Carbon budget aviation

CE Delft

Committed to the Environment

Content

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Management summary

Purpose and approach of this study
- Royal Schiphol Group has commissioned CE Delft to determine remaining carbon budgets for Dutch aviation which are in line with the Paris Agreement and to investigate the consequences for the possible number of flights departing from Amsterdam Airport Schiphol.
- The remaining carbon budget is determined based on the latest IPCC report and different assumptions and choices.
- As background information a concise overview of the relevant national and international policies is given.

Climate change
- Today, climate change has impacts on both nature and human beings. In the next decades the intensity will increase.
- Evidence accumulates that the physical impacts of a temperature increase of 2 °C above pre-industrial levels may be disproportionally larger than those of a 1.5 °C increase.
- Therefore, the global leaders have agreed in the Paris Agreement to limit global warming to well below 2 °C and to aim for 1.5 °C.

Remaining carbon budgets
- The key driver of global warming is CO_2, which adds up cumulatively in the atmosphere.
- A net zero target in a specific year is not sufficient, the path towards net zero determines the global temperature increase.
- IPCC has estimated remaining global carbon budgets after 2020 corresponding with specific temperature increases with certain likelihoods.

Tabel 1 - Estimated remaining carbon budgets from the beginning of 2020 in Gt CO_2

Temperature increase/probability	50%	67%	83%
1.5 °C	**500**	400	300
1.7 °C	850	**700**	550
2.0 °C	1,350	1,150	900

Source: IPCC.

- In this study we consider two budgets:
  - **500 Gt**: 50% likelihood that global warming is limited to below 1.5 °C.
  - **700 Gt**: 67% likelihood that global warming is limited to below 1.7 °C**.** Note that this budget is not in line with limiting global warming to 1.5 °C, and the extent to which this budget is Paris-aligned is debatable.

Net zero in 2050 is not enough in itself. Global warming is driven by the cumulative Greenhouse Gas emissions between today and the moment when global net zero is achieved.

Decarbonisation challenge for global aviation

- In 2019, the share of aviation in global CO_2 emissions was 2.4% (Tank-To-Wing emissions from fuel combustion) and 3.9% (Well-To-Wing emissions, taking into account emissions from fuel production and distribution).
- In the last decades aviation emissions grew by 3-4% per year. In the past, growth in flights has always outperformed the efficiency improvements by new aircraft types and more efficient operations, leading to growth in emissions.
- Aviation is generally considered as a ‘hard-to-abate’ sector, however replacing fossil fuel with Sustainable Aviation Fuel (SAF) is technically relatively easy but expensive (‘costly-to-abate’ sector).
  - The downsides of the increasing requirement of SAFs are:
    - biomass competes for land needed for nature-based carbon removal and other land-use;
    - clean energy could be used more effectively to decarbonize other sectors.
  - Costly-to-abate implies that decarbonization is cheaper in other sectors (especially in developing countries). As a result, aviation buys EU ETS allowances from other sectors (for intra-EU flights) and uses offsets in CORSIA (for intercontinental flights). For the latter it is doubtful that the current prices lead to additional CO_2 reductions at all.
- Technological breakthroughs like battery electric or hydrogen aircraft will not contribute to a significant reduction of emissions in the next two decades.
- New aircraft types that are currently developed will be in operation in 2050 and those still require kerosine or SAFs. Therefore, immediate scaling-up of biofuel production and pre-commercial development of the synthetic fuel production are essential.
- It must be noted that availability for biomass and green energy will be limited in the next decades, and there is strong competition between different sectors and global regions for these resources. Further growth in aviation exacerbates this issue.

Technological breakthroughs will come too late and SAF production has limits. Demand management measures are necessary to align the aviation sector with the goals of the Paris Agreement.

Remaining carbon budgets for global and Dutch aviation

- The allocation of a remaining carbon budget for aviation can be based on different societal and political choices:
  - Maintain current share of 2.4%.
  - Increase share since aviation is a 'hard-to-abate' sector. The International Energy Agency IEA has estimated an increase to 3.9%.
  - Decrease share since aviation is a luxury product and access is not fairly/equally distributed between developed and developing countries.
- The decrease option is not further investigated in this report. Therefore, the resulting aviation budgets have to be considered as upper limits.

Table 2 - Remaining carbon budgets from the beginning of 2020 for Global aviation

Global aviation carbon budget	50% 1.5° (500 Gt)	66% 1.7° (700 Gt)
Current aviation share 2.4%	12.0 Gt	16.8 Gt
IEA NZE aviation share 3.9%	19.5 Gt	27.3 Gt

Non-CO_2 climate impact

- Non-CO_2 effects of aviation are estimated to be responsible for 2/3 of the total aviation climate effect. The two largest climate impacts come from contrail-cirrus formation and NO_x emissions.
- In contrast to CO_2, the time horizon of the non-CO_2 effects is much shorter, as they break down quicker through chemical reactions.
- Since they do not add up cumulatively, they are not considered in the remaining carbon budgets.
- However, non-CO_2 emissions lead to global warming for a short period of time. During this period they increase the probability of reaching tipping points in global warming and therefore contribute to irreversible processes.
- It is very important to develop efficient non-CO_2 policies and to reduce them as soon and as fast as possible.
- In a net zero situation non-CO_2 emissions have to be compensated.

- Currently, aviation departing from Dutch airports has a share of 1.16% of global aviation.
- Within the Dutch budget Schiphol has a share of 96%.
- For the future allocation between Dutch and global aviation, different ethical frames can be applied:
  - Maintaining the share of 1.16% continues the disproportional high emissions of Dutch citizens.
  - Distributing the budget to countries by shares of the world population, leads to a Dutch share of 0.21%.
  - Applying socio-economic forecasts on the current market share leads to a share of 1.05%. The Dutch share decreases slightly since the population and economy growths faster in other parts of the world. This share is applied in the further analysis leading to Dutch carbon budgets between 126 Mt and 287 Mt.

Table 3 - Remaining carbon budgets from the beginning of 2020 for Dutch aviation

	50% 1.5° (500 Gt)	66% 1.7° (700 Gt)
Current share 2.4%	126 Mt	176 Mt
IEA NZE share 3.9%	205 Mt	287 Mt

Personal aviation budget - a theoretical exercise

The remaining budget of 205 Mt is an abstract number. To give the reader a feeling for what this implies a personal aviation budget for the average Dutch citizen is calculated. It is a theoretical exercise that does not take into account any variations in the population.

- The budget is allocated between freight/passengers, OD-/transfer passengers and Dutch citizen/visitors (based on the CO_2 share in 2019).
- The personal budget for the average Dutch person is 6 ton CO_2.
- For the average world citizen the analogue calculation leads to a remaining budget of 1.6 ton, which is 27% for the average Dutch person.

With the current aircraft and fuels, the budget of 6 ton CO_2 corresponds to (based on the online version of the ICAO carbon emissions calculator):

- 25.5 return flights to Barcelona (economy class);
- 9.5 return flights to New York (economy class);
- 7.3 return flights to Tokyo (economy class);
- 2.4-3.6 return flights to Tokyo depending on the chair configuration (business class).

— From these four budgets we consider the 205 Mt budget to be the upper bound for Dutch aviation for the following reasons:
  - aim of Paris Agreement is to limit global warming to 1.5 °C;
  - not aiming for ambitious targets increases the risk of overshoots;
  - aviation is a non-essential industry and should not claim a disproportionate share of green energy and biomass;
  - due to its high historic aviation emissions and national welfare, the Dutch aviation sector should set ambitious targets;
  - the budget allocated to the Netherlands per capita is still almost a factor four larger than the world average;
  - non-CO_2 effects are not included in the budgets and require compensation.

Hard-to-abate curves vs. immediate reduction

— The form of a logical reduction path depends on the remaining carbon budget.

— For the highest budget (287 Mt) different reduction paths are possible, which require moderate emission reduction until 2030.

— For the other three budgets much stricter reduction targets have to be defined and immediate action is required (see Figure 10 for three indicative examples corresponding with the 205 Mt budget):
  - Linear reduction: This approach reaches zero emissions in 2052.
  - Accelerating speed: Moderate reduction in the first years requires zero emissions much earlier than 2050.

- Immediate action: Fast emission reduction before 2030 allows that zero emissions could be reached after 2050, for instance by increasing SAF blending from 70 to 100% between 2050 and 2060.
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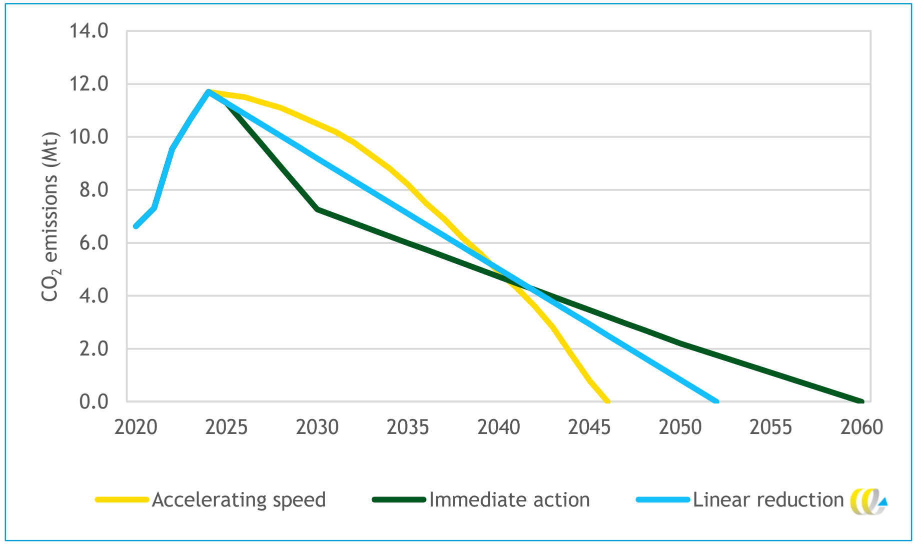
Figure 1 – Potential reduction paths for a remaining carbon budget of 205 Mt



- Both the linear and the accelerating speed variants depend on breakthroughs in aircraft technology, carbon removal or SAF production way before 2050, and therefore have a high risk of exceeding the carbon budget.
- Whether electric/hydrogen aircrafts or large-scale carbon capture and storage (in addition to direct air capture for the production of synthetic fuels) will be available in time is very uncertain. The aircraft that are currently being developed will dominate the fleets in 2050, and these still rely on fossil fuel or SAF.
- SAF production capacities will probably be scaled up significantly in the next decades. Whether sufficient clean energy and biomass is available for global demand is highly uncertain. A risk is that additional blending in Europe cannibalises the world market, due to the scarcity of biomass and clean energy.
- The potential energy demand for all these technologies puts additional pressure on the decarbonization of other sectors and regions worldwide.

Immediate reduction of carbon emissions is necessary. Otherwise aviation requires disproportional amounts of clean energy and land or depends on uncertain technological breakthroughs.

- To prevent dependency on technological breakthroughs, and limit the risk of overshooting the carbon budget, immediate reduction is required to prevent even more drastic measures in the future.
- An accelerating speed curve is commonly used in sustainability roadmaps, motivated by the time needed to ‘scale up’ new technologies. Considering the remaining available budget and the speed at which this is running

out, such a pathway is no longer feasible without immediate action.

Paris-aligned pathways for Dutch aviation and 2030 reduction targets

- During the period 2020 to 2024, approximately 46 Mt of the remaining budgets will be used despite the reduced activities caused by the COVID19 pandemic.
- With the current level of emissions, the 205 Mt budget is exhausted in 2038 (13.6 years), the 126 Mt budget in less than 7 years.

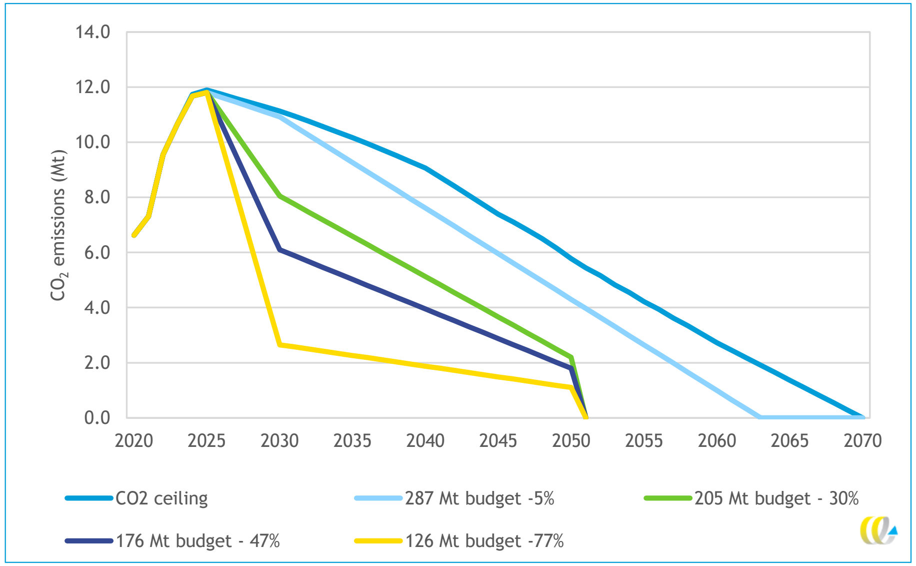
If the sector aspires to limit global warming to 1.5 °C, the remaining budget is exhausted in 2038, with the current level of emissions.

- Decling in-sector CO_2 reduction paths are needed to keep emissions within the budgets.
- The 287 Mt can be reached by setting a zero-emission target in 2063 and defining a linear path between the current 2030 target (equal to 2005 level) and 2063.
- The other budgets require immediate action. However, we assume linear reductions between 2025 and 2030 and no hard jumps.
- Our 'immediate reduction' pathways have a linear reduction between 2025 and an immediate action goal in 2030. They contain SAF blending according to RefuelEU, and full carbon removals for any remaining emissions after 2050 in line with Destination2050 (see Figure 2).
- The required reduction targets for 2030 and 2050 are summarized in Table 3.

Table 4 - In-sector reduction targets for 2030 and 2050 compared to 2019 emissions for the four remaining carbon budgets

	2030	2050
287 Mt budget (1.7 °C, 3.9%)	-5%	-63%
205 Mt budget (1.5 °C, 3.9%)	-30%	-81%
176 Mt budget (1.7 °C, 2.4%)	-47%	-84%
126 Mt budget (1.5 °C, 2.4%)	-77%	-90%

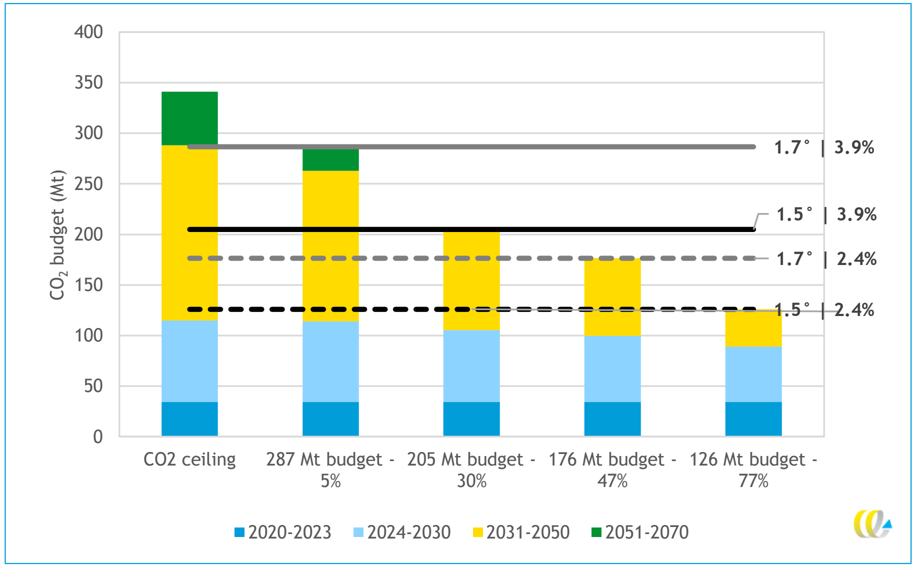
Figure 2 - Reduction paths for the four remaining carbon budgets



- To align with a 1.5 °C pathway, at least 30% CO_2 reduction is needed in 2030, based on a 3.9% share of aviation in total emissions. If aviation maintains its current share, CO_2 emissions must be around 77% lower in 2030.
- The cumulative emissions that fit within the current Dutch national aviation CO_2 ceiling proposal[1] overshoots the Paris aligned budgets, even those which aim for 1.7 °C.

[1] The Dutch ministry of transport is preparing legislation for a Dutch CO2 ceiling that sets in-sector emission targets for aircraft departing from Durch airport for the years 2030, 2050 and 2070.

Figure 3 - Overview of emission in time periods. The CO_2 ceiling shows the potential budget that would fit in the proposed CO_2 ceiling (and which would exceed Paris aligned carbon budgets). The percentages illustrate the reduction targets for 2030.

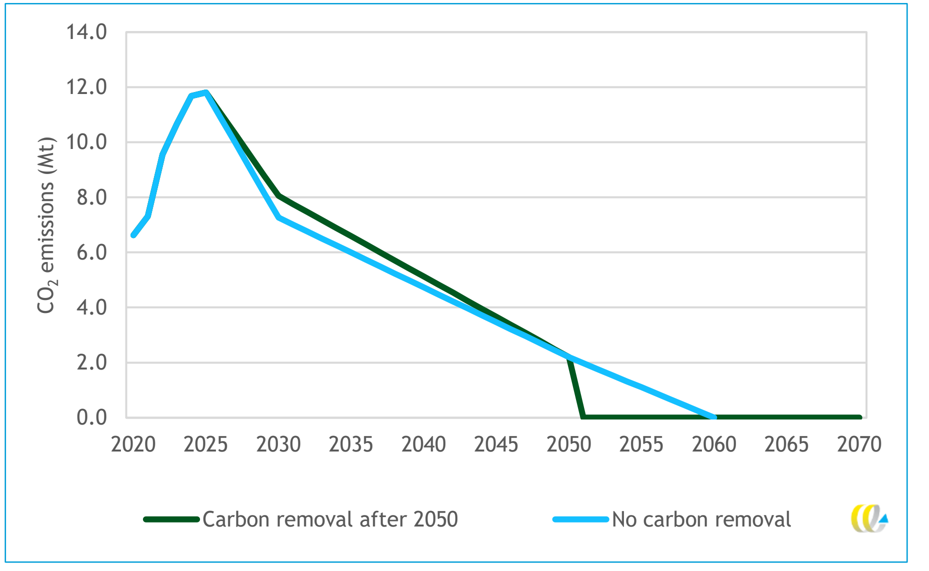


Reduction paths with and without carbon removal

- For the 205 Mt budget a sensitivity analysis is performed for situations with and without carbon removal (Figure 4):
  - A scenario with moderate carbon removal from 2050 onwards (8% compared to the ‘hypothetical no-action

growth' scenario) as proposed in Destination 2050 requiring 30% CO_2 reduction in 2030.
   - A scenario without carbon removal, which assumes an increase in SAF blending from 70 in 2050 to 100% in 2060 requiring 37% CO_2 reduction in 2030.
- An 'earlier carbon removal' path with large scale carbon removal way before 2050 is not considered, since this is considered to be very unlikely.
- In 2050, emissions have to be reduced by 81% compared to 2019 in both scenarios.
- In 2030 a reduction between 30 and 37% compared to 2019 has to be achieved, which is significantly more than the goal of -9% (2030 = 2005 emissions) of the Duurzame Luchtvaarttafel.

