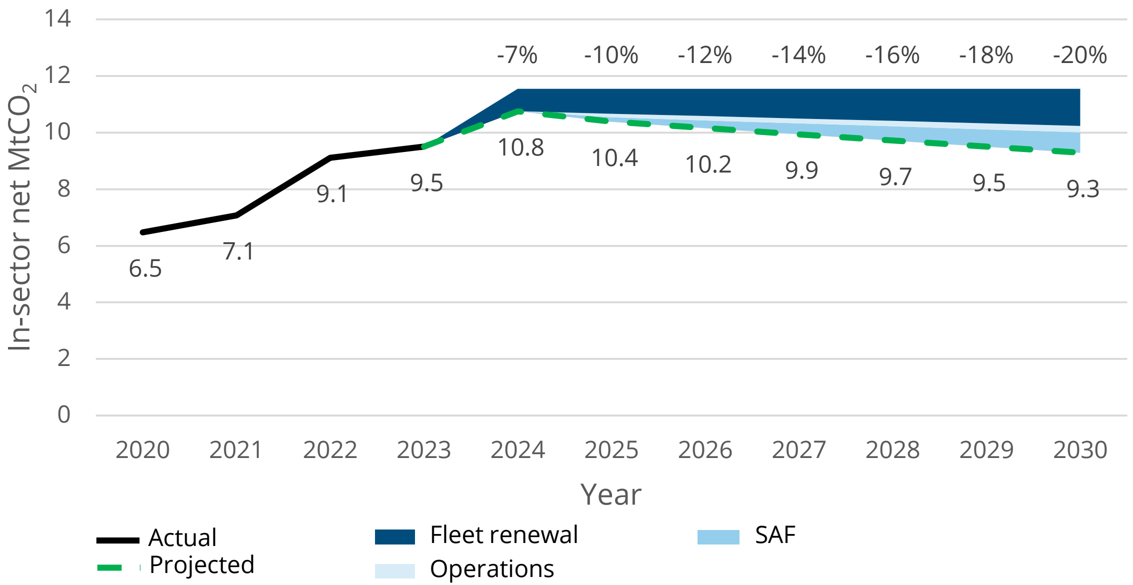




Fleet renewal based on operator announcements and additional NLR research. \\ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \\ SAF according to ReFuelEU (linear interpolation). \\ 2019 network maintained.

A: Cumulative CO_2 emissions 2020 – 2030

Best estimate for 2030: 10% SAF, EUR -0%, ICA -0%, compared to 50%/1.5˚C/3.9%



2030: 9.3 Mt

Total budget
50%/1.5˚C/3.9%: 197 Mt
2020 to 2030: 102 Mt

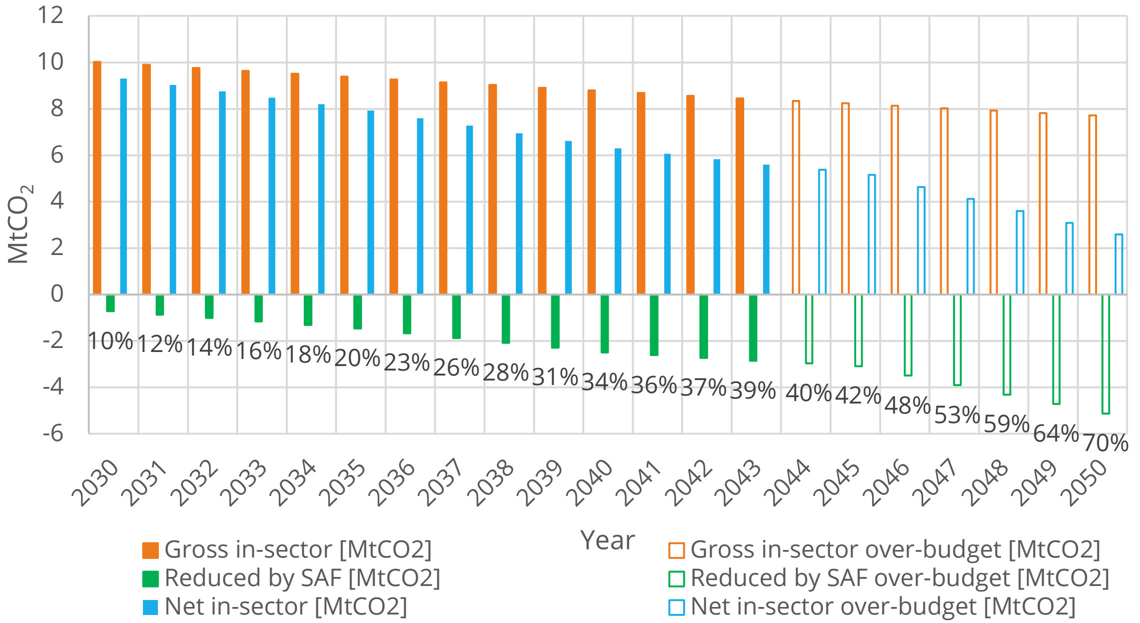
Budget for
2031 to 2050: 95 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation.

