CO₂ reduction targets for Amsterdam Airport Schiphol based on remaining IPCC CO₂ 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

- Duurzame Luchtvaarttafel: -9% v. 2019
- current measures: -20% v. 2019

-32% up to -66% v. 2019
required CO$_2$ reduction

- Current measures:
  - Fleet renewal
  - Operational improvements
  - SAF (up to 10%)

- Additional measures:
  - Significant demand management measures from 2025
    - Potentially by reduction of long-distance, high emission flights from 2025

Net-zero with carbon removals

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

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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In 2015, the world committed to limit global warming through the Paris Agreement. Since this commitment, the IPCC has stressed the relevance of cumulative emissions and has determined global CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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.

<table>
<thead>
<tr>
<th>°C</th>
<th>50%</th>
<th>66%</th>
<th>83%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>500 Gt</td>
<td>400 Gt</td>
<td>300 Gt</td>
</tr>
<tr>
<td>1.7</td>
<td>850 Gt</td>
<td>700 Gt</td>
<td>550 Gt</td>
</tr>
<tr>
<td>2</td>
<td>1350 Gt</td>
<td>1150 Gt</td>
<td>900 Gt</td>
</tr>
</tbody>
</table>

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\textsubscript{2} budgets, CO\textsubscript{2} budgets for aviation in general and CO\textsubscript{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\%.
In-sector emissions between 2020 and 2050 are calculated, modelled and estimated based on suitable data and methods.

<table>
<thead>
<tr>
<th>Year</th>
<th>Calculated</th>
<th>Modelled</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>from fuel bunkers</td>
<td>based on planned fleet renewal, including upgauging depending on plans, operational improvements, SAF usage</td>
<td>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)</td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2040</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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 CO₂ 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 CO₂ emissions but overshoots majority of airport carbon budgets

1. Maintaining emissions at 2019 level (11.5 MtCO₂) overshoots all budgets.
2. Best-estimate for 2030 CO₂ 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% CO₂ reduction with respect to 2019: recovery to 2019 CO₂ (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% CO₂ in 2030 v. 2019).
CO₂ 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 CO₂ emissions in 2030 is the key determinant for cumulative emissions over the 2020 – 2050 period

<table>
<thead>
<tr>
<th>In-sector net MtCO₂</th>
<th>Budget 2020-2050</th>
<th>Cumulative emissions 2031 to 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>66% / 1.7°C / 3.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% / 1.5°C / 3.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>66% / 1.7°C / 2.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% / 1.5°C / 2.4%</td>
</tr>
</tbody>
</table>

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 $\times$ from 2035 onwards

<table>
<thead>
<tr>
<th>Year</th>
<th>Base estimate</th>
<th>Alternative estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2035</td>
<td>20%</td>
<td>24%</td>
</tr>
<tr>
<td>2040</td>
<td>34%</td>
<td>41%</td>
</tr>
<tr>
<td>2045</td>
<td>42%</td>
<td>50%</td>
</tr>
<tr>
<td>2050</td>
<td>70%</td>
<td>84%</td>
</tr>
</tbody>
</table>

**Higher quality SAF**

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Base estimate</th>
<th>Alternative estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>72%</td>
<td>86%</td>
</tr>
<tr>
<td>2050</td>
<td>95%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Result**

- Base estimate: 123 MtCO$_2$
- Alternative estimate: 119 MtCO$_2$
- $\text{Result} = 2\%$

**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")

<table>
<thead>
<tr>
<th>Year</th>
<th>Base estimate</th>
<th>Alternative estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>1.3% p.a.</td>
<td>1.7% p.a.</td>
</tr>
<tr>
<td>2050</td>
<td>1.7% p.a.</td>
<td></td>
</tr>
</tbody>
</table>

**Result**

- Base estimate: 123 MtCO$_2$
- Alternative estimate: 119 MtCO$_2$
- $\text{Result} = 3\%$

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 CO₂ 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 CO₂
As such: demand management measures in ICA prevent more CO₂ emissions than measures in EUR

About 15% longest distance flights (> 5000 km) contribute some 75% of CO₂
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**

- **2019**
  - 500k
  - 458k
  - 489k

- **-32% CO₂**
  - 1.5°C/3.9%
  - 417k
  - 6% 0%
  - -15% -18% 11%

- **-44% CO₂**
  - 1.7°C/2.4%
  - 349k
  - 12% 0%
  - -31% -36% -23%

- **-66% CO₂**
  - 1.5°C/2.4%
  - 211k
  - 24%
  - -57% -66% -53%

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 CO₂ leakage to other areas. Capacity reductions modelled from 2025 onwards.