Figure 4 - Scenarios for 205 Mt budgets with and without carbon removal after 2030 and its implications on the reduction targets for 2030

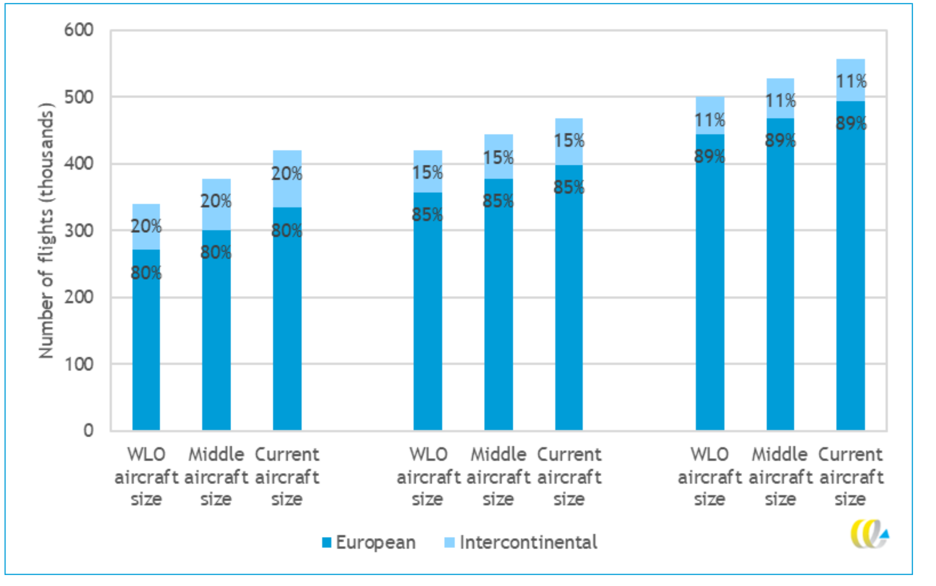


For a limitation of global warming to 1.5 °C, emissions should be reduced by 30 to 37% in 2030 compared to 2019 levels.

Impacts on the number of flights at Schiphol in 2030

- The 'immediate action without carbon removal' variant, for the 205 Mt budget, has a carbon budget for the year 2030 of 7.3 Mt. For the share of Schiphol 96% is assumed (same as 2019).
- The number of flights that fit into this budget depends on the development of the key variables:
  - aircraft and operational efficiency improvements;
  - SAF blending (6% according to RefuelEU Aviation);
  - aircraft size;
  - flight distance.
- We derive potential numbers of aircraft movements that fit into this budget in 2030 based on the results of the Dutch WLO aviation scenarios.
- The average forecast of the WLO Low and High scenario's for 2030 are (compared to 2019):
  - 500,000 aircraft movements (+0%):
    - 375,000 European flights (-6%);
    - 125,000 intercontinental flights (+25%).
  - 96.6 million passengers (+35%);
  - 1.05% annual fuel efficiency improvement (-11%);
  - 6% SAF blending (+6%);
  - 11.4 Mt CO_2 (-1%).
- In the WLO the efficiency improvements, SAF blending and constant capacity restriction do not lead to a CO_2 emission reduction, since they are compensated by larger aircraft (more passengers, +2.7%[2] per year) and longer flight distances (more ICA).
- The possible number of flights is investigated for different shares of intercontinental flights and different developments in aircraft size (see Figure 5).

Figure 5 - Potential number of flights in 2030 at Schiphol in line with the 205 Mt budget



[2] In the 25 years before the Covid pandemic the number of passengers per flight at Schiphol has grown on average by 2.3% per year.

With the current aircraft sizes and distribution between European (80%) and intercontinental flights (20%) this would limit operations to 419,000 flights.

- With an increase in aircraft size (and 20% intercontinental flights) the limit would be 340,000 flights.
- With a reduction of the intercontinental flights to hypothetical share of 11% and the current aircraft size up to 557,000 flights could fit into the budget.
- With additional SAF blending (14% instead of 6% in 2030) about 6% additional flights are possible within the budget. However, the availability for biomass and green energy will be limited in the next decades, and there is strong competition between different sectors and global regions for these resources. Further growth in aviation exacerbates this issue.

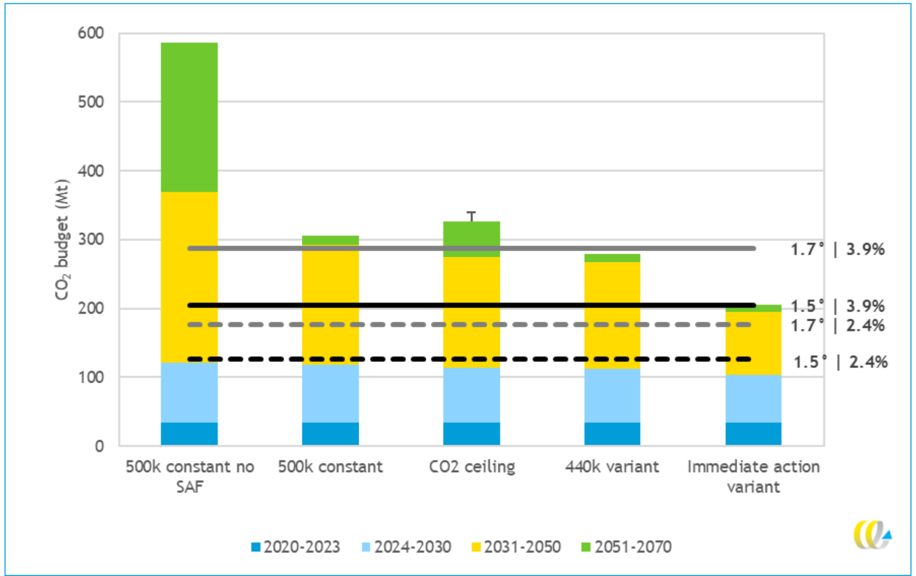
In 2030, the maximum number of flights depends strongly on the share of intercontinental flights and the development in aircraft size.

Comparison with policies and options

We compare a number of existing policies or policy options against the Paris-aligned carbon budgets. The following policies are assessed:

- '500k constant no SAF': A hypothetical variant with a limit of 500,000 flights at Schiphol and no SAF uptake. It shows that using SAFs instead of fossil fuels is a basic requirement for the decarbonization of aviation.
- '500k constant': the announced SAF blending obligation of RefuelEU Aviation is applied and nearly halves the cumulative emissions to 306 Mt.
- 'CO_2 ceiling': The CO_2 ceiling has reduction targets for 2030 (equal to 2005), 2050 (50% reduction) and 2070 (zero). The cumulative budget overshoots all considered budgets for Dutch aviation.
- '440k variant': The previously announced limit for the capacity reduction at Schiphol.
- 'Immediate action variant': Option with a cumulative carbon budget of 205 Mt.

The cumulative CO_2 emissions under the CO_2 ceiling would overshoot all of the 1.5 °C and 1.7 °C budgets.



None of the announced national (policy) options are in line with a remaining carbon budget for 1.5 °C.

Global aviation

- Measures for sustainable aviation should preferably be introduced on the largest possible geographic scale due to the international and highly competitive character of aviation.
- National policies, for example flight reductions at Schiphol, will partly lead to passengers and cargo deviating to other (foreign) airports, in particular for transfer passengers. Therefore, part of the emission reduction at Dutch airports will be compensated by more emissions at other airports (waterbed effect or carbon leakage).
- However, another part of the passengers and cargo will fly less as a consequence of higher ticket prices and fewer available flight options. Detailed model calculations show that capacity restrictions at Schiphol lead to a net decrease in CO_2 emissions on a global scale.

The aviation industry worldwide has to answer the question on how to prevent a substantial overshoot of the remaining carbon budget. But until now global institutions and the sector itself have failed to implement policies aiming at 1.5 °C targets for aviation. Since the time window to turn the development of aviation emissions from a fast growth into a fast decline is very limited, key players have to move now. Wealthy nations with disproportional high historic emissions have a special responsibility to act. By leading the way and setting an example of how to transition the Dutch aviation sector to a 1.5 °C consistent path, global and EU institutions could follow.

2 Introduction

Impacts of global warming

In 2015 in Paris, the world agreed to hold global warming well below 2 °C above pre-industrial levels and to pursue efforts to limit it to 1.5 °C. Eight years later, this last objective seems almost out of reach. On 8 June 2023, while this report was being written, climate scientists published a paper concluding that global warming reached 1.26 °C in 2022 and increased faster than ever before (0.2 °C over 2013-2022), fuelled by global greenhouse gas (GHG) emissions that were higher than during any previous decade (Forster et al., 2023). July 2023 then turned out to be the hottest month on record globally, with the 1.5 °C threshold being temporarily exceeded during the first and third week of the month (WMO, 2023).

At the same time, evidence accumulates that the physical impacts of a temperature increase of 2 °C above pre-industrial levels may be disproportionally larger than those of a 1.5 °C increase. This has partly to do with so-called tipping points in the climate system. As this system is complex and contains many feedback loops, crossing a certain (temperature) threshold can indirectly cause very large and almost irreversible changes in the wider system. Some main examples of tipping points are (UCAR, n.d.):

- **Melting of the polar ice sheets**. As loss of ice surface reinforces itself through the albedo effect, the melting of the Antarctic and/or Greenland ice sheets could become irreversible - as would the associated massive sea level rise.
- **Weakening Gulf Stream**. Melting ice sheets would also affect ocean circulation patterns through the influx of cold fresh water. In particular, this could lead to an irreversible weakening or even reversal of the Atlantic Gulf Stream, fundamentally changing existing weather patterns.
- **Collapse of rainforest**. If the destruction of rainforest, such as in the Amazon region, passes the associated tipping point, the rainforest is not able to sustain itself anymore and would further collapse, releasing large amounts of CO_2 into the atmosphere.

Partly because of the tipping point mechanisms, limiting global warming to 1.5 °C instead of just 2 °C makes a significant difference in terms of projected impacts on both nature and human beings. Allowing global warming to rise to 2 °C, compared with 1.5 °C, could for instance:

- increase the share of the world population **exposed to at least one extreme heat wave per 5 years** from 14% to 37% (Dosio et al., 2018); increase the share of the world population **exposed to at least one extreme heat wave per 5 years** from 14 to 37% (Dosio et al., 2018);

- increase the number of people **both exposed to climate-related risks and susceptible to poverty** by up to several hundred million by 2050 (IPCC, 2018);
- increase the share of the world population **exposed to a climate-change induced increase in water stress** by up to 50% (IPCC, 2018);
- double the **very high extinction risk for endemic species** in biodiversity hotspots (IPCC, 2022);
- increase the probability of an **ice-free Arctic region** to 1 in 10 years instead of 1 in 100 years (IPCC, 2018);
  increase the probability of an **ice-free Arctic region** to 1 in 10 years instead of 1 in 100 years (IPCC, 2018).

Furthermore, climate impacts such as the ones mentioned above could force the displacement of more than 200 million people by 2050 (World Bank, 2021). This may also lead to increased migration flows towards regions that are better placed to adapt to climate change, such as North America and Europe (EP, 2022).

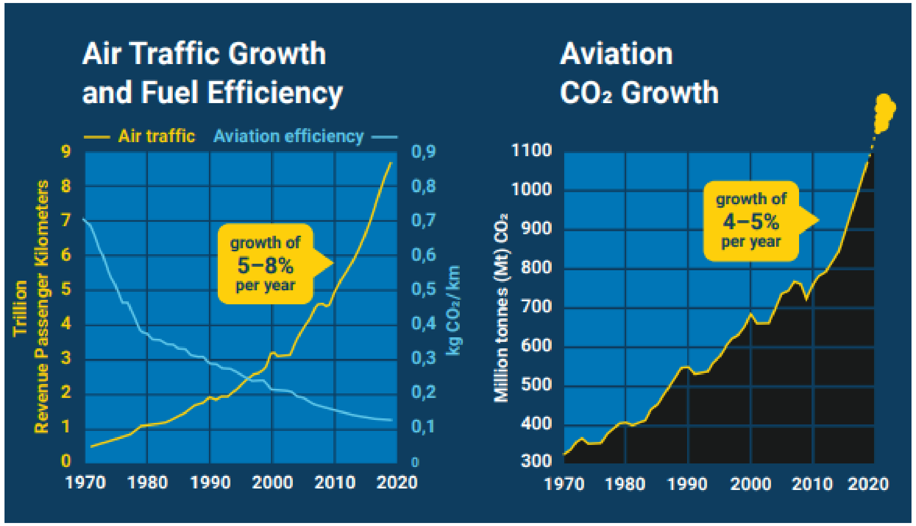
These examples illustrate the importance of keeping global warming limited to 1.5 °C. In order to keep this goal within reach, GHG emissions will have to be reduced economy-wide at an unprecedented rate over the coming years.

Aviation contributes to 3.7% of global CO_2 emissions[3]. Within aviation the Netherlands have a share of approximately 1.2%. Apart from this, also non-CO_2 effects such as contrail-cirrus formation and NO_x emissions cause radiative forcing, hence climate impacts. Efficiency improvements only partially compensate for growth of demand, meaning global aviation emissions are increasing. Between 2013 and 2019, global passenger transport-related aviation CO_2 emissions grew by 33% (ICCT, 2020).

Figure 6 illustrates the difference in speed between the growth in global air traffic and the technological improvements leading to more fuel efficient operations. The result is that aviation CO_2 emissions increased with a rate of 4 to 5% per year. In order to limit global warming to well below 2 °C, this trend has to be turned into a fast decline within a short period of time.

[3] Well-to-Wing, so including emissions from fuel production and distribution. The emission from fuel combustions in the aircraft engines is called Tank-to-Wing emissions and has a share of 2.4%.

Figure 6 - Historic development of global air traffic growth, fuel efficiency gains and CO_2 emissions between 1970 and 2019



Source: stay-grounded.org (Lee et al., 2021),

Purpose of the study

In this report, we investigate the consequences that the limited remaining global carbon budget has for Dutch aviation, in particular for flights departing from Amsterdam Airport Schiphol and the other Dutch airports. We analyse the various types of assumptions that need to be made explicit in order to estimate a remaining carbon budget for Dutch aviation and we explain our choice of a coherent set of assumptions. Finally, we translate the resulting carbon budget in a remaining number of flights, again for a certain set of assumptions.

Reading guide

In Chapter 3, we present an overview of all climate-related targets and instruments in force that are relevant to aviation, at different governance levels: global, Europe (EU) and national (the Netherlands). We also pay attention to the special status of aviation in worldwide climate action and to the ambitions of the aviation sector itself. We analyse the targets and instrument systematically and present an overview of their main features, such as scope, legal status and target year.

In Chapter 4, we derive remaining CO_2 budgets for global and Dutch aviation. Starting points are the remaining global budgets as published by the IPCC. We discuss the challenge to decarbonize the aviation sector and estimate remaining carbon budgets for global and Dutch aviation based on technological and ethical considerations. For illustration purposes the remaining aviation CO_2 budget for the average Dutch citizen is calculated. For four remaining carbon budgets possible decarbonisation paths are defined and resulting emission targets for 2030 are discussed. These targets are compared to current policies.

Finally, in Chapter 5, the impacts on the number of flights at Schiphol in 2030 are described and the key variables are discussed.

Policy landscape of aviation in climate policies

In this chapter, we present a concise overview of the policy landscape with regard to the role of international aviation in global climate policies. That is, we assess the existing climate targets, their character and legal status, and relevant policy instruments and focus on its meaning and consequences for aviation. We perform this analysis for three policy levels (global, EU and national for NL) as well as for the level of the aviation sector itself. But first, we have a brief look at the special position of aviation in global climate policy.

3.1 Status of aviation in climate policy

Together with the maritime sector, aviation holds a distinct position in global climate policy due to its international character. Unlike emissions in industry, built environment, agriculture and most other transport sectors, GHG emissions from maritime and aviation are not easily assigned to a specific country. Furthermore, the 1944 Chicago Convention on Aviation (see Text box 1) stressed the importance of an unhampered post-war development of international civil aviation, which was believed to contribute to welfare and human connection.

Section Summary
Aviation has a special position in international climate action because of historical reasons and because of its international character.
The International Civil Aviation Organization (ICAO) is the main entity dealing with international efforts to curb aviation emissions.

Text box 1 - The Chicago Convention on Aviation

The Second World War was an important driver of technical developments in aviation. Forced by the needs of warfare and large-scale displacements of people, a network of passenger and freight flights was created, but in order to turn this into a proper functioning civilian aviation system, many technical and political obstacles had to be overcome. Therefore, the US government invited 55 other countries, some still under occupation, to attend an International Civil Aviation Conference in Chicago in 1944 (ICAO, n.d.-b).

The main objective of the Chicago Convention, as it became commonly known, was to lay the foundation for uniform standards and procedures to ensure safe and peaceful global air navigation. As a means to this goal, the Convention foresaw the creation of an International Civil Aviation Organization (ICAO) to organize and support the international coordination between countries - see main text.

At the time of the Convention, the large potential of international air traffic, both economically and in terms of bringing together people from all over the world, was widely recognized. With the end of the devastating war visible at the horizon, the Convention was drafted with the aim to 'create and preserve friendship and understanding among the nations and peoples around the world'. From this perspective, it seemed desirable to put as little as possible barriers in the way of a swift development of international civil aviation. Also, global warming was not yet widely considered a major issue hence reducing aviation emissions was not covered in the original Convention. Still, contrary to common belief, the Chicago Convention does not include a general ban on taxation of aviation fuels. Only the taxation of fuel present in a plane by the country of arrival of that plane was prohibited. Under the current EU Energy Tax Directive (ETD) fuel consumed on commercial flights between EU Member States is exempt from taxes, although it is allowed for Member States to waive this exemption through the establishment of bilateral agreements (CE Delft, 2018).

See also under Energy Tax Directive in Section 3.3.

The special position of international aviation has been reflected in the relevant agreements and frameworks since the beginning of international action against climate change.

UNFCCC

In 1992, at the Earth Summit in Rio de Janeiro, the United Nations Framework Convention on Climate Change (UNFCCC) was established, committing its signatories to reduce atmospheric concentrations of greenhouse gases with the goal of preventing dangerous anthropogenic interference with the Earth's climate system (UN, 1992).

Emissions from fuel used for international aviation have been addressed since the UNFCCC's first Conference of the Parties (COP) in 1995. In particular, there has been discussion on the allocation of these emissions (together with those from bunker fuels for shipping) in the Subsidiary Body for Scientific and Technological Advice (SBSTA), one of the two permanent subsidiary bodies under the Convention. ICAO and IMO have always been closely involved in the work of SBSTA (UNFCCC, n.d.). In 1996, SBSTA identified seven different options for allocation of international aviation and maritime emissions to individual countries (the eighth option being no allocation). The availability and consistency of statistical data needed to establish the consequences of the different options turned out to be challenging (CE Delft & Resource Analysis, 2000), and no agreement was reached on one of the options for allocation to individual countries.

Therefore, when in 1997 the Kyoto Protocol under the UNFCCC was adopted, requiring developed countries[4] to reduce or limit their GHG emissions according to individual targets[5], it was explicitly included that developed countries had to limit or reduce aviation and maritime emissions ‘working through the International Civil Aviation Organization and International Maritime Organization, respectively’ (Art. 2.2) (UNFCCC, 1998).

Under the UNFCCC, developed countries are also required to annually report all the GHG emissions in their territory, through a method based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Under these reporting guidelines, emissions from international aviation (and marine) bunker fuels should not be added to the national totals but reported separately (UNFCCC, n.d.).

Under the Paris Agreement, both practices have in fact been continued: international aviation and shipping emissions are to be addressed by ICAO and IMO, respectively, and should be reported as two separate entities and not be included in the national totals, as confirmed at UNFCCC COP 24 in Katowice (Poland) (UNFCCC, 2019)[6].

4 Formally: Annex I countries.

5 Ranging from -8% compared to 1990 levels for EU Member States and most other European countries to +10% for Iceland.

ICAO

In 1944, the Chicago Convention laid the foundation for the establishment of the International Civil Aviation Organization (ICAO). At first, a Provisional ICAO was created because of delays in the ratification of the Convention, but in 1947 ICAO was formally established and its first assembly was held in Montreal (ICAO, n.d.-b). Later that year, ICAO became a Specialized Agency of the United Nations (UN).

In recent history, ICAO has sustained various pathways in its actions for environmental protection, directed at climate change and aviation emissions, aircraft noise and local air quality. Measures often address all three categories at the same time and include the support of technological innovations, optimizing flight procedures, increasing the production and use of sustainable fuels and clean energy, development of a global market-based measure and the adoption of long-term goals for international aviation (ICAO, n.d.-a).

In the next paragraph we go into more detail on the instruments and policies developed by ICAO to counter GHG emissions from international aviation.