Total budget based on 50% likelihood of 1.5˚C global warming, 3.9% share of aviation (vs. all activity) and 1.01% share of Schiphol (vs. all aviation)

A: Budget and CO_2 pathway 2031 – 2050

Best estimate for 2030: 10% SAF, EUR -0%, ICA -0%, compared to 50%/1.5˚C/3.9%



Budget: 102 Mt
Used: 123 Mt

Budget overrun by 28 Mt
Budget overrun after 2043

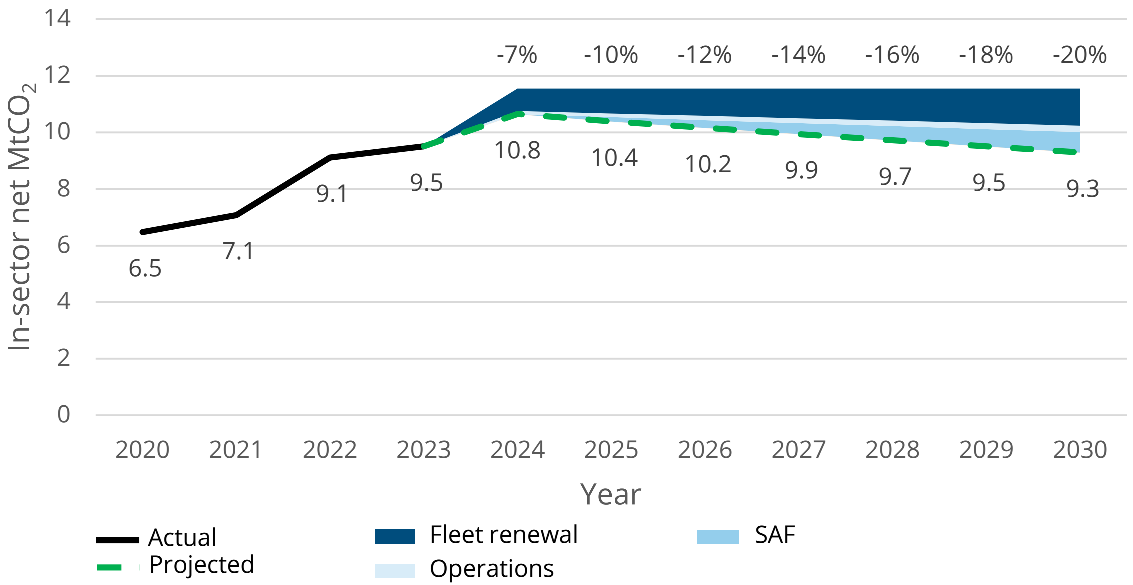
Required SAF between 2031-2043: 8 Mt

Required out-of-sector removal starting from 2044: 5.4 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

A: Cumulative CO_2 emissions 2020 – 2030

Best estimate for 2030: 10% SAF, EUR -0%, ICA -0%, compared to 66%/1.7˚C/3.9%



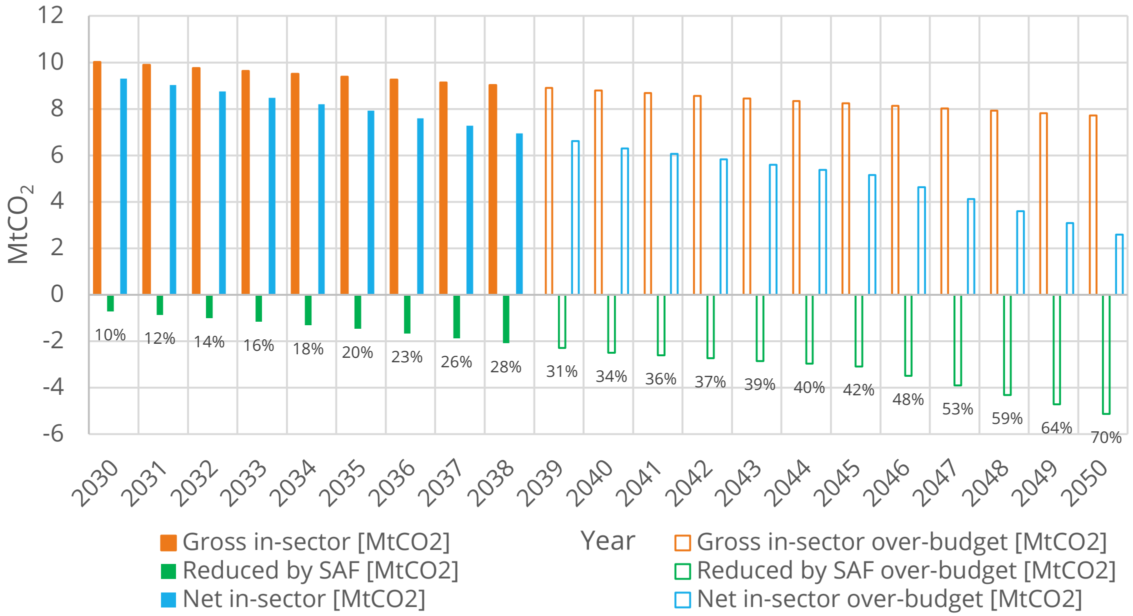
Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation.