**Flight distance restrictions**

- -11%
- -5%
- -3%

CO₂ 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, CO₂ 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 $\text{CO}_2$ emissions required additional out-of-sector carbon removal.

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.

Non-linear behaviour caused by non-linearly increasing ReFuelEU Aviation SAF blending mandate (2040: 34% // 2040: 42% // 2050: 70%).
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.
- CO₂ can be removed out-of-sector for which 9.97 PJ/MtCO₂ 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).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SAF in 2050</th>
<th>Carbon removal in 2050</th>
<th>Total primary energy required in 2050</th>
<th>Total energy share of aviation of primary energy supply in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% 1.5°C</td>
<td>0.7 Mt</td>
<td>1.1 Mt</td>
<td>72 PJ</td>
<td>2.7% (~36% v. 2015)</td>
</tr>
<tr>
<td>2.4%</td>
<td>61 PJ</td>
<td>11 PJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50% 1.5°C</td>
<td>1.4 Mt</td>
<td>2.2 Mt</td>
<td>142 PJ</td>
<td>5.2% (+24% v. 2015)</td>
</tr>
<tr>
<td>3.9%</td>
<td>120 PJ</td>
<td>22 PJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>66% 1.7°C</td>
<td>1.1 Mt</td>
<td>1.8 Mt</td>
<td>116 PJ</td>
<td>4.3% (+2% v. 2015)</td>
</tr>
<tr>
<td>2.4%</td>
<td>98 PJ</td>
<td>18 PJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>66% 1.7°C</td>
<td>1.6 Mt</td>
<td>2.5 Mt</td>
<td>167 PJ</td>
<td>6.0% (+43% v. 2015)</td>
</tr>
<tr>
<td>3.9%</td>
<td>142 PJ</td>
<td>25 PJ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 CO₂ reductions and less flights in 2030

<table>
<thead>
<tr>
<th>Warming</th>
<th>Budget share for aviation</th>
<th>Required CO₂ reduction in 2030</th>
<th>Indicative number of annual flights compatible with required CO₂ reduction (2025-2050)</th>
<th>Distance limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% likelihood of 1.5°C (500 Gt)</td>
<td>2.4%</td>
<td>-66% v. 2019 -62% v. 2005</td>
<td>210k</td>
<td>450k (6450 km)</td>
</tr>
<tr>
<td></td>
<td>3.9%</td>
<td>-32% v. 2019 -25% v. 2005</td>
<td>420k</td>
<td>490k (9300 km)</td>
</tr>
<tr>
<td>66% likelihood of 1.7°C (700 Gt)</td>
<td>2.4%</td>
<td>-44% v. 2019 -39% v. 2005</td>
<td>350k</td>
<td>480k (8850 km)</td>
</tr>
<tr>
<td></td>
<td>3.9%</td>
<td>Not required</td>
<td>500k</td>
<td></td>
</tr>
</tbody>
</table>

No flight distance restriction
In determining the CO₂ budgets, IPCC (2022) has taken into account non-CO₂ emissions, such as methane emissions from the agricultural sector. These non-CO₂ emissions impact the CO₂ budget (Annex I.A).

It is unclear if aviation-specific non-CO₂ climate effects (NOₓ interactions with methane and ozone, persistent contrails and cirrus, ...) are also explicitly taken into account by IPCC.

If non-CO₂ climate effects of aviation are accounted for, the current study is rightfully limited to CO₂ emissions only. To align to IPCC modelling and assumptions, it is in this case required to reduce non-CO₂ climate effects of aviation in line with CO₂ emissions. This requires additional and dedicated measures.