6 A key difference, though, is that under the Paris Agreement all countries have to report their national emissions annually, not only developed countries as under the Kyoto Protocol.

3.2 Climate targets at global level

Section Summary
The 2015 Paris Agreement is the main reference for international climate action. All parties committed to hold the global average temperature increase to maximum 2 °C and pursue efforts to limit it to 1.5 °C. As all emissions contribute to global warming, international aviation is not excluded from this objective. However, the Nationally Determined Contributions that parties have to submit do not include measures directed at international aviation. The main instrument covering those emissions is ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

IPCC

The global efforts to mitigate climate change are supported by the scientific work of the International Panel on Climate Change (IPCC). The IPCC periodically publishes a series of coherent reports (collectively referred to as Assessment Reports) covering several aspects of climate change, such as the physical science basis, impacts and mitigation options, followed by a synthesis report. The 6th and so far last cycle of these series was concluded in March 2023 with the publication of the Synthesis Report (IPCC, 2023).

Apart from the Assessment Reports, the IPCC also delivers Special Reports on specific issues related to climate change, such as impacts on oceans or risk preparedness. In October 2018, a Special Report on the 1.5 °C target was published. In its Summary for Policymakers (SPM), the IPCC concluded with high confidence that global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018), which means there is little time left to curb emissions and avoid a large overshoot of the 1.5 °C target.

Text box 2 - CO_2, other greenhouse gases (GHG) and non-CO_2 climate effects

CO_2 is by far the most well-known greenhouse gas and is indeed the main GHG emitted by planes. However, other economic sectors emit also different GHGs, such as methane (CH_4), N_2O (nitrous oxide) and many types of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). In the Netherlands, the contribution of these well-understood non-CO_2 emissions is about 15% of the total GHG emissions (PBL, 2022).
The contribution of aviation to the stable non-CO_2 emissions is relatively low due to the high combustion temperatures. Both their global warming potential and their lifetime in the atmosphere differ strongly.

Apart from GHGs, aviation emissions also contain other elements with global warming potential, such as NO_x, sulfur dioxide and particular matter. These emissions also occur at ground level from other sectors, but there they do not contribute as greenhouse gases. In the atmosphere they have chemical and physical effects which contribute to global warming. The two largest non-CO_2 climate impacts of aviation come from contrail-cirrus formation and NO_x emissions (EASA et al., 2020). These are referred to as the non-CO_2 effects of aviation (different from non-CO_2 GHGs) and are believed to account for two-thirds of aviation's climate impact (Lee et al., 2021; T&E, n.d.). In this study, we will refer to the non-CO_2 impacts of aviation where relevant but do not take them into consideration in the remaining carbon budgets. Nonetheless, these emissions should be addressed with specific additional policies.

Paris Agreement

In December 2015, at the 21st COP of the UNFCCC in Paris, a far-reaching international treaty on global climate action was established among almost all countries of the world, since then referred to as the 'Paris Agreement' (UN, 2015). This agreement is legally binding to all the parties that ratified it, including all EU Member States as well as the EU itself. Its most well-known provision, already quoted in the Introduction, is the overall objective to hold the global average temperature increase to well below 2 °C above pre-industrial levels and to pursue efforts to limit this increase to 1.5 °C.

Text box 3 - Climate neutrality target in the Paris Agreement

The main objective in the Paris Agreement is formulated as a temperature target in Article 2: the average global temperature should be limited to 2 °C above pre-industrial levels at the most and preferably to 1.5 °C. In the Introduction, some examples were given on what difference this 0.5 degree could make in terms of impacts on nature and human beings. Contrary to common belief, the Paris temperature target is not linked to a specific year, 2050 or otherwise, and is instead referred to as a 'long-term target'.
As a means to achieve the long-term temperature target, the Agreement also includes a climate neutrality target in Article 4. There, parties declare to reach a global peak in GHG emissions as soon as possible and initiate a strong decrease in emissions afterwards, such that in the second half of this century a balance should be achieved between anthropogenic emissions by sources and removals by sinks.
Since then, it became clear that to keep the 1.5 degree target within reach, climate neutrality should be achieved well before the end of this century. Indeed, the International Panel on Climate Change (IPCC) estimates that in model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions reach net-zero around 2050 (IPCC, 2018). It should be realised though, that whether the global temperature will be limited to 1.5 (or 2) °C, depends on the cumulative amount of GHGs that are emitted before net zero is reached, rather than on the moment in time when this happens. In other words, the reduction *pathway* is essential for the climate outcome.

Since the establishment of the Paris Agreement, many companies, organizations, countries and the EU as a whole committed themselves to reach 'climate neutrality' or 'net zero emissions', mostly to be achieved in 2050 but in some cases earlier or later.

The working mechanism of the Paris Agreement is based on national climate mitigation policies that are put forward in Nationally Determined Contributions (NDCs), which are mandatory for all parties to submit. These documents are to be reviewed periodically and should reflect an increasing level of ambition over time. Every five years (starting in 2023) a so-called global stocktake is organised to determine whether all NDCs add up to be on track for the long-term temperature target.

NDCs do in principle only address domestic emissions, including those resulting from domestic aviation. It is not mandatory for the NDCs to also cover emissions from international aviation, although the EU has chosen to include in its initial NDC emissions from outgoing flights starting in the EU (EC, 2020).
This means that the Paris Agreement does not impose obligations on its Parties related to the reduction of international aviation emissions, which are covered by ICAO as explained in the previous section. However, it is not entirely correct to state that aviation is out of the scope of the Paris Agreement (see Text box 4).

Text box 4 - Aviation in the Paris Agreement

Aviation is not mentioned specifically in the text of the Paris Agreement, and there has been some debate on whether this means they are outside its scope (T&E, 2021). Looking at the central objective of the Paris agreement though - limiting the global temperature – no economic sector should be considered outside its scope, as global temperature depends on all GHGs emitted, regardless of their origin. Moreover, the parties to the Agreement commit themselves to undertake 'economy-wide' reduction efforts (UN, 2015). However, in the current understanding Nationally Determined Contributions, the basis of the Agreement's working mechanism, are limited to include measures directed at mitigating emissions taking place within the country's own territory (including domestic flights), while mitigating actions in international aviation are left to ICAO, as explained in Section 3.2.

ICAO Instruments

CORSIA

In 2016, ICAO adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as a global market-based measure to address CO_2 emissions from international aviation. In particular, CORSIA was developed as an instrument to implement the Carbon Neutral Growth target ICAO agreed on in 2013 (Climate Action Tracker, n.d.).

Under CORSIA, all eligible airlines[7] have to report their emissions from international flights since 1 January 2019. From 2021 on, flights between states that participate in CORSIA are additionally subject to offsetting requirements. This means that emissions above the CORSIA baseline are compensated by purchasing the corresponding amount of carbon credits (IATA, 2023), see also Text box 5. This means that emissions above the CORSIA baseline are compensated by purchasing the corresponding amount of carbon credits (IATA, 2023), see also Text box 5.

[7] Responsible for at least 10,000 tons of annual CO_2 emissions from international flights.

Text box 5 – The role of offsets

Currently many airlines offer the possibility to offset or 'compensate' the CO_2 emissions of their flight by purchasing some kind of carbon credits. Also, under the CORSIA mechanism airlines are required to offset the emissions that result from their flights above a certain threshold.

In this study, we take the climate mitigation impact of offsets before 2050 as zero and we consider offsets as a barrier to useful climate action in aviation, for the following reasons:

- Offsets do not meet the requirements of Carbon Dioxide Removal (CDR). CDR is necessary to achieve climate neutrality in 2050 according to all IPCC scenarios, by compensating for the so-called residual emissions. To do so, CO_2 needs to be physically extracted from the atmosphere and permanently stored, and emissions associated with the capture and storage process need to be taken into account (Tanzer & Ramirez, 2019). To do so, CO_2 needs to be physically extracted from the atmosphere and permanently stored, and emissions associated with the capture and storage process need to be taken into account (Tanzer & Ramirez, 2019).
  Offsetting projects often involve temporal storage (for instance in trees), do not take into account associated emissions and/or claim to realize emission avoidance or emission reduction, which is not the same as CDR. Emission avoidance or reduction does not involve physical removal of CO_2 from the atmosphere and is often not additional (i.e. it would also happen without the offset credits being sold).
  Also, even reductions from avoided-deforestation projects turn out to be substantially lower than claimed (West et al., 2023). Therefore, any claim by offsetting projects to compensate for residual aviation emissions should not be granted (CE Delft, 2023).
- The use of offsets creates an unjustified impression that the emissions hence the climate impact of a flight truly have been compensated for – which is not the case for the arguments presented above. This hampers awareness – by both the public and the aviation sector – that more needs to be done to curb aviation emissions, including the reduction of the number of flights.
- Financial resources dedicated to creating offsets cannot be used for measures leading to emission reductions in aviation, such as the development of SAF, or for proper CDR projects, thus decelerating the transition of the aviation sector.
  The upscaling of sufficient SAF production for a significant share in the fuel mix will take a long time (see also Section 3.3 on the EU's blending obligation), therefore measures such as SAF uptake need to be kickstarted on a short term.

In this study, (limited) negative emissions in other sectors are considered to compensate for the remaining emissions from aviation after 2050. These have to be fully additional and high quality. In case CDR would become a cost-efficient technology on large scale way before 2050, this could make offsets a viable option before 2050. However, we advise not to rely on the required uncertain technological breakthroughs when allocating a carbon budget to the aviation sector.

The CORSIA baseline equals the 2019 aviation emissions covered by CORSIA for the years 2021-2023 and 85% of 2019 emissions from 2024 until the end of the scheme in 2035. Offsetting is described as an action by a company or individual to compensate for emissions by financing emission reductions elsewhere. Certain criteria apply to the projects and activities that are eligible under the CORSIA offsetting requirements, such as additionality, the establishment of a baseline against which the emission reduction or avoidance is measured, procedures to prevent double counting and safeguards to prevent negative environmental and social effects (IATA, 2023).

As also indicated in Text box 5, this type of projects often does not truly compensate for the aviation emissions it offsets, as the CO_2 emitted by the flights involved is not removed from the atmosphere. While this amount of CO_2 certainly continues to strengthen the anthropogenic greenhouse gas effect, the additionality, quality and permanence of the reduced or avoided emissions associated with the offsetting projects cannot be guaranteed.

Apart from offsetting projects in other economic sectors, CORSIA also allows offsetting through the use of CORSIA eligible fuels, which include Sustainable Aviation Fuels and Low-Carbon Aviation Fuels. The criteria for both types of fuels are defined by ICAO, which means a fuel considered a SAF under CORSIA is not necessarily a SAF under the EU's RED3 (see Section 3.3) (ICAO, 2022).

During CORSIA's pilot phase (2021-2023) and first phase (2024-2026), participation is on a voluntary basis. The second phase (2027-2035) applies to all Member States, but there are two types of exemptions from the offsetting requirements. States whose individual share in international aviation is very limited[8] and states that are socio-economically less developed[9] are not required to participate in the second phase, but can still do so voluntarily (ICAO, 2022). This means that probably not all global aviation emissions will be regulated by CORSIA, hence its baseline (from which sector growth should be climate neutral according to the Carbon Neutral Growth target) cannot be considered an absolute one.

Long-Term Global Aspirational Goal (LTAG)

Apart from the development of a global market-based mechanism, which resulted in the launch of CORSIA in 2016, another strand of prolonged debate within ICAO relates to a long-term climate goal for aviation and came to an (temporary) end in 2022. At the 41st ICAO Assembly, a Long-Term Global Aspirational Goal (LTAG) for aviation of net-zero carbon emissions by 2050 was adopted. The LTAG does not involve specific targets or commitments for individual Member States, and allows for all states to work towards the target at their own pace, taking into account national circumstances and respective capabilities.
This renders the LTAG legally non-binding to Member States.

The long-term goal having been set, its implementation and the pathways are now subject to discussion at working group level and will be on the agenda of the next ICAO Assembly in 2025.

[8] Operationalised by two criteria: the state should have a share of less than 0.5% of total Revenue Tonne Kilometers (RTKs) in 2018 and/or should not be part of the list of states responsible for 90% of total RTKs, when sorted from highest to lowest individual RTKs.

[9] Countries eligible to this exemption are those listed as Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs).

3.3 Climate policies for aviation at EU level

Through the European Climate Law, as part of its Green Deal, the EU committed itself to a net target of 55% reduction of GHG emissions in 2030 compared to 1990 and to become climate neutral by 2050 (EU, 2021). All EU Member States are obliged to draft National Energy and Climate Plans (NECPs), in which they explain how they intend to fulfil their obligations under EU climate and energy policies, comparable to the NDCs in the context of the Paris Agreement.

Although there is no specific target for GHG emissions reduction in aviation in the EU, emissions from all departing flights are included in both the 55% reduction target for 2030 and the climate neutrality target for 2050. As we will see below, the EU regulates both intra- and extra-EU aviation through different policy instruments. Aviation is part of the transport sector, emissions from which should be reduced by 90% in 2050 to achieve climate neutrality (EP, 2021).

In its 2021 Fit for 55 package, intended to implement the 2030 emissions reduction target, the Commission proposed several legal instruments (or revisions thereof) that act upon aviation emissions (Council of the EU, 2023c). These are the Emission

Section Summary

The EU has no specific emission reduction target for aviation but regulates both domestic and international aviation emissions through several instruments:

- The Emissions Trading System (ETS) requires airlines to submit emission allowances for all intra-EEA flights. Free allowances will be phased out over the time period 2024-2026. The cap of allowances made available (including the ETS for stationary installations) will decrease annually and reach zero around 2040.
- The ReFuelEU Aviation Regulation includes a blending obligation for Sustainable Aviation Fuels for all departing flights.
- The revised Renewable Energy Directive (RED3) includes a target for renewable energy in transport, including aviation, and a specific subtarget for Renewable Fuels of Non-Biological Origin (RFNBOs) and advanced biofuels.
- In the revision of the Energy Tax Directive it is proposed to include aviation fuels into its scope, introducing a minimum tax rate for intra-EU passenger flights. However, agreement on this proposal is not foreseen in the near future.

For the time being, the blending obligation is the most well-placed instrument to effectively reduce emissions within the sector, albeit imited due to the small share of SAF blending required in the coming years.

Trading System (ETS) for aviation, the ReFuelEU Aviation Regulation, the recast of the Renewable Energy Directive (RED3), and the Energy Tax Directive (ETD). Except for the ETD, (provisional) agreement has been reached among the Council, European Parliament and Commission on a final text. We will briefly go into each of these instruments below.
In CE Delft (2021) the impacts of the Fit for 55 proposals on the Dutch aviation sector were assessed.

ETS Aviation

Since 2012 aviation has been subject to the European Emissions Trading System (ETS), requiring airlines to submit allowances covering emissions from flights taking place withing the European Economic Area (EEA). Originally, the scope of the ETS for aviation was meant to include extra-EEA flights as well, but following international concerns, its application to extra-EEA flights was suspended through the so-called 'Stop-the-clock'-decision in 2013. This derogation was extended in 2016 after ICAO agreed to work on a global market-based measure to reduce aviation emissions, which ultimately developed into CORSIA (see Section 3.2) (Jensen, 2022).
In the 2021 revision of the ETS Aviation, its scope was confirmed to include only intra-EEA flights[10], although it was established that after the 2025 ICAO Assembly, a review on the effectiveness of CORSIA will take place to decide on a possible future inclusion of extra-EEA flights into the ETS.

Before the revision, 82% of the allowances under the cap were distributed for free, based on benchmarks[11]. The final text of the revision states that these free allowances will be phased out gradually over the period 2024-2026, resulting in 100% auctioned allowances from 2026 on (Council of the EU, 2022).

Although the annually decreasing cap of the ETS for aviation guarantees a reduction of the number of allowances that becomes available, this does not automatically lead to a reduction in emissions from intra-EEA aviation. This is because the allowances for the ETS for aviation and for stationary installations[12] are interchangeable, and therefore the actual reductions can also take place in industrial installations.
In other words, the aviation sector buys allowances from other sectors. Indeed, actual verified GHG emissions from intra-EU aviation have increased by 44% over the period 2013-2019 (EEA, 2023). The phasing out of free allowances will lead to increasing costs for airlines, which can probably be passed on to passengers. This may lead to a reduction in demand, which could indirectly reduce emissions, but this also depends

[10] And flights to the UK and Switzerland, which are not EEA Members.
[11] 3% was put in a reserve and 15% was auctioned.
[12] In the future also for the ETS for the maritime sector, which was established as part of the Fit for 55 package and will be phased in from 2024-2026.

on whether the capacity of airports is limited compared to total demand.

In the longer term, the options for the aviation sector to buy ETS allowances in other sectors will diminish. Based on recent revisions, the ETS cap, which includes the stationary ETS and the ETS for aviation, would reach zero around 2040, meaning that no new ETS allowances would become available. Therefore, intra-EEA aviation emissions would need to reach zero as well, unless they can be covered by saved allowances or allowances created by future revisions, for instance related to carbon removals.

While the ETS currently only covers CO_2 emissions, the revision stipulates that non-CO_2 effects will have to be monitored and reported from 2025. In 2028 the Commission will have to present a proposal on how to address non-CO_2 effects (Council of the EU, 2022).

Text box 6 – EU ETS and remaining carbon budget

In Chapter 4, remaining carbon budget of global and Dutch aviation are estimated based on global carbon budgets estimated by IPCC that correspond to global temperature increases. This approach is very different from the policy background of the EU ETS.

The 2022 revision of the EU ETS itself is part of the EU Fit For 55 package, which has the goal to reduce EU's greenhouse gas emissions in 2030 by 55% compared to 1990.

However, the ETS on its own is not 'aligned with a specific temperature target'. In addition, the EU ETS does not set specific reduction targets for aviation for two reasons:

- allowances for the ETS for aviation and for stationary installations are interchangeable, and therefore reductions can take place outside the aviation sector (at least up to 2030);
- most of the emissions are emitted on intercontinental flights that are not covered by the EU ETS. Whether a potential inclusion of these flights in the EU ETS would lead to a reduction of CO_2 emissions would depend on the number of additional allowances that would be added to the system and the reduction path over time.

Due to the recent revision of the ETS cap, the number of new ETS allowances would become zero around 2040. This implies that intra-EU flights after 2040 that combust fossil fuel (blended with SAF) would also require saved ETS allowances or created allowances. Potential (but not yet classified) options to create certified allowances could be permanent carbon storage or carbon removals from the atmosphere (direct air capture). However, it is still very uncertain if these technologies are available on large scale in 2040 and wat the consequences would be if compensation of remaining greenhouse gas emissions within the EU is not possible. Without adaption, not fully decarbonized industrial processes or intra-EU transport would have to stop at the moment when all saved certificates are used. This seems to be a unlikely situation given the enormous consequences and risks.

ReFuelEU Aviation Regulation (blending obligation)

The main provision of the ReFuelEU Aviation Regulation is a mandatory blending obligation of Sustainable Aviation Fuels (SAF) in the fuel mix supplied at airports in the European Union[13]. The minimum share of SAF increases from 2% in 2025 to 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050. In addition, a specific share of the fuel mix should comprise synthetic fuels: 1.2% in 2030, 2% in 2032, 5% in 2035 and progressively increasing to 35% in 2050 (EP, 2023). The types of SAF that are allowed to contribute to the blending obligation are renewable synthetic fuels, renewable hydrogen, certain categories of biofuels and recycled jet fuels produced from waste gases and waste plastic. Biofuels based on feed or food crops or derived from palm and soy materials are not considered sustainable, in line with the criteria of the RED (see below) (EP, 2023).

To prevent tankering practices and the associated additional emissions, the Regulation includes the obligation for aircraft operators to ensure that the quantity of fuel uplifted at EU airports is at least 90% of the annually required aviation fuel (Council of the EU, 2023a).

RED3

The revision of the Renewable Energy Directive (RED) includes a target for the use of renewable energy in the transport sector. Member States can choose whether they accept a binding target of 14.5% reduction of greenhouse gas intensity in transport from the use of renewables in 2030, or a binding share of at least 29% of renewables within the final consumption of energy in the transport sector by 2030 (Council of the EU, 2023b). Aviation is part of the transport sector, but Member States are free to decide what the contributions of the various transport modes to the target will be.

