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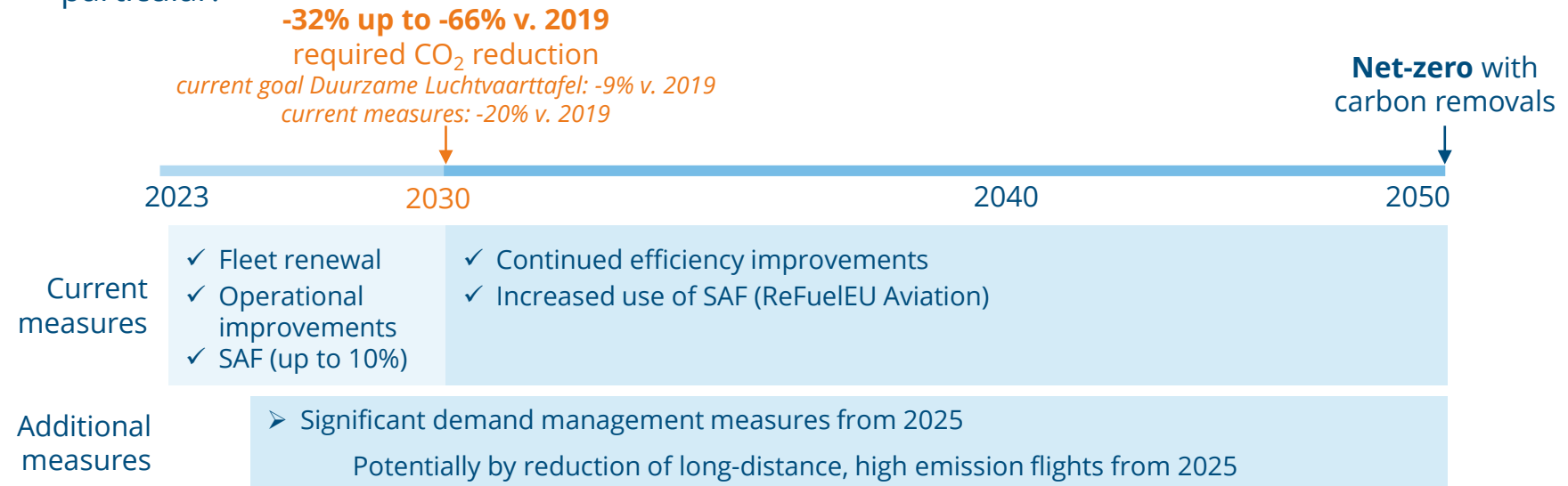
**CO<sub>2</sub> reduction targets for Amsterdam Airport Schiphol based  
on remaining IPCC CO<sub>2</sub> budgets up to 2050**

January 2024



# Stringent reductions in CO<sub>2</sub> 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.





# CO<sub>2</sub> reduction targets for Amsterdam Airport Schiphol based on remaining IPCC CO<sub>2</sub> 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<sub>2</sub> 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.

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# How much aviation fits in a Paris-compatible CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> budgets, which specify how much CO<sub>2</sub> 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.

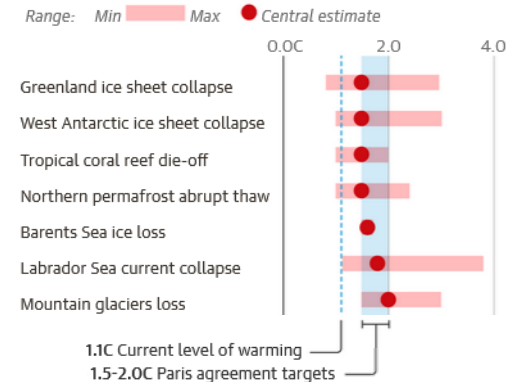
°C	Likelihood		
	50%	66%	83%
<b>1.5</b>	<b>500 Gt</b>	400 Gt	300 Gt
<b>1.7</b>	850 Gt	<b>700 Gt</b>	550 Gt
<b>2</b>	1350 Gt	1150 Gt	900 Gt

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 overshoot, 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<sub>2</sub> budgets, CO<sub>2</sub> budgets for aviation in general and CO<sub>2</sub> 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%**.

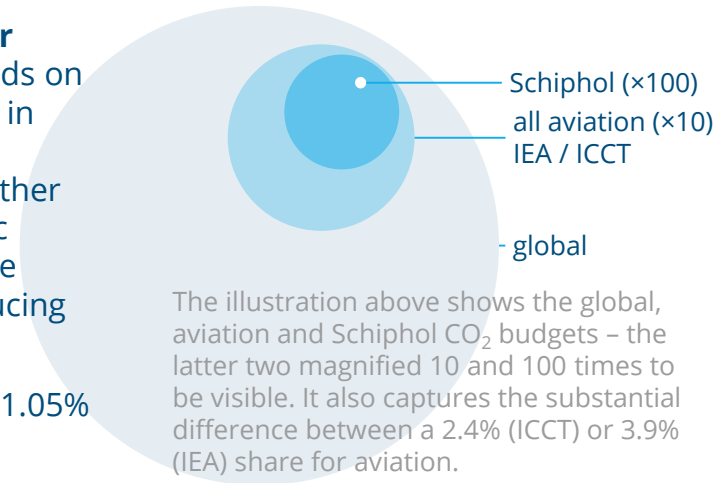
The **share of the budget for aviation at Schiphol** depends on the share of aviation activity in the Netherlands (vs. global). Currently, this is 1.16%. As other regions will see higher traffic growth, this share will reduce over time (in line with a reducing share of Europe).

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%**



If global aviation today would be responsible for 3.9% of global CO<sub>2</sub> 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.

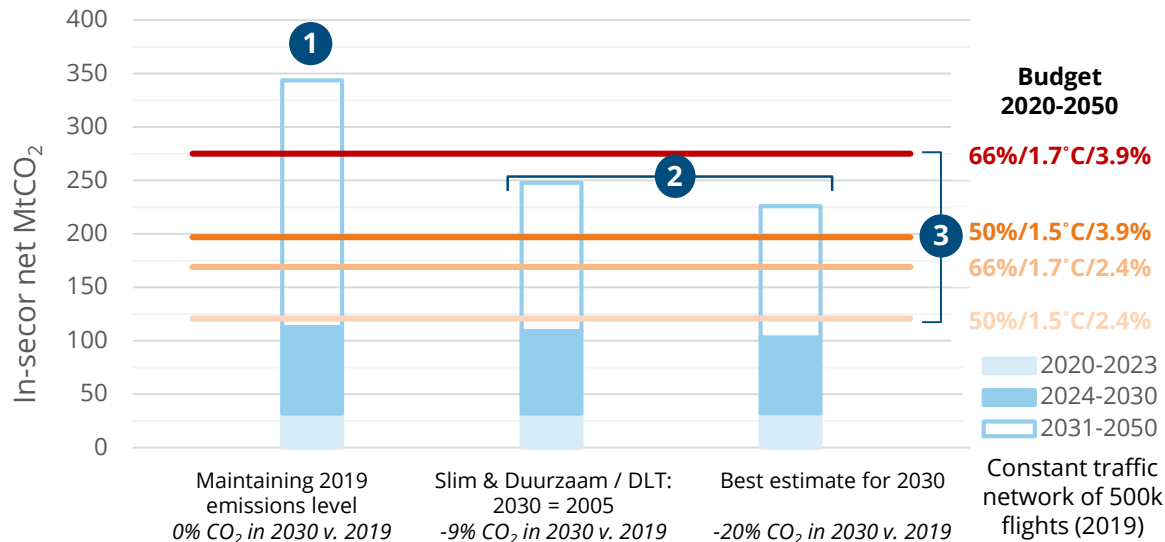
# In-sector emissions between 2020 and 2050 are calculated, modelled and estimated based on suitable data and methods



**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<sub>2</sub> 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

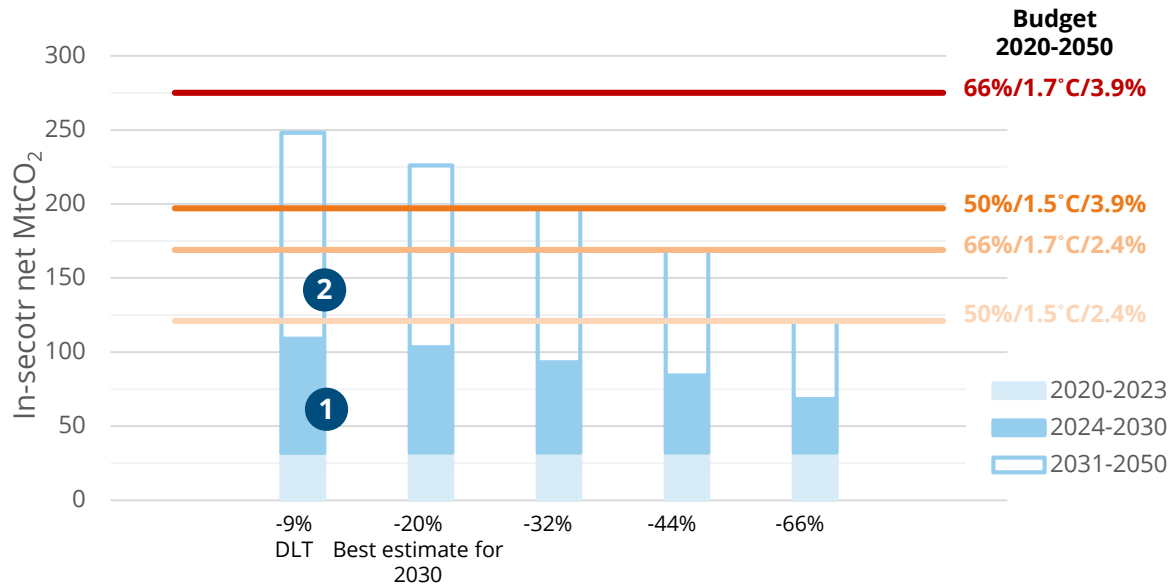
# In-sector action between now and 2030 reduces cumulative CO<sub>2</sub> emissions but overshoots majority of airport carbon budgets



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

Maintaining 2019 emissions level: 0% CO<sub>2</sub> reduction with respect to 2019: recovery to 2019 CO<sub>2</sub> (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<sub>2</sub> in 2030 v. 2019).

# CO<sub>2</sub> emissions in 2030 have to reduce by 32%, 44% and 66% compared to 2019 to meet more ambitious airport carbon budgets

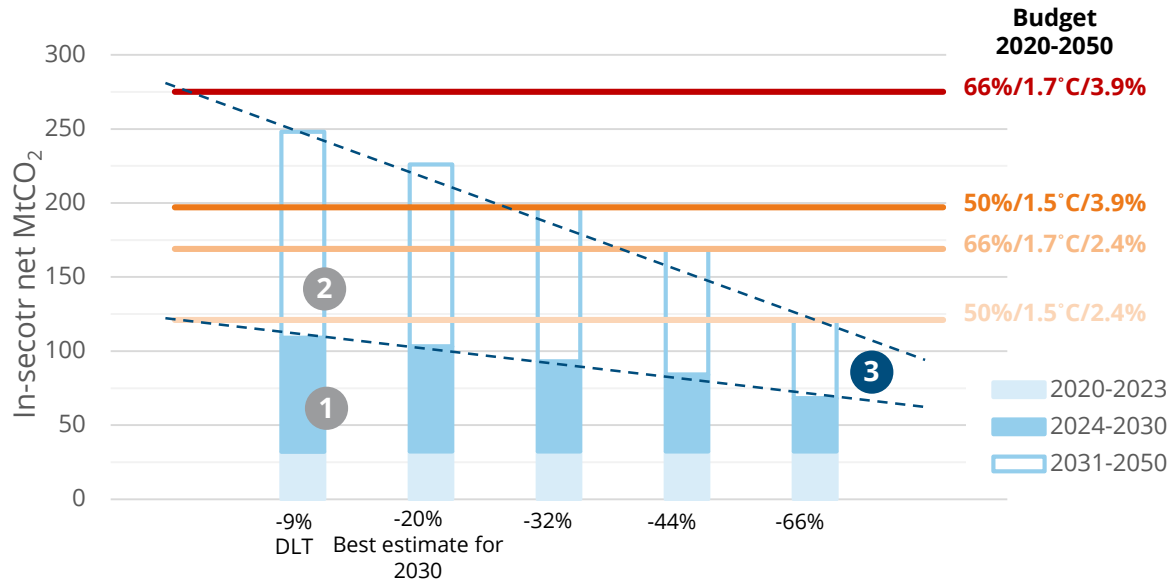


Required change in in-sector net cumulative CO<sub>2</sub> emissions for 2030 (v. 2019)

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<sub>2</sub> 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<sub>2</sub> 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 <sub>2</sub>	113 MtCO <sub>2</sub>
		– 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 <sub>2</sub>	120 MtCO <sub>2</sub>
		– 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 <sub>2</sub>	119 MtCO <sub>2</sub>
		– 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.