If non-CO₂ 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-CO₂ climate effects will then appear ‘on both sides of the equation’, the conclusions presented here remain valid.
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   D. -66% CO₂ 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
are defined as the remaining amount of CO₂ emissions that can be
eroded if the target temperature increase due to human
activities to be below a certain temperature
limit (spccip, 2018). The interest
in CO₂ budgets is not only scientifically
relevant, but also policy-relevant. CO₂
budgets can be used as a concept that allows
to set transition scenarios for emissions reductions, for instance, respecting
emissions and probabilities for remaining
within temperature targets.

The budgets are presented in IPCC 2020.

B: Aviation growth, CO₂ intensity and cumulative CO₂ emissions

Global air traffic and aviation-related GHG emissions have been rising in line with passenger growth for the last 60 years, consistently tracking growth in air travel demand.

Aviation growth has boosted 7
to 8% per annum in recent decades (IATA).

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 setting a target, all science-based targets must be aligned with the Paris Agreement (spccip, 2018).

The aviation sector guidelines for setting targets following the SBTi targets are that 75% of all SBTi companies per default strive for 1.5°C alignment, for instance, setting a target to reach net zero emissions by 2050. This implies a reduction of 75% emissions by 2050 compared to 2019.

The SBTi methodology is based on the idea of growth rate differentials across sectors, which are used to estimate sectoral emissions reductions.

The SBTi methodology is based on the idea of growth rate differentials across sectors, which are used to estimate sectoral emissions reductions.

According to the methodology, emissions reductions are calculated using the SBTi methodology, which is applied to the aviation sector. The methodology takes into account the historical growth rate of aviation and the projected growth rate in the future.

The SBTi methodology is based on the idea of growth rate differentials across sectors, which are used to estimate sectoral emissions reductions.
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.
A: IPCC global carbon budgets

As shown in the figure by IPCC (2022) on the previous page, anticipated reductions in non-CO₂ emissions (such as methane emissions from the agricultural sector) are taken into account in determining the CO₂-budgets. As indicated by IPCC, “higher or lower reductions in accompanying non-CO₂ emissions can increase or decrease the values on the left [the CO₂-budgets].”

The figure on the right (based on Rogelj et al., 2019, Fig. 1) illustrates in a simplified manner how an ‘allowed’ amount of CO₂ emissions is determined from an amount of remaining warming. Relevant to note is the ‘split’ of the total emissions or impacts over contributions by CO₂ and non-CO₂. As the IPCC (2022, Table SPM.2) explicitly notes, higher or lower reductions in non-CO₂ emissions also impact the remaining CO₂ 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 CO₂ budget for limiting warming to 1.5⁰C 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 1.7⁰C 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 CO₂ 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 CO₂ emissions by 2030 based on the reduced budget for limiting warming to 1.5⁰C 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, CO₂ intensity and cumulative CO₂ emissions

Activity growth in revenue passenger kilometre (RPK)

Between 1970 and 2019, revenue passenger kilometres (RPKs) have grown by a factor 20. CO₂ intensity per revenue passenger kilometre has, however, decreased by a factor 11 since 1960.
B: Aviation growth, CO₂ intensity and cumulative CO₂ emissions

CO₂ intensity in CO₂ 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

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.
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 gCO₂/RTK today, to some 350 gCO₂/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 GtCO₂] are lower than those of the IEA NZE scenario [20.5 GtCO₂], 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.

<table>
<thead>
<tr>
<th>Topic</th>
<th>IEA Net-Zero Emissions Scenario</th>
<th>ICCT Breakthrough Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model time frame</td>
<td>Up to 2050</td>
<td>Up to 2050</td>
</tr>
<tr>
<td>Cumulative emissions from aviation, 2019-2050 time period (Tank to Wake basis)</td>
<td>20.5 Gt CO₂</td>
<td>19.6 Gt CO₂</td>
</tr>
<tr>
<td>Assumed annual activity growth, revenue passenger kilometers (RPK) (2019-2050)</td>
<td>2.5%</td>
<td>2.9%</td>
</tr>
<tr>
<td>Assumed annual efficiency improvement (2019-2050)</td>
<td>1.7%</td>
<td>2%</td>
</tr>
<tr>
<td>Alternative fuel share by 2050 (SAF + hydrogen)</td>
<td>70%</td>
<td>100%</td>
</tr>
</tbody>
</table>

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 gCO₂/RTK (N.B.: per revenue tonne kilometer; -98% versus current CO₂ intensity). By 2050, global sector emissions should be reduced to about 100 MtCO₂.