Furthermore, the RED3 strengthens the sustainability criteria for biofuels and introduces a combined target for advanced biofuels and Renewable Fuels of Non-Biological Origin (RFNBOs)[14]. It requires a share of at least 5.5% advanced biofuels and RFNBOs in the renewable energy mix supplied to the transport sector in 2030, with a minimum of 1% RFNBOs (Council of the EU, 2023b).

This target should be assessed in conjunction with the ReFuelEU Aviation Regulation (see above), which includes a

[13] Airports that process small amounts of passengers or cargo are excluded from the obligations of the Regulation. In the original proposal, the limit was set at 1 million passengers or 100,000 tons of cargo annually. According to Council of the EU. (2023a). *Council and Parliament agree to decarbonise the aviation sector*. Council of the European Union. https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/council-and-parliament-agree-to-decarbonise-the-aviation-sector/, this scope was altered during the negotiations, but at the moment of writing the final text of the Regulation was not available yet to check for changes of scope in this respect.

[14] Mostly renewable hydrogen and hydrogen-derived synthetic fuels.

blending obligation of Sustainable Aviation Fuels (SAF) for the aviation sector in particular. Indeed, the Commission indicates that the ReFuelEU Aviation Regulation should be considered a special case of these RED provisions for the aviation sector (CE Delft, 2021). Looking at the blending obligation provisions, it can be easily concluded that when these are met, the combined target for advances biofuels and RFNBOs is automatically met as well in the aviation sector. Member States have to assure that this target will be achieved in all transport fuels collectively.

Energy Tax Directive (ETD)

The revision of the ETD aims to bring it in line with the EU's climate and energy policy objectives. To do so, it introduces different categories for energy products, such as fuels and electricity, and a ranking of these categories based on their environmental performance. Energy tax rates should, according to the proposal, follow this ranking by applying the highest rate to most environmentally damaging energy products and the lowest rate to clean energy products (CE Delft, 2021). Energy tax rates should, according to the proposal, follow this ranking by applying the highest rate to most environmentally damaging energy products and the lowest rate to clean energy products (CE Delft, 2021).
In the context of this study, the most relevant provision of the revision proposal is the extension of the ETD scope to aviation and shipping. This means that the ETD revision would end the EU tax exemption on kerosene (see Text box 1). Over a period of ten years, the aviation fuel tax rate for intra-EU commercial, scheduled passenger flights would increase from zero to the minimum rate for motor fuels. For sustainable aviation fuels, the rate would be zero for the same transitional period and after that correspond to the minimum rate according to the ranking mentioned above (CE Delft, 2021).

Application of a tax on aviation fuels for full freighter flights and for extra-EU flights is optional, to be decided on by the Member States. It would require separate bilateral agreements with those extra-EU states.

As tax matters are a Member State competence in the EU, the ordinary legislative procedure, with co-decision by the Council and the European Parliament (EP), does not apply to the ETD. Instead, the EP only has the right to be consulted and the members of the Council have to vote unanimously, which renders a decision in the short term improbable.

Conclusions

With the adoption of almost all legal proposals from the Fit for 55 package, aviation is now much more incorporated into the EU's climate policy toolbox than before.
The transport targets of the RED now include aviation and the blending obligation mandates the uptake of SAF. The ETS for aviation, although preceding Fit for 55, was significantly strengthened by the decision to phase out free allowances.

On the other hand, the emission reduction associated with the decreasing cap of the ETS can still easily materialize in other sectors than aviation. This will become harder towards 2040, when the cap will approach zero. In the meantime, the ETD has not proceeded much in terms of decision-making. Therefore, at this moment in time only the SAF blending obligation (against the background of the related RED transport targets) seems well-placed to effectively reduce EU aviation emissions within the sector itself in the near future, but still in a limited way due to the relatively low mandatory SAF percentages up to 2030.

Section Summary
In the Luchtvaartnota, national emission targets for aviation have been established for 2030, 2050 and 2070, but these are not yet legally enshrined. The main instrument to reduce aviation emissions at the national level is the introduction of CO_2 emission ceilings for Dutch airports by 2025 at the soonest.

3.4 National climate policies for aviation

The coalition agreement of the current (outgoing) Dutch cabinet (Rijksoverheid, 2021) includes a number of policy plans on aviation:
- sustainable aviation fuels should be stimulated, including through a blending obligation for bio-kerosene and through investments in the development and production of synthetic kerosene in the Netherlands;
- the Dutch government supports the inclusion of kerosene into the ETD revision (see above);
- flying over short distances will be discouraged, leading to emission reductions on top of those arising from the Fit for 55 package;

- within Europe, train transport should become a proper alternative to flying as soon as possible, in terms of both costs and time;
- proposals in the framework policy document on aviation, Luchtvaartnota 2020-2050 (Ministerie van I&W, 2020) will be implemented, such as the recent increase of the passenger ticket tax and the introduction of the aviation CO_2 ceiling for departing aircraft from Dutch airports. Proposals in the framework policy document on aviation, Luchtvaartnota 2020-2050 (Ministerie van I&W, 2020) will be implemented, such as the recent increase of the passenger ticket tax and the introduction of the aviation CO_2 ceiling for departing aircrafts from Dutch airports.

In the Luchtvaartnota, which was established under the previous government, the general long-term policies on aviation are outlined. It also adopts the 2019 Agreement on Sustainable Aviation[15] , which was the result of a broad stakeholder involvement and includes relative CO_2 emission targets for the Dutch aviation sector[16]:
- in 2030, the emissions equal 2005 emissions;
- in 2050, the emissions are maximum half of the 2005 emissions;
- in 2070, the emissions are zero.

It is important to note that these emission targets have not been legally enshrined yet. The main (future) policy instrument for securing them is the introduction of the CO_2 ceiling, as announced in the coalition agreement and formally decided by the cabinet in March 2023 (Minister van I&W, 2023a). On each of the 'relevant' airports[17] in the Netherlands, a CO_2 emission ceiling for departing international flights will be imposed for 2030, 2050 and 2070, with a linear emission decrease assumed between the different projection years. The exact design of the emission ceiling instrument is subject of current study by the ministry, allowing for the input from relevant stakeholders. It will enter into force in 2025 at the soonest.

Another policy instrument that was included in the Sustainable Aviation Agreement and hence in the Luchtvaart-nota was a target of a 14% SAF share in the fuel intake at Dutch airports in 2030, and 100% SAF in 2050. However, recently the European Commission indicated that it will not allow the Netherlands to impose a higher blending obligation

[15] Akkoord Duurzame Luchtvaart.

[16] On the basis of fuel intake at Dutch airports.

[17] All airports with international traffic should be included under the emission ceiling, but a distinction is being made between the three airports with slot coordination (Schiphol Airport, Eindhoven Airport and Rotterdam The Hague Airport) and airports without slot coordination.

than the one required by the ReFuelEU Aviation Regulation (6% in 2030 and 70% in 2050, see above) (Loupatty, 2023).

Other proposed measures included in the Luchtvaartnota may also affect the climate impact of aviation, apart from impacts in other areas such as noise or local air pollution.
These include for instance a cap on the total number of flights allowed from Schiphol Airport, new generation airplanes, operational improvements and changes in the airspace design.

The national emission targets and the emission ceilings apply only to CO_2. However, attention for non-CO_2 climate impacts of aviation is increasing and the Dutch cabinet is developing a policy framework to address these non-CO_2 impacts as well.
In a recent letter to Parliament (Minister van I&W, 2023b), the cabinet outlined this framework, centred on three different strands: 1) more research, for instance on the non-CO_2 effects of different types of sustainable fuels; 2) efforts to strengthen policies on non-CO_2 effects at EU and ICAO level and 3) enhancing national and international cooperation to bridge the gap between scientific insights and the day-to-day business of the aviation sector.
In a recent letter to Parliament (Minister van I&W, 2023b), the cabinet outlined this framework, centred on three different strands: 1) more research, for instance on the non-CO_2 effects of different types of sustainable fuels; 2) efforts to strengthen policies on non-CO_2 effects at EU and ICAO level, and 3) enhancing national and international cooperation to bridge the gap between scientific insights and the day-to-day business of the aviation sector.

Section Summary
The International Air Transport Association (IATA) has committed to achieve net-zero carbon emissions from flying operations in 2050. About 340 Mton of the projected 1.8 Gigaton CO_2 emissions to be mitigated would be covered by CCS and offsets.
The European aviation industry presented its own roadmap to realise this target in the Destination 2050 report. This roadmap is more ambitious than the IATA target as it projects to make use of carbon removals rather than offsets.
The Science Based Target initiative (SBTi) supports companies in setting their own emission reduction targets. Its current guidance for aviation is based on a pathway corresponding to global warming of ‘well-below 2 ºC’.

3.5 Sectoral ambitions

Apart from policy targets and instruments at the various levels of governance, the aviation sector itself has also formulated targets and policies with respect to emission reduction from international aviation.

IATA Fly Net Zero target

The International Air Transport Association (IATA), the global trade association for airlines, adopted a resolution in 2021 committing itself to achieving net-zero carbon emissions from their operations in 2050 (IATA, n.d.). Note that this is one year earlier than ICAO did – see Section 3.2. In IATA's own projections, the net-zero target, called Fly Net Zero, implies that in 2050 1.8 Gigaton of CO_2 emissions need to be mitigated. IATA estimates that 65% of this reduction can be achieved by using SAF, 13% by applying new propulsion technologies such as hydrogen, and 3% by efficiency improvements. The remaining 19% (about 340 Mton) could be dealt with by carbon capture and storage (CCS, 11%) and offsets (8%) (IATA, 2021). IATA defines a goal for 2050 but does not explicitly take into account a specific path towards 2050 (cumulative emissions).

Destination 2050

Earlier in 2021, the European aviation industry presented its own roadmap to reaching net-zero emissions from all flights within and departing from the EU, called Destination 2050. According to the Destination 2050 report (NLR & SEO, 2021), the EU aviation sector seeks to achieve this by reducing emissions with 92% and remove the remaining 8% from the atmosphere through negative emissions (carbon dioxide removals, CDR). Like IATA, Destination 2050 defines a goal for 2050 with specific requirements for the path that sets a limit to the carbon emissions (carbon budget).

It is important to note that negative emissions are not the same as offsets, which are used under CORSIA and mentioned in the IATA scenario for achieving net-zero emissions. Contrary to offsets, negative emissions do actually remove carbon from the atmosphere and thus are able to physically compensate for emissions. To ensure this compensation is real and permanent, though, negative emissions need to fulfil several strict criteria (Tanzer & Ramirez, 2019). Furthermore, permanent carbon removal is not being applied yet at any significant scale as most available technologies are not yet technologically mature, are still very expensive per tonne of CO_2 captured or cope with other types of uncertainties, such as limited availability of sustainable biomass (CE Delft, 2023).

Science Based Target initiative (SBTi)

The Science Based Target initiative (SBTi) supports companies from different sectors with a clear-defined and science-based decarbonization pathway in order to reduce their emissions in line with the Paris Agreement (Science Based Targets, n.d.). Its guidance for the aviation sector was developed by the World Wildlife Fund (WWF) with support from the International Council for Clean Transportation (ICCT) and the Boston Consultancy Group (BCG) (Science Based Targets, 2021). It states that, to be in line with the Paris targets, the aviation sector should reduce average carbon intensity by ~35-40% between 2019-2035 or ~65% from 2019-2050.

The methodology used in the guidance focuses on jet fuel emissions (WTW) and does not take into account ground operations. Currently, it does not take into account non-CO_2 effects either and it is based on a global warming target of 'well-below 2 ºC'. A 1.5 ºC pathway is under development (Science Based Targets, 2021).

The SBTi approach is centred on companies submitting and communicating their own emission reduction target. It does not prescribe how the target should be achieved, although the guidance does provide possible elements of an emission reduction strategy. It only considers emission reductions and does not take into account carbon removals (Science Based Targets, 2021).

The SBTi 1.5˚C (50% likelihood) interim pathway has approximately constant emissions until 2030. From 2030, it anticipates a drastic decline in CO_2 intensity of about 10% per annum on average. This reduction is to be delivered by technological breakthroughs and massive use of SAF. With this approach it postpones urgently required action, as will be discussed in the next sections.

3.6 Conclusions

In Table 1, an overview is presented of the targets and instruments directed at reducing aviation emissions at various governance levels, as described in the previous sections.

Table 1 - Overview of the targets and instruments directed at reducing aviation emissions treated in the sections above

Overview of targets and policy instruments for aviation at different levels of governance				
Agreement or instrument	**Target**	**Legal status/actors**	**Scope**	**Remarks**
Global level (Section 3.2)				
Paris Agreement	Long-term temperature goal (2, preferably 1,5 °C global warming)	Binding for all parties to the Agreement	All emissions	All aviation included in target, but mandatory NDCs only have to cover domestic aviation.
CORSIA	Carbon neutral growth from 2020	Binding for non-exempted Member States from 2027	All aviation emissions covered by CORSIA above CORSIA baseline	Based on offsetting of emissions. Instrument ends in 2035.
LTAG	Net-zero emissions in 2050	Non-binding	All aviation emissions	
European level (Section 3.3)				
EU Climate Law	55% GHG emission reduction in 2030; climate neutrality in 2050	Binding at EU level	All domestic EU emissions, also departing flights are included	Targets do not apply at national level but all Member States should contribute their fair share.
ETS Aviation Directive	No (only in combination with stationary ETS)	Binding for airlines	Intra-EEA aviation	Reductions can also be realised in other sectors as ETS allowances are interchangeable; ETS cap will reach zero around 2040.
RED3	Transport target in 2030; RFNBO/advanced biofuels subtarget (5.5% of which 1% RFNBOs) in 2030	Binding for Member States	All transport fuels used in EU	For the transport target, Member States can choose between 14.5% GHG intensity reduction or 29% renewables. Member States can decide on the contribution of aviation to these targets.

Overview of targets and policy instruments for aviation at different levels of governance				
Agreement or instrument	**Target**	**Legal status/actors**	**Scope**	**Remarks**
ReFuelEU Aviation Regulation	SAF blending obligation of 2% in 2025 increasing to 70% in 2050	Binding for Member States/fuel suppliers	Aviation fuel uptake in EU, some exemptions	
Energy Tax Directive (ETD) proposal	-	Binding for Member States (when implemented)	All energy products. For aviation fuel: mandatory for intra-EU passenger flights, optional for cargo and extra-EU flights.	In proposal phase, no agreement yet (and not expected in the short term). If adopted, Member States are required to apply a minimum tax rate on aviation fuel for intra-EU passenger flights.
National level (Section 3.4)				
Luchtvaartnota	In 2030, emissions equal 2005 emissions. In 2050; emissions equal half of 2005 emissions. In 2070, emissions are zero.	Non-binding	Departing flights from Dutch airports	Policy ambition, but not enshrined in law.
CO_2 ceiling	No concrete ceilings yet	Binding (when implemented)	Departing flights from Dutch airports	Not yet translated into concrete emission ceilings for Dutch airports; only then the instrument would become legally binding.
Sectoral level (Section 3.5)				
IATA	Net-zero emissions in 2050	Non-binding	All aviation emissions	Offsets allowed.
Destination 2050	Net-zero emissions in 2050	Non-binding	All emissions from flights within and departing from the EU	Negative emissions (CDR) foreseen.
Science Based Target initiative (SBTi)	Global warming of well below 2 °C	Non-binding	CO_2 emissions from fuel (WTW)	The SBTi invites companies to formulate and communicate their own GHG emission reduction target. A 1.5 °C pathway is under development.

From this Table and what was covered in the previous sections, we can draw the following main conclusions:
at the global level, the Paris Agreement is the main standard for climate policy. Although its scope includes all emissions, the inclusion of international aviation in its main instrument, the NDCs, is not mandatory. Instead, to reduce international aviation emissions, countries should ‘work through ICAO’.

ICAO sets a target of carbon neutral growth for aviation from 2020, which means it only aims to mitigate *additional* emissions compared to 2020 levels. Even so, its main instrument, CORSIA, is not sufficient to achieve this target. In the first place because not all aviation emissions will be included in its baseline due to exemptions, and in the second place because it allows for carbon offsets to compensate for emissions. As offsets are not the same as carbon removals from the atmosphere, a true compensation of emissions is not guaranteed.

Although the EU does not apply a specific target for GHG emissions reduction in aviation, it regulates both intra- and extra-EU aviation through different policy instruments. At this moment in time, however, only the SAF blending obligation seems well-placed to effectively reduce EU aviation emissions within the sector in the near future, and still in a limited way due to the relatively low mandatory SAF percentages up to 2030. Under current legislation no new ETS allowances would become available from 2040, which would mean intra-EEA emissions should be zero by then, unless other ways of acquiring allowances would be available.

Different sectoral initiatives have emerged at different levels, mainly directed at net-zero emissions in 2050, but none of them implies a legal obligation to reduce emissions.

At the level of the Dutch government, emission targets for all departing flights have been set and a carbon ceiling for Dutch airports to implement these targets is in preparation, but none of this has been legally enshrined yet.

All-in-all, partly because of the sector’s tendency to continue to grow, current climate policies at different governance levels seem insufficient to realise a reduction of emissions from international (and Dutch) aviation that would be in line with the Paris objectives.

Remaining CO_2 budget for global and Dutch aviation

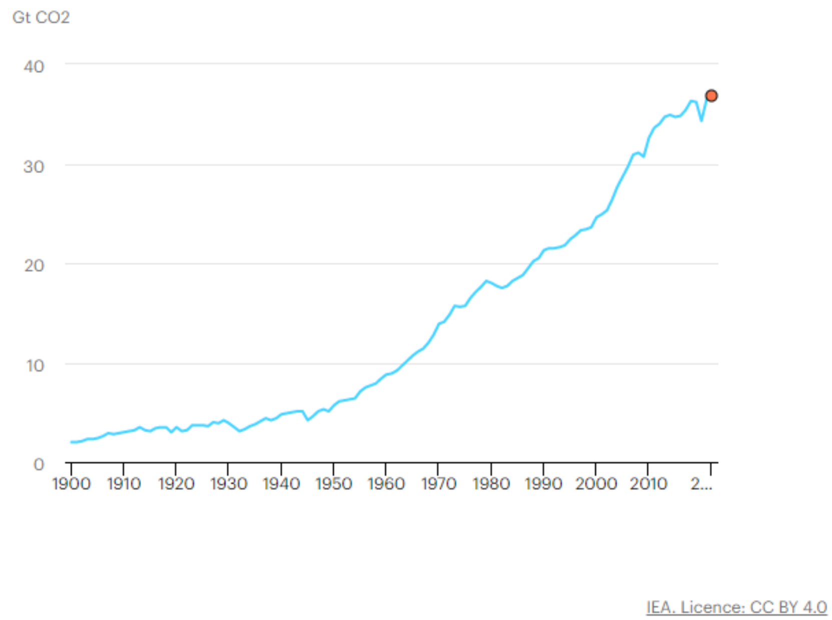
4.1 Introduction

Since 1900, global CO_2 emissions per year have increased from 2 Gt in 1900 to 37 Gt in 2022 (see Figure 7). The increase was moderate in the first 50 years (6 Gt emissions in 1950) and increased during the last 70 years with a dip during the COVID19 pandemic and a fast recovery in the last two years.

In the Paris agreement the overall objective was set to hold the global average temperature increase to well below 2 °C above pre-industrial levels and to pursue efforts to limit this increase to 1.5 °C. This implies that not only the increase in CO_2 emissions has to be stopped, but the trend has to be turned into a fast decrease in global GHG emissions. In this chapter we answer the question:

'Which CO_2 budget in 2030 for global and Dutch aviation is in line with global warming of 1.5 °C and well below 2.0 °C?'

Figure 7 - Global CO_2 emissions from energy combustion and industrial processes, 1900-2022



Source: (IEA, 2023b).

In this chapter, first a qualitative description of the required development of the global aviation sector towards 2050 is presented. Afterwards, the remaining global CO_2 budget is discussed. Different ethical frameworks are applied for the distribution of the remaining CO_2 budget between sectors and countries resulting in the budgets for the global and Dutch aviation sector in 2030.

