NON-CO_2 AVIATION CLIMATE EFFECTS IN COST-BENEFIT ANALYSIS

RESEARCH NOTE

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Executive summary

The precise non-CO_2 climate effects of aviation remain uncertain. This study explores how to monetarily valuate these non-CO_2 impacts and concludes that price differentiation between CO_2 and non-CO_2 emissions is currently not possible Dutch aviation-specific SCBAs.

Research question

Given the evolving aviation climate research on the impact of non-CO_2 emissions and the importance of climate effects in SCBA, this study examines whether the Dutch guideline for aviation-specific SCBA remains sufficient with regard to this topic. The key issues to consider are: the use of a (constant) non-CO_2 to CO_2 emissions ratio, the use of identical monetary valuations for CO_2 and non-CO_2 impacts and addressing the accompanying (scientific) uncertainties. This study looks at the underlying methods and assumptions, but does not assess the numerical values of, for example, the price or weighting factor. We recommend to periodically evaluate these numerical values.

The Dutch aviation-specific SCBA

- The Dutch guideline on aviation-specific SCBA recommends using the efficient price of CO_2 emissions to monetarily valuate CO_2 emissions.
- The Dutch aviation-specific SCBA guideline recommends to derive the impact of the non-CO_2 emissions by converting these emissions to CO_2 equivalents via an emission weighting factor. The guideline recommends using an emission weighting factor of two. This approach is recommended until more precise identification of individual non-CO_2 components at flight level becomes available and can be applied. Furthermore, the guideline recommends sensitivity analyses using emission weighting factors one and four.

Main findings

- CO_2 equivalents are popular for assessing the impact of different greenhouse gases relative to CO_2. Emission weighting factors are multipliers to represent the additional climate impact of non-CO_2 emissions. They are the ratio of total CO_2 equivalent emissions to CO_2 emissions and follow from climate metrics and their time horizons.
- From the perspective of climate and atmospheric science related to aviation, there is no unique and objectively correct emissions weighting factor. A metric applying a shorter time horizon will yield a higher non-CO_2 to CO_2 ratio, and hence gives greater weight to non-CO_2.
- For aviation-related non-CO_2 emissions in particular, the chemical processes and the interaction with other aerosols and gases is very complex to measure, leading to parametric uncertainty.
- In the Dutch policy context, the efficient price is based on the abatement cost approach applying integrated climate assessment models. Using the efficient price in SCBA implies using CO_2 equivalents, the need for weighting factors and the use of a single price for the climate-related greenhouse gas emissions. Identifying different efficient prices for different greenhouse gases in the current abatement cost approach is inconsistent. Therefore, the recommendation in the guideline to apply the efficient CO_2 (equivalent) price for both CO_2 and non-CO_2 emissions remains valid.
- From a theoretical perspective, the social damage cost approach is often considered preferable to the abatement cost approach. The marginal benefits of emission reduction, however, are hard to estimate. This fact prevents the application of this approach in the Dutch SCBA context.

Recommendations

- The recommendations to use a constant emission weighting factor, or to use differentiated factors when identification of individual non-CO_2 components at flight level becomes available, also remain valid.
- Although different climate metrics can be applied with different time horizons, we advise to align the time horizon of the climate metric with the applied time horizon in SCBAs. This implies a time horizon of 100 years.
- Sensitivity analyses applying a lower and upper limit of the weighting factor are appropriate to address parametric uncertainty. However, this bandwidth should not reflect variation in weighting factors due to the choice of climate metric, time horizon or other observed factors. Furthermore, when differentiated factors become available, a single lower and upper limit will most likely not be sufficient. Differentiated factors, hence, should come with differentiated lower and upper limits to reflect the underlying parametric uncertainty.
- Although this study looks only at the underlying methods and assumptions and does not assess the numerical values of the weighting factors, we recommend to periodically evaluate these values. The anticipated update of the efficient price path of CO_2 emissions for the Netherlands would be an opportune moment to evaluate the recommended emission weighting factors, including lower and upper limits.

Samenvatting

Er is geen consensus over de precieze omvang van het niet-CO_2 klimaateffect van luchtvaart en de verhouding tussen CO_2 en niet-CO_2 daarin. De in Nederland voorgeschreven prijs van CO_2 biedt geen ruimte voor het toepassen van een separate prijs van niet-CO_2 in maatschappelijke kosten-batenanalyses.