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 CO₂ 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.
II: Carbon budgets and comparison to aviation decarbonisation pathways

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

B. Dutch aviation: Carbon budgets for aviation in the Netherlands and Schiphol
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 GtCO₂ (range 14 - 20 GtCO₂)
- Cumulative emissions 2020 – 2070:
  - 28 GtCO₂ (range 23 - 34 GtCO₂)

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 GtCO₂ (range 9 - 15 GtCO₂)
- Cumulative emissions 2020 – 2070:
  - 16 GtCO₂ (range 12 - 20 GtCO₂)

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%)

### Comparison of ICAO decarbonisation pathways to carbon budgets

<table>
<thead>
<tr>
<th>°C, 1.5% share</th>
<th>Likelihood</th>
<th>50%</th>
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<tbody>
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<td>1.7</td>
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<td>19.9 Gt</td>
<td>16.9 Gt</td>
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<table>
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<td>32.3 Gt</td>
<td>27.5 Gt</td>
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</table>
### A: Comparison of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO₂ 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 GtCO₂

<table>
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<td>4.7%</td>
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<tr>
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<td>1.0%</td>
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<td>1.6%</td>
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</table>

#### Integrated scenario 3
Based on cumulative emissions up to 2050 – 9 GtCO₂

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<td>1.8%</td>
<td>2.3%</td>
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<td>0.8%</td>
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</table>

**Based on cumulative emissions up to 2070 – 23 GtCO₂**

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</table>

**Based on cumulative emissions up to 2070 – 12 GtCO₂**

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<td>3.0%</td>
<td>4.0%</td>
</tr>
<tr>
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<td>1.4%</td>
<td>1.7%</td>
<td>2.2%</td>
</tr>
<tr>
<td>2</td>
<td>0.9%</td>
<td>1.0%</td>
<td>1.3%</td>
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</tbody>
</table>
A: Comparison of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO₂ 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 GtCO₂

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<td>1.9%</td>
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---

### Integrated scenario 3
Based on cumulative emissions up to 2050 – 12 GtCO₂

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<th>50%</th>
<th>66%</th>
<th>83%</th>
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</thead>
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<td>1.7%</td>
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<tr>
<td>2</td>
<td>0.9%</td>
<td>1.0%</td>
<td>1.3%</td>
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</table>

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### Based on cumulative emissions up to 2070 – 28 GtCO₂

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### Based on cumulative emissions up to 2070 – 16 GtCO₂

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<td>2.9%</td>
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<td>2</td>
<td>1.2%</td>
<td>1.4%</td>
<td>1.8%</td>
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</table>
### Integration of ICAO decarbonisation pathways to carbon budgets

International aviation share resulting from cumulative CO₂ emissions of LTAG scenarios with a high traffic forecast

Global aviation share (2.4% and 3.9%) × 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 GtCO₂

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<tr>
<td>2</td>
<td>1.5%</td>
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<td>2.2%</td>
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#### Integrated scenario 3
Based on cumulative emissions up to 2050 – 15 GtCO₂

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<td>5.0%</td>
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#### Integrated scenario 2 (2070 – 34 GtCO₂)

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<td>8.5%</td>
<td>11.3%</td>
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#### Integrated scenario 3 (2070 – 20 GtCO₂)

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<td>5.0%</td>
<td>6.7%</td>
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<tr>
<td>1.7</td>
<td>2.4%</td>
<td>2.9%</td>
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</tr>
<tr>
<td>2</td>
<td>1.5%</td>
<td>1.7%</td>
<td>2.2%</td>
</tr>
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</table>
A: Comparison of ICAO decarbonisation pathways to carbon budgets