4.2 Aviation development towards 2050

In this section, it is assumed that global net-zero emissions in all sectors is reached around 2050. To assess what this would mean for the aviation sector, we first give a short description of the current situation. Afterwards, the final state of global net-zero emissions is described, which should be reached around 2050 depending on the exact global reduction path. Finally, the path towards 2050 is discussed, since the focus of this study is 2030.

Aviation current situation

Currently, the aviation sector depends for almost 100% on fossil kerosene. Overall aviation contributed to 2.4% (TTW) or 3.7% (WTW) of global CO_2 emissions in 2019. The difference between the Tank-To-Wing (TTW) and the Well-To-Wing (WTW) emissions is whether the energy that is required for the fuel production and distribution (Well-To-Tank emissions) are associated to the aviation or to the energy sector (for details see Text box 7). Despite efficiency improvements in aircraft technology and operations, the sector's emissions have increased by 2.3% per year on average between 1990 and 2019, as growth in air travel demand outpaced efficiency improvements in aircraft technology and operations (IEA, 2023a).

In addition to CO_2, aviation emits NO_x, sulphate aerosols, soot particles and water vapour on a cruise height of about 10 km. These emissions also occur at ground level from other sectors, but they only contribute to global warming at high altitudes due to chemical and physical processes. The two largest non-CO_2 climate impacts of aviation come from contrail-cirrus formation and NO_x emissions. The impact of non-CO_2 depends, in addition to the emitted amounts, on the emission location (mainly altitude and latitude) and the actual atmospheric conditions (weather, day-time).

In contrast to CO_2, the time horizon of the non-CO_2 effects is much shorter. The different timescales of the CO_2 and non-CO_2 effects make it difficult to compare the effects to global warming. The best estimate of the combined worldwide non-CO_2 climate impacts of aviation is that in 2018, they were responsible for the same amount of radiative forcing as the cumulative CO_2 emissions between 1940 and 2018 (Lee et al., 2021).

The main takeaways from the current situation in the aviation sector are:
- aviation contributes to 3.7% of global CO_2 emissions if emissions of fuel production and distribution are included;
- energy demand is almost 100% fossil kerosene;
- globally demand grows faster than efficiency improvements leading to an annual growth of CO_2 emissions by 2.3% over the last three decades;
- large non-CO_2 climate impact of aviation.

Aviation 2050 situation

The Paris agreement ambition to limit climate warming to 1.5 °C requires net zero emissions around 2050. The 'lower' the temperature goal, the faster the decarbonization has to happen. Net zero emissions means that emissions and carbon sequestration have to be balanced from that date for the sum of all sectors. Due to the cumulative character of CO_2 in the atmosphere, emission overshoots in specific sectors or periods have to be compensated by negative emissions in other sectors or different periods in time. It is expected that in the transportation sector some emissions remain in 2050, which require compensation from other sectors, for instance from agriculture or forestry. Still, transportation emissions would need to decrease by around 90% in 2050.

The goal of net zero emissions in 2050 for all sectors implies:
- almost 100% clean energy generation;
- complete and permanent compensation for remaining emissions (removal of storage);
- sufficient clean energy, biomass and carbon storage for the decarbonization of all sectors worldwide.

Text box 7 - Well-to-Wing (WTW) vs. Tank-to-Wing (TTW) emissions

Fuel emissions can be associated with either fuel production or fuel combustion.
Fuel production emissions are well-to-tank (WTT) emissions, while fuel combustion emissions are tank-to-wing (TTW) emissions. WTT and TTW emissions combines result in well-to-wing (WTW) emissions. For fossil kerosene the WTW emission is 3.203 kg CO_2-eq./litre, with a 78% share for TTW and 22% for WTT (CO2emissiefactoren.nl, 2023). Solely considering TTW emissions means that the emissions associated with fuel production are assigned to the energy sector. The Science Based Target (SBTi) transport guidance prescribes that it is desired that scenarios are developed on a WTW basis (Science Based Targets, 2021). There are two key reasons for this:
1. Including upstream production and distribution (WTT) emissions is required to credibly account for the use of Sustainable Aviation Fuels (SAFs).
2. Inclusion of upstream production and distribution (WTT) emissions best captures emissions reduction from future alternative power plants, including those that consume electricity and hydrogen.

Sustainable aviation fuels (SAF) are either biofuels or synthetic fuels. The emissions related to the combustion of these fuels are comparable to fossil-based jet fuels, except for marginal efficiency gains. By far the majority of the emissions reductions are due to the production process. In order to take this into account the WTW emissions are assessed with a Lifecycle Analysis (LCA) approach, which includes feedstock recovery, fuel production, transportation at all stages of the chain and the fuel combustion in aircraft engines.

For the SAF production energy is required, for instance for biomass to be converted in biofuels. Currently, most energy is 'grey', produced using fossil fuels. Green energy is produced using renewable sources, thus no emissions are associated with this process. The 2050 goal is that all energy is produced using renewable 'green' sources. Only considering TTW emissions would not capture this shift from 'grey' to 'green' energy.

The majority of the generated energy will be produced by renewable sources as wind, sun and water, but biomass and nuclear energy will also play a certain role. Some energy might still be generated through fossil fuels, although volumes will decrease drastically and remaining emissions from fossil fuels must be compensated.

Permanent and complete carbon sequestration is either done naturally by trees, plants or the ocean who capture CO_2 from the air or by permanent carbon storage in the ground. Carbon storage is currently still challenging and expensive, which makes it an uncertain 'solution' (see Text box 5). Therefore, it is undesirable to completely rely on this and not take action to curb carbon emissions.

The availability of sufficient clean energy has a large impact on the WTW emissions of SAF (see Text box 8). Assuming 100% green electricity, results in WTW emission reductions compared to kerosene of more than 95% for all SAF types (NLR & SEO, 2021). Synthetic fuels are produced using green energy and CO_2 from the atmosphere or industrial processes. The carbon is first captured at the production phase – either through DAC or at industrial emitters - and later during combustion in the jet engine released in the atmosphere. Hence, the net emissions of synthetic fuels are zero.
The same applies to biofuels. Biofuels are produced using (clean) energy and biomass. The biomass has captured the CO_2 during the growing phase of the plant and that is released in the atmosphere during the flight. However, there a several arguments why biofuels are not entirely carbon neutral (see Text box 8).

Text box 8 - Overview Sustainable Aviation Fuels (SAFs)

Sustainable aviation fuels are developed to replace fossil kerosene, as they bring a significant emission reduction. The production or SAFs require feedstocks, which are either biomass feedstock or clean energy.

The following available or most promising SAFs can be distinguished:
- Hydro-processed esters and fatty acids (HEFA);
- Fischer-Tropsch (FT);
- Alcohol-to-Jet (AtJ);
- Power-to-Liquid (PtL).

The first three are biofuels and the latter is a synthetic fuel. Biofuels are made from biomass or residues, in combination with (clean) energy. HEFA is commercially the most mature biomass for biofuel production. The main feedstock for HEFA are waste and vegetable oils – of which future availability is limited (see Text box 11) - in combination with (green) hydrogen (Becken et al., 2023). Currently, almost all hydrogen is produced using fossil fuels. In 2019, less than 0.1 % of all hydrogen was produced using clean energy, and thus labelled as green hydrogen (IEA, 2019). FT mainly uses agricultural and forestry residues in combination with (clean) energy to produce biofuel (Becken et al., 2023). The AtJ process mainly uses sugarcane, corn grain and switchgrass and converts this to ethanol or other alcohol via fermentation (Becken et al., 2023). Synthetic fuels use captured CO_2 – either direct air capture (DAC) or residual industry CO_2 – and (clean) energy and through a chemical process this results in synthetic kerosene, hence no biomass is required. In essence, this process is the reverse of combustion.

The average current life-cycle CO_2 savings for 2030 of the different SAFs compared to kerosene are (EU, 2018):
- HEFA: 65%;
- FT and AtJ: 65%;
- PtL: 85%.

As more clean energy becomes available and the share of green hydrogen increases in the future, the average life-cycle CO_2 savings of all SAFs is expected to increase to 95% for biofuels and to 100% for synthetic fuels (NLR & SEO, 2021).As more clean energy becomes available and the share of green hydrogen increases in the future, the average life-cycle CO_2 savings of all SAFs is expected to increase to 95 % for biofuels and to 100 % for synthetic fuels (NLR & SEO, 2021).

The aviation sector is not the only sector which needs to decarbonize. All sectors require sufficient green energy, biomass and if necessary, carbon storage. As a consequence, these inputs are probably scarce in 2050 leading to competition between sectors for green energy and biomass. A more detailed explanation on the future availability of green energy and biomass is given in Text box 11.

Text box 9 – Are biofuels carbon-neutral?

There is no consensus in science/literature whether biofuels, and to be more specific biomass, should be defined as carbon neutral (Becken et al., 2023). In essence, plant material (biomass) is not a clean energy source as it releases CO_2 emissions when burned. However, plant growth is an ongoing process, subjected to the availability of land (or water for algae fuels). The emissions from burning biomass are in the past absorbed from the atmosphere during plant growth. The issue arises from the time lag between the carbon emissions and the equivalent amount being removed from the atmosphere and stored in new plants (biomass). Forest biomass is the most critical given the age of trees in natural ecosystems. The lag time is equal to the age of a feedstock. If the feedstock is from a 100-year-old tree, then the time lag is 100 years. It must however be noted that after 50 years, it can be assumed that a large part of the carbon is already sequestrated.

In addition, there will always be more CO_2 in the atmosphere as long as biomass is burned (Becken et al., 2023). The net effect of accumulated atmospheric CO_2 of biomass harvesting results in a permanent increase of atmospheric CO_2 levels compared to a scenario where forests remain intact. In order for bioenergy to effectively decrease atmospheric CO_2 levels, it must be guaranteed that the total emissions from growing, processing, distributing and burning biomass are not larger than all alternative actions that would have happened to the biomass if it was not used as a green energy source. According to (Becken et al., 2023) it is therefore invalid to assume that biomass is carbon neutral.

Furthermore, it is argued that energy from renewable sources is not entirely carbon neutral (Becken et al., 2023). Energy-infrastructure is required for production and transport of this green energy. For instance, materials needed for the production of wind turbines or solar panels require scare materials and releases CO_2 emissions during the manufacturing process of these sustainable energy technologies. The emissions are referred to as embodied emissions.

In 2050, offsets are infeasible since all countries and sectors need to reach net-zero emissions (see Text box 5). Examples of offsets are compensating aviation's CO_2 emissions by for instance planting trees or building new public transport in developing countries that replaces more CO_2-intens transport. However, it is not guaranteed that the trees are not destroyed by wild fires or that the public transport would not have been built without the offsets. Hence, these kind of offsets do not guarantee CO_2 reduction while at the same time they extract money from the aviation sector, which could also be invested in decarbonization of aviation.
Worldwide demand of aviation is expected to increase significantly due to the expected worldwide economic growth. In addition, demand implications will occur due to changes in costs. On the one hand, fuel costs are expected to rise leading to higher ticket prices and resulting in a deceleration of aviation growths. Reasons for the expected fuel cost increase are additional costs for fossil fuels for instance due to increasing CO_2 pricing via the EU ETS and higher costs for SAF compared to kerosine. On the other hand, fuel costs will decrease due to efficiency improvements in aircraft technology and operations, resulting in lower ticket prices and thus accelerating aviation growth.

For the aviation sector specific, net-zero emissions in 2050 implies:
- offsets for CO_2 emissions are not possible since all countries and sectors need to reach net-zero emissions;
- non-CO_2 emissions require compensation;
- remaining TTW emissions from fossil kerosene must be compensated by Carbon Dioxide Removal.

Aviation GHG emission pathway towards 2050

The remaining carbon budget towards the net-zero goal, has to be shared globally with all sectors, resulting in competition between aviation and other sectors for this carbon budget.
This carbon budget is a total fixed budget for all years until 2050. High emissions in the next years automatically results in less carbon budget in the years further ahead, which makes it more challenging to reach net-zero in 2050. It thus requires

immediate action to decarbonize and reduce emissions in all sectors including aviation.

To reach the goal of net-zero emissions in 2050, the aviation sector relies on SAFs to reduce their emissions. Scaling-up SAF production takes time. Even with historically high year-on-year growth rates of renewable electricity and green hydrogen production, and when DAC will be technically mature and ready to be scaled up, this takes decades (Bauen et al., 2020). Hence, the immediate scaling-up of biofuel production and pre-commercial development of the synthetic fuel production becomes imperative, as solely relying on depleting the remaining carbon budget and switching to SAFs overnight is impossible.

Production of SAFs require green energy and biomass, but the aviation sector is not the only sector requiring green energy and biomass for its decarbonization. Demand for green energy and biomass will increase in the future, resulting in competition between sectors for these goods not only in 2050 but already in the next years. More information regarding the availability of clean energy and biomass is given in Text box 11.

Text box 10 – Hard-to-abate or Costly-to-abate

Aviation is usually referred to as a hard-to-abate sector, meaning that GHG emissions from this sector are difficult to bring down. Although the projected global growth of aviation is not working to the advantage of quickly achieving absolute reductions, we want to clarify that emissions in the aviation sector are technically not hard-to-abate. Although there are initiatives for electric and hydrogen planes, or innovative aircraft designs as the flying V, which would reduce fuel consumption (TU Delft, 2023), using drop-in SAFs instead of fossil-based fuels will in fact do the job and is both easily applicable and technically proven. Bio-based SAFs are already being produced on a limited scale and e-SAFs have reached TRL 8, meaning that pilot plants have shown that their production is technically feasible (ITF, 2023). Almost all aspects related to aviation – airplanes, engines, airports, fuel infrastructure – only need moderate adaptions (technological and operational efficiency improvements) or can even be maintained in their current form. Only fuel production processes have to change and need significant scaling-up. In contrast, the decarbonization in other sectors is considerably more complex, as can be seen for instance in heating of residential houses. The transformation from natural gas heating and cooking towards other alternatives often requires fundamental renovation to improve isolation, as well as installation of new stoves and heat pumps. The investment costs are however offset by the reduction in utility expenses, given that electricity proves to be cheaper than gas. In aviation, this is not the case since SAF production is more expensive than fossil kerosene. Hence, the 'hard' part is actually not technically hard but 'costly'.

Text box 11 – Availability of clean energy and biomass

For the decarbonization, the aviation sector heavily relies on the shift from fossil fuels to sustainable aviation fuels (SAFs). In the medium-term, these are mostly biofuels, while in the long-term the share of synthetic e-kerosene is expected to increase significantly. There are two essential components required to produce biofuels, (clean) energy and biomass. Synthetization of different (aviation) roadmaps shows that in 2050, the aviation sector could require 9% (20 EJ) of all global renewable energy and 30% (15 EJ) of the worldwide available biomass energy (Becken et al., 2023) The increasing share of SAFs in aviation could therefore be problematic for two reasons:

1. Biomass competes for land needed for nature-based carbon removal and other land use.
2. Clean energy could be used more effectively to decarbonize other sectors.

The first point refers to land use implications associated with biomass. Food, municipal and industry waste only delivers a fraction of the total volume of biomass needed. Energy crops, agriculture and forest residues will become essential to meet the biomass demand. Potential feedstocks for SAFs are:

- Energy crops: 5-10 EJ;
- Waste (food, municipal and industry): 5 EJ;
- Agricultural residues: 5-12 EJ;
- Forest products: 10-20 EJ.

The latter three all have substantial impact on land use. In addition, for forest biomass there is a significant time lag in re-sequestering biocarbon, leading to a discussion whether it can be stated biofuels are carbon-neutral when produced using clean energy (see the textbox *Are biofuels carbon-neutral?* for more information).

To understand the second point, it is important to realize that large energy losses occur in the production chain of SAFs. At each stage there is energy 'lost' as heat waste – for turning non-fossil primary energy into final energy for SAFs that delivers the required energy density for aircraft engines. The 'energy return to energy invested' (EROI) is a ratio of the returned usable energy, to all the energy invested to make this useable energy. $EROI_{standard}$ indicates the energy content of the primary energy source and $EROI_{final}$ indicates the energy content of the final energy carrier. The $EROI_{final}$ incorporates $EROI_{standard}$ plus additional required energy to produce this final energy carrier. The EROI of a fuel decreases when energy becomes more scarce and more difficult to produce or extract. The $EROI_{standard}$ of oil is 20 and the $EROI_{final}$ of fossil jet fuel is 5.8.The $EROI_{standard}$ of bioenergy for biogenic SAF lies between 3 and 4 for sugar cane and is less than for others. The $EROI_{final}$ from biogenic SAF ranges from 1.64 of palm oil (HEFA) to 0.36 of sugarcane (AtJ). In the process of fuel conversion from bioenergy to SAFs between 9-60% of the energy is lost. For producing synthetic kerosene, more than half of the primary input energy is lost due to conversion and distribution. This increase to the order of 70% if the synthetic kerosene is used for propulsion.

The aviation sector is not the only sector that requires clean energy and biomass to reduce its emissions, leading to the fact that clean energy is a scarce good. The fact that the production of bio-SAF is energetically costly ($EROI_{final}$ values of around 1), raises the question whether there is a net climate benefit from a wider cross-sectoral perspective if around 9% of all clean energy is used for SAFs, where the majority of electricity is wasted (Becken et al., 2023).

Conclusion

- Aviation is a technically easy-to-abate but costly-to-abate sector.
- Immediate scaling-up of biofuel production and pre-commercial development of the synthetic fuel production are essential.
- High energy requirements in the SAF production chain and competition between sectors for sufficient green energy and biomass result in an allocation problem of these resources between sectors and countries. In the following section the allocation problem is discussed for different ethical frames.

4.3 Global GHG budgets

IPCC has estimated remaining carbon budgets from the beginning of 2020 onwards for different temperature limits and probabilities that these budgets will limit global warming to the temperature limit.

Table 1 - Estimated remaining carbon budgets from the beginning of 2020 in Gt CO_2

Estimated remaining carbon budgets from the beginning of 2020 (Gt CO_2)	50%	67%	83%
1.5 °C	**500**	400	300
1.7 °C	850	**700**	550
2.0 °C	1350	1150	900

Source: (IPCC, 2022).

Today (mid 2023), 3.5 years later almost 130 Gt CO_2 of the budget is already emitted to the atmosphere, 36.0 Gt in 2020 37.9 Gt in 2021, 36.8 Gt in 2022 and assuming half of 2022 emissions for the first half of 2023 (Crippa et al., 2021) (Crippa et al., 2022) (IEA, 2023b). As an illustration we have estimated the number of years that remain until the global GHG budgets are reached, if the current emissions stay constant (see Table 2).

Table 2 - Remaining CO_2 budget mid-2023 and remaining number of years until the budgets are exhausted when the current worldwide emissions stay constant

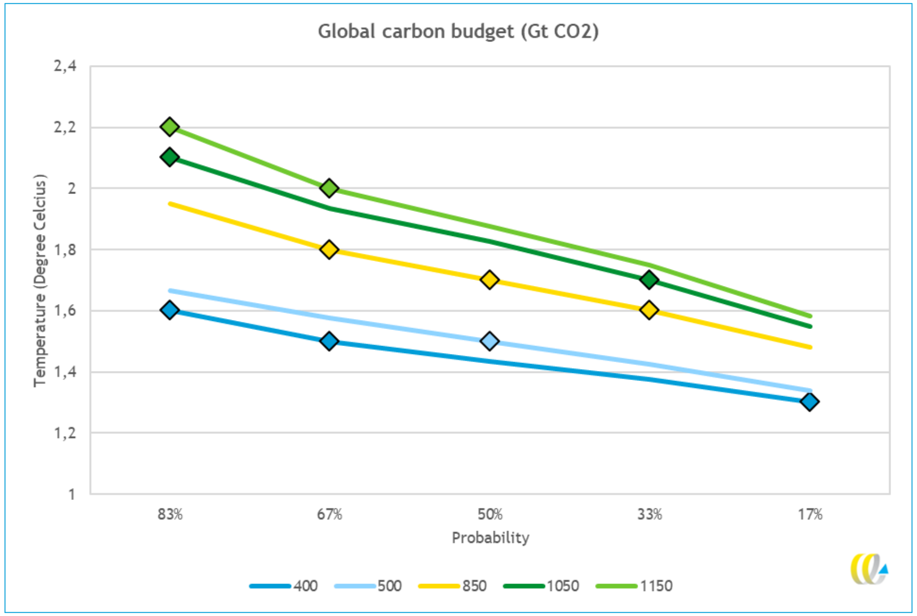
Temperature increase (probability that limit is exceeded)	Remaining carbon budget (50% likelihood)	Remaining years with current emissions (36.8 GT per year)
1.5 °C (50%)	370	10.1
1.7 °C (66%)	570	15.5

Figure 8 illustrates the relationship between the temperature increase and the probability that this limit is reached for 4 carbon budgets, 400 Gt, 500 Gt, 850 Gt, 1,150 Gt.
The 1,150 Gt budget has a probability of approximately 33% that the critical limit of 2 °C will be exceeded. Since the Paris Agreement sets the goals to hold global warming well below 2 °C and to pursue efforts to limit it to 1.5 °C, this budget cannot be considered to be in line with the Paris agreement.
The 400 Gt budget, seems to be out of reach given the fact that already 130 Gt have already been used in the last 3.5 years despite a reduction in global economic activities due to the COVID19 pandemic.