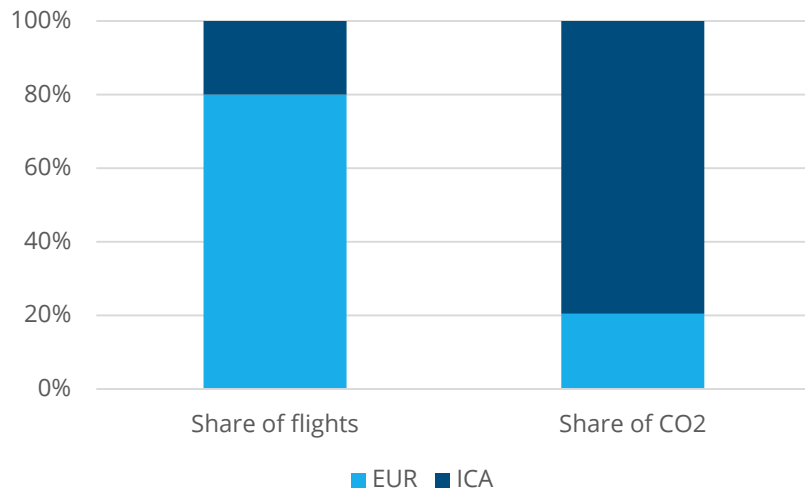


# Given no more in-sector decarbonisation opportunities, demand management remains as only option to reduce 2030 CO<sub>2</sub> levels v. 2019

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

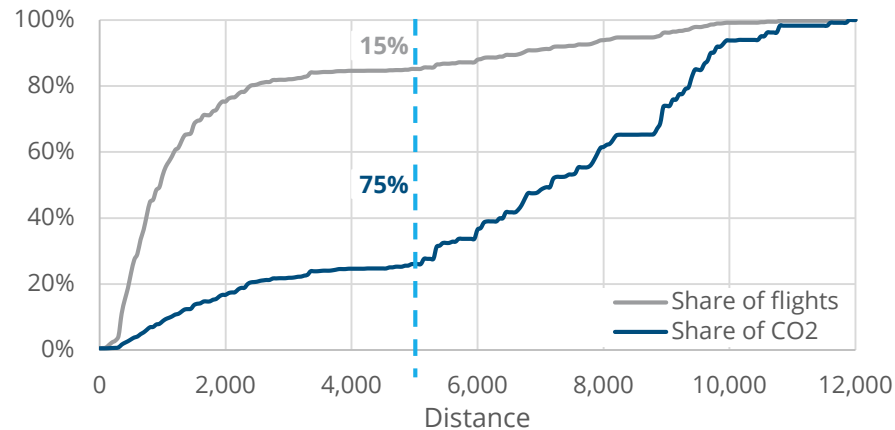
80% of flights are intra-EU and contribute about 20% of CO<sub>2</sub>

As such: demand management measures in ICA prevent more CO<sub>2</sub> emissions than measures in EUR



About 15% longest distance flights (> 5000 km) contribute some 75% of CO<sub>2</sub>

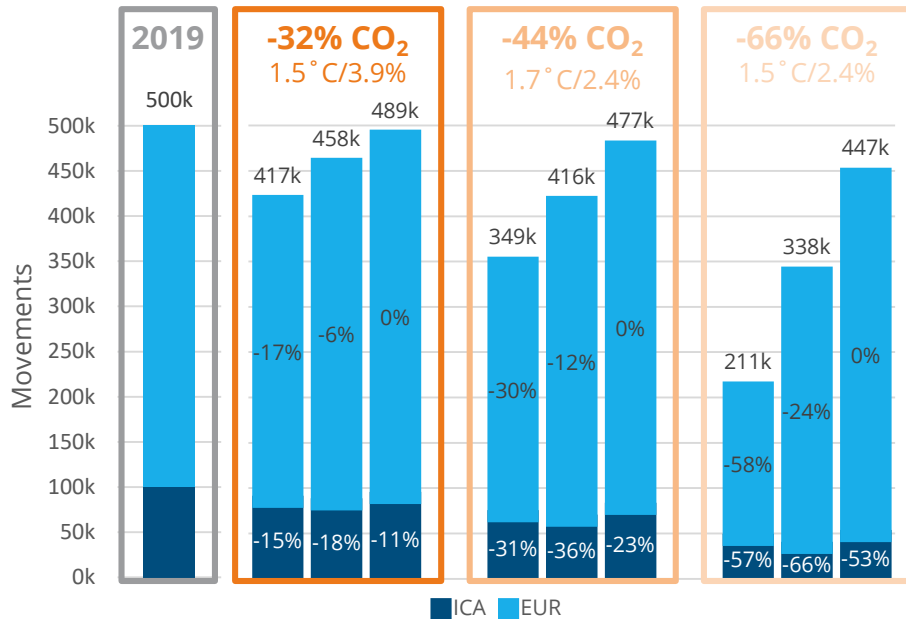
As such: demand management measures targeting long distance flights are more effective than measures reducing total demand





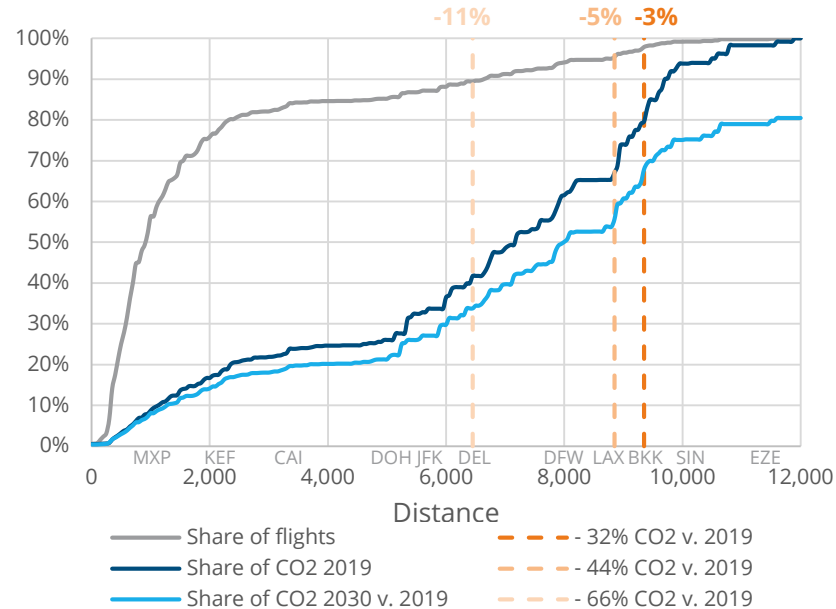
# Demand management can be achieved by more generic capacity reductions or specifically targeting the longest flights

## 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<sub>2</sub> leakage to other areas. Capacity reductions modelled from 2025 onwards.

## Flight distance restrictions

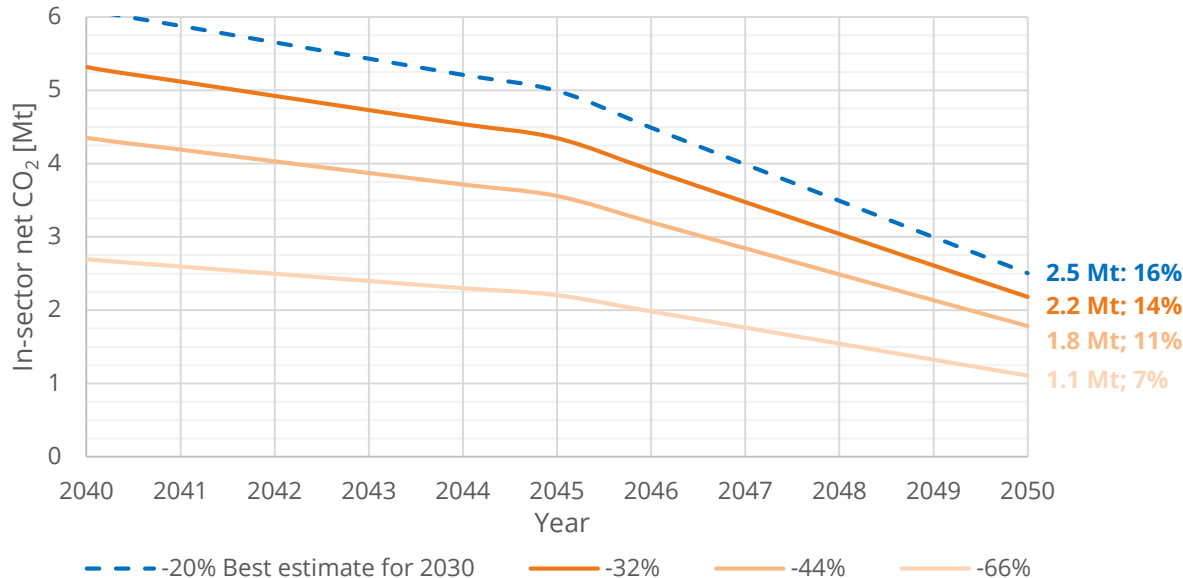


CO<sub>2</sub> budgets for 2030 can be respected by limiting maximum flight distance – reducing flights by 3%, 5% or 11%, respectively. The modelling assumes these long-distance flights are not replaced by shorter flights. Also, it must be noted that by reducing long-haul flights, CO<sub>2</sub> emissions 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<sub>2</sub> 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<sub>2</sub>.

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<sub>2</sub> can be removed out-of-sector for which 9.97 PJ/MtCO<sub>2</sub> 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	Total energy share of aviation of primary energy supply in 2050
			SAF, carbon removal	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).

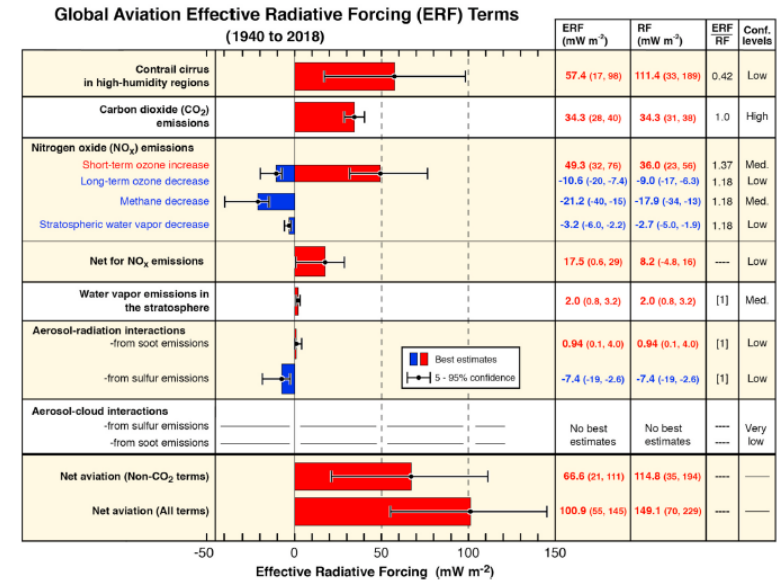


# Smaller airport carbon budgets require larger CO<sub>2</sub> reductions and less flights in 2030

Warming	Budget share for aviation	Required CO <sub>2</sub> reduction in 2030	Indicative number of annual flights compatible with required CO <sub>2</sub> reduction (2025-2050)		
			EUR:ICA reduced 1:1 (current)	EUR:ICA reduced 1:3 (less ICA)	Distance limit
<b>50% likelihood of 1.5 °C</b> (500 Gt)	2.4%	<b>-66% v. 2019</b> -62% v. 2005	210k	340k	450k (6450 km)
	3.9%	<b>-32% v. 2019</b> -25% v. 2005	420k	460k	490k (9300 km)
<b>66% likelihood of 1.7 °C</b> (700 Gt)	2.4%	<b>-44% v. 2019</b> -39% v. 2005	350k	420k	480k (8850 km)
	3.9%	<b>Not required</b>	500k No flight distance restriction		

# Notwithstanding the conclusions drawn, additional and dedicated measures are required to tackle non-CO<sub>2</sub> impact of aviation

- In determining the CO<sub>2</sub> budgets, IPCC (2022) has taken into account non-CO<sub>2</sub> emissions, such as methane emissions from the agricultural sector. These non-CO<sub>2</sub> emissions impact the CO<sub>2</sub> budget (Annex I.A).
- It is unclear if aviation-specific non-CO<sub>2</sub> climate effects (NO<sub>x</sub> interactions with methane and ozone, persistent contrails and cirrus, ...) are also explicitly taken into account by IPCC.
- If non-CO<sub>2</sub> climate effects of aviation are accounted for, the current study is rightfully limited to CO<sub>2</sub> emissions only. To align to IPCC modelling and assumptions, it is in this case required to reduce non-CO<sub>2</sub> climate effects of aviation in line with CO<sub>2</sub> emissions. This requires additional and dedicated measures.
- If non-CO<sub>2</sub> 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<sub>2</sub> climate effects will then appear 'on both sides of the equation', the conclusions presented here remain valid.