2030:	9.3 Mt
Total budget 66%/1.7˚C/3.9%:	169 Mt
2020 to 2030:	102 Mt
Budget for 2031 to 2050:	65 Mt

Total budget based on 66% likelihood of 1.7˚C global warming, 3.9% share of aviation (vs. all activity) and 1.01% share of Schiphol (vs. all aviation)

A: Budget and CO_2 pathway 2031 – 2050

Best estimate for 2030: 10% SAF, EUR -0%, ICA -0% compared to 66%/1.7˚C/3.9%



Budget:	102 Mt
Used:	123 Mt

Budget overrun by 58 Mt
Budget overrun after 2038

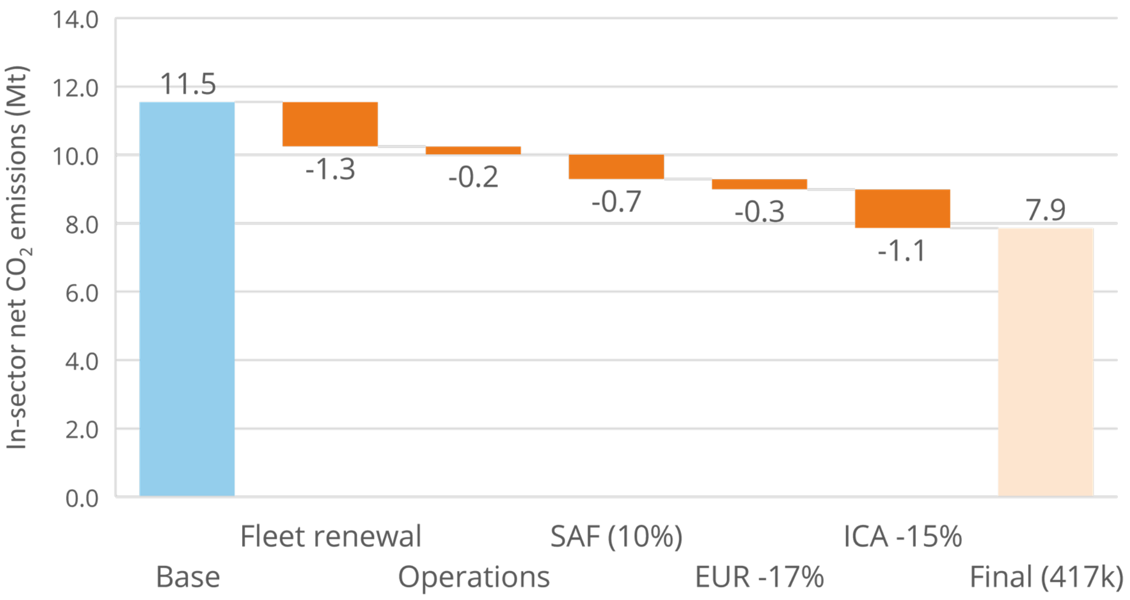
Required SAF between 2031-2038: 4 Mt

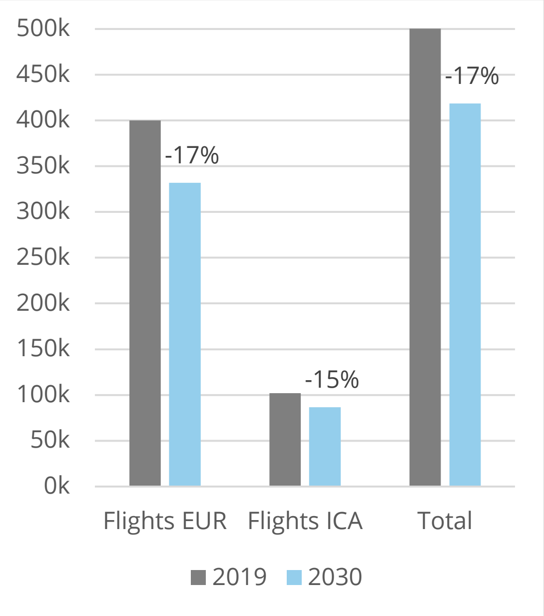
Required out-of-sector removal starting from 2039: 6.6 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