Achtergrond en onderzoeksvragen

Tegen de achtergrond van de toenemende kennis over de niet-CO_2 klimaateffecten van luchtvaart en het belang van de klimaateffecten in luchtvaartspecifieke maatschappelijke kosten-batenanalyses (MKBA's), evalueren we in deze studie in hoeverre de huidige werkwijzer luchtvaartspecifieke MKBA's op dit terrein nog aansluit bij de wetenschappelijke kennisbasis. We kijken hierbij, onder andere, naar de aanbeveling om een constante verhouding (wegingsfactor) tussen CO_2 en niet-CO_2 effecten te hanteren, het toepassen van één prijs voor de gezamenlijke effecten, en op welke manier een MKBA recht kan doen aan de huidige kennisonzekerheid rondom niet-CO_2 klimaateffecten. Deze studie kijkt naar de onderliggende methoden en veronderstellingen, maar beoordeelt niet de cijfermatige invulling van, bijvoorbeeld, de prijs of wegingsfactor. Wel bevelen we aan om deze cijfermatige invulling periodiek te toetsen aan de meest recente wetenschappelijke inzichten.

De werkwijzer luchtvaartspecifieke MKBA's

- De werkwijzer luchtvaartspecifieke MKBA's beveelt aan om een efficiënte prijs voor CO_2 emissies te hanteren.
- Zolang het niet mogelijk is om de klimaateffecten van niet-CO_2-componenten nauwkeurig en op vluchtniveau te bepalen, beveelt de werkwijzer aan om het niet-CO_2-effect af te leiden uit het CO_2-effect door omrekening naar CO_2-equivalenten. Bij deze omrekening hoort de aanbeveling om uit te gaan van een opslagfactor van twee en een gevoeligheidsanalyse met opslagfactoren één en vier.

Bevindingen

- Het gebruik van CO_2-equivalenten is populair om de impact van verschillende broeikasgassen ten opzichte van CO_2 te becijferen. Er zijn verschillende manieren (*climate metrics*) om de impact van niet-CO_2 effecten in relatie tot CO_2 effecten in kaart te brengen. Deze manieren verschillen onder andere in de gehanteerde tijdshorizon van de klimaateffecten en resulteren in verschillende ratio's van niet-CO_2 en CO_2 effecten.
- Er is vanuit de klimaat- en atmosfeerwetenschap unieke en objectieve correcte ratio tussen niet-CO_2 en CO_2 effecten (*climate metrics*) vast te stellen. Zo bepaalt de keuze van de tijdshorizon voor een groot deel de verhouding tussen niet-CO_2 en CO_2 effecten, waarbij een kortere tijdshorizon een hoger gewicht geeft aan de niet-CO_2 effecten.
- In tegenstelling tot CO_2-effecten kennen niet-CO_2 emissies in de luchtvaart een grote parametrische onzekerheid vanwege de complexe samenhang tussen de emissies en interactie met contextuele factoren, zoals de omstandigheden op het moment van de uitstoot van de broeikasgassen.
- De efficiënte prijs van CO_2 is voor Nederland vastgesteld op basis van de preventiekostenmethode. Deze methode definieert deze prijs als de minimale (maatschappelijke) marginale komsten om de emissies te reduceren tot het vastgestelde reductiedoel. Het hanteren van verschillende efficiënte prijzen is daarbij inconsistent. Het aanbevolen gebruik van de efficiënte prijs in MKBA's impliceert het gebruik van CO_2-equivalenten, en dus het gebruik van wegingsfactoren en het hanteren van één prijs voor de verschillende broeikasgassen. De aanbeveling in de werkwijzer luchtvaartspecifieke MKBA's om één prijs te hanteren sluit daarbij aan.

- Vanuit economisch perspectief is het hanteren van de schadekostenmethoden (*social cost of carbon*) te prefereren boven de preventiekostenmethode. Echter, in de praktijk is de noodzakelijke informatie over de deze schade van emissies niet in te schatten. Daarom wordt voor MKBA's in Nederland gekozen voor de preventiekostenmethode.