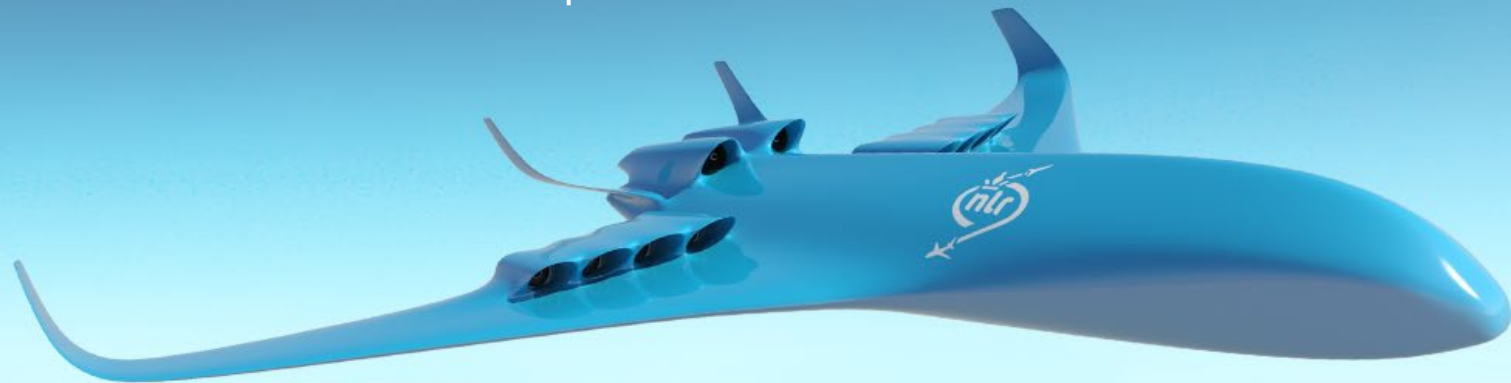
This figure, from Lee *et al.* (2021), shows non-CO<sub>2</sub> effects are estimated to have been responsible for two-thirds of the total aviation climate effect between 1940 and 2018. Although this ratio might be different over other periods, the non-CO<sub>2</sub> climate impact is nonnegligible. Additional and dedicated measures will be required to address these non-CO<sub>2</sub> effects.



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  - D. -66% CO<sub>2</sub> emissions in 2030 v. 2019; in line with 1.5°C/2.4%
- V. References

 A: IPCC global carbon budgets

Carbon budgets as used in this report “can be defined as the remaining amount of CO<sub>2</sub> 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<sub>2</sub> budgets are not legally or scientifically ‘binding’ CO<sub>2</sub> ‘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)

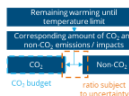
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\*Values at each 0.1°C increment of warming are available in tables T1.1 and 5.8.

 A: IPCC global carbon budgets

As shown in the figure by IPCC (2022) on the previous page, anticipated reductions in non-CO<sub>2</sub> emissions (such as methane emissions from the agricultural sector) are taken into account in determining the CO<sub>2</sub>-budgets. As indicated by IPCC, "higher or lower reductions in accompanying non-CO<sub>2</sub> emissions can increase or decrease the values on the left (the CO<sub>2</sub>-budgets)".

The figure on the right (based on Rogelj *et al.*, 2019, Fig. 1) illustrates in a similar manner how an 'allowed' amount of CO<sub>2</sub> 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<sub>2</sub> and non-CO<sub>2</sub>. As the IPCC (2022, Table SPMA.2) explicitly notes, higher or lower reductions in non-CO<sub>2</sub> emissions also impact the remaining CO<sub>2</sub> budget, quantifying that uncertainty as "220Gt or more" (equivalent to 44% of the 500 Gt budget corresponding to a 50% likelihood of 1.5°C warming).



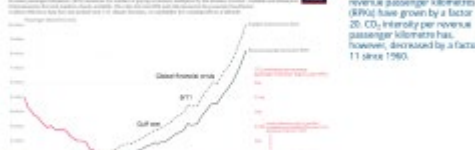
 A: IPCC global carbon budgets

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<sub>2</sub> budget for limiting warming to 1.5°C with a 50% likelihood is not 500 Gt but 400 Gt over the period from 2020 up to and including 2050. The budget for limiting warming to 1.5°C with a 66% likelihood is not 500 Gt but 350 Gt over the period from 2020 up to and including 2050. 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 (WG1) report”, the present analysis of CO<sub>2</sub> 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 Foguel et al. (2023) – “diversity that may confuse”. Put simply: the authors of this present work cannot judge whether the methods of Forster et al. (2023) are better than those of the IPCC (2022). By the way, the IPCC is “close enough”. A short analysis shows that the required reduction in CO<sub>2</sub> emissions by 2020 based on the reduced budget for limiting warming to 1.5°C 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<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissions

Global airline traffic and aviation efficiency



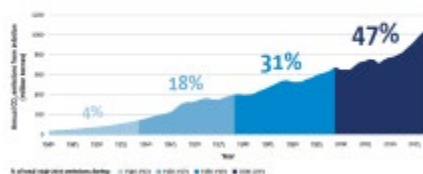
Between 1970 and 2010, revenue passenger kilometers (RPK) have grown by a factor 20. CO<sub>2</sub> intensity per revenue passenger kilometre has, however, decreased by a factor 11, since 1960.

 B: Aviation growth, CO<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissionsCO<sub>2</sub> intensity (kg CO<sub>2</sub>e/kWh) per average gross electricity output

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 2015, the compound reduction rate was even higher at 1.3%, due to the introduction of widebody aircraft.

 B: Aviation growth, CO<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissions

The figure below shows annual global CO<sub>2</sub> emissions from global aviation and indicates the share of total cumulative emissions in each 20-year period.



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 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, 28 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 -55-60% between 2019-2035 or -65% from 2015-2035” - from approximately 1000 gCO<sub>2</sub>/RTK today, to some 350 gCO<sub>2</sub>/RTK in 2035. Long-term industry forecasts are based on the IEA ETP Sustainable Development Scenario (SDS), which anticipates an annual growth forecast of 2.5% per annum (2019-2035). The SDS 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 ICCC to Vision 2050. Whereas this Breakthrough scenario was developed to be compatible with 67% likelihood of 1.5°C warming, its 'cumulative emissions' [...] over the time period 2019-2050 [19-8 GtCO<sub>2</sub>] are lower than those of the IFA-NZE scenario [20.5 GtCO<sub>2</sub>], which is consistent, with limiting global temperature increase to 1.5°C without overshoot'. To 0.6 of the 1.5°C technical report, 50% assesses the Breakthrough scenario compatible with

 C: Science Based Targets initiative (SBTi)

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

[illegible]

Modeling along the Intergovernmental Panel on Climate Change's 1.5°C Shared Socioeconomic Pathway, the target-setting tool for that warming scenario outlines a 2050 sector intensity target of 24 gCO<sub>2</sub>-e/kWh (9.0 per revenue tonne kilowatt-hour, 98% versus current CO<sub>2</sub> intensity). By 2050, global sector emissions should be reduced to about 100 MtCO<sub>2</sub>.

Compared to the analysis presented here, the current, Intergovernmental Panel on Climate Change (IPCC) 5.5°C SSG1 pathway will likely lead to a somewhat higher carbon budget, as regional growth differences are not taken into account by SSG1. Moreover, the targeted CO<sub>2</sub> intensity reduction of 50% compared to 2019 levels seems more technology-optimistic, compared to the analysis presented here. The 'link' in the sector emissions pathway (graph on the right) from 2030 seems to match that technology-assessment.

Some have argued that the [author's] theory was never published. It is not true. It was published in the *Journal of the American Medical Association* in 1954.

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# A: IPCC global carbon budgets

Carbon budgets as used in this report “can be defined as the remaining amount of CO<sub>2</sub> 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<sub>2</sub> budgets are not legally or scientifically ‘binding’ CO<sub>2</sub> ‘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<sub>2</sub>) emissions and remaining carbon budgets.** Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO<sub>2</sub> emissions are reached. They refer to CO<sub>2</sub> emissions, while accounting for the global warming effect of non-CO<sub>2</sub> 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 <sub>2</sub> Emissions from 1850 to 2019 (GtCO <sub>2</sub> )				
1.07 (0.8–1.3; likely range)		2390 (± 240; likely range)				
Approximate global warming relative to 1850–1900 until temperature limit (°C) <sup>a</sup>	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 (GtCO <sub>2</sub> )				
		Likelihood of limiting global warming to temperature limit <sup>b</sup>				
		17%	33%	50%	67%	83%
1.5	0.43	900	650	500	400	300
1.7	0.63	1450	1050	850	700	550
2.0	0.93	2300	1700	1350	1150	900

Variations in reductions in non-CO<sub>2</sub> emissions<sup>c</sup>

Higher or lower reductions in accompanying non-CO<sub>2</sub> emissions can increase or decrease the values on the left by 220 GtCO<sub>2</sub> or more

<sup>a</sup> Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

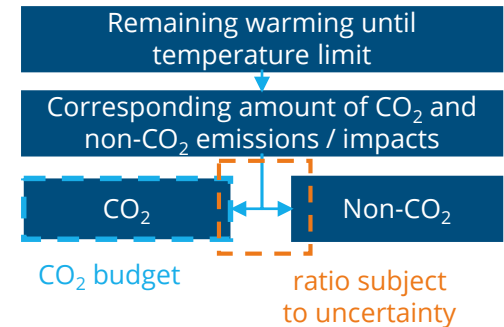
<sup>b</sup> This likelihood is based on the uncertainty in transient climate response to cumulative CO<sub>2</sub> emissions (TCRE) and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 GtCO<sub>2</sub>) and non-CO<sub>2</sub> forcing and response (±220 GtCO<sub>2</sub>) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 GtCO<sub>2</sub>) and the climate response after net zero CO<sub>2</sub> emissions are reached (±420 GtCO<sub>2</sub>) are separate.

<sup>c</sup> Remaining carbon budget estimates consider the warming from non-CO<sub>2</sub> drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO<sub>2</sub> emissions.

## A: IPCC global carbon budgets

As shown in the figure by IPCC (2022) on the previous page, anticipated reductions in non-CO<sub>2</sub> emissions (such as methane emissions from the agricultural sector) are taken into account in determining the CO<sub>2</sub>-budgets. As indicated by IPCC, “higher or lower reductions in accompanying non-CO<sub>2</sub> emissions can increase or decrease the values on the left [the CO<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub> and non-CO<sub>2</sub>. As the IPCC (2022, Table SPM.2) explicitly notes, higher or lower reductions in non-CO<sub>2</sub> emissions also impact the remaining CO<sub>2</sub> budget, quantifying that uncertainty as “220Gt or more” (equivalent to 44% of the 500 Gt budget corresponding to a 50% likelihood of 1.5°C 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<sub>2</sub> budget for limiting warming to 1.5°C 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 1.7°C 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<sub>2</sub> 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<sub>2</sub> emissions by 2030 based on the reduced budget for limiting warming to 1.5°C 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%.

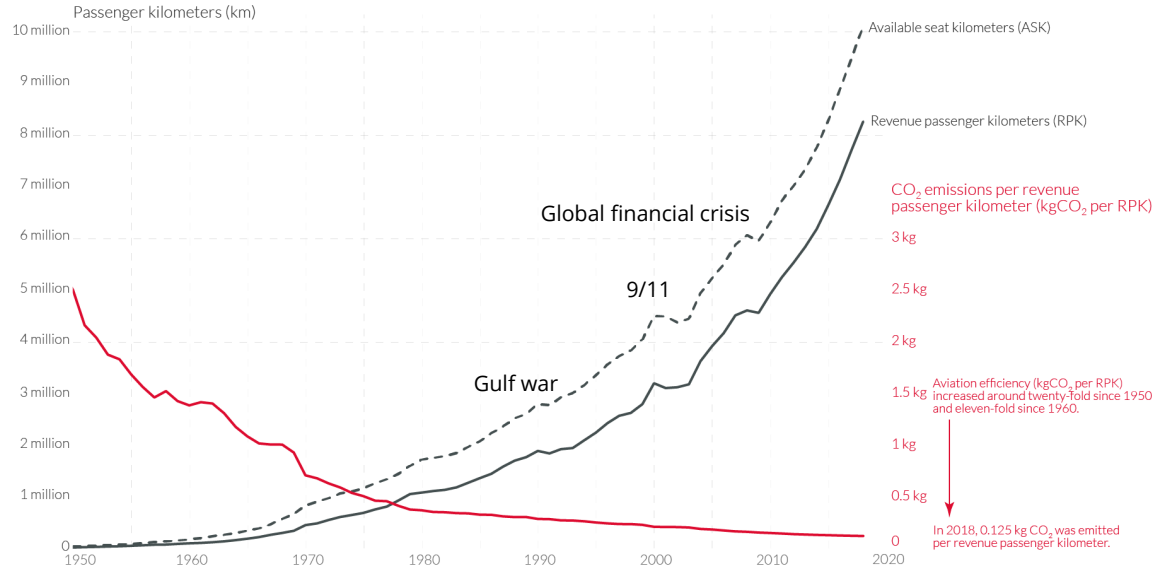
# B: Aviation growth, CO<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissions

Activity growth in revenue passenger kilometre (RPK)

## Global airline traffic and aviation efficiency

Revenue passenger kilometers (RPK) measures the number of paying customers multiplied by the distance traveled. Available seat kilometers (ASK) measures the total number of seats available. The ratio between RPK and ASK measures the passenger load factor. Aviation efficiency data does not include non-CO<sub>2</sub> climate forcings, or a multiplier for warming effects at altitude.