In the further analysis of this study two budgets will be considered in two scenarios:

- 500 Gt budget scenario: has a 50% likelihood that global warming is limited to below 1.5 °C and >83% for below 1.7 °C. With this budget the temperature increase may be limited to 1.5 °C and is likely to stay below 1.7 °C.
- 700 Gt budget scenario: has a 67% likelihood that global warming is limited to below 1.7 °C and about 90% for below 2.0 °C. With this budget the temperature increase may be limited to 1.7 °C and is very likely to stay below 2.0 °C. The extent to which this budget is Paris-aligned is debatable.

Figure 8 - Visualization of the relation between the global temperature increase and the probability that this limit is exceeded for four CO_2 budgets. The markers correspond to original values from IPCC (see (IPCC, 2022)), the lines illustrate the trend for all probabilities between 17 and 83%.



4.4 Global aviation CO_2 budgets

To determine the share of aviation from the remaining global carbon budget, the following scenarios have been considered:
- constant share of aviation in global CO_2 emissions from 2019 onwards;
- share of aviation according to the carbon budget in the IEA Net Zero Emissions (NZE) scenario.

Table 3 presents the share of aviation in the global carbon budget according to the different scenarios.

Table 3 - Share of aviation in global carbon budget

Share of aviation in global carbon budget	TTW emissions
CO_2 emissions 2019	2.4%
IEA NZE carbon budget	3.9%

With these estimates a bandwidth for the share of aviation in the global carbon budget can be constructed. The lower end of the bandwidth would be equal to 2.4%, a constant scenario represented by the 2019 share of aviation in global CO_2 emissions. The upper end of the bandwidth would be 3.9%, a growth scenario represented by the share of aviation in the IEA NZE carbon budget. The IEA scenario assumes cost-efficient global decarbonisation, in which the less costly-to-abate sectors decarbonise first. This means that the share of aviation is allowed to grow with respect to other sectors. This principle of cost-efficient decarbonisation is also reflected in the global reduction targets, see Text box 12, in which the reduction targets for aviation are clearly lower.

Based on this bandwidth the remaining global carbon budgets for aviation are estimated (see Table 4). The budgets vary between 12.0 Gt and 27.3 Gt.

Note, that non-CO_2 climate effects of aviation are not considered in these budgets. The main reason is that these emissions do not cumulatively add up, since their lifetime in the atmosphere is much shorter. Hence, they do not ‘eat’ the budget. However, non-CO_2 emissions lead to global warming for a short period in time. During this period they increase the probability of reaching tipping points in global warming and to contribute to irreversible processes. Therefore, it is very important to develop efficient non-CO_2 policies and to reduce them as soon and as fast as possible. In a net zero situation non-CO_2 emissions have to be compensated for example by means of permanent carbon storage or carbon removal.
For a detailed explanation see Annex A.

Table 4 - Carbon budget for aviation

Global aviation carbon budget	50% 1.5° (500 Gt)	66% 1.7° (700 Gt)
Current share 2.4%	12.0 Gt	16.8 Gt
IEA NZE share 3.9%	19.5 Gt	27.3 Gt

Text box 12 - Aviation reduction compared to other sectors

Every sector is required to reduce its CO_2 emissions to achieve global net-zero in 2050. The reduction path in the IEA NZE scenario of the aviation sector is compared to other sectors here, to gain insight in the differences in the speed of reduction. The projected CO_2 for 2050 and the percentage decrease compared to 2019 for all sectors is shown in Table 5. The comparison shows that the reduction targets are lower for the transport sector compared to other sectors and within transport the required reduction is the lowest for aviation, since aviation is costly-to-abate.

Table 5 - Aviation reduction compared to other sectors (IEA, 2021)

Sector	Subsector	CO_2 emissions 2019 (Mt)	CO_2 emissions 2050 (Mt)	% change
Electricity and heat sectors		13,821	-368	-102.7%
Industry		8,903	519	-94.2%
Transport		8,290	689	-91.7%
	Road	6,116	340	-94.4%
	Aviation	1,019	210	-79.4%
	Shipping	883	122	-86.2%
Buildings		3,007	122	-95.9%

4.5 Dutch aviation CO_2 budgets

What is a fair share for Dutch aviation? This is a complex question, which cannot be answered satisfactory by purely weighing technical or economic arguments, since it implies ethical issues. It boils down to the question how uniform or heterogenous the budget should be distributed between global citizens.

A starting point could be the current share of Dutch aviation of 1.16% of global aviation. This share would manifest the disproportional high amount of flights from Dutch citizens compared to population groups elsewhere. When the global budget would be distributed to countries by shares of the world population in the period of 2019-2050[18], the share of the Netherlands would be only 0.21%, thus more than a factor five less. However, this allocation method is very theoretical given the current differences in economic development and aviation activities between the countries of the world. It would allow the same aviation emission between today and approximately 2050 for individual persons in developing and developed countries.

Given the fact that the population growth and economic growth is expected to be larger in other parts of the world than in the Netherlands, it is also expected that the aviation

[18] Based on forecasts from the United Nations and CBS.

sector grows faster in developing countries. Using forecasts for the socio-economic development of countries as a proxy leads to a share for the Netherlands of 1.05%. This share for the Netherlands is used for further analysis.

Table 6 combines the global carbon budgets with the global shares of aviation and the Dutch share, leading to four carbon budgets for Dutch aviation.

Table 6 - Dutch aviation carbon budget

Dutch aviation carbon budget	50% 1.5° (500 Gt)	66% 1.7° (700 Gt)
Current share 2.4%	126 Mt	176 Mt
IEA NZE share 3.9%	205 Mt	287 Mt

Reflections on the budgets:
- The ambition of the Paris agreement is to limit global warming to 1.5 °C and to enforce warming well below 2 °C. This fits best with a global budget of 500 Gt. As explained in Chapter 2, the physical impacts of a global warming of over 1.5 °C may be disproportionally larger than that of 1.5 °C due to tipping points. To not risk overshooting this level of global warming, the Netherlands, being one of the wealthiest nations on Earth, should at least aim for the 1.5 °C. Therefore, the 126 Mt and 205 Mt budgets for Dutch aviation are considered to be fully in line with the Paris agreement, whereas the other two budgets explore the upper boundary.
- An economic approach for the decarbonisation leads to an increase of aviation compared to other sectors due to the fact that aviation is a ‘costly to abate’ sector.
- However, aviation is not a basic need and for many people a luxury product. One might also argue that aviation has to follow the same or even a more restrictive path than other sectors. If a family has not enough money they probably will skip the summer holiday before they stop drastically reduce eating or heating.
- In the distribution of the aviation budget between the Netherlands and other countries, the historic high amount of emissions is used as a starting point for determining the Dutch budget. This implies that the Dutch budgets have to be interpreted as maximum budgets. An approach that would require more efforts by developed countries than by developing countries would lead to lower budgets.

Budget per average person

Since a budget of 205 Mt or any other of these budgets is very abstract, we have made the effort to translate it to a budget for the average Dutch person and compare it to the average global citizen. This is a theoretical exercise and we are aware of the fact that different ethical considerations would lead to very different results.

To derive the remaining budgets for Dutch passengers, we first subtract the realized emission between 2020 and 2023 from the initial budget. Despite the significantly reduced aviation activities as a consequence of the COVID19 pandemic, 34 Mt or 17% of the budget has already been used. The remaining budget of 171 Mt is associated with 19% to freight and 81% to passenger leading to a remaining budget of 138 Mt (ICCT, 2019).

This budget is further distributed between transfer passengers (38%), visitors of the Netherlands (24%) and Dutch inhabitants (38%) according to the distribution of CO_2 emissions in 2019. The remaining budget for Dutch passengers is 52.3 Mt, but includes only the departing flights. Therefore, the budget is multiplied by a factor two (104,6 Mt), since these passengers are counted as visitors in the budgets of other countries according to this method. Dividing this budget by 17.5 million inhabitants leads to a personal budget of 6 ton CO_2 for the average Dutch person.

As a comparison, we have estimated the carbon budget for the average global citizen. When subtracting the global aviation emission between 2020 and 2023 and 19% for air freight, the remaining global budget for passengers is 13 Gt. Dividing by 8 trillion people leads to a personal budget of 1.6 ton. The budget of the average Dutch person is 3.7 times larger than the budget of the average citizen according to this theoretical allocation method.

With the current aircrafts and fuels, the budget of 6 ton CO_2 corresponds to:
- 25.5 flights[19] to Barcelona (economy class); or
- 9.5 flights to New York (economy class); or
- 7.3 flights to Tokyo (economy class); or
- 2.4-3.6 flights to Tokyo depending on the chair configuration (business class).

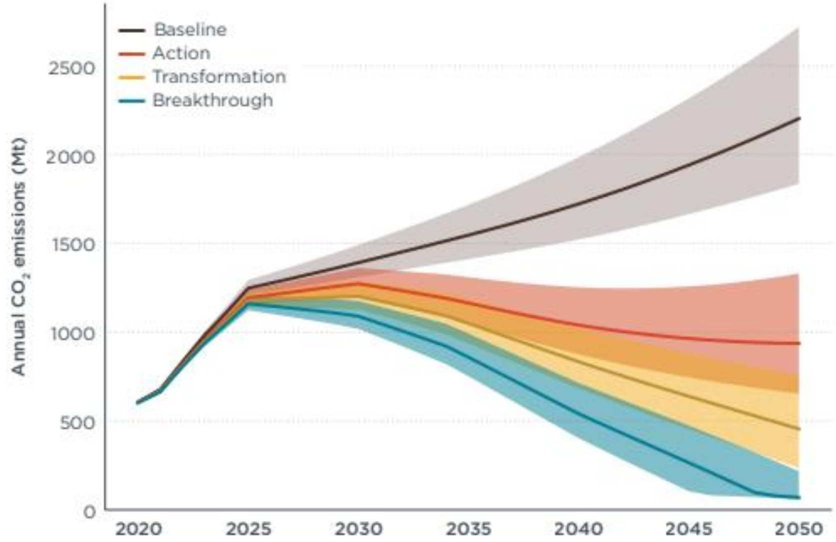
These numbers increase, with the expected efficiency improvements and SAF blending. If we assume ambitious climate policies that lead to zero-emission aviation in 2050 and a linear path for the years in between, the average Dutch person could fly twice a year to Barcelona or almost once a year to New York (and back) based on this budget.

[19] CO_2 emissions per flight are estimated with the ICAO carbon emissions calculator https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx

4.6 Hard-to-abate curves vs. immediate reduction

In aviation decarbonization roadmaps (see Figure 9 for an example), net-zero in a specific year is usually reached by a path that has lower reduction targets in the first years and accelerates after 2030. This accelerating speed curves are motivated by the time needed to 'scale up' new technologies.

Figure 9 - Annual global aviation CO_2 emissions (well-to-wing) until 2050 for different aviation forecasts

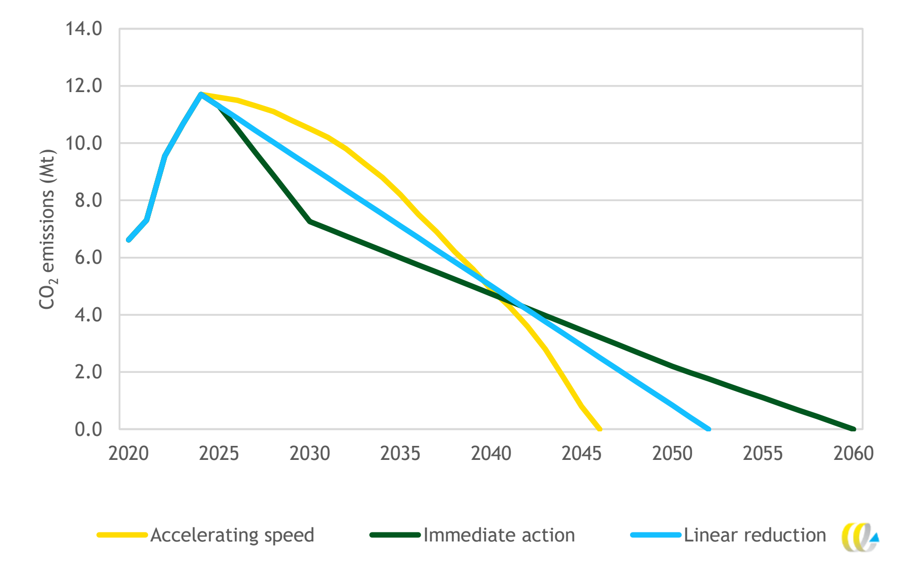


Source: (ICCT, 2022).

This is in line with the shape of the SAF blending targets in the ReFuelEU Aviation proposal (6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050).

Considering the remaining available budgets and the speed at which they are running out, such a pathway is no longer feasible for three of the four budgets without immediate action.

Figure 10 - Potential reduction paths for a remaining carbon budget of 205 Mt



In Figure 10 three indicative reduction paths for the 205 Mt budget are shown. Since the area under all curves is identical the shape determines the year in which zero has to be reached. The three examples are:

- Linear reduction path: This approach reaches zero emissions in 2052.
- Accelerating speed: Moderate reduction in the first years requires zero emissions much earlier than 2050.
- Immediate action: Fast emission reduction before 2030 allows that zero emissions could be reached after 2050, for instance by increasing SAF blending from 70 to 100% between 2050 and 2060.

Both the linear and the accelerating speed variants depend on breakthroughs in aircraft technology, carbon removal or SAF production way before 2050. Whether electric/hydrogen aircrafts or large scale carbon capture and storage (in addition to direct air capture for the production of synthetic fuels) will be available in time is very uncertain. The aircraft that are currently being developed will dominate the fleets in 2050, and these still rely on fossil fuel or SAF.

SAF production capacities will probably be scaled up significantly in the next decades. Whether sufficient clean energy and biomass is available for the global demand is highly uncertain. A risk is that additional blending in Europe cannibalizes the world market. However, this would probably be necessary to reach zero before 2050.

The potential energy demand for all these technologies puts additional pressure on the decarbonization of other sectors and regions worldwide (see also Text box 13).

Text box 13 - Consequences for renewable energy sources in NL

NLR (2023) has estimated the total primary energy required for aviation in the Netherlands in 2050 for each of the four scenarios considered. In the least ambitious scenario (66% likelihood of 1.7 °C, 3.9%) this primary energy use is about 100 PJ higher than the most ambitious scenario (50% likelihood of 1.5 °C warming, 2.4% aviation share), as in the least ambitious scenario the number of remaining flights is higher hence more SAF and carbon removal is needed. As we assume climate neutrality in 2050, all energy needs to be generated from renewable sources. To put this 100 PJ in perspective, about 550 wind turbines of 10 MW each are needed to generate this amount of energy in the form of electricity on an annual basis[20]. This is almost one-third of all wind turbines that are projected to have been constructed in the Dutch part of the North Sea around 2030 (Rijksoverheid, n.d.)[21]. To be sure, these 550 wind turbines would only produce the electricity corresponding to the additional renewable energy required to make the least ambitious scenario for aviation possible, compared to the most ambitious scenario.

[20] Assuming 5,000 full-load hours per wind turbine.

[21] The number of wind turbines in the North Sea in 2050 is still very uncertain.

Apart from the renewable energy needs associated with the production of SAF, bio-based SAF also requires sustainable biomass, which is then not available anymore for other economic sectors. In the least ambitious scenario, about 0.9 Mt of SAF would be needed additionally in 2050 (NLR, 2023), which corresponds to about 1.6 Mt or 60 PJ of biomass[22]. According to CE Delft and Royal HaskoningDHV (2020) the availability of sustainable biomass for the Netherlands in 2050 is estimated at 372-454 PJ annually. This would mean the Dutch aviation sector would lay hold of 13-16% of the available sustainable biomass only for the difference between the most and least ambitious scenarios.

For the highest budget (287 Mt) different reduction paths are possible, although those imply moderate emission reduction until 2030.

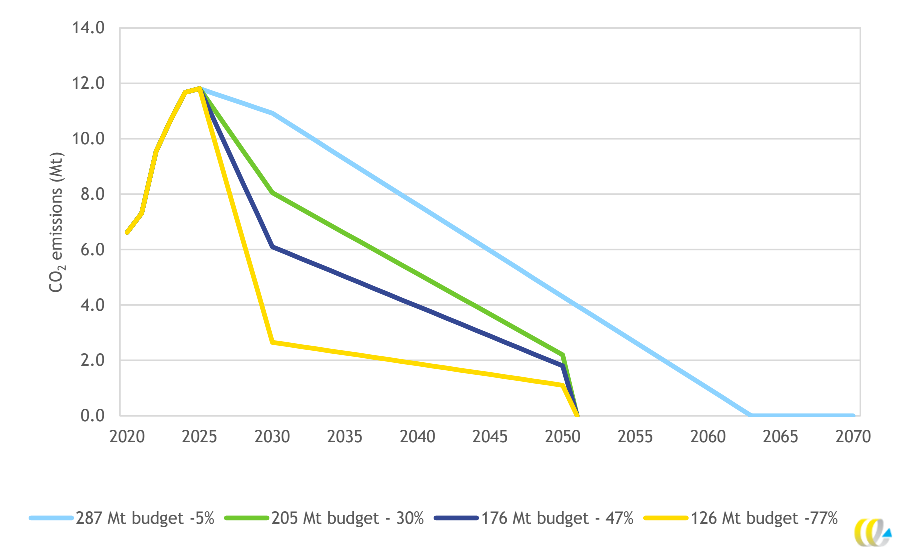
For the other three budgets (205 Mt, 176 Mt and 126 Mt) immediate action is required to prevent dependency on technological breakthroughs, and to limit the risk of overshooting the carbon budget. Otherwise, even more drastic measures are necessary in the future to stay within the remaining carbon budgets.

4.7 Reduction paths and 2030 targets

During the period 2020 to 2024, approximately 46 Mt of the remaining budgets will be used despite the reduced activities caused by the COVID19 pandemic. With the current level of emissions the 205 Mt budget is exhausted in 2038 (13.6 years), the 126 Mt budget in less than 7 years.
We have defined logical stepwise-linear reduction paths for Dutch aviation that fit to the four remaining carbon budgets calculated in Section 4.5. The immediate action is assumed to start in 2025. Later action would require more drastic measures.

[22] Using the conversion factor of 0.04 EJ/Mt from NLR, & SEO. (2021). *Destination 2050: A Route to Net-Zero European Aviation.*

Figure 11 - Reduction paths for the four remaining carbon budgets



The 287 Mt can be reached by setting a zero emission target in 2063 and defining a linear path between the current 2030 target (equal to 2005 level) and 2063. The other budgets require immediate action. Our 'immediate reduction' pathways have a linear reduction between 2025 and goal in 2030 to prevent very strong declines from one year to another. In addition, they contain SAF blending according to RefuelEU and full carbon removals for any remaining emissions after 2050 in line with Destination2050 (see Figure 11 and Figure 12).