B: CO_2 emissions in the year 2030

-32% CO_2: 10% SAF, EUR -17%, ICA -15%, in line with 50%/1.5˚C/3.9%



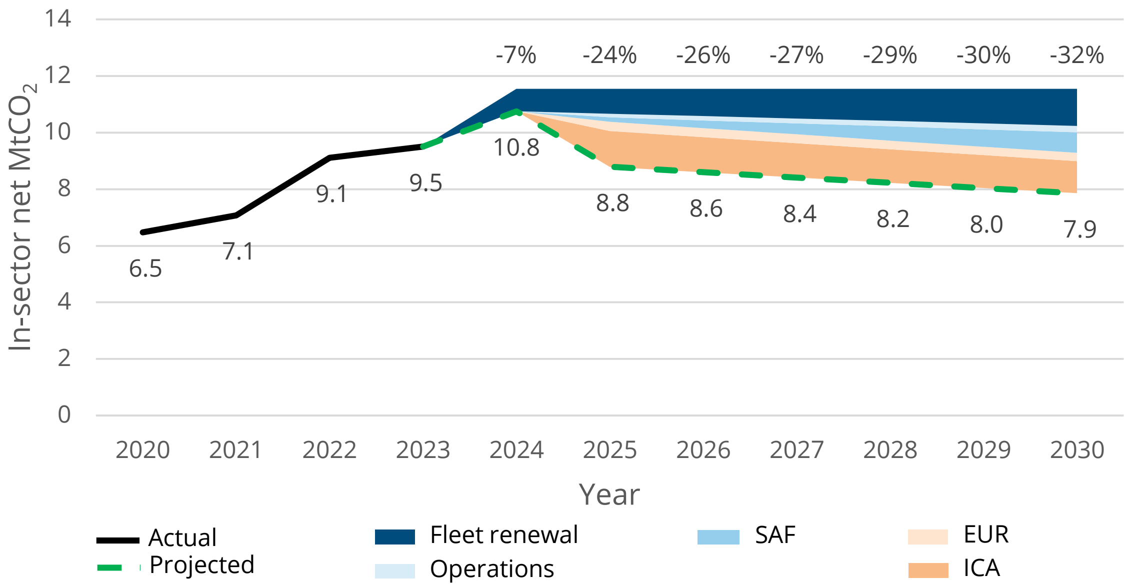


Fleet renewal based on operator announcements and additional NLR research. \\ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \\ SAF according to ReFuelEU (linear interpolation). \\ 2019 network maintained, except for EUR and ICA capacity restrictions.

Exemplary traffic scenario resulting in required -32% CO_2 in 2030 (v. 2019)

B: Cumulative CO_2 emissions 2020 – 2030

-32% CO_2: 10% SAF, EUR -17%, ICA -15%, in line with 50%/1.5˚C/3.9%



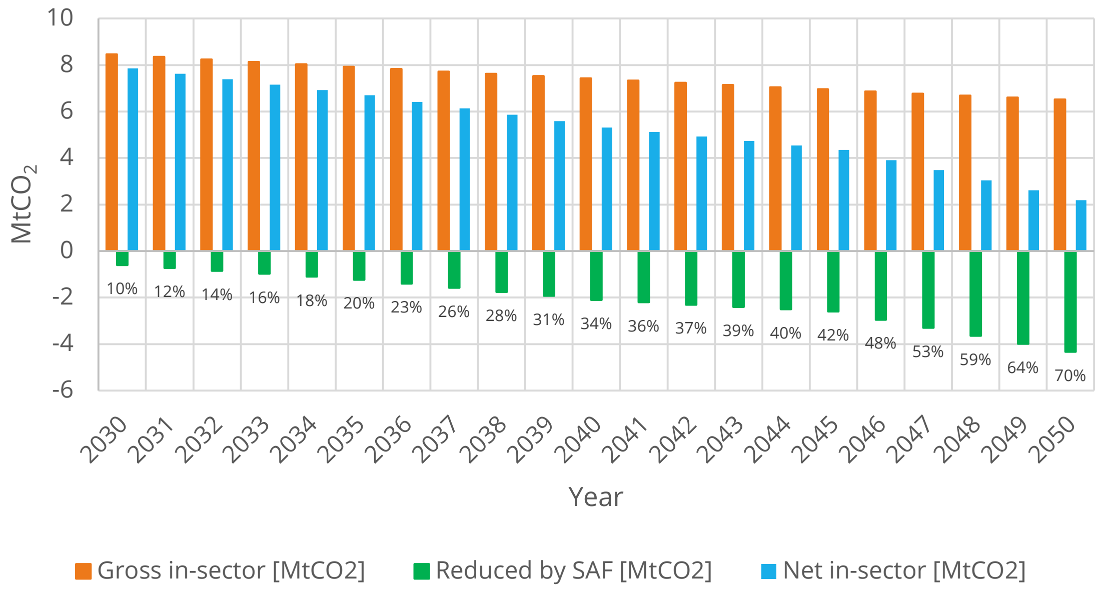
CO_2 in 2030:	7.9 Mt
Total budget:	197 Mt
2020 to 2030:	93 Mt
Budget for 2031 to 2050:	104 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