Our World in Data



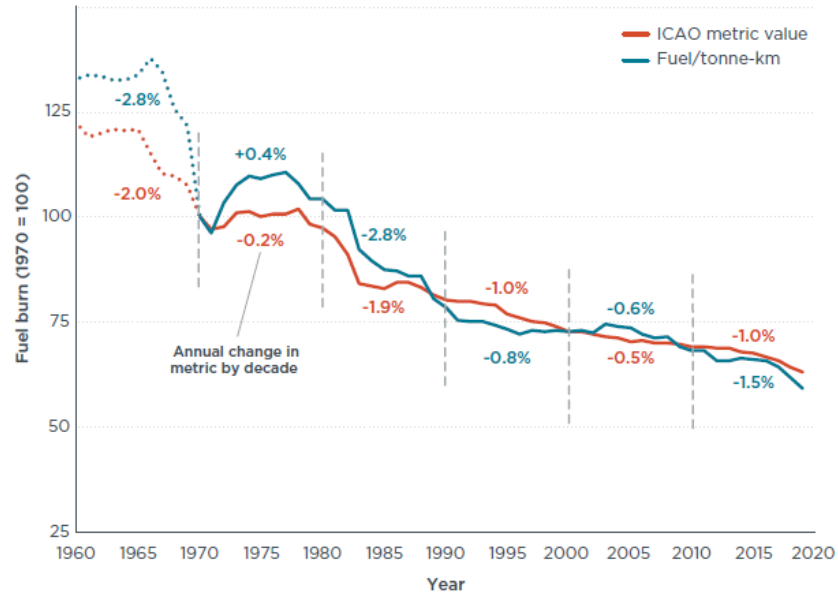
OurWorldinData.org – Research and data to make progress against the world's largest problems.  
Source: Lee et al. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018; based on Sausen and Schumann (2000) & IEA. Aviation efficiency calculated based on global aircraft traffic data from the International Civil Aviation Organization (ICAO) via airlines.org.

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Between 1970 and 2019, revenue passenger kilometres (RPKs) have grown by a factor 20. CO<sub>2</sub> intensity per revenue passenger kilometre has, however, decreased by a factor 11 since 1960.

## B: Aviation growth, CO<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissions

CO<sub>2</sub> intensity in CO<sub>2</sub> per revenue tonne kilometre (RTK)

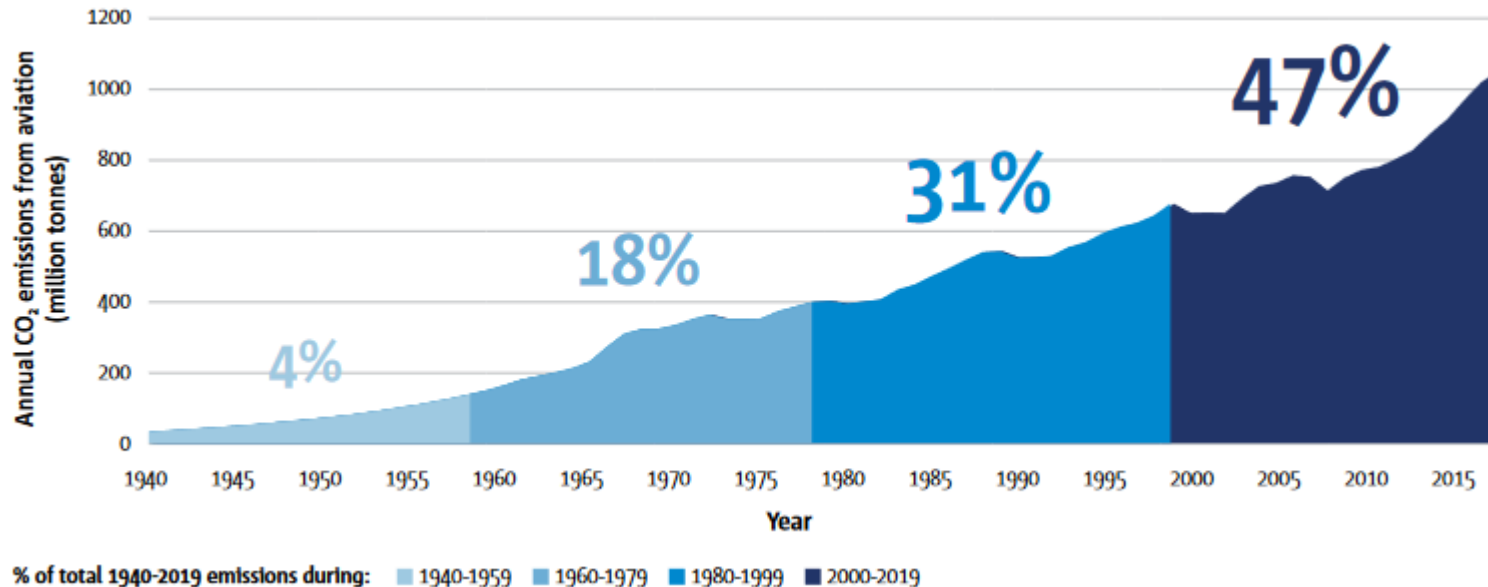


This figure shows that fuel consumption of new aircraft has reduced by 41% over the past 50 years (1970 = 100), corresponding to a 1.0% compound annual reduction rate. Over the period from 1960 to 2019, the compound reduction rate was even higher at 1.3%, due to the introduction of widebody aircraft.

## B: Aviation growth, CO<sub>2</sub> intensity and cumulative CO<sub>2</sub> emissions

### Cumulative aviation CO<sub>2</sub> emissions

The figure below shows annual global CO<sub>2</sub> emissions from global aviation and indicates the share of total cumulative emissions in each 20-year period.





## 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<sub>2</sub>/RTK today, to some 350 gCO<sub>2</sub>/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<sub>2</sub>] are lower than those of the IEA NZE scenario [20.5 GtCO<sub>2</sub>], 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

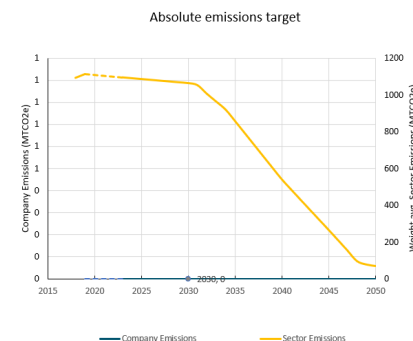
# C: Science Based Targets initiative (SBTi)

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 <sub>2</sub>	19.6 Gt CO <sub>2</sub>
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<sub>2</sub>/RTK (N.B.: per revenue **tonne** kilometre; -98% versus current CO<sub>2</sub> intensity). By 2050, global sector emissions should be reduced to about 100 MtCO<sub>2</sub>.

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<sub>2</sub> 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.



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

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

- 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%**)

**Integrated scenario 3**  
Based on cumulative emissions up to 2050 – 15 GtCO<sub>2</sub>

- Various warming scenarios (1.5°C and 1.7°C) and two budget shares for aviation (2.4% and 3.5%) – as used in main study
- Further reduced by the anticipated future share of NL to all global aviation (1.66% → 0.6252% and 0.0410%) and by the share of Schiphol to all NL

Key: < 1.5% / 1.5% - 2.4% / > 2.4%



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%

- 2.4% / > 2.4%

°C	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%

°C	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

## 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<sub>2</sub> (range 14 - 20 GtCO<sub>2</sub>)
- Cumulative emissions 2020 – 2070:
  - 28 GtCO<sub>2</sub> (range 23 - 34 GtCO<sub>2</sub>)

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<sub>2</sub> (range 9 - 15 GtCO<sub>2</sub>)
- Cumulative emissions 2020 – 2070:
  - 16 GtCO<sub>2</sub> (range 12 - 20 GtCO<sub>2</sub>)

### 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%**)

°C, 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

°C, 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<sub>2</sub> 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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub> 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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub> 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<sub>2</sub>

°C	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<sub>2</sub>

°C	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<sub>2</sub>

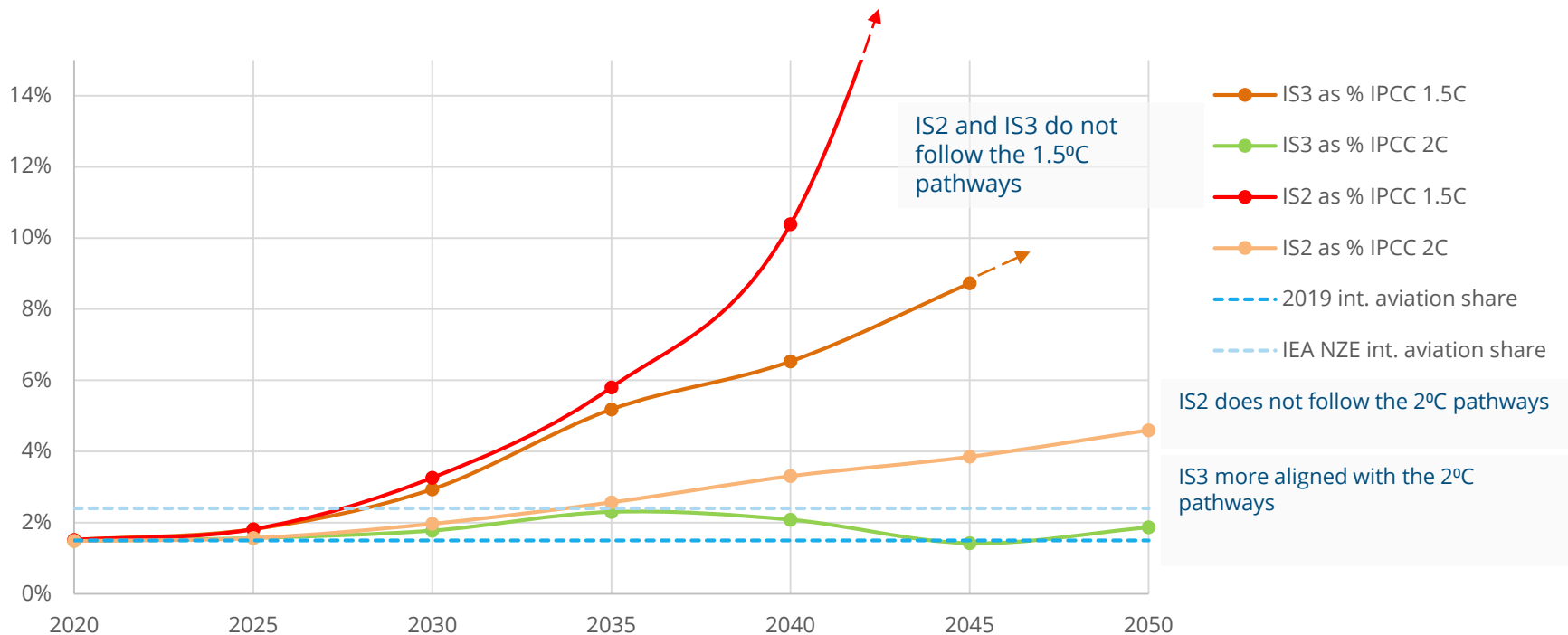
°C	Likelihood		
	50%	66%	83%
1.5	3.0%	3.8%	5.0%
1.7	1.8%	2.1%	2.7%
2	1.1%	1.3%	1.7%

Based on cumulative emissions up to 2070 – 20 GtCO<sub>2</sub>

°C	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%)

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

°C, 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%)

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

°C, 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
<b>Grandfathering</b>	Sovereignty	Allocation of national carbon budgets based on current emissions (shades)
<b>Immediate per capita convergence</b>	Equality	Allocation of national carbon budgets based on equal per capita emissions (shades) on the present day or projected cumulative emissions
<b>Per capita convergence</b>	Sovereignty/equality	Allocation of national carbon budgets based on both current emission shares and population shares (a combination of grandfathering and immediate per capita convergence)
<b>Equal cumulative per capita emissions</b>	Equality/equality	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 (grandfathering)
<b>Ability to pay</b>	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 larger budget
<b>Greenhouse development rights</b>	Responsibility/capability/need	Carbon budget is reduced (compared to the 2015 emissions level) according to the country's historical responsibility and high capacity. Emissions are reduced where this is most cost effective (e.g. marginal abatement cost) as assessed by models of marginal abatement cost curves
<b>Cost-optimal</b>	Cost effectiveness	

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. In the methodology of this work a grandfathering approach is used (2.4%) as well as the IEA NZE scenario (3.9%).

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## 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<sub>2</sub> need to have an allowance (permit) to do so (van der Sar et al., 2023).

Parties can buy allowances from:

A. Other parties, if they 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 (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 emissions, "subsidised" from the budget.

### CORSIA

ICAO's CORSIA is an offsetting scheme, designed to keep CO<sub>2</sub> emissions of international aviation at 80% of the 2015 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 "stave" a reduction in net aviation emissions.

In this study, offsets are not taken into account, as the baseline emissions level (80% of 2015) 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 substantial carbon removal, the associated availability of sufficient renewable energy.