Aanbevelingen

- De aanbeveling in de werkwijzer luchtvaartspecifieke MKBA's om een constante wegingsfactor te hanteren zolang het niet mogelijk is om de klimaateffecten van niet-CO_2-componenten nauwkeurig en op vluchtniveau te bepalen sluit nog aan bij de huidige wetenschappelijke kennis en onzekerheid daarin.
- Bij het vaststellen van de ratio tussen niet-CO_2 en CO_2 effecten worden in de literatuur verschillende tijdshorizonnen gebruikt. We raden aan om in de context van de MKBA enkel die ratio's te hanteren die uitgaan van een tijdshorizon van honderd jaar. Daarmee sluit de tijdshorizon aan bij de generieke tijdshorizon voor alle kosten en baten in de MKBA.
- De werkwijzer bevat de aanbeveling om via gevoeligheidsanalyse de effecten met een onder- en bovengrens van de constante wegingsfactor door te rekenen. Dit is een adequate werkwijze om de bandbreedte van de effecten als gevolg van parametrische onzekerheid te belichten. Hiervoor is het echter wel noodzakelijk dat de onder- en bovengrens de parametrische onzekerheid reflecteren, en niet andere factoren zoals de keuze voor de *climate metric* of tijdshorizon. Daarbij merken we verder op dat zodra het mogelijk is om klimaateffecten van niet-CO_2-componenten nauwkeurig en op vluchtniveau te bepalen er ook informatie beschikbaar dient te zijn over de onder- en bovengrens van deze inschattingen. Het is aannemelijk dat de enkele onder- en bovengrens van één aanbevolen constante wegingsfactor dan niet langer voldoet.
- Deze studie beoordeelt niet de cijfermatige invulling van de aanbevolen wegingsfactor. Wel bevelen we aan om deze periodiek te toetsen aan de meest recente wetenschappelijke inzichten. Deze eerste toetsing kan bijvoorbeeld plaatsvinden in navolging van de verwachte update van de efficiënte prijs van CO_2 voor Nederland in 2025.

1 Introduction

The precise non-CO_2 climate effects of aviation remain uncertain. From an economic perspective, it is important to know how to monetarily valuate non-CO_2 impacts. This study explores the alternative ways to do so in the context of aviation-specific social cost benefit analysis in the Netherlands.

Background

Air transport is an important enabler of global connectivity, fostering international trade, economic development and cultural exchange (ICAO, 2019). However, it also contributes to observed anthropogenic global warming. In fact, it is responsible for approximately four per cent of the total global temperature increase, more than fifty per cent of which is related to non-CO_2 climate pollutants (Klöwer et al., 2021). Lee et al. (2021) estimate that the net positive warming of non-CO_2 in aviation accounted for 66 per cent of aviation's net global warming in 2018. The most significant warming effects, in addition to CO_2, come from contrail cirrus formation and NO_X-induced changes in atmospheric chemical composition (Lee et al., 2021).

Monetary valuation means assigning a price to effects. Via monetary valuation of CO_2 emissions and non-CO_2 emissions, policymakers and other (private) stakeholders can better assess the economic impact of emissions. This allows for more informed decision making regarding economic activities that cause these emissions, such as air traffic movements. This price can be used in social cost-benefit analysis (SCBA) for evaluating projects and investments. To do so, the emissions and their climate effect(s) need to be identified first. Currently, the Dutch guideline for aviation-specific SCBA recommends to derive the impact of the non-CO_2 emissions by converting these emissions to CO_2 equivalents via an emission weighting factor. This approach is recommended until more precise identification of individual non-CO_2 components at flight level becomes available and can be applied (SEO et al., 2021). The weighting factor recommended is currently two. The factor is defined as the total climate effect of CO_2 equivalents – CO_2 plus non-CO_2 effects – over the total CO_2 effects. This implies that the non-CO_2 effect is assumed to be just as large as the CO_2 effect.

Notwithstanding the economic perspective, significant uncertainties around (measuring) the impacts of non-CO_2 emissions remain. It is a hot topic in current scientific (climate science) literature. For example, a tool recently built by CE Delft and DLR by commission of the Dutch Ministry of Infrastructure and Water Management, implies a non-CO_2 to CO_2 emissions ratio from aviation that is higher on average but less stable than reported in earlier studies (CE Delft, 2023a). Their analysis shows that this ratio differs depending on, amongst other things, the applied climate metric, the time horizon of the climate analysis, the aircraft type, and route characteristics. The first two causes for differences are subjective choices made by the researcher, whereas the latter two causes are based on actual flying circumstances.

Research questions and methodology

Given the evolving aviation climate research on the impact of non-CO_2 emissions and the importance of climate effects in SCBA, the question can be raised whether the Dutch guideline for aviation-specific SCBA should be specifically adjusted regarding this topic. The main considerations here are whether the (recent) insights from aviation climate research require us to reconsider applying a (constant) non-CO_2 to CO_2 emissions ratio, whether to use a different value for such a weighting factor, to use separate monetary valuations for CO_2 and non-CO_2 impacts and how to address the (scientific) uncertainties around measuring these impacts in a SCBA.