Total budget based on 50% likelihood of 1.5˚C global warming, 3.9% share of aviation (vs. all activity) and 1.01% share of Schiphol (vs. all aviation)

B: Budget and CO_2 pathway 2031 – 2050

-32% CO_2: 10% SAF, EUR -17%, ICA -15%, in line with 50%/1.5˚C/3.9%



Budget: 104 Mt
Used: 104 Mt

Required SAF between 2031-2050: 14 Mt

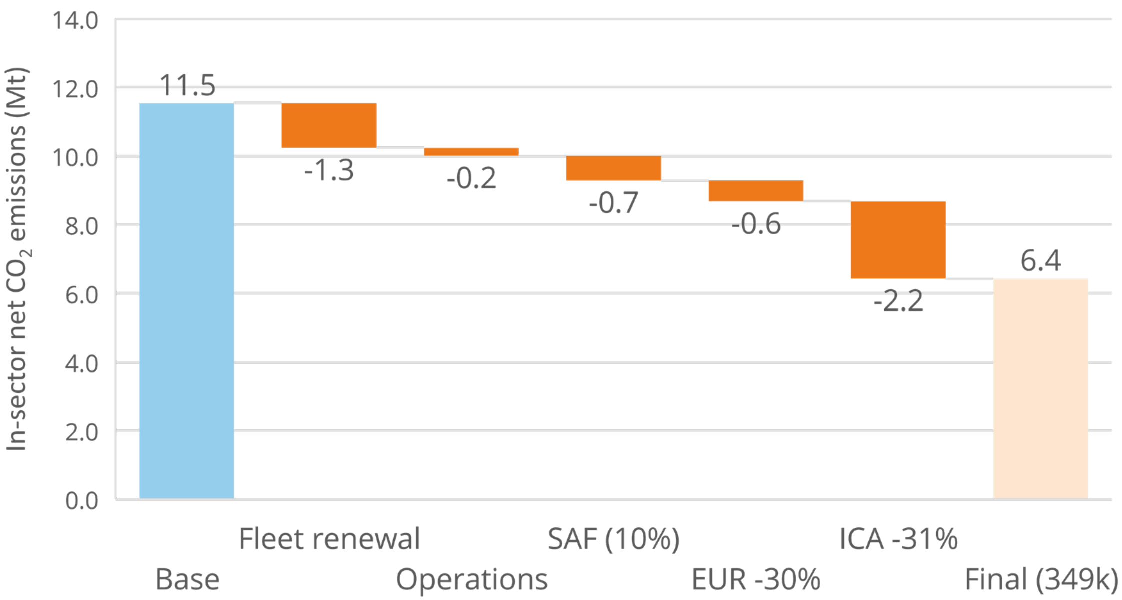
Required out-of-sector removal starting from 2050: 2.2 Mt

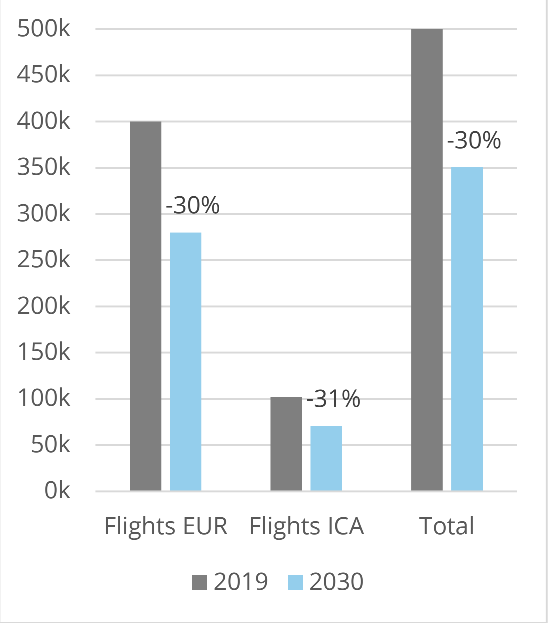
Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

8% contribution compared to 'hypothetical no-action growth' scenario by out-of-sector carbon removal anticipated by Destination 2050. 2.2 Mt equals 14%, requires additional out-of-sector removal or traffic reduction.