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## C: Methods

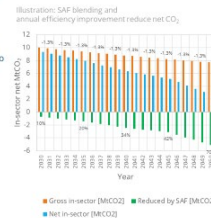
Decarbonisation modelling / Constant factors across scenarios

### Up to 2030

- Fleet renewal (based on operator announcements and NLR research), including limited upgearing due to 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%



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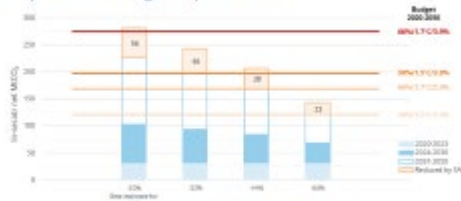
## D: Summarised results for net CO<sub>2</sub> emissions for 2020 - 2030 Compared to carbon budgets for 2020 - 2050, showing remaining budget shares in %



## E: Required CO<sub>2</sub> emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement



## F: Required reduction in net in-sector CO<sub>2</sub> emissions in 2030 for airport carbon budgets depends on SAF



Required change in in-sector airport CO<sub>2</sub> emissions for 2030 (vs. 2019)

Assumptions: emissions scenarios 2020 and 2030 are constant as per all scenarios, 2035 emissions for 2030 and 2040 are as per all scenarios, 2035 SAF from 2020 (ReFuelEU Aviation), 10% in 2030, 1.3% p.a. efficiency improvement 2031 - 2050.

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# A: Approaches to emission shares

Approach	Equity principle	Description
<b>Grandfathering</b>	Sovereignty	Allocations of carbon budgets based on current emission shares
<b>Immediate per capita convergence</b>	Equality	Allocation of national carbon budgets based entirely on population shares (which can be present day or projected cumulative population)
<b>Per capita convergence</b>	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)
<b>Equal cumulative per capita emissions</b>	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)
<b>Ability to pay</b>	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
<b>Greenhouse development rights</b>	Responsibility/capability/need	Carbon budget is reduced (compared to baseline) for countries with high historical responsibility and high capacity
<b>Cost-optimal</b>	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.

## 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<sub>2</sub> 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<sub>2</sub> 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.

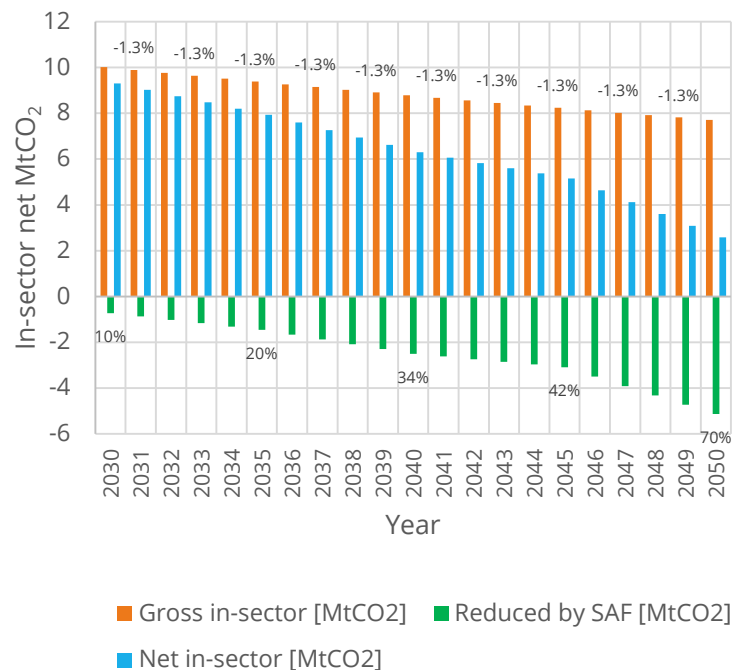
### Up to 2030

- 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

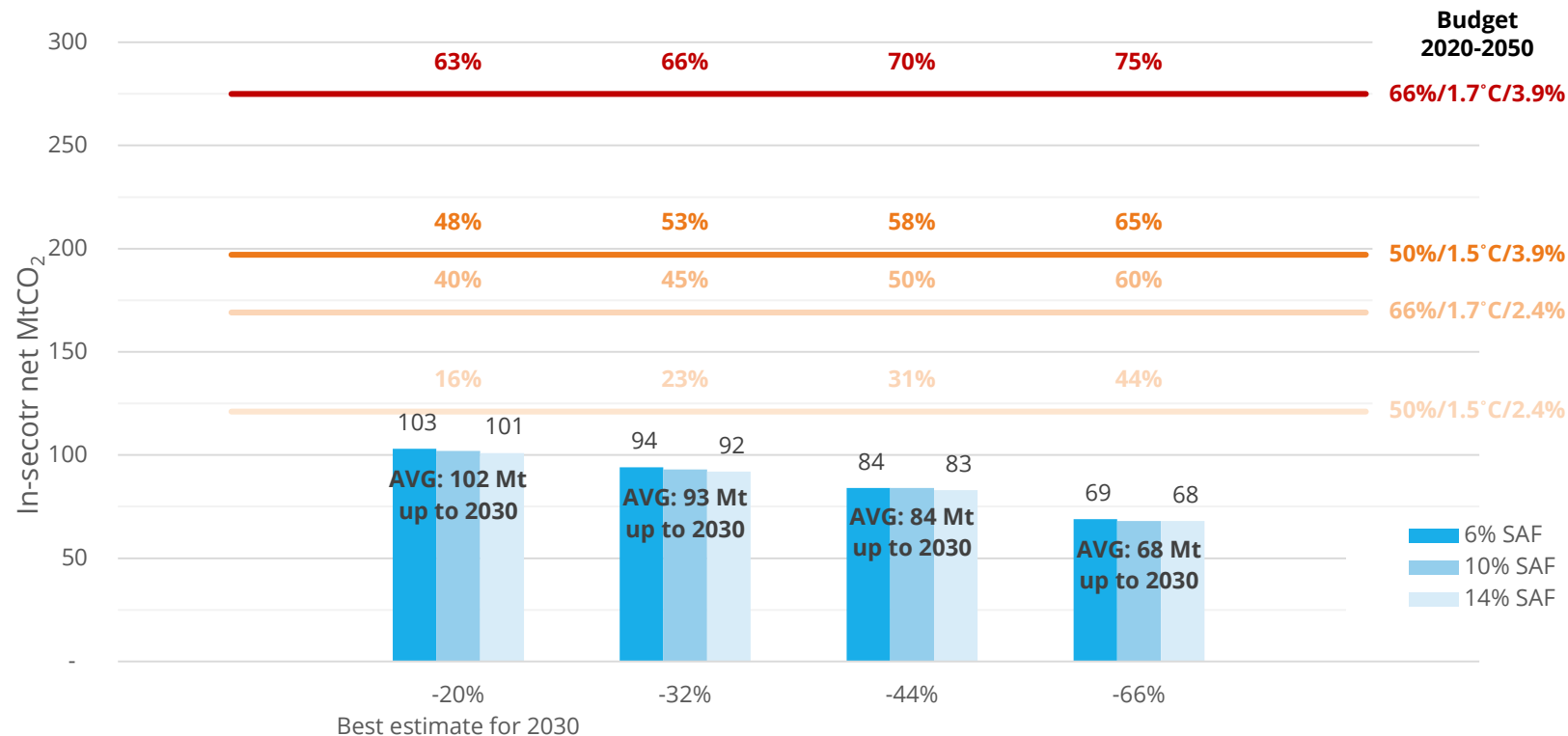
- Annual efficiency improvement of 1.3%
- SAF uptake according to ReFuelEU Aviation
  - 2035: 20%
  - 2040: 34%
  - 2045: 42%
  - 2050: 70%

Illustration: SAF blending and annual efficiency improvement reduce net CO<sub>2</sub>

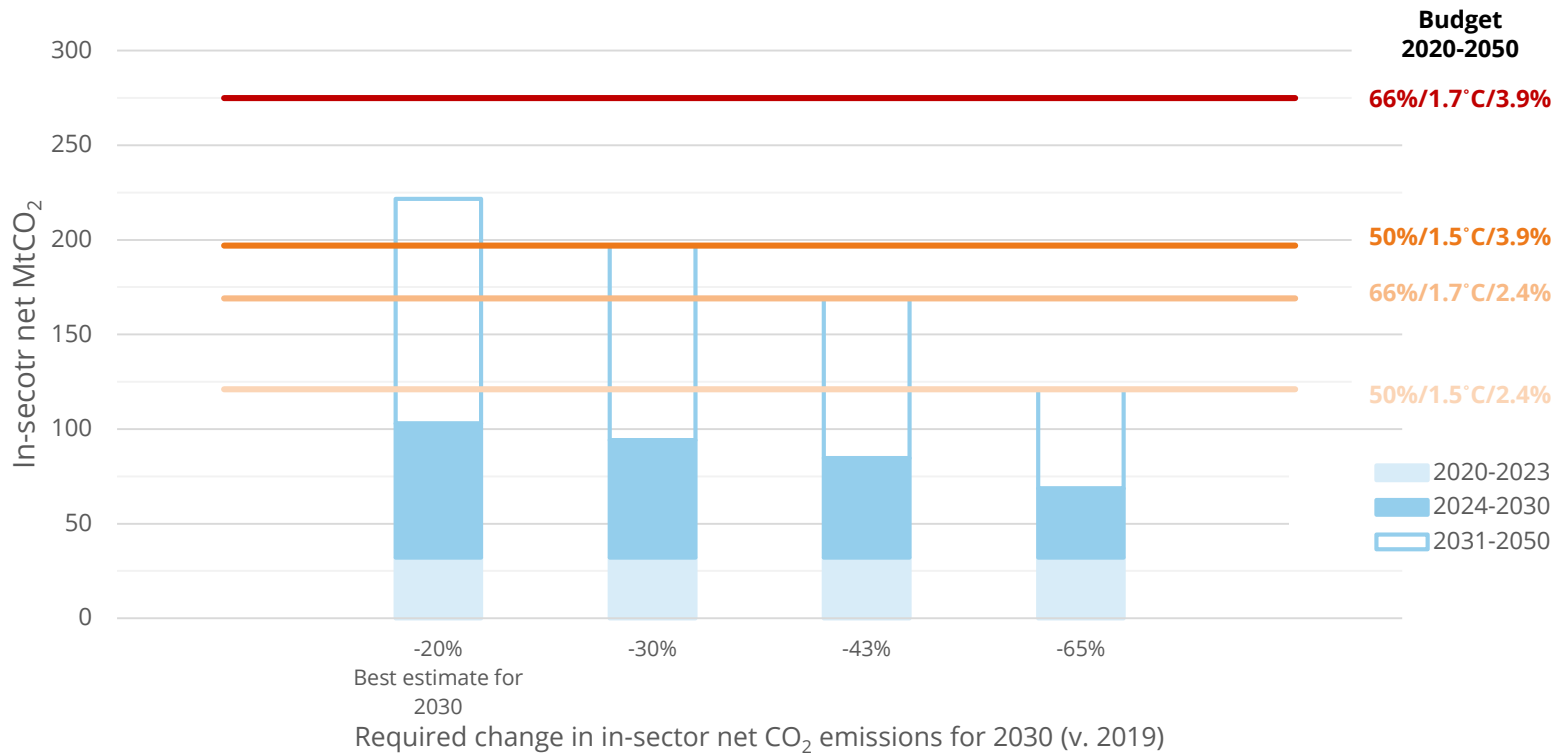


# D: Summarised results for net CO<sub>2</sub> emissions for 2020 – 2030

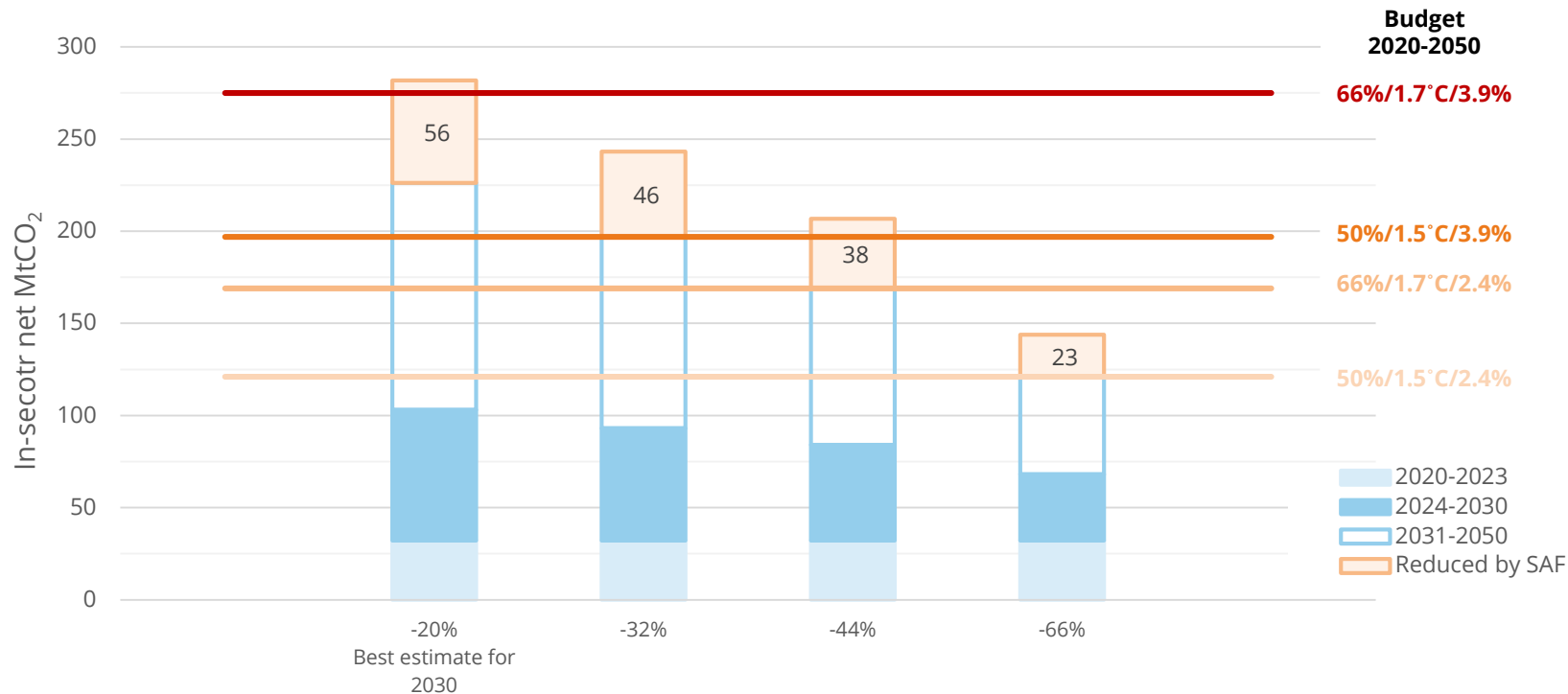
Compared to carbon budgets for 2020 – 2050, showing remaining budget shares in %