To address these research topics, the Ministry of Infrastructure and Water Management commissioned SEO Amsterdam Economics to conduct a study into the following specific research questions:

1. In what way does the conversion of non-CO_2 emissions into CO_2 equivalents consider the differences in climate effects between CO_2 emissions and non-CO_2 emissions, both in general and in the tool developed by CE Delft and DLR?
2. Can the conversion of non-CO_2 emissions to CO_2 equivalents exist alongside a potential separate monetary valuation of the non-CO_2 climate effects? What implicit assumptions about the trade-off between CO_2 and non-CO_2 emissions are applied in that case from the perspective of the SCBA, and under what conditions is this economically consistent (i.e., does this not lead to the application of two different valuations for what is ultimately the same (climate) effect)?
3. What information is available in existing (scientific) studies on the economic/monetary valuation of non-CO_2 emissions, or the climate effects of non-CO_2 emissions? And, is this information applicable to the valuation of non-CO_2 emissions in SCBA concerning aviation?
4. What are suitable methods to derive such figures, and what is the expected impact of using accurate/alternative figures on the qualitative conclusions of existing SCBA (in other words: does it matter)?
5. In what way should the uncertainty surrounding non-CO_2 effects be incorporated in the SCBA, and does this depend on how non-CO_2 effects are (monetarily) valued?

To answer the research questions, we combine desk research and economic theory. In a series of interviews, we have discussed and exchanged the results of our initial analysis and answers with various experts in the field of climate science, aviation, and welfare economics.[1] Based on these discussions, we were able to refine the analysis. Furthermore, we received feedback on preliminary versions of this study by the members of a guidance committee, including experts from the Ministry of Infrastructure and Water Management, PBL Netherlands Environmental Assessment Agency, CPB Netherlands Bureau for Economic Policy Analysis and KiM Netherlands Institute for Transport Policy Analysis.

Our study focuses on the economic perspective of the non-CO_2 climate effects of aviation. To this aim, we discuss the ongoing research and available insights from the climate science perspective regarding, for example, the conversion of non-CO_2 emissions into CO_2 equivalents. It is, however, not within the scope of our study to offer conclusions about the conversion method to be used and the role therein of the tool developed by CE Delft and DLR. Neither are quantifying the most likely emissions ratios and/or efficient greenhouse gas prices within the scope of this study.

Outline

The remainder of this study contains four sections. Except for the concluding section, Section 5, each section ends with the main takeaways of that section. Section 2 discusses how non-CO_2 emissions are measured and accounted for in unit levels within aviation related studies. Furthermore, it provides a brief overview of the ANCO tool. Section 3 describes the available (economic) methods to monetize these unit levels of non-CO_2 emissions and discusses how non-CO_2 emissions are included in these types of analyses in other countries. Section 4 provides a more in-depth analysis of the various valuation approaches and the consequences for SCBA, including ways in which to deal with discounting and uncertainty. Section 5 offers conclusions and provides recommendations.

1 Appendix A provides an overview of the interviewees.

2 Accounting for non-CO_2 emissions

The global warming effect of greenhouse gases differs per type of emission. Different climate metrics and time horizons may reflect the specific characteristics of non-CO_2 emissions. There is no single objectively correct way to express the impact of each emission in CO_2-equivalent factors.

2.1 Non-CO_2 emissions in aviation

Overview of aviation emissions

Jet engines emit primarily through the combustion of jet fuel during the flight of an aircraft. Combustion emissions result from oxygen (O_2) and nitrogen (N_2), which are taken up from the air by a fan at the front of the engine, mixing with the hydrocarbons (HC), sulphur (S) and aromatics in the jet fuel.

Carbon dioxide (CO_2) makes up about seventy per cent of the mass of the exhaust (FAA, 2015). With an atmospheric lifetime of 300 to 1,000 years, it belongs to the long-lived gases (NASA, 2019). About thirty per cent of the emissions are mostly water H_2O (FAA, 2015). Less than one per cent consists of pollutants such as nitrogen oxides (NO_X), oxides of sulphur (SO_X), carbon monoxide (CO), partially combusted or unburned hydrocarbons (HC) and aerosols such as soot (black and organic carbon) sulphur and nitrogen (Lee et al., 2021). These emissions can undergo different transformations after exiting the combustor within the engine or downstream from the engine in the hot exhaust plume, or after they have cooled and mixed with ambient atmosphere (FAA, 2015). Some gases condense in supersaturated air to form contrails (Lee et al., 2021).