C: CO_2 emissions in the year 2030

-44% CO_2: 10% SAF, EUR -30%, ICA -31%, in line with 66%/1.7˚C/2.4%



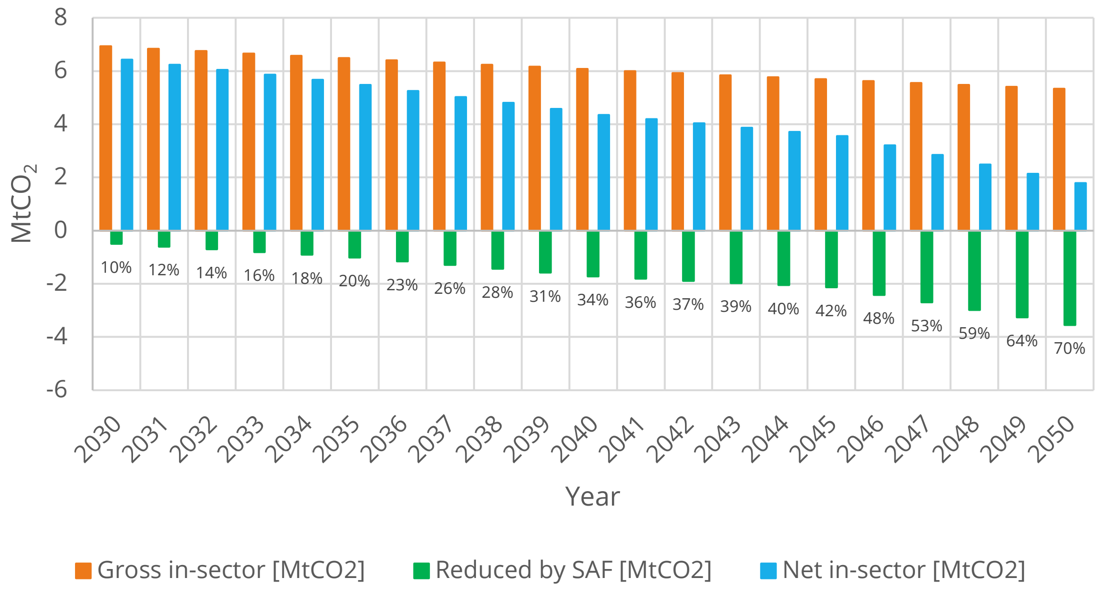


Fleet renewal based on operator announcements and additional NLR research. \\ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \\ SAF according to ReFuelEU (linear interpolation). \\ 2019 network maintained, except for EUR and ICA capacity restrictions.

Exemplary traffic scenario resulting in required -44% CO_2 in 2030 (v. 2019)

C: Budget and CO_2 pathway 2031 – 2050

-44% CO_2: 10% SAF, EUR -30%, ICA -31%, in line with 66%/1.7˚C/2.4%



Budget: 85 Mt
Used: 85 Mt

Required SAF between 2031-2050: 11 Mt

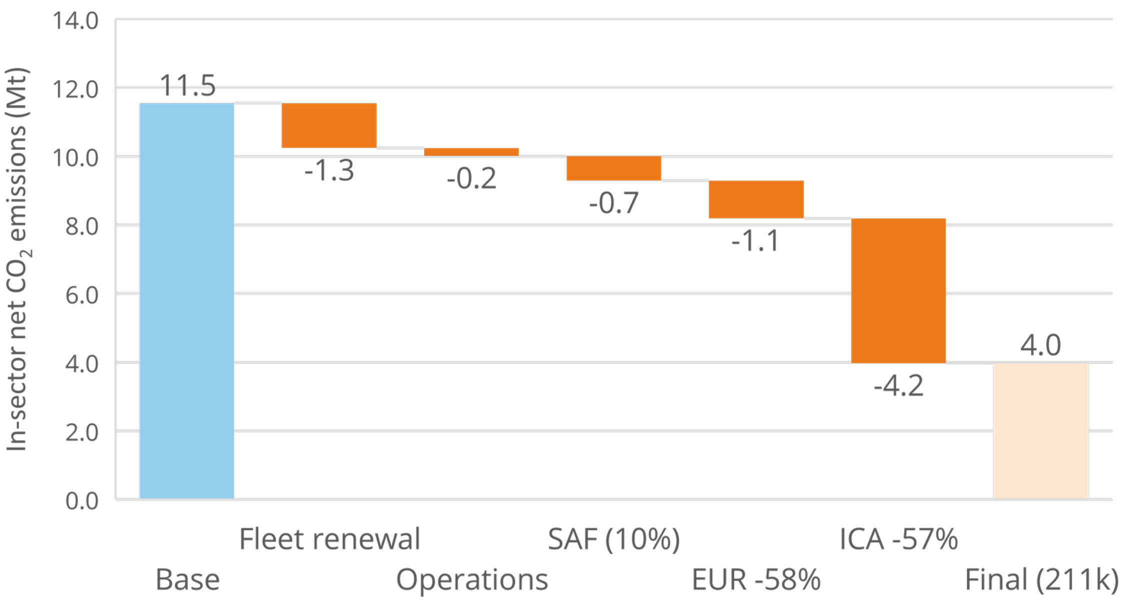
Required out-of-sector removal starting from 2050: 1.8 Mt