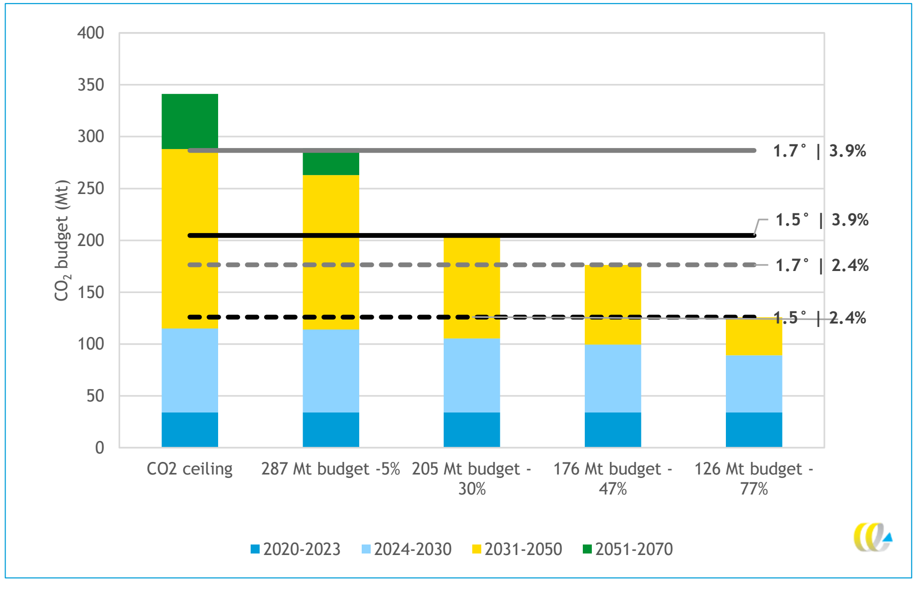
Table 7 - Reduction targets for 2030 and 2050 compared to 2019 emissions for the four remaining carbon budgets

	2030	2050
287 Mt budget (1.7 °C, 3.9%)	-5%	-63%
205 Mt budget (1.5 °C, 3.9%)	-30%	-81%
176 Mt budget (1.7 °C, 2.4%)	-47%	-84%
126 Mt budget (1.5 °C, 2.4%)	-77%	-90%

The targets for 2030 and 2050 are summarized in Table 7. To align with a 1.5 °C pathway, at least 30% CO_2 reduction is needed in 2030, based on a 3.9% share of aviation in total emissions. If aviation maintains its current share, CO_2 emissions must be around 77% lower in 2030. For three of the four scenarios the 2030 reduction targets are significantly more ambitious than the goal of -9% of the Duurzame Luchtvaarttafel. For the 287 Mt budget the extent to which this budget is Paris-aligned is debatable. Worthwhile to mention is that the -5% for 2030 in the existing commitment of the industry itself (Destination2050 and LTAG) cannot be considered anymore as to be aligned with 1.5 °C.

In the 287 Mt budget remaining emission after 2050 can be reduced to zero by increasing SAF blending or by carbon removal. For the other three carbon budgets carbon removal is required from 2050 onwards. In the 205 Mt budget the assumed demand for carbon removal is higher (19% of 2019 emissions) than in the 126 Mt budget (10%). This implies that the clean energy demand and the dependence of large scale carbon removal after 2050 is much higher in the 205 Mt variant.

Figure 12 – Overview of emission in time periods. The CO_2 ceiling shows the potential budget that would fit in the proposed CO_2 ceiling. The percentages illustrate the reduction targets for 2030



Reduction paths with and without carbon removal

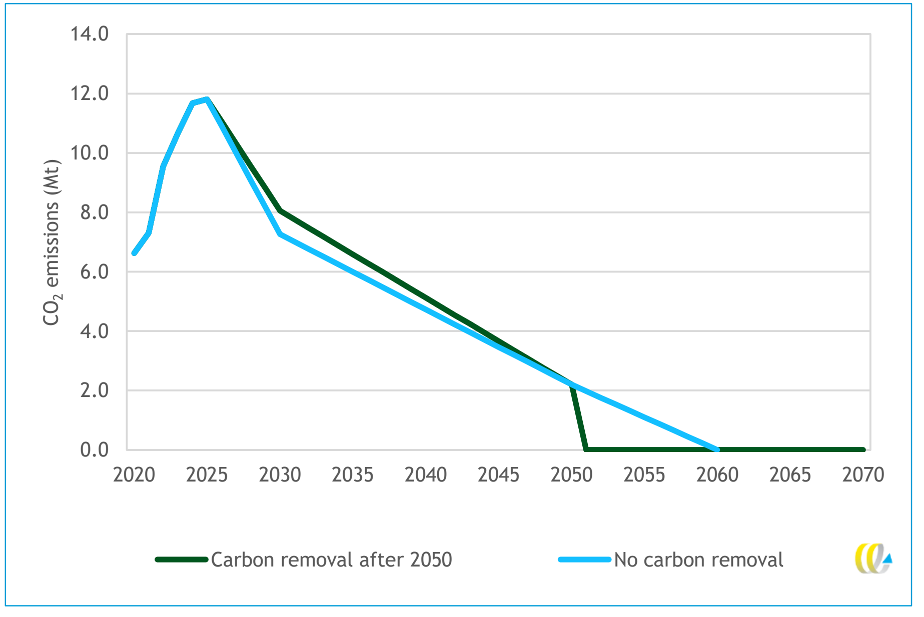
For the 205 Mt budget a sensitivity analysis is performed for situations with and without carbon removal after 2050.
The defined scenarios are:

- A scenario with moderate carbon removal from 2050 onwards (8% compared to the ‘hypothetical no-action growth’ scenario) as proposed in Destination 2050.
- A scenario without carbon removal, which assumes an increase in SAF blending from 70% in 2050 to 100% in 2060.

Th scenario with carbon removal requires a CO_2 reduction of 30% in 2030, without carbon removal this target needs to be increased to 37%. In 2050, emissions have to be reduced by 81% compared to 2019 in both scenarios. See Figure 13 for a comparison of the reduction paths.

We conclude that in 2030 a reduction between 30 and 37% compared to 2019 has to be achieved, which is significantly more than the goal of -9% of the Duurzame Luchtvaarttafel.

Figure 13 - Scenarios for 205 Mt budgets with and without carbon removal after 2030 and its implications on the reduction targets for 2030



4.8 Comparison of budgets to current and planned policies

The Dutch emission reduction goals for aviation are defined in the Civil Aviation Policy Memorandum 'Luchtvaartnota' and acknowledged in the coalition agreement of the current government. Currently, legislation is in preparation to enforce these goals by introducing a national CO_2 ceiling for all commercial flights departing from Dutch airports. The goals are:

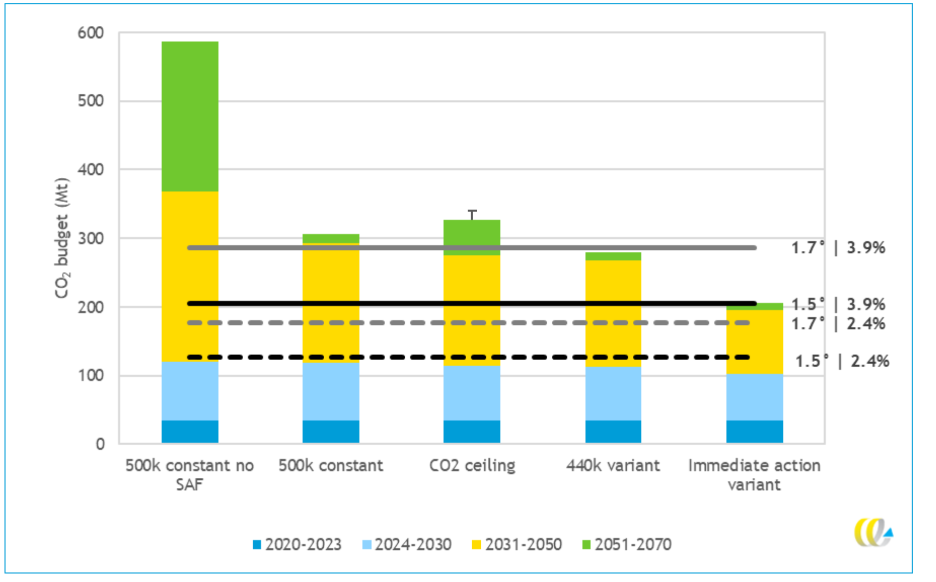
- limit CO_2 emissions to 2005-levels by 2030;
- reduce them by 50% (relative to 2005) by 2050;
- reach zero by 2070.

In the CO_2 ceiling, SAF is counted as zero emissions, which implies that the actual climate impact is higher than the budget of the CO_2 ceiling. Currently, biofuels have life-cycle savings around 65%. In the future, these percentage will increase and synthetic fuels might even become 100% carbon neutral when produced with 100% renewable energy. In the meanwhile this choice leads to a higher remaining budget than a choice in which SAF emissions would be taken into account.

Next to this policy, the current government has announced the reduction of the annual capacity at Schiphol Airport from 500,000 to 440,000[23] flights per year in the period 2025-2029. Afterwards, the sector is given the perspective to grow under not yet defined conditions.

We compare the different options with the four carbon budgets that we have derived from the global IPCC budgets and investigate whether the policies are sufficient to comply. We will also discuss how policies could be adjusted to cope with smaller budgets for Dutch aviation.
Figure 14 compares current and planned policies with the four found Dutch CO_2 budgets, Figure 15 visualises their emissions over time.

Figure 14 - Cumulative CO_2 emissions of policies compared to the Dutch CO_2 budgets

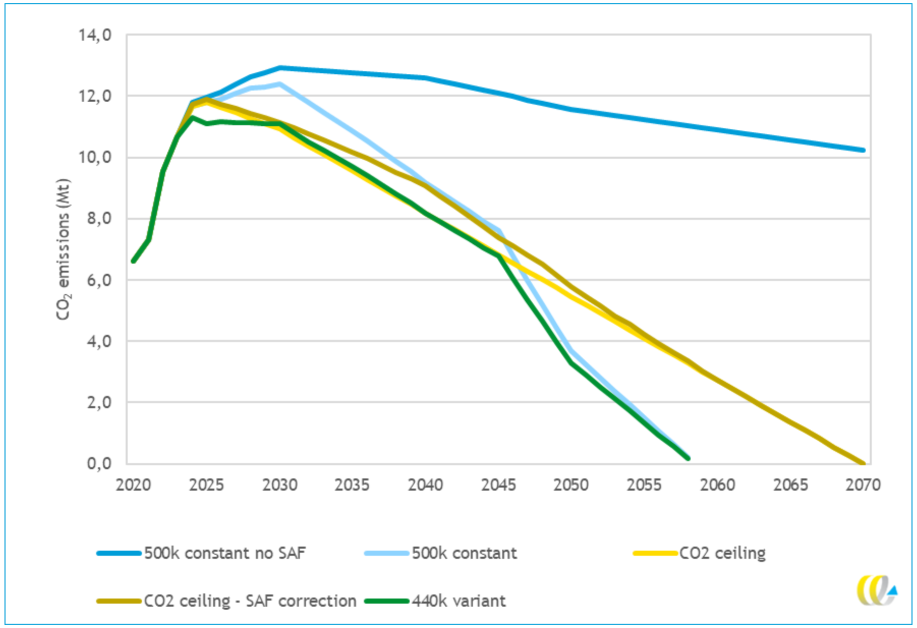


[23] In a revised plan from 1 September 2023 this number has been adjusted to 452,000 flights.

The ‘500k constant no SAF’ scenario assumes the current capacity restrictions at Schiphol of 500,000 flights, no SAF uptake, medium socio-economic growth (average of WLO Low and High) and associated efficiency improvements.

It illustrates a scenario in which no additional sustainability measures are taken, and decarbonisation is only driven by efficiency improvements of aircraft. This scenario would lead to cumulative emissions of 586 Mt and severely overshoot all of the 1.5 °C and 1.7 °C budgets. It shows that using SAFs instead of fossil fuels is a basic requirement for the decarbonization of aviation.

Figure 15 - CO_2 emissions of various scenarios and policies



All visualised scenarios (except the CO_2 ceiling) are AEOLUS model runs. WLO Low and High results are averaged. The CO_2 emissions from SAF are corrected by using the CORSIA guidelines.

The ‘500k constant’ scenario has a capacity limit of 500,000 flights for Schiphol and assumes medium socio-economic growth. The difference is that the announced SAF blending obligation of the RefuelEU Aviation policy is applied.
The impact of SAF blending nearly halves the cumulative emissions to 306 Mt. Note, that we apply a life-cycle approach

here in which SAF is not counted as zero emissions but emission savings compared to fossil kerosene are applied[24]. These cumulative emissions are still higher than all of the 1,5 ºC and 1,7 ºC budgets, but get closer to the '1.7 ºC| 3.9%' budget of 287 Mt. This '500k constant' scenario can be interpreted as a 'baseline scenario' without national policies.

In Figure 14 and Figure 15 two proposed national policies are investigated: the announced national CO_2 ceiling and a capacity reduction at Schiphol to 440.000 movements per year (440k variant).

The cumulative CO_2 emissions under the CO_2 ceiling would overshoot all of the 1.5° and 1.7° budgets with 327 Mt. It is even higher than the '500k constant' baseline scenario. The main reason for this is that the CO_2 ceiling assumes linear decreasing emissions until decarbonisation in 2070 (see Figure 14). Our baseline scenario shows an acceleration in decarbonisation after 2045, in line with the RefuelEU Aviation blending proposal, leaving quite some 'unused' CO_2 budget between 2050 and 2070.

An important sidenote is that the CO_2 ceiling as it is currently proposed by the Ministry of Infrastructure and Water Management does only include emissions from kerosene, SAFs are counted as zero CO_2 emissions. In fact, SAFs do still have remaining CO_2 emissions. For example current biofuels used for aviation have 65% life-cycle savings (EC, 2021), which means that 35% of the CO_2 is still emitted. When taking this into account, using the blending percentages from RefuelEU Aviation, the cumulative emissions until 2050 are increased by 13 Mt visualised with the errorbar.

The '440k variant' represents a 440,000 flights restriction at Schiphol starting in 2024, medium socio-economic growth and SAF blending according to RefuelEU Aviation. We find that this policy would reduce the cumulative CO_2 emissions of Dutch aviation to 280 Mt. This is in line with the '1.7º | 3.9%' budget. However, the emissions are still much higher than the other carbon budgets.

[24] For biofuels the assumed emission savings are 65% until 2030 and increase linearly to 95% in 2050. For RFNBOs/synthetic fuels the savings are 85% in 2030 and 100% in 2050.

4.9 Considerations on global scale of aviation

Measures for sustainable aviation should in principle be introduced on the largest possible geographic scale due to the international character of aviation. If the number of (intercontinental) flights from the Netherlands is reduced, a large fraction of passengers and cargo operators will switch to other airports. Another part will fly less as a consequence of a decline in connectivity and higher ticket prices.

Part of the emission reduction at Dutch airports will be compensated by more emissions at other airports if they have less ambitious reduction targets. However, in all detailed model calculations overall reduction was found when the capacity is decreased at Schiphol (CE Delft et al., Ongoing) (CE Delft, 2022). If the ambition to reduce CO_2 is much higher in the Netherlands than in neighbouring or competing countries worldwide, this may lead to competitive disadvantages on the short term. Not taking this action, will have tremendous consequences on the long term.

The aviation industry worldwide has to answer the question how they prevent a substantial overshoot of the remaining carbon budget. Action is necessary in all parts of the world.

This includes the development of new technology, fast upscaling of sustainable fuels but also ambitious demand management. The instruments that are currently in place are not sufficient. They need to be updated or replaced as soon as possible.

Impacts on the number of flights at Schiphol in 2030

In the previous chapter different remaining CO_2 budgets for Dutch aviation have been estimated. For logical reduction paths for each of these budgets, reduction targets for 2030 have been calculated. The resulting annual CO_2 budgets for Schiphol in 2030 are summarized in Table 8. In the analysis the share of Schiphol from the total Dutch budget is set to 95%, which is the current share.

Table 8 - Remaining annual carbon budgets for Schiphol in 2030

	2030 budget (Mt CO_2/yr)	Carbon removal after 2050
287 Mt budget (1.7 °C, 3.9%)	10.4	No
205 Mt budget (1.5 °C, 3.9%)	7.6	Yes
	6.9	No
176 Mt budget (1.7 °C, 2.4%)	5.8	Yes
126 Mt budget (1.5 °C, 2.4%)	2.5	Yes

This chapter investigates the impacts of the 2030 target on the number of flights for the '1.5 °C, 3.9%' variant without carbon removal. The annual budget in 2030 is 6.9 Mt CO_2.

The number of flights that fits into this budget depends on the development of the key variables:

- aircraft and operational efficiency improvements;
- SAF blending (6% in RefuelEU Aviation);
- aircraft size;
- flight distance.

The fuel efficiency of new aircraft increases due to more efficient engines, improved aircraft designs and different material use. Replacement of old aircraft with new models leads to lower fuel use per revenue passenger kilometre. The average aircraft is operable for about 30 years. This implies that aircraft that will be replaced in the upcoming years will still be in operation in 2050, when the aviation sector wants to be net-zero. Aircraft that are currently in planning at the large manufacturers still make use of the current technology and will require fossil kerosine or SAF for the operations. Hence, the major part of the aircraft in operation will still use the current technology in 2050 with improved efficiency. 1 to 1.5% improvements per year are realistic (ICCT, 2022) (NLR & SEO, 2021). In addition, operational improvements might lead to additional fuel savings of a few percent, Until 2030, efficiency improvements between 10 and 15% are realistic.

SAF blending will increase significantly in the next decades. ReFuelEU includes a blending obligation of 70% SAF in 2050 for departures from European airports. Due to more efficient production chains, upscale of clean energy production and the production of synthetic fuels at large scale, the life-cycle emissions for SAF are expected to decline significantly. However, in 2030 SAF blending will still be in the fledgling stages, with a blending obligation of 6% in ReFuelEU Aviation[25].

In recent decades aviation emissions have been growing due to an increase in the number of aircraft movements but also due to larger aircraft types (that require more fuel than smaller ones) and an increase in flight distance. It is important to realize that a capacity limit on the number of aircraft limit stimulates the use of larger aircraft types.

For our estimation of the number of aircraft movements that fit into the budget, we take the expected efficiency improvement until 2030 and blending into account.
We show the results for different shares of European and intercontinental flights as a proxy for the change in average flight distance and for different developments in aircraft size.

We derive potential numbers of aircraft movements that fit into this budget in 2030 based on the results of the Dutch WLO aviation scenarios. The average forecast of the WLO Low and High scenario's for 2030 has the following characteristics (compared to 2019):

- 500,000 aircraft movements (+0%):
  - 375,000 European flights (-6%);
  - 125,000 intercontinental flights (+25%).
- 96.6 million passengers (+35%);
- 1.05% annual fuel efficiency improvement (-11%);
- 6% SAF blending (+6%);
- 11.4 Mt CO_2 (-1%).

In the WLO the efficiency improvements, SAF blending and constant capacity restriction do not lead to a CO_2 emission reduction until 2030 even with a constant number of aircraft movements, since they are compensated by larger aircraft (more passengers) and longer flight distances (more ICA).

In the WLO scenarios an increase in the number of passengers per flight of 2.7% per year is modelled. This is slightly higher than the historic growths of 2.3% per year, in the 25 years before the Covid pandemic. The reason is that the ceiling on the number of aircraft movements at Schiphol is an incentive to operate larger aircraft types within a limit number of slots.

25 The Dutch ministry of transport has formulated the ambition to introduce a national blending obligation of 14% in 2030. However, this is prohibited by ReFuelEU Aviation.