Global warming effects of emissions

The most well-known greenhouse gas is CO_2. CO_2 has a net warming effect that can be determined with relatively high certainty (Lee et al., 2021). In contrast to CO_2, the impact of non-CO_2 emissions depends on the specific atmospheric conditions in place and hence depends on flight trajectory, latitude and altitude (Dahlmann et al., 2023). NO_X and contrail-cirrus formation are known to be the non-CO_2 emissions that have the biggest climate impact (EASA et al., 2020).

NO_X emissions alter the radiative balance of other gases such as CH_4, O_3, H_2O and CO. NO_X emissions lead to a short-term ozone increase, a long-term ozone decrease, a methane (CH_4) decrease and a stratospheric water vapor (H_2O) decrease (Lee et al., 2021). The net radiative forcing effect is estimated to be warming, but depends, for example, on the emission scenarios and background concentrations. Box 2.1 explains the concept of radiative forcing, which is used as concept in climate science.

A study by Lee et al. (2021) presents estimates and confidence intervals for global aviation effective radiative forcing over the period of 1940 to 2018 for individual emissions and interactions of these emissions. The authors label the (size of the) confidence intervals as very low, low, medium and high. A very small confidence interval implies a high certainty of the estimate, whereas a large confidence interval implies a large bandwidth around the estimate, in other words a high uncertainty.

The overview by Lee et al. (2021) shows that the short-term ozone increase and the methane decrease are estimated with a medium confidence level. The cooling effects of long-term ozone and stratospheric water vapor are estimated with relatively high uncertainty. Short-term ozone persist for weeks to months, long-term ozone for decades, and methane has a lifetime of around 12 years (CE Delft, 2023a). Water emissions account for a larger portion of total aviation emissions. The radiative forcing of water is estimated to be relatively low with medium confidence levels (Lee et al., 2021). Water vapor has a lifetime ranging from hours at ground level to months at the cruise altitudes of aircraft in the stratosphere (CE Delft, 2023a). Soot aerosols consist of black carbon and organic carbon and can cause sulphate and nitrate aerosols. Soot aerosols result from the condensation of unburnt aromatic compounds in the combustor. Aerosols can influence cloud formation and lead to different warming and cooling effects. Their estimation comes with large uncertainty (Lee et al., 2021). Contrails are known as the linear exhaust stripes seen in the sky behind the plane. They can form cirrus clouds and exhibit cooling and warming effects, dependent on the time of day, the altitude and the latitude. Contrails can have a climate forcing effect up to 24 hours, though their global warming effect may persist for years. The estimation of contrails is therefore quite complex. In Lee et al. (2021) the estimation comes with a wide uncertainty range.

Box 2.1 Radiative forcing and its efficacy explained

Radiative forcing describes the change in net irradiance, measured in units of Watts per square metre (of earth surface) in a given climate system (Perman et al., 2011). It is thus the difference between the incoming short-wave radiation energy and the outgoing long-wave radiation energy. The change in radiation is measured at the tropopause where clouds and weather phenomena occur and which lies between the lower troposphere and the stratosphere). Radiative forcing is presented as the change in net irradiance in the present relative to pre-industrial times. It is therefore a "backward-looking" metric (Fuglestvedt et al., 2010).

Long-lived and spatially homogeneously climate impacts from CO_2 or methane can be estimated fairly well with radiative forcing (RF). For more heterogeneously distributed climate impacts, such as ice albedo effects, Hansen and Nazarenko (2004) introduced efficacy *r* of climate forcing, to measure how effective a certain emission is at changing the Earth's surface temperature compared to CO_2. In this way, radiative forcing can be modified with efficacy. Efficacy measures the ratio of the equilibrium temperature change for an emission's radiative forcing to the temperature change for the same magnitude of forcing by CO_2 (Hansen & Nazarenko, 2004). Efficacy is therefore the climate sensitivity of one emission relative to CO_2's climate sensitivity. To accurately estimate efficacy, a climate model is run until it reaches its new equilibrium and the corresponding temperature change, accounting for changing atmosphere, land and ocean conditions. However, the calculation of this is rather cumbersome. Another, more practical indicator is effective radiative forcing (ERF). Instead of determining the equilibrium temperature change, ERF captures the immediate atmospheric responses, holding ocean conditions at a fixed level (Lee et al., 2021; EASA, 2020). Lying somewhere in between the RF and the radiative forcing modified by efficacy, ERF offers a more complete measure of the climate's energy imbalance compared to RF alone, reflecting how different forcing agents influence global temperatures with varying efficacy. Global Warming Potential (GWP) can be modified using efficacy as well.