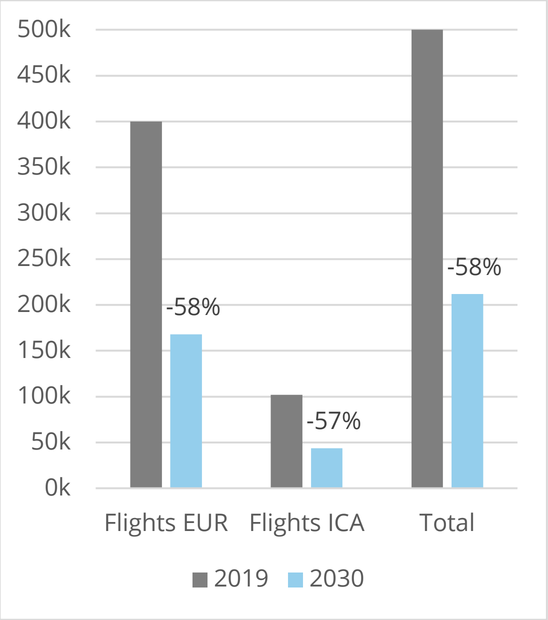
Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

8% contribution compared to 'hypothetical no-action growth' scenario by out-of-sector carbon removal anticipated by Destination 2050. 1.8 Mt equals 11%, requires additional out-of-sector removal or traffic reduction.

D: CO_2 emissions in the year 2030

-66% CO_2: 10% SAF, EUR -58%, ICA -57%, in line with 50%/1.5˚C/2.4%



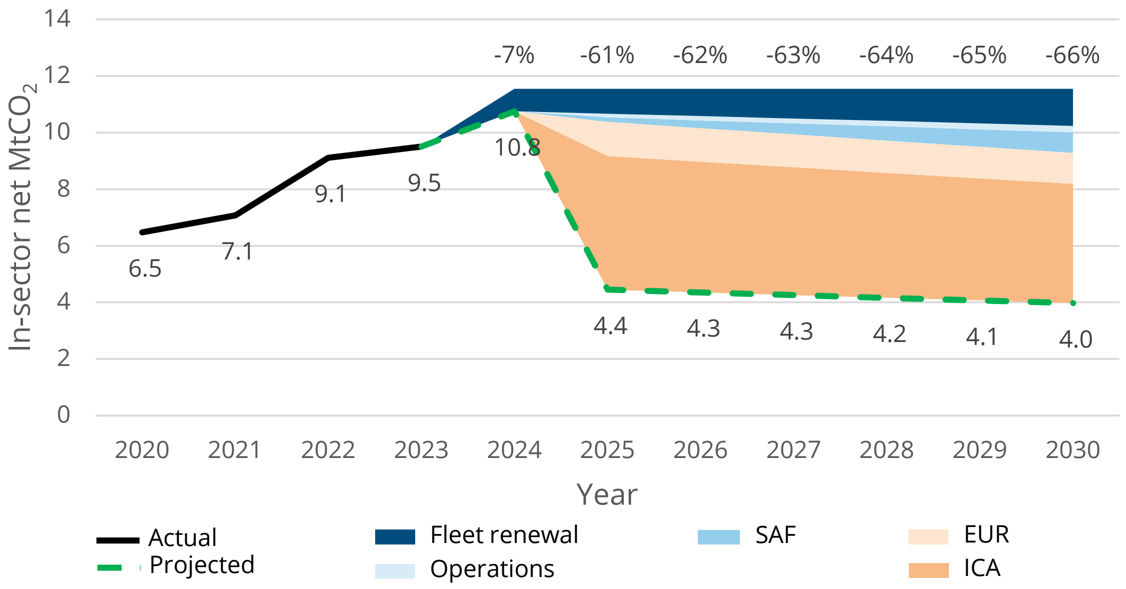


Fleet renewal based on operator announcements and additional NLR research. \\ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \\ SAF according to ReFuelEU (linear interpolation). \\ 2019 network maintained, except for EUR and ICA capacity restrictions.

Exemplary traffic scenario resulting in required -66% CO_2 in 2030 (v. 2019)