Comparison over time for mid traffic forecast

- **IS3 as % IPCC 1.5C**
- **IS3 as % IPCC 2C**
- **IS2 as % IPCC 1.5C**
- **IS2 as % IPCC 2C**
- **2019 int. aviation share**
- **IEA NZE int. aviation share**

**Graph Analysis:**
- **IS2 and IS3 do not follow the 1.5°C pathways**
- **IS3 more aligned with the 2°C pathways**
- **IS2 does not follow the 2°C pathways**
**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%)

<table>
<thead>
<tr>
<th>°C, 0.252% share</th>
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<tr>
<td>1.5</td>
<td>126 Mt</td>
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<td>1.7</td>
<td>176 Mt</td>
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<table>
<thead>
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<th>°C, 0.410% share</th>
<th>Likelihood</th>
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<td>205 Mt</td>
</tr>
<tr>
<td>1.7</td>
<td>287 Mt</td>
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</table>

**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%)

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<td>1.7</td>
<td>169 Mt</td>
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<td>197 Mt</td>
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<tr>
<td>1.7</td>
<td>275 Mt</td>
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III: Supplementary methods and results

A: Approaches to emission shares

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<th>Method</th>
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<td>Base scenario with no changes to emissions</td>
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<tr>
<td>情景 1</td>
<td>Reduced demand</td>
<td>Reduced demand for aviation due to economic downturn</td>
</tr>
<tr>
<td>情景 2</td>
<td>Technological improvements</td>
<td>Incorporates technological advancements in aircraft design and engine efficiency</td>
</tr>
</tbody>
</table>

Carbon budget for aviation can be derived via various approaches, each addressing different aspects of environmental impact. The baseline scenario assumes no change in emissions, while the scenario 1 includes reduced demand due to economic downturn, and scenario 2 incorporates technological improvements in aircraft design and engine efficiency.

B: Relevance of economic measures and accounting principles

EU ETS
- The EU ETS is a cap-and-trade system that limits CO2 emitted by various sectors, including aviation.
- Parties can buy allowances from others, making it a competitive market.
- This ensures that costs of emissions are reflected in the market.
- The carbon footprint of aviation is significantly reduced through the EU ETS.

EPA
- The EPA sets emissions standards for various industries, including aviation.
- These standards ensure that aviation industries comply with environmental regulations.
- The EPA monitors emissions and enforces penalties for non-compliance.

C: Methods

Decarbonization modeling and constant factors across scenarios

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<th>Scenario 2</th>
<th>Scenario 3</th>
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<tbody>
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<td>5%</td>
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<td>2025-2030</td>
<td>6%</td>
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D: Summarized results for net CO2 emissions for 2020–2030

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

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<th>Share of Remaining Budget</th>
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<td>90%</td>
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<tr>
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<td>80%</td>
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<td>70%</td>
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<td>2023</td>
<td>60%</td>
</tr>
<tr>
<td>2024</td>
<td>50%</td>
</tr>
<tr>
<td>2025</td>
<td>40%</td>
</tr>
<tr>
<td>2026</td>
<td>30%</td>
</tr>
<tr>
<td>2027</td>
<td>20%</td>
</tr>
<tr>
<td>2028</td>
<td>10%</td>
</tr>
</tbody>
</table>

E: Required CO2 emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Required Reductions by 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic Flights</td>
<td>80%</td>
</tr>
<tr>
<td>International Flights</td>
<td>70%</td>
</tr>
<tr>
<td>Business Flights</td>
<td>60%</td>
</tr>
<tr>
<td>Private Flights</td>
<td>50%</td>
</tr>
</tbody>
</table>

F: Required reduction in net-in-sector CO2 emissions in 2030 for airport carbon budgets depends on SAF

<table>
<thead>
<tr>
<th>SAF Type</th>
<th>Required Reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet fuel</td>
<td>80%</td>
</tr>
<tr>
<td>Biofuel</td>
<td>70%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>60%</td>
</tr>
<tr>
<td>Electric</td>
<td>50%</td>
</tr>
</tbody>
</table>

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A: Approaches to emission shares