Source: SEO Amsterdam Economics (2024)

Climate metrics

Despite their low occurrence, many non-CO_2 gases have a higher capacity to absorb infrared radiation and hence warm the planet. This capacity is accounted for when calculating climate metrics. The IPCC defines an emission metric as follows: "*A relative greenhouse gas emission metric expresses the effect from one gas relative to the effect of emitting a unit mass of a reference greenhouse gas on the same measure of climate change*" (IPCC, 2023, p.20). Throughout this study, we will use this definition of a climate metric. The metrics are often referred to as CO_2 equivalent when using CO_2 as a reference gas. The wide range of emission lifetimes in aviation, spanning from just hours to several centuries, and the dependence on contextual factors add significant complexity to the comparison of these emissions on a single (stable) scale. Despite these complexities, CO_2 equivalents are popular for assessing the impact of different greenhouse gases related to certain economic activities, for example in social cost benefit analysis.

Whereas radiative forcing expresses the immediate change in energy balance caused by greenhouse gases, other metrics extend this concept to assess future impacts of these gases on global warming and temperature, often in relation to CO_2. Climate metrics can then apply to a single emission pulse, emissions sustained over time or increasing emissions over time, the latter two depending on assumptions regarding technical and economic growth in the future (IPCC, 2009). The following metrics are available:

- The Global Warming Potential (**GWP**) compares the integrated radiative forcing of two greenhouse gases over a certain chosen time period resulting from pulse emissions of an equal mass (IPCC, 2009). As CO_2 is the reference gas, it has a GWP of 1. Common time horizons are 20, 50 or 100 years. A GWP100 gives the average warming potential over 100 years compared to CO_2.
- Global Temperature change Potential (**GTP**) measures the change in global mean surface temperature at a specific future point in time, caused by a unit mass of emitted greenhouse gas at present, divided by the temperature response at that future point in time from a unit mass of emitted reference gas at present. GTPs incorporate a broader range of physical processes than GWPs by factoring in the climate's sensitivity to radiative forcing and the heat exchange between the atmosphere and the ocean (IPCC, 2009). Since it focuses on a single point in an end-year, it is considered an 'end point' metric (CE Delft, 2023a; Fuglestvedt et al., 2010).
- Average Temperature Response (**ATR**) measures the average near-surface temperature change over a specific time horizon, by averaging the temperature response to a certain climate species over a chosen time horizon. This is an application of the GTP (CE Delft, 2023a).
- **GWP*** is an alternative application of GWP where an increase in the emission rate of short-lived climate forcers is equated to the impact of a one-time 'pulse' emission of CO_2 (CE Delft, 2023a). It is 'flow-based' (EASA, 2020). Instead of focusing on fixed quantities of emissions, GWP* focuses on the change in the rate of emissions over time. GWP* gives a time series, rather than a constant value over time. Although GWP* provides a more detailed picture of how emissions evolve over time, it is more complicated to calculate and there is no clear point in time at which to select a value for comparing fleets and individual flights. The latter is necessary for including non-CO_2 emissions in policy implementation (Megill et al., 2024).
- **EGWP** adjusts GWP by multiplying it by the efficacy of the gas in question. It therefore accounts for the fact that various greenhouse gas emissions affect global temperature responses differently, even if they have the same radiative forcing. It allows for atmospheric and land temperature to adjust while ocean conditions are fixed (EASA, 2020).

Choice of a climate metric

As can be seen, each metric highlights different characteristics of different emissions. From an economic perspective, understanding the essence of each metric is important because the climate metric may include implicit assumptions about the economic trade-offs between the different greenhouse gases. It is, however, not within the scope of our study to offer conclusions about the conversion method to be used.

All metrics consider radiative forcing. However, instead of solely looking at the present-day forcing relative to pre-industrial levels, these metrics provide forward-looking perspectives by considering the long-term effects of current emissions (either by integrated radiative forcing or temperature change) and projecting the future climate impact of these emissions. The most used and internationally accepted metric is the GWP100 (Lynch et al., 2020). The GWP measure is relatively easy to implement in applied analysis. For example, unlike GWP*, GWP provides a single value for a given time horizon without yearly variation (Megill et al., 2024).