D: Cumulative CO_2 emissions 2020 – 2030

-66% CO_2: 10% SAF, EUR -58%, ICA -57%, in line with 50%/1.5˚C/2.4%



2030: 4.0 Mt

Total budget: 121 Mt
2020 to 2030: 68 Mt

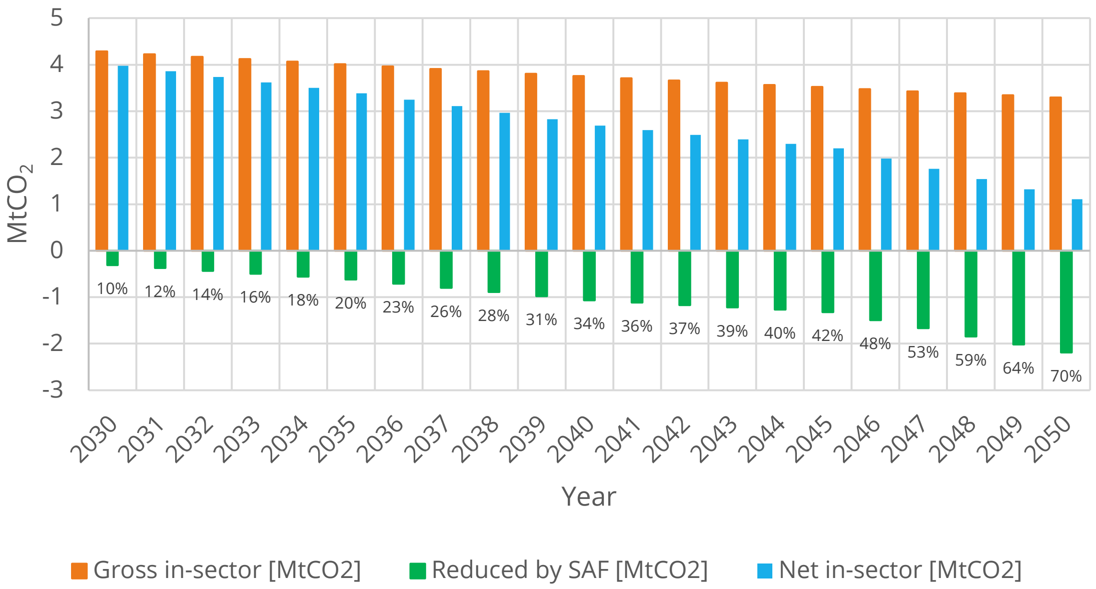
budget for
2031 to 2050: 53 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

Total budget based on 50% likelihood of 1.5˚C global warming, 2.4% share of aviation (vs. all activity) and 1.01% share of Schiphol (vs. all aviation)

D: Budget and CO_2 pathway 2031 – 2050

-66% CO_2: 10% SAF, EUR -58%, ICA -57%, in line with 50%/1.5˚C/2.4%



Budget: 53 Mt

Used: 53 Mt

Required SAF between 2031-2050: 7 Mt

Required out-of-sector removal starting from 2050: 1.1 Mt

Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

8% contribution compared to 'hypothetical no-action growth' scenario by out-of-sector carbon removal anticipated by Destination 2050. 1.1 Mt equals 7%, requires additional out-of-sector removal or traffic reduction.

V: References

- Armstrong McKay *et al.* (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* **377**(6611).
- Beevor & Alexander (2022). Missed Targets: A brief history of aviation climate targets of the early 21st century.
- Beuttler *et al.* (2019). The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Frontiers in climate* **1**
- Carrington (2022). World on brink of five 'disastrous' climate tipping points, study finds. *The Guardian.*
- CBS (2023). StatLine: Motorbrandstoffen; afzet in petajoule, gewicht en volume, 1946-april 2021.
- den Ouden *et al.* (2020). Klimaatneutrale energiescenario's 2050: Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050.
- Forster *et al.* (2023). Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence. *Earth System Science Data* **15**(6), 2295–2327.
- ICCT (2020). Vision 2050: Aligning Aviation with the Paris Agreement.
- International Energy Agency (2020). Net Zero by 2050 – A Roadmap for the Global Energy Sector.
- IPCC (2022). Climate Change 2022 Mitigation of Climate Change – Summary for Policymakers (Working Group III contribution to the Sixth Assessment Report)
- Keith et al. (2018). A Process for Capturing CO2 from the Atmosphere. *Joule* **2**, 1573–1594.
- Lamboll *et al.* (2023). Assessing the size and uncertainty of remaining carbon budgets. *Nature Climate Change* **13**, 1360–1367.
- Lee *et al.* (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2019. *Atmospheric Environment* **244**, 117834.
- Lenton *et al.* (2023). The Global Tipping Points Report 2023. University of Exeter, Exeter, UK.
- NLR (2022). Fleet development in the Netherlands. *Presented at Airneth seminar "Airline fleet renewal strategies", July 2022.*

V: References

- ReFuelEU Aviation (2023/05/08). REGULATION OF THE EUROPEAN PARLIAMANT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport. Analysis of the final compromise text with a view to agreement. Interinstitutional File 2021/0205 (COD).
- Rogelj *et al*. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342.
- Sustainable Aviation UK (2023). NET ZERO CARBON ROAD-MAP SUMMARY REPORT. Enabling delivery of a UK-led zero carbon aviation revolution.
- United Nations (2015). Paris Agreement.
- van den Berg *et al.* (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change* **162**, 1805–1822.
- van der Sman *et al.* (2021). Destination 2050 – A Route To Net Zero European Aviation. NLR-CR-2020-510, Amsterdam, the Netherlands.
- van der Sman *et al.* (2022). Energiebehoefte voor synthetische kerosine voor de Nederlandse luchtvaart in 2030 en 2050. NLR-TR-2022-341, Amsterdam, the Netherlands.