<table>
<thead>
<tr>
<th>Approach</th>
<th>Equity principle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grandfathering</td>
<td>Sovereignty</td>
<td>Allocations of carbon budgets based on current emission shares.</td>
</tr>
<tr>
<td>Immediate per capita convergence</td>
<td>Equality</td>
<td>Allocation of national carbon budgets based entirely on population shares (which can be present day or projected cumulative population).</td>
</tr>
<tr>
<td>Per capita convergence</td>
<td>Sovereignty/equality</td>
<td>Allocation of national carbon budgets based on both current emission shares and population shares (i.e., a combination of grandparenting and immediate per capita convergence).</td>
</tr>
<tr>
<td>Equal cumulative per capita emissions</td>
<td>Equality/responsibility</td>
<td>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).</td>
</tr>
<tr>
<td>Ability to pay</td>
<td>Capability/need</td>
<td>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.</td>
</tr>
<tr>
<td>Greenhouse development rights</td>
<td>Responsibility/capability/need</td>
<td>Carbon budget is reduced (compared to baseline) for countries with high historical responsibility and high capacity.</td>
</tr>
<tr>
<td>Cost-optimal</td>
<td>Cost-effectiveness</td>
<td>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).</td>
</tr>
</tbody>
</table>

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 CO₂ 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 CO₂ 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 CO₂
D: Summarised results for net CO\textsubscript{2} emissions for 2020 – 2030

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

Best estimate for 2030

<table>
<thead>
<tr>
<th>Budget 2020-2050</th>
<th>In-sector net MtCO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>66%/1.7°C/3.9%</td>
<td>63%</td>
</tr>
<tr>
<td>50%/1.5°C/3.9%</td>
<td>48%</td>
</tr>
<tr>
<td>66%/1.7°C/2.4%</td>
<td>16%</td>
</tr>
<tr>
<td>50%/1.5°C/2.4%</td>
<td>40%</td>
</tr>
</tbody>
</table>

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E: Required CO₂ emissions reductions by 2030 in case of 1.7% p.a. efficiency improvement

Required change in in-sector net CO₂ emissions for 2030 (v. 2019)

-20%  -30%  -43%  -65%

Best estimate for 2030

Budget 2020-2050

66%/1.7°C/3.9%

50%/1.5°C/3.9%

66%/1.7°C/2.4%

50%/1.5°C/2.4%

2020-2023

2024-2030

2031-2050
F: Required reduction in net in-sector CO₂ 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.
CO₂ emissions in the year 2030
Cumulative CO₂ emissions 2020 – 2030
Budget and CO₂ 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% CO₂ emissions in 2030 v. 2019; in line with 1.5°C/3.9%
C. -44% CO₂ emissions in 2030 v. 2019; in line with 1.7°C/2.4%
D. -66% CO₂ emissions in 2030 v. 2019; in line with 1.5°C/2.4%
A: CO₂ 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%

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 CO₂ pathway 2031 – 2050

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; capacity restrictions introduced from 2025.

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
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 CO₂ pathway 2031 – 2050

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; capacity restrictions introduced from 2025.

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

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B: CO₂ emissions in the year 2030

-32% CO₂: 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% CO₂ 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%

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.

**CO$_2$ in 2030:** 7.9 Mt

**Total budget:** 197 Mt

**2020 to 2030:** 93 Mt

**Budget for 2031 to 2050:** 104 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)
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%

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.

Budget: 104 Mt
Used: 104 Mt

Required SAF between 2031-2050: 14 Mt

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

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: CO₂ emissions in the year 2030

-44% CO₂: 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% CO₂ in 2030 (v. 2019)
C: Budget and CO₂ pathway 2031 – 2050

-44% CO₂: 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.

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D: CO₂ emissions in the year 2030

-66% CO₂: 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% CO₂ 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%

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.

2030: 4.0 Mt
Total budget: 121 Mt
2020 to 2030: 68 Mt
budget for 2031 to 2050: 53 Mt

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 CO₂ pathway 2031 – 2050

-66% CO₂: 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

- Beuttler et al. (2019). The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. Frontiers in climate **1**
- 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.
V: References

- van der Sman et al. (2021). Destination 2050 – A Route To Net Zero European Aviation. NLR-CR-2020-510, Amsterdam, the Netherlands.