Figure 16 - Potential number of flights in 2030 at Schiphol in line with the 205 Mt budget

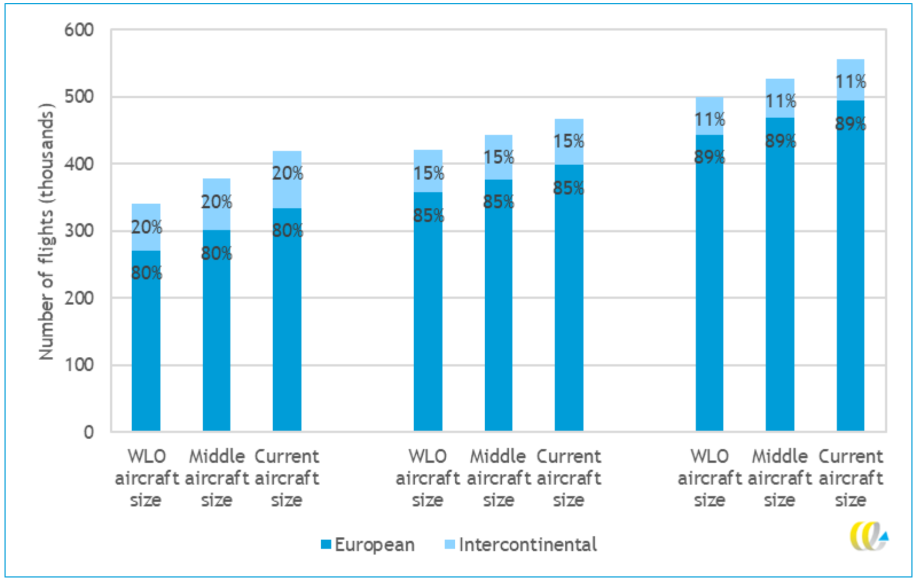


Figure 16 shows the possible number of flights in 2030 for different shares of intercontinental flights and different developments in aircraft size. For the average aircraft size three options are considered:

— the current size (no growth);
— the assumed growth in the WLO scenario's (high growth);
— and the average between the two (low growth).

With the current aircraft sizes and distribution between European (80%) and intercontinental flights (20%) this would limit operations to 419,000 flights. With an increase in aircraft size (and 10% intercontinental flights) the limit would be 340,000 flights only. However, with a reduction of the share of intercontinental flights to 11% and the current aircraft size up to 557,000 flights could fit into the budget.

This estimation shows that the maximum number of flights that fits into the budget strongly depends on the share of intercontinental flights and the assumed development in aircraft sizes. With additional SAF blending for all departing flights from Dutch airports the emissions per flight can be reduced making more flights possible within the same budget. If the blending percentage would be 14% instead of 6% in 2030 about 6% additional flights are possible assuming 70% LCA-emission reduction of SAF compared to fossil fuels.

For the largest budget of 10.4 Mt ('1.7°C, 3.9%-variant') the announced 452,000 aircraft movements could be reached with a decrease in the number of intercontinental flights. For the two smaller budgets of 5.8 Mt ('1.7 °C, 2.4%-variant') and especially for the budget of 2.5 Mt ('1.5 °C, 2.4%-variant') the total number of flights and especially the number of intercontinental flights has to be reduced very significantly. A quantitative estimation is not included in this report.

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Annexes

CE Delft

Committed to the Environment

A Non-CO_2 effects

Next to the emissions of greenhouse gases (GHGs), aviation impacts climate through indirect effects of emissions and changes to the atmosphere. The best estimate of the combined worldwide non-CO_2 climate impacts of aviation from 1940 to 2018 in terms of the current effective radiative forcing are twice as large as the CO_2 impacts, although there is still a considerable scientific uncertainty about their quantification. Despite their importance, there has been very limited policy action to address the non-CO_2 impact.

In addition to CO_2, aviation emits NO_x, sulphate aerosols, soot particles and water vapour on a cruise height of about 10 km. These emissions also occur at ground level from other sectors, but there they do not contribute as greenhouse gases. In the atmosphere they have chemical and physical effects which contribute to global warming. The two largest non-CO_2 climate impacts of aviation come from contrail-cirrus formation and NO_x emissions. The impact of non-CO_2 depends in addition to the emitted amounts on the emission location (mainly altitude and latitude) and the actual atmospheric conditions (weather, day-time).

In contrast to CO_2, the time horizon of the non-CO_2 effects is much shorter, as CO_2 remains in the atmosphere for a relatively long period of time, but the non-CO_2 emissions are short-lived as they break down quicker through chemical reactions. The different timescales of the CO_2 and non-CO_2 effects make it difficult to compare the effects to global warming. An attempt to make them comparable is to define CO_2 equivalents (CO_2e). They can be estimated for different metrics and time horizons.

We have developed a simplified conceptual model to illustrate the effect of the different time horizons, since this is essential to answer the question how the non-CO_2 climate impact should be considered in the IPCC GHG-budgets.

The lifetimes of the most important climate forcers are:
- CO_2: centuries to millenniums;
- water vapour: months;
- higher ozone concentrations as a consequence of nitrogen oxides: weeks;
- lower methane concentrations as a consequence of nitrogen oxides: 12 years.

In the conceptual model the lifetime of CO_2 is approximated with more than 100 years and for the non-CO_2 effects one year is assumed. The development of aviation is described for a fictive period of 100 years, 50 years in the past and 50 years in the future. For the development in the past an annual growth rate for fuel of 5% is assumed. For the period

1971-2020 the warming effect of CO_2 and non-CO_2 emissions are calibrated[26] to 1/3 and 2/3 according to Lee et al. (2021).

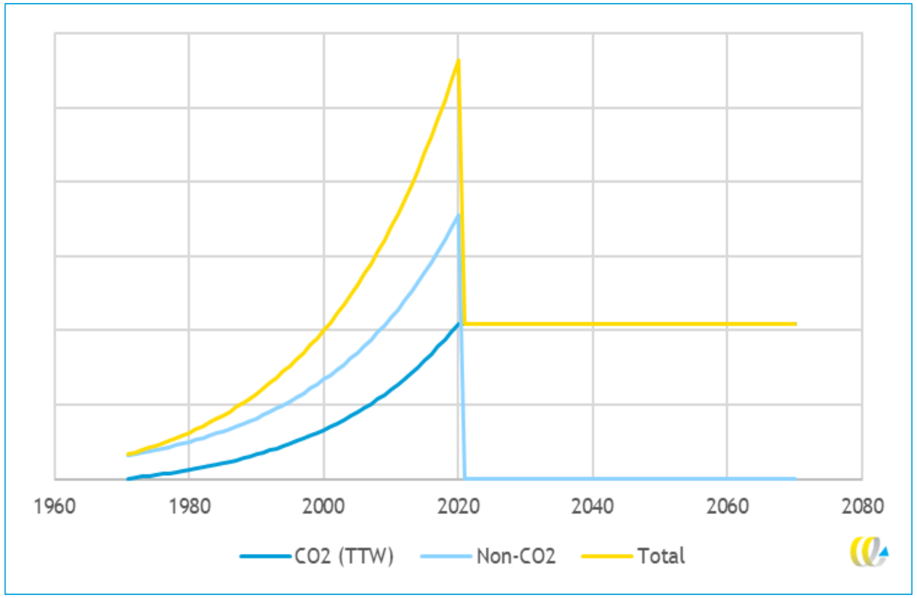
Table 9 illustrates that the share depends on the time period considered, due to the difference between cumulative CO_2 and short-lived non-CO_2. Just considering a single year (2020) leads to a lower non-CO_2 share than when evaluating the entire period.

Table 9 - Share of the non-CO_2 effects in effective radiative forcing (ERF) for different time periods in time according to the conceptual modelTable

Period	Share of non-CO_2
1971-2020	66.7%
1996-2020	64.5%
2011-2020	63.4%
2020	62.9%

In Figure 17, the historic development of the CO_2 and non-CO_2 impact is illustrated for flights until 2020. After 2020, the warming effect of the historic CO_2 emissions persists and is equal to the overall effect, since non-CO_2 has no effect in future years in the conceptual model. In reality, this is not completely true since some agents have a longer lifetime, but this is negligible when long-term effects are considered.

Figure 17 - Results of the conceptual model for CO_2, non-CO_2 and total effect of aviation on global warming



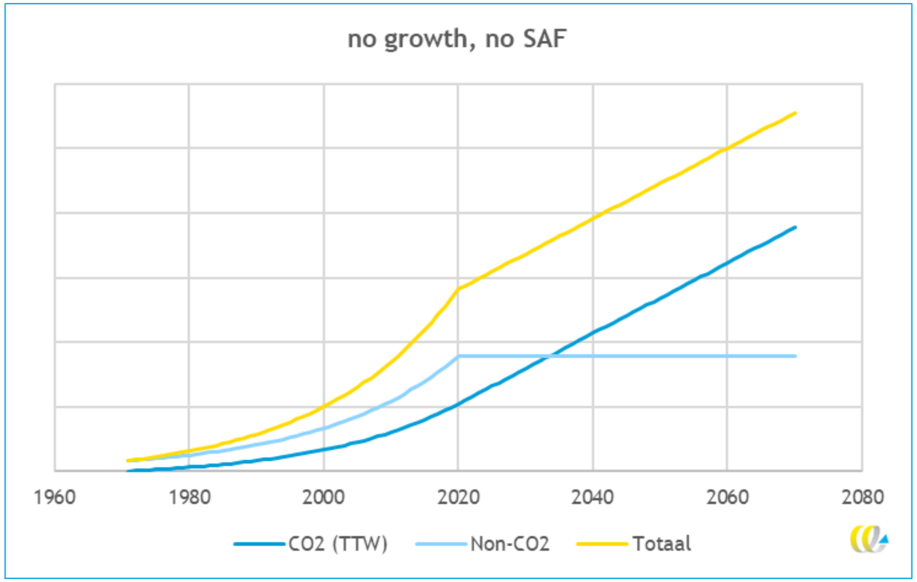
[26] The calibration factor between non-CO_2 and CO_2 used in this model is 32.5.

Hypothetical future developments

We now discus the effects of hypothetical future developments of aviation and its implications on the CO_2 and non-CO_2 climate impact.

Assuming that the growths of aviation would be equal to the efficiency improvements and no SAF would be blended in the future. This scenario would lead to a constant demand of kerosine. The consequences are shown in Figure 18.
The non-CO_2 effects are at a constant level and CO_2 increases over time. Hence, the share of climate impact of non-CO_2-emissions decreases over time.

Figure 18 - Forecast of the conceptual model in case efficiency gains are equal to demand growths and no SAF blending

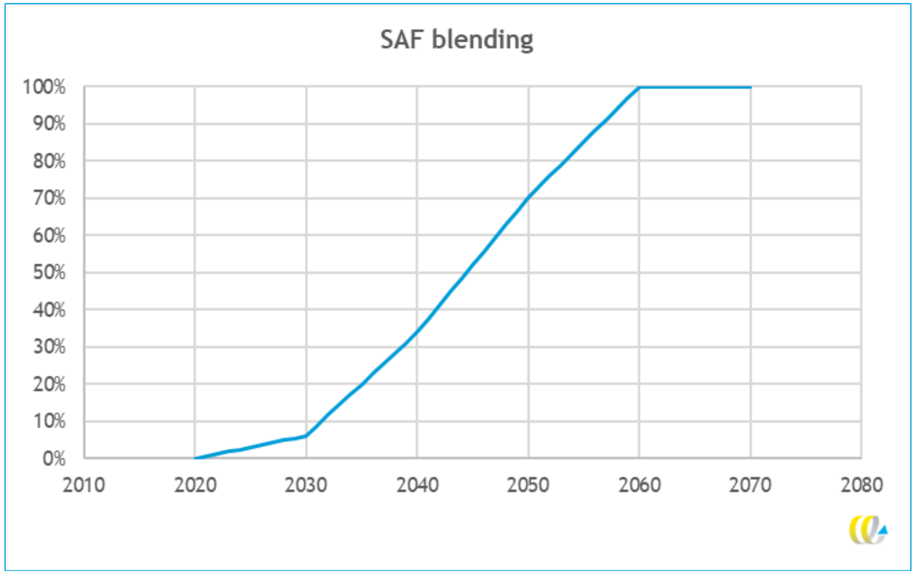


When SAF blending is assumed according to the ReFuel EU Aviation proposal (see Figure 19), the WTW CO_2 emissions decrease significantly[27]. Here, zero emissions for SAF is assumed, which is not completely in line with the 95% emission reduction we assume in the main study for biofuels in 2050. It is likely that SAF will have lower non-CO_2 emissions since it has less aromatics (CE Delft et al., 2022).

[27] This is an optimistic scenario, in which the announced EU-blending obligations is applied to all flights globally.

However, there is still a large uncertainty about the magnitude of the climate impact reduction, which will be realized. Here, we chose two variants, a reduction of the non-CO_2 effects by 25% and by 75%. The latter is very optimistic, when considering the fuels only. We consider this is a combined effect of adjusted flight paths together with additional technical and operational measures.

Figure 19 - Assumed SAF blending. The share of SAF until 2050 is taken from the ReFuelEU aviation proposal and between 2050 and 2060 a linear increase from 70 to 100% is assumed



The results are shown in Figure 20 and Figure 21 for two scenario's, namely one with no growth in aviation fuel demand and the other with a 5% increase per year, the latter is in line with the historic develop of the last decades. In both scenarios, the climate impact of the CO_2 emissions increases until 2060. Afterwards, no additional CO_2 is emitted due to the usage of 100% SAFs. In case, of a constant fuel demand the non-CO_2 effects are a constant offset from 2060 onwards. In the case of growths, the share of SAFs on global warming increases after 2060. The impact strongly depends on the non-CO_2 emission reduction factor.

Figure 20 - Development of emissions in case efficiency gains are equal to demand growths. SAF blending increases as proposed in the ReFuelEU Aviation proposal and reaches 100% in 2060. For the reduction of the non-CO_2 effects two scenarios are distinguished, 25 and 75% reduction compared to fossil kerosine

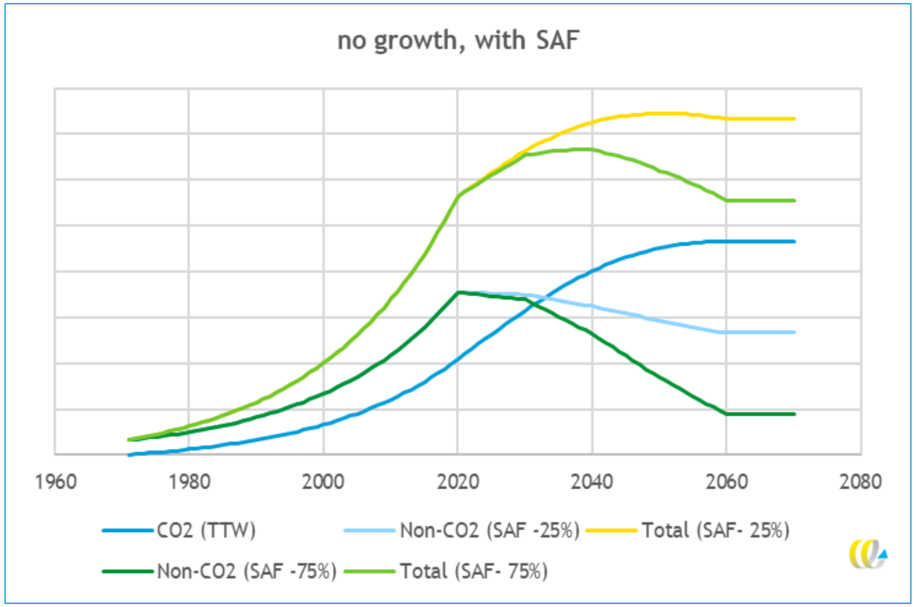
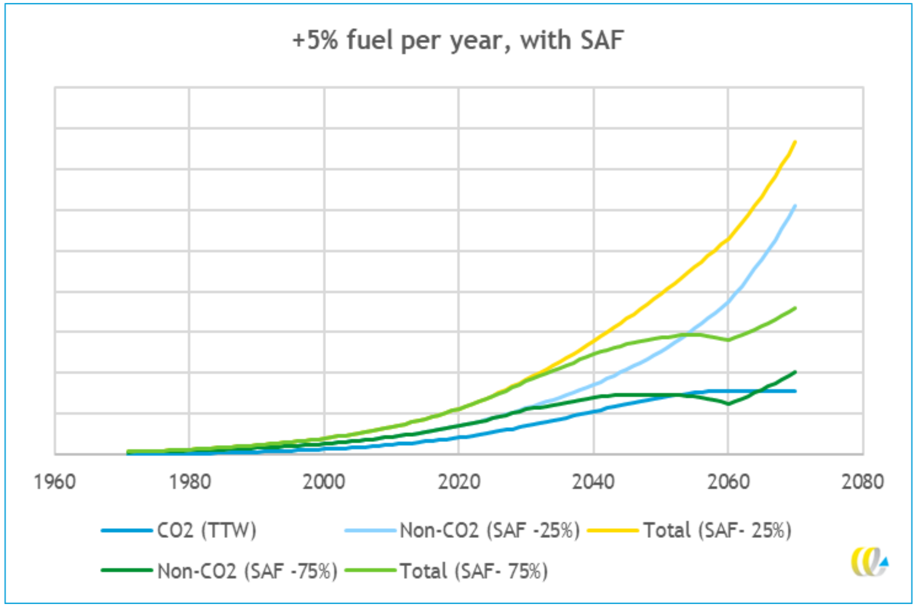


Figure 21 - Development of emissions in case demand growths faster than efficiency improvements. SAF blending increases as proposed in the ReFuelEU Aviation proposal and reaches 100% in 2060. For the reduction of the non-CO_2 effects two scenarios are distinguished, 25 and 75% reduction compared to fossil kerosine



Trade-off between CO_2 and non-CO_2 emissions

Although, there is still a large scientific uncertainty on the non-CO_2 effects of aviation, a very significant reduction is required to bring aviation in line with the Paris agreement. Trading between CO_2 and non-CO_2 emissions is difficult due to the large differences in the lifetimes in the atmosphere. A bit of extra CO_2 emissions could lead to significance reductions of the non-CO_2 effects, for instance by adjusted route choices per lower flight altitudes. However, the extra-CO_2 would lead to global warming for a much longer time than the short-lived non-CO_2 effects. This makes only sense in case the ratio between extra CO_2 and non-CO_2 reduction is very small. After 2060, the TTW CO_2 emissions will be equal to zero. An adjusted route choice and hence extra fuel demand makes much more sense in this situation if it reduces the non-CO_2 effects significantly.

We assume for this study that effective policies will be developed to reduce the non-CO_2 emission of aviation in the next decades. Adjusted route choices and a slight increase in sustainable fuel demand should be considered as realistic options. This should lead to a significant reduction of non-CO_2 emissions. As a consequence, the non-CO_2 effects do not have to be subtracted from the IPCC carbon budgets.

We want to stress that the non-CO_2 emissions lead to global warming for a short period in time. During this period they increase the probability of reaching tipping points in global warming and to contribute to irreversible processes. Hence, it is very important to develop efficient non-CO_2 policies and to reduce them as soon and as fast as possible.

B Scenario assumptions

All scenarios (except the CO_2 ceiling) used in Section 4.6 are AEOLUS model runs. For the calculations in this report, the results of the two WLO scenarios (Low and High) are averaged to keep the analysis simple. The SAF assumptions are based on the RefuelEU Aviation blending obligations, and are stated in Table 10.

Table 10 - RefuelEU Aviation blending obligation

Fuel type	2019	2030	2040	2050
Fossil kerosene	100%	94%	66%	30%
Biofuels	0%	5%	15%	35%
Synthetic fuels	0%	1%	19%	35%

Since this study focusses on an aviation in-sector CO_2 budget, the emission scope here is TTW. For SAF we follow the CORSIA guidelines for TTW emissions (Annex 16, Volume IV, Section 3.3).
For kerosine a TTW emission factor of 3.11 $kgCO_2/kg$ fuel is used. To calculate the TTW emissions of SAFs, the emission factor of kerosine is multiplied by the life-cycle CO_2 savings listed in Table 11.

Table 11 - Life-cycle CO_2 savings for the average SAFs

Fuel type	2019	2030	2040	2050
Biofuels	65%	65%	75%	95%
Synthetic fuels	85%	85%	90%	100%

Source: (NLR & SEO, 2021).

For the period after 2050, we assume that the blending obligation of RefuelEU Aviation will reach 100% SAF in 2060, with an equal mixture of biofuels and synthetic fuels.
The life-cycle CO_2 savings are assumed to be constant after 2050 in line with Table 11.

Colophon

Delft, CE Delft, January 2024

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