# E: Required CO<sub>2</sub> emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement



# F: Required reduction in net in-sector CO<sub>2</sub> emissions in 2030 for airport carbon budgets depends on SAF



Required change in in-sector brutto CO<sub>2</sub> emissions for 2030 (v. 2019)

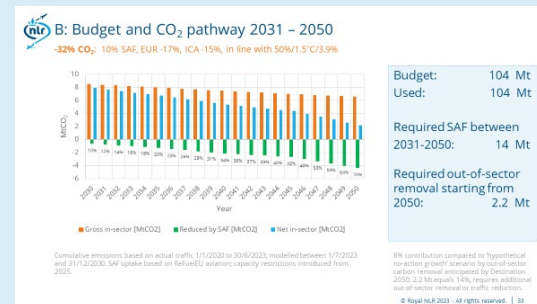
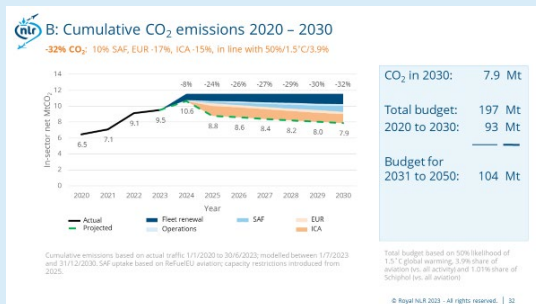
Cumulative emissions between 2020 and 2023 are constant across all scenarios. // Best estimate for 2030: best estimate of pathway for 2020 – 2030; SAF from 2025 (ReFuelEU Aviation, 10% in 2030); 1.3% p.a. efficiency improvement 2031 – 2050.

# IV: Detailed results

CO<sub>2</sub> emissions in the year 2030  
Cumulative CO<sub>2</sub> emissions 2020 – 2030  
Budget and CO<sub>2</sub> pathway 2031 – 2050

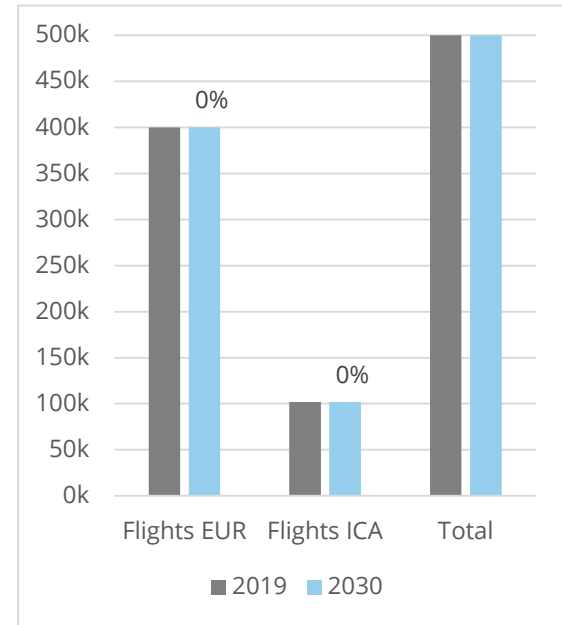
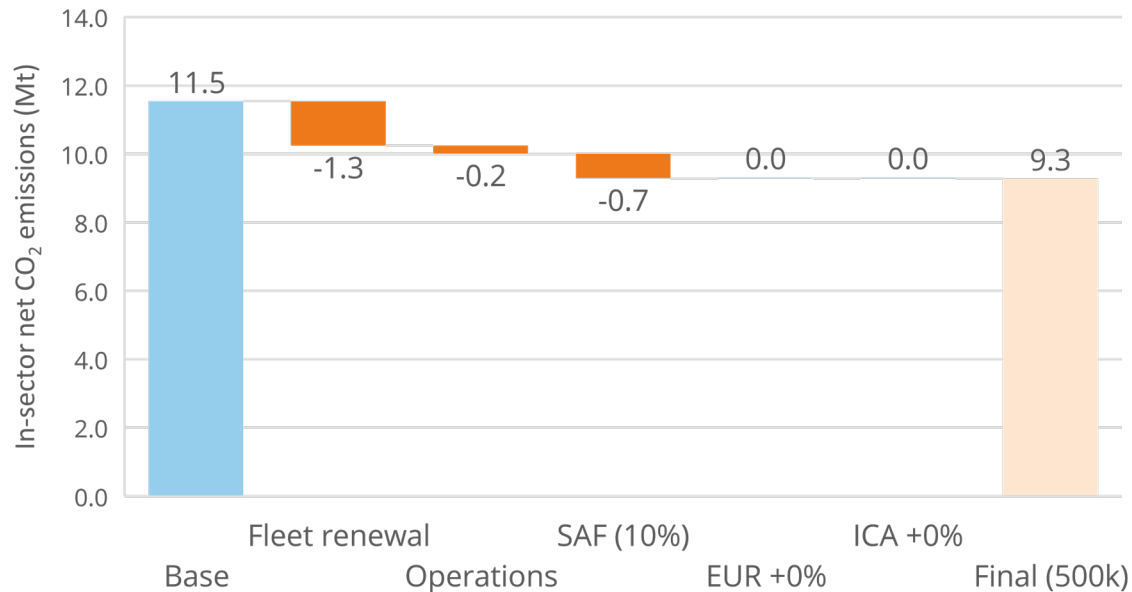
For scenarios:

- A. Best estimate for 2030 compared to 1.5°C/3.9% and 1.7°C/3.9%
- B. -32% CO<sub>2</sub> emissions in 2030 v. 2019; in line with 1.5°C/3.9%
- C. -44% CO<sub>2</sub> emissions in 2030 v. 2019; in line with 1.7°C/2.4%
- D. -66% CO<sub>2</sub> emissions in 2030 v. 2019; in line with 1.5°C/2.4%



# A: CO<sub>2</sub> 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%

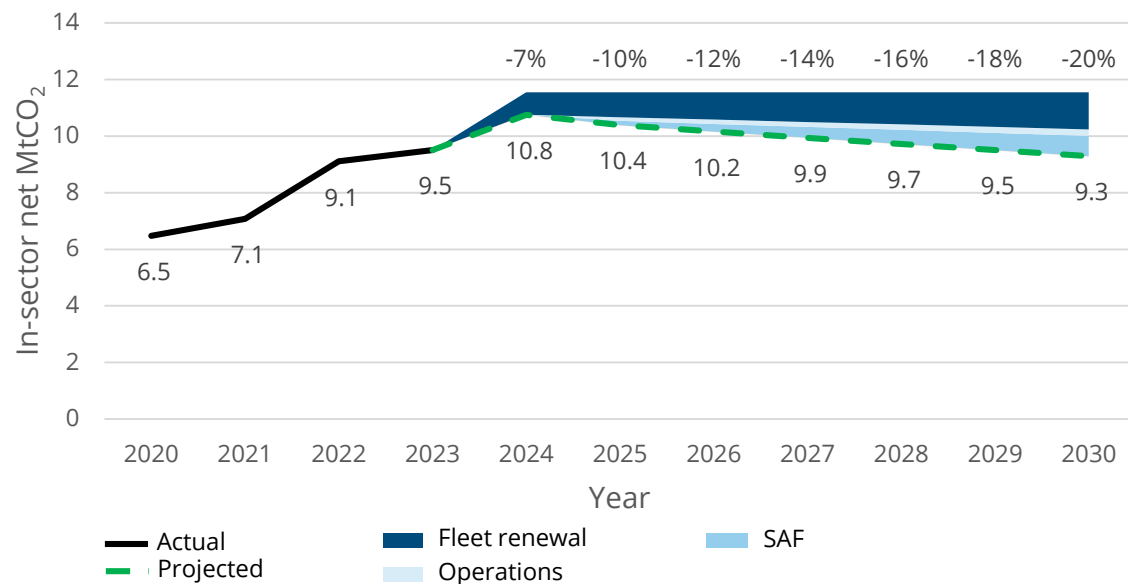


Fleet renewal based on operator announcements and additional NLR research. \ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \ SAF according to ReFuelEU (linear interpolation). \ 2019 network maintained.



# A: Cumulative CO<sub>2</sub> emissions 2020 – 2030

**Best estimate for 2030:** 10% SAF, EUR -0%, ICA -0%, compared to 50%/1.5°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

50%/1.5°C/3.9%: 197 Mt

2020 to 2030: 102 Mt

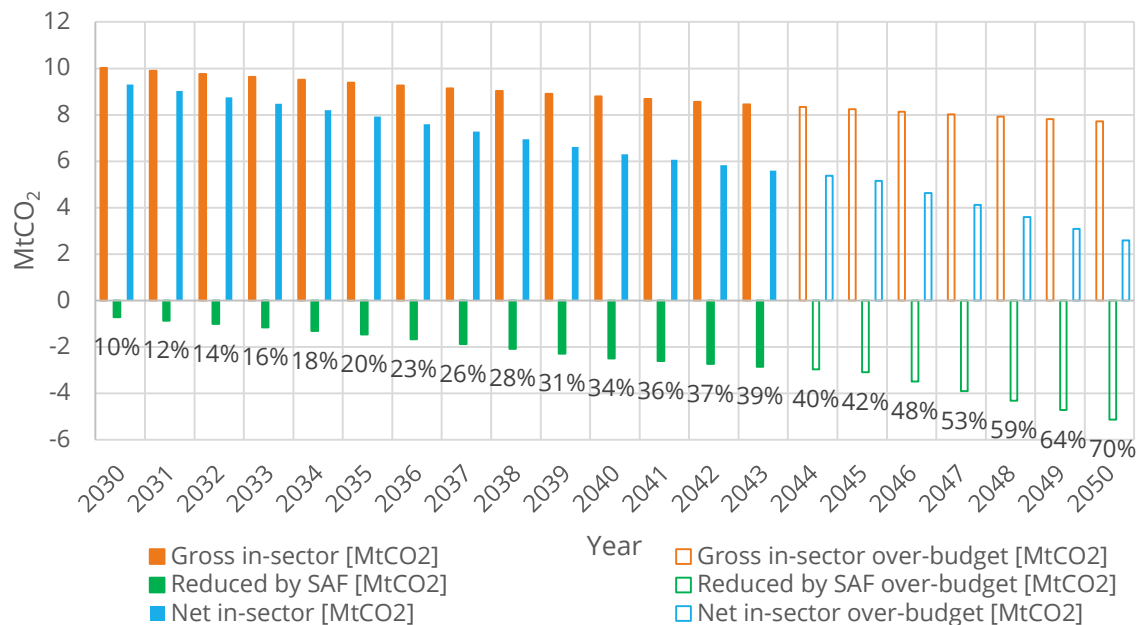
Budget for

2031 to 2050: 95 Mt

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<sub>2</sub> 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

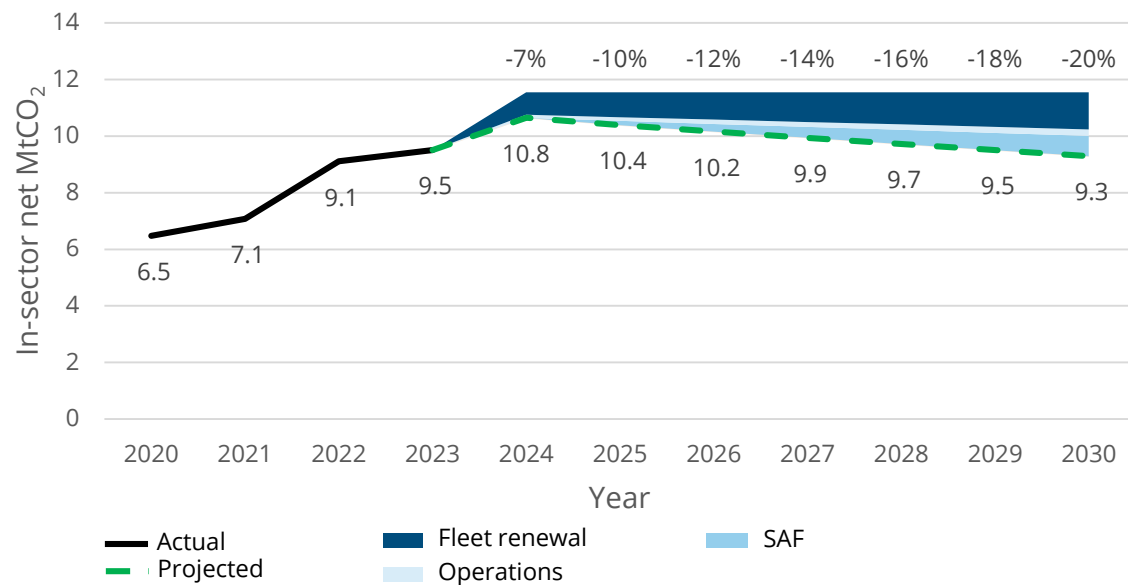
Required out-of-sector  
removal starting from  
2044: 5.4 Mt