Emission weighting factors are multipliers to represent the additional climate impact of aviation's non-CO_2 emissions. They are the ratio of total CO_2 equivalent emissions to CO_2 emissions and follow from climate metrics and their time horizons. However, as underlined by Azar & Joansson (2012, p.560), there is no "*unique and objectively correct way [to use an emission weighting factor] since it depends on subjective choices, such as the time horizon and the question of what to value*". For instance, using GWP100 for gases with a longer atmospheric lifetime than 100 years would ignore the impact of that gas in the further future. GTP partially addresses this issue by only focussing on the temperature change at a specific future point in time (Lee et al. 2021; Fuglestvedt et al., 2010). This can be fitting for policies that impose a limit on the allowed change in global temperatures (Fuglestvedt et al., 2010). The GTP50 or GTP100 metric suggests that focusing on reducing emissions of longer-lived gases may be more effective, as their impact continues over time. As the emissions target nears, attention should shift to shorter-lived gases, which become more relevant closer to the target date (Fuglestvedt et al., 2010; Manne & Richels, 2001). This is because a ton of a short-lived gas emitted in the early 21st century will have only a small influence on temperature changes in the late 21st century (Manne & Richels, 2001). ATR measures the average temperature change over a specific time horizon. To illustrate, ozone (O_3) and contrail cirrus have a relative short lifetime. GTP100 underestimates ozone's short-term power by focusing on the temperature at the end of the century. GWP100 does not consider the temperature response at all. ATR100 provides a balance, showing the intense short-term effect of contrail or O_3 while acknowledging its decline over time. This makes it a more accurate reflection of the overall climate impact of short-lived gases like O_3.

Megill et al. (2024) evaluate each metric to determine its neutrality, temporal stability, alignment with existing climate policies, and ease of understanding. The efficacy-weighted GWP (EGWP) and ATR score best in their study. Endpoint metrics like radiative forcing or GTP exhibit higher dependence on the time horizon. By relying solely on a single temperature at a time, information about peak or average temperature is less well indicated (Megill et al., 2024). Furthermore, metrics using efficacy (like EGWP), as explained in Box 1, tend to capture how effective non-CO_2 gases can contribute to temperature change. As a temperature-based climate metric, ATR is based on the temperature response caused by a unit of radiative forcing from a certain emission. It also includes time lags, where the climate system has not yet fully adjusted to the temperature change. Therefore, it is more aligned with temperature-based targets than GWP (Megill et al., 2024). Some of the experts interviewed have expressed that ATR might therefore also be easier to understand than EGWP. Calculating ATR comes with more uncertainties, since it goes one step further in estimating climate effects (from radiative forcing to temperature response). Both GWP and ATR are easier to understand and implement than GWP*. GWP is based on radiative forcing and ATR on temperature. Thus, they emphasize different types of climate effects. For instance, GWP emphasizes contrail cirrus while ATR highlights the warming effect of ozone (O_3) induced by nitrogen oxides (NO_X), see Megill et al. (2024).[2] On a general level, ATR and GWP are quite similar, having long time horizons.

Choice of time horizon

In the end, choosing a climate metric always comes with a trade-off, which is highly dependent on the time horizon and the lifetime of certain gases. As indicated by Fuglestvedt et al. (2010), the policy evaluation of climate impacts always involves value judgements. GWP20 takes into account the strong impact of short-lived gases but neglects the impact of gases that remain beyond 20 years from now, such as CO_2.

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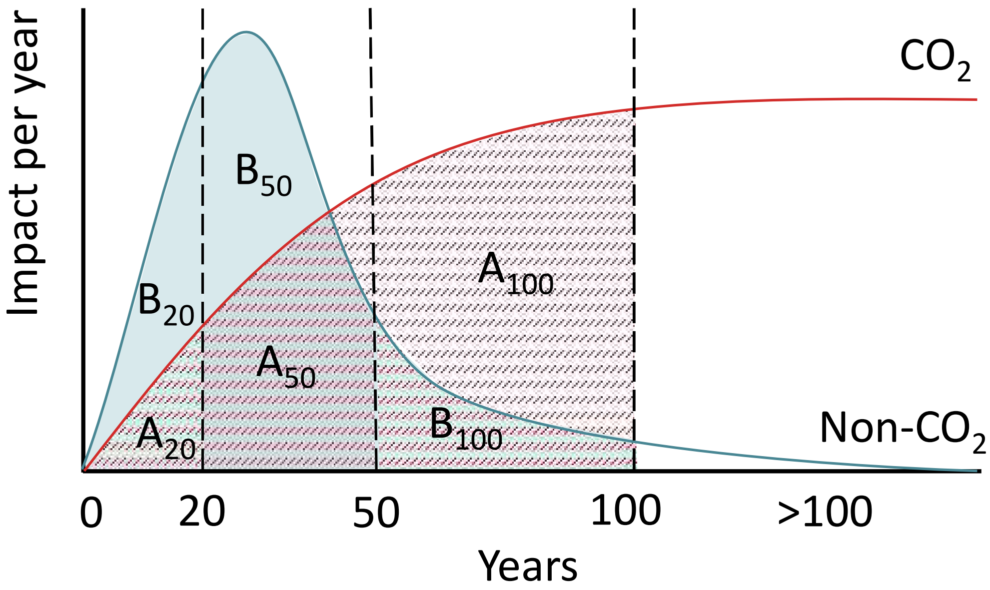
2 This is because contrail has a significant short-term contribution by trapping outgoing infrared radiation and changing the energy balance of the atmosphere. The formation of ozone and its temperature effect builds up over time and therefore gets greater emphasis with ATR.

For illustrative purposes only, Figure 2.1 shows this trade-off in a stylised way. The red line shows the hypothetical CO_2 climate impact per year of one flight today over a time horizon of more than 100 years. In the same way, the blue line shows the same flights' non-CO_2 impact per year. Any accumulated measure, for example GWP, will arrive at a different CO_2 equivalent depending on the subjectively chosen time horizon. In general, the climate metric – with CO_2 as denominator – will be higher for shorter time horizons considered. In our illustrative example, the GWP20 would yield the blue area B_{20} divided by the red dotted area A_{20}. Clearly, B_{20}/A_{20} is larger than 1. Taking GWP50 instead, the total CO_2 impact equals the areas $A_{20}+A_{50}$, whereas the non-CO_2 impact equals $B_{20}+B_{50}$. By the same logic, the single CO_2 equivalent for GWP100 would be $(B_{20}+B_{50}+B_{100})/(A_{20}+A_{50}+A_{100})$. Because the non-$CO_2$ diminishes more quickly than the more persistent CO_2, the CO_2 equivalent for GWP20 is higher than for GWP100. With regard to a cost-benefit analysis, by using GWP20 one would place more weight on emissions in the nearby future than in the later future. In terms of policy and decision making via cost-benefit analysis, the time horizon will emphasize short-term urgency or long-term stability. Limiting the assessment of CO_2's impact to just 20, 50 or 100 years overlooks its long-term effects, as it continues to influence the climate well beyond those timeframes.

Figure 2.1 The non-CO_2 to CO_2 ratio differs depending on the chosen time horizon (hypothetical example for illustration purposes only)



Source: SEO (2024)

The values over time differ once again for different climate metrics. Interviews and studies (Megill et al., 2024) reveal that values for EGWP, ATR and GWP converge, the longer the time horizon. Megill et al. (2024) recommend a time horizon longer than 70 years for integrated climate metrics, such as ATR and EGWP. GWPs with time horizons of 100 years have been adopted in the Kyoto Protocol but are not based on any conclusive discussion (Fuglestvedt et al., 2010).[3]

The choice of time horizon is quite arbitrary. From our discussions with the various experts, we conclude that the need to differentiate the impact over the different years in the time horizon is less urgent for climate and atmospheric

3 Based on numerical simulation, Mallapragada & Mignone (2020) conclude that, under certain reasonable conditions, the time horizon in the GWP100 is consistent with discount rates of approximately three per cent and the time horizon in the GWP20 with a rate of approximately seven per cent (or greater).

researchers than for economists. Although arbitrary, the choice of metric and time horizon most likely lead to different economic outcomes in SCBA, as the above example of the climate metric GWP suggests.

2.2 The Dutch Aviation non-CO_2 estimator ANCO

ANCO

CE Delft and Deutsches Zentrum für Luft- und Raumfahrt (DLR) recently developed a tool called ANCO to address non-CO_2 climate impacts in aviation, see CE Delft (2023a). ANCO estimates the total non-CO_2 effect in terms of CO_2 equivalents for all flights departing from Dutch airports. This total non-CO_2 effect is given by the CO_2e factors, which represent the ratio between total emissions (CO_2 and non-CO_2 in CO_2 equivalents) and CO_2 emissions. In this tool, the effects for the years 2017, 2030, 2040 and 2050 are available. The model distinguishes between scenarios of low and high economic/demographic growth (WLO Low and WLO High). These are the scenarios used in SCBA for aviation related policy in the Netherlands. The ANCO tool starts by processing the data of aviation forecasts obtained from the Dutch aviation model AEOLUS. The data include passenger and full freighter flights across different years and scenarios. The AEOLUS output serves as input for ANCO. The input includes