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<sub>2</sub> 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

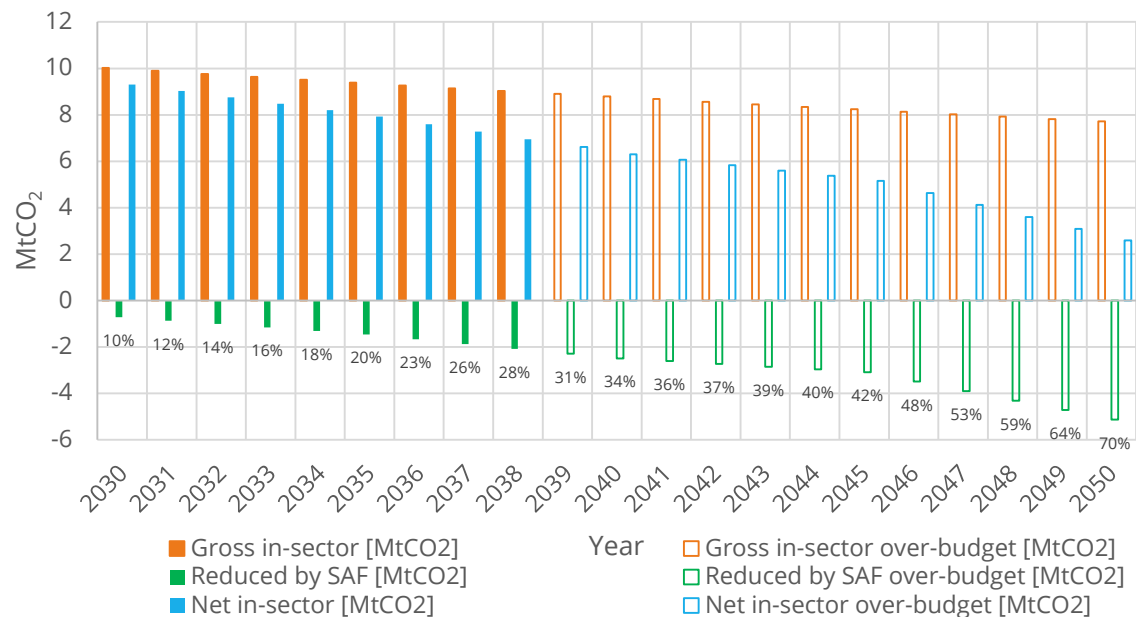
Total budget  
66%/1.7°C/3.9%: 169 Mt  
2020 to 2030: 102 Mt

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<sub>2</sub> 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**

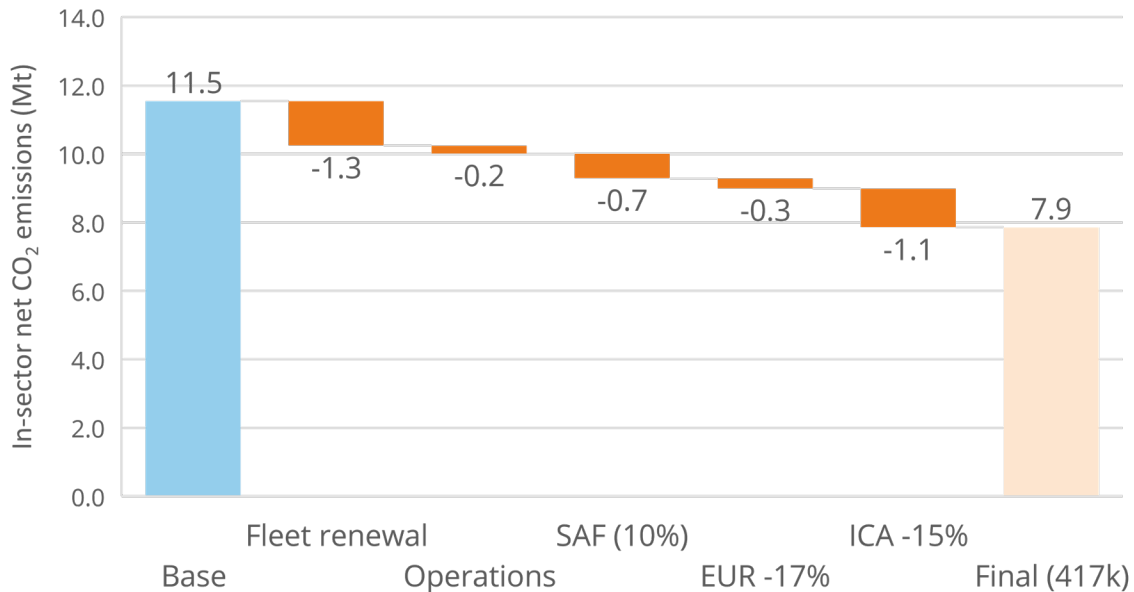
Required SAF between  
2031-2038: 4 Mt

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

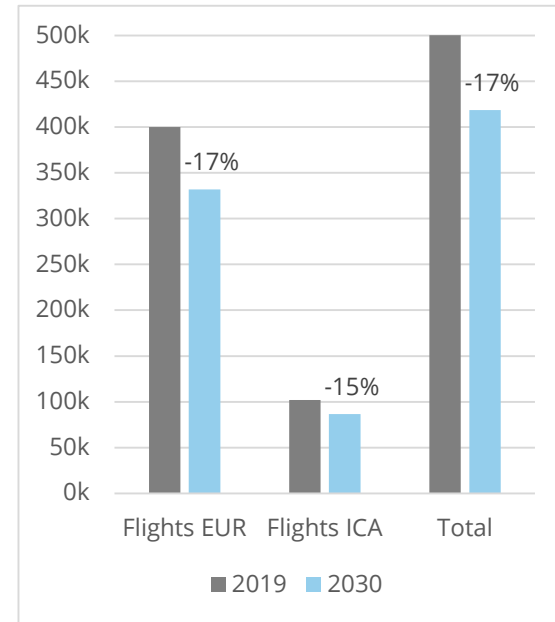
Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

## B: CO<sub>2</sub> emissions in the year 2030

**-32% CO<sub>2</sub>:** 10% SAF, EUR -17%, ICA -15%, in line with 50%/1.5°C/3.9%



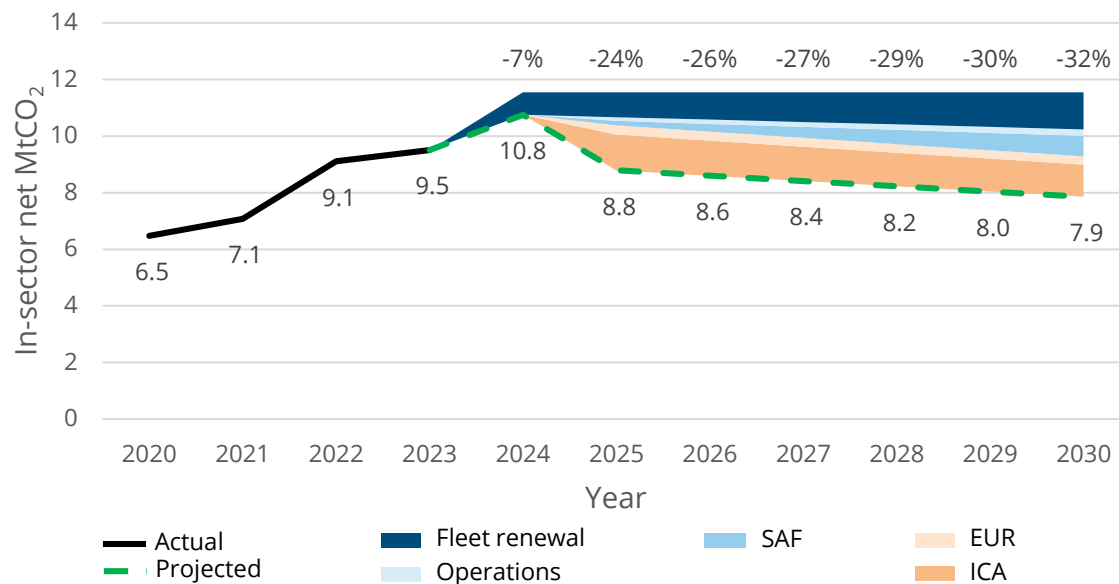
Fleet renewal based on operator announcements and additional NLR research. \ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \ SAF according to ReFuelEU (linear interpolation). \ 2019 network maintained, except for EUR and ICA capacity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



Exemplary traffic scenario resulting in required -32% CO<sub>2</sub> in 2030 (v. 2019)

# B: Cumulative CO<sub>2</sub> emissions 2020 – 2030

-32% CO<sub>2</sub>: 10% SAF, EUR -17%, ICA -15%, in line with 50%/1.5°C/3.9%



CO<sub>2</sub> in 2030: 7.9 Mt

Total budget: 197 Mt

2020 to 2030: 93 Mt

Budget for  
2031 to 2050: 104 Mt

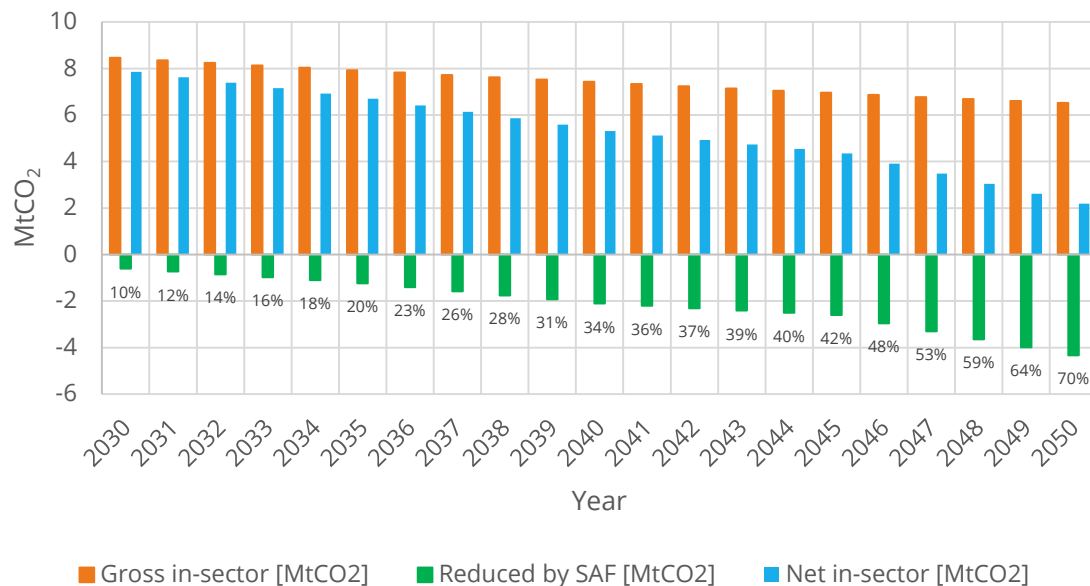
Cumulative emissions based on actual traffic 1/1/2020 to 30/6/2023; modelled between 1/7/2023 and 31/12/2030. SAF uptake based on ReFuelEU aviation; capacity restrictions introduced from 2025.

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<sub>2</sub> pathway 2031 – 2050

**-32% CO<sub>2</sub>:** 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

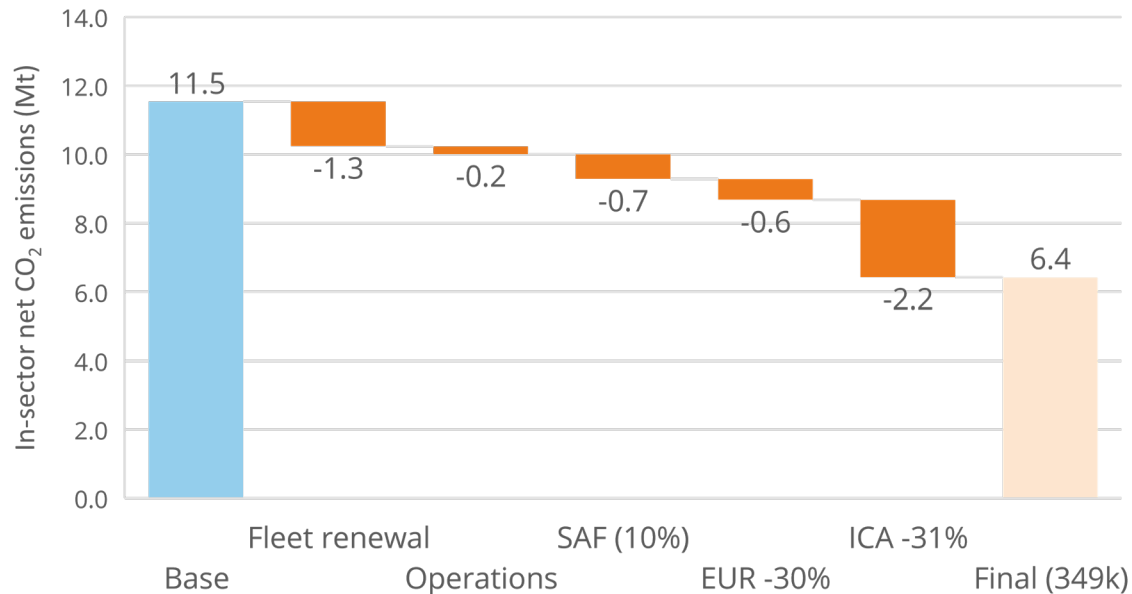
Required out-of-sector  
removal starting from  
2050: 2.2 Mt

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.

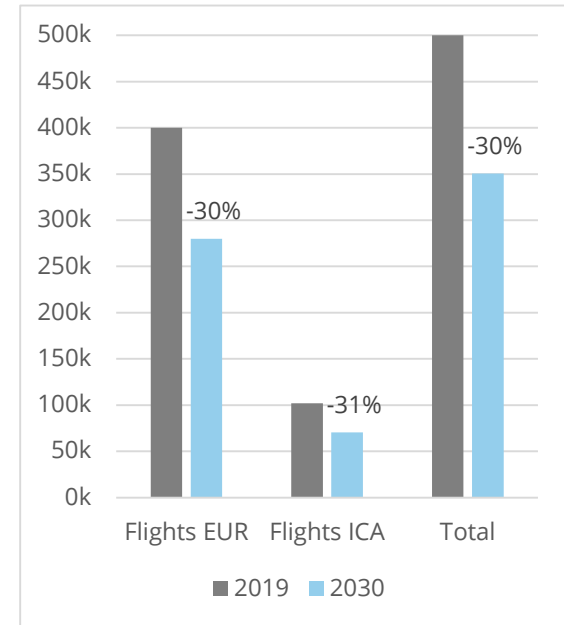
8% contribution compared to 'hypothetical no-action growth' scenario by out-of-sector carbon removal anticipated by Destination 2050. 2.2 Mt equals 14%, requires additional out-of-sector removal or traffic reduction.

# C: CO<sub>2</sub> emissions in the year 2030

**-44% CO<sub>2</sub>:** 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.

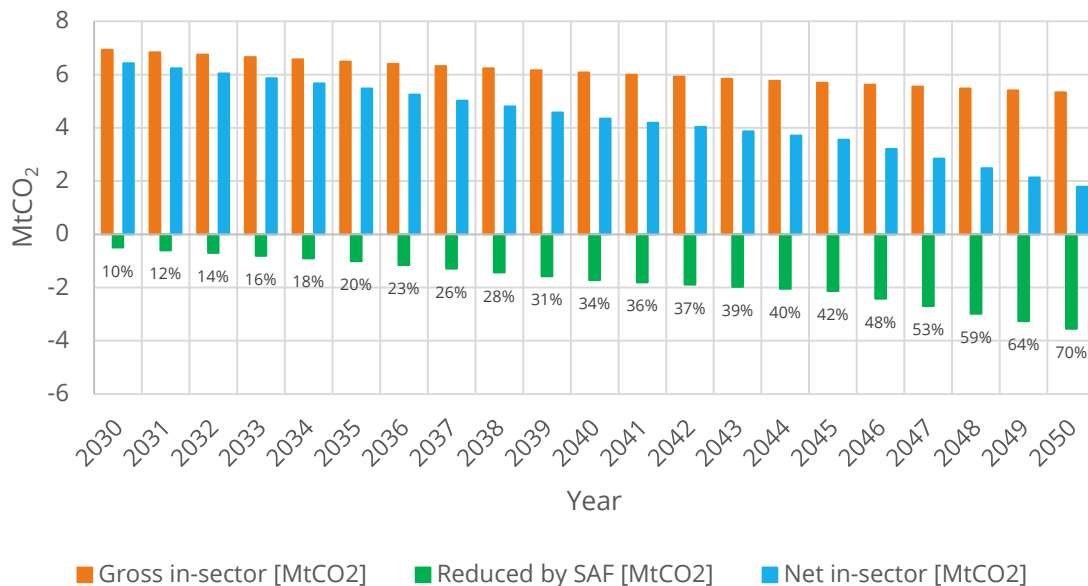


Exemplary traffic scenario resulting in required -44% CO<sub>2</sub> in 2030 (v. 2019)



# C: Budget and CO<sub>2</sub> pathway 2031 – 2050

-44% CO<sub>2</sub>: 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

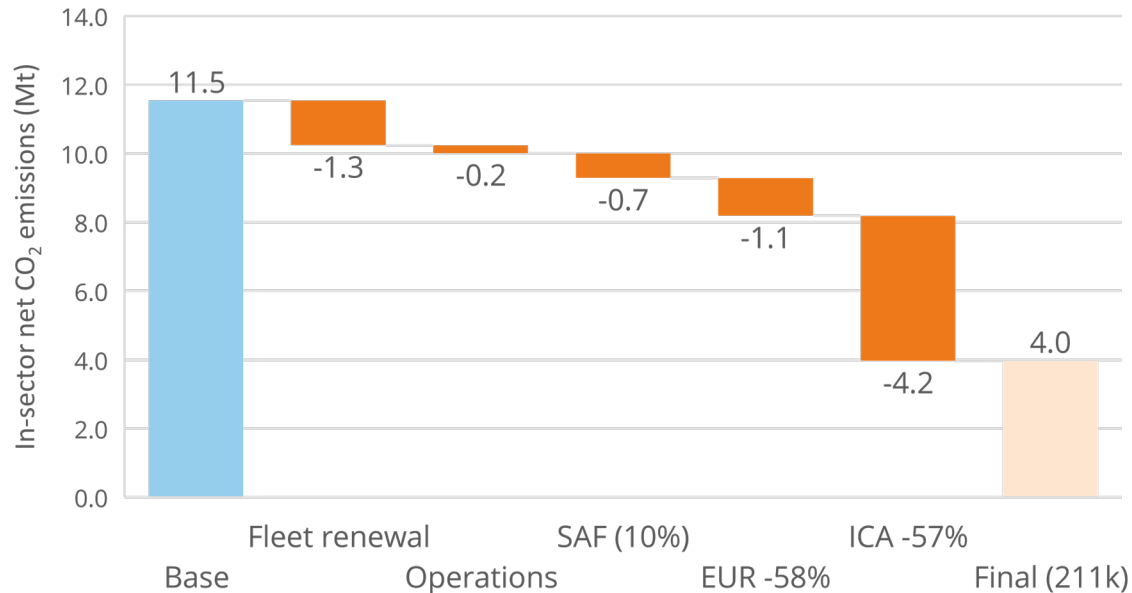
Required out-of-sector  
removal starting from  
2050: 1.8 Mt

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.

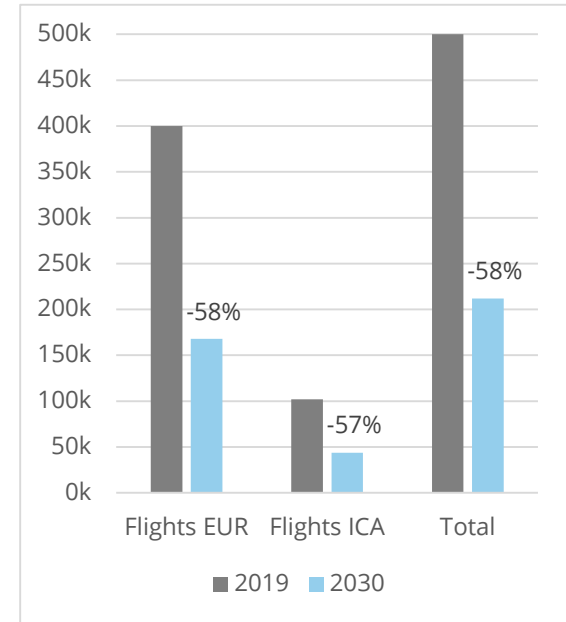
8% contribution compared to 'hypothetical no-action growth' scenario by out-of-sector carbon removal anticipated by Destination 2050. 1.8 Mt equals 11%, requires additional out-of-sector removal or traffic reduction.

# D: CO<sub>2</sub> emissions in the year 2030

**-66% CO<sub>2</sub>:** 10% SAF, EUR -58%, ICA -57%, in line with 50%/1.5°C/2.4%



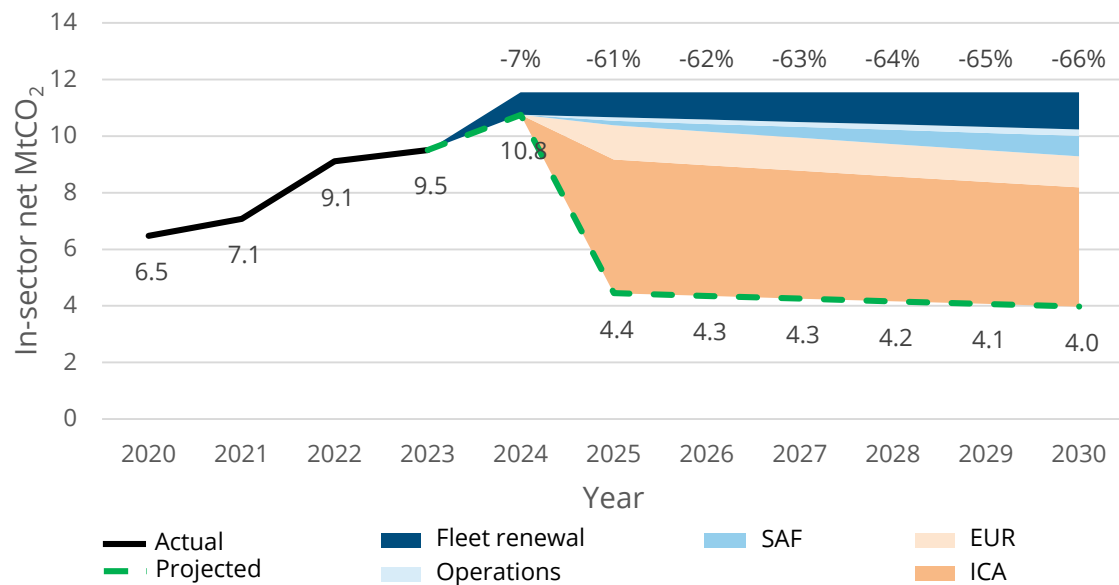
Fleet renewal based on operator announcements and additional NLR research. \ Operational improvements include improved ATM efficiency, increased CDA application and (some) alternative taxiing. \ SAF according to ReFuelEU (linear interpolation). \ 2019 network maintained, except for EUR and ICA capacity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



Exemplary traffic scenario resulting in required -66% CO<sub>2</sub> in 2030 (v. 2019)

# D: Cumulative CO<sub>2</sub> emissions 2020 – 2030

-66% CO<sub>2</sub>: 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

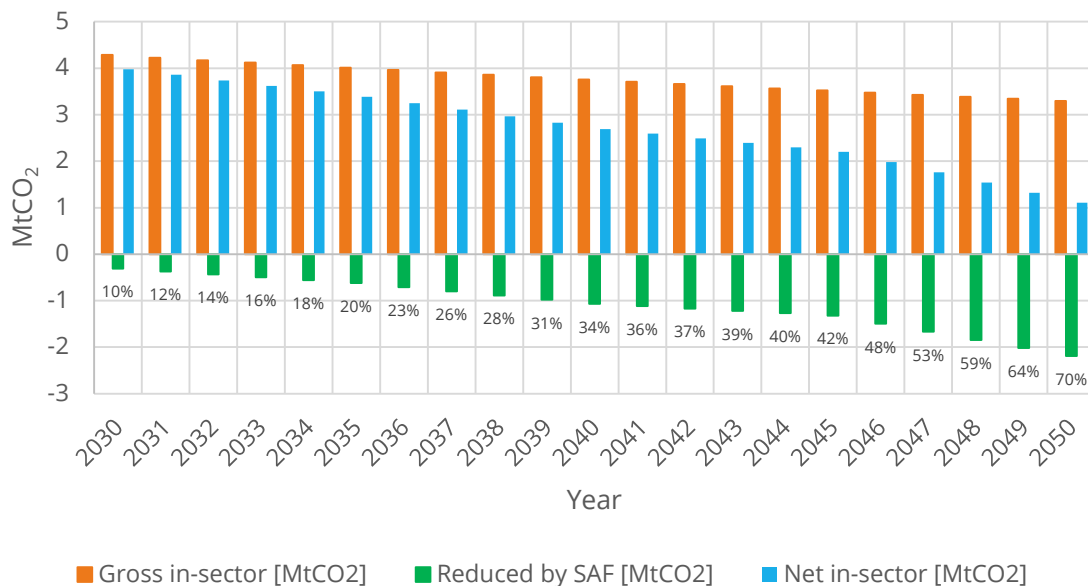
budget for  
2031 to 2050: 53 Mt

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<sub>2</sub> pathway 2031 – 2050

**-66% CO<sub>2</sub>:** 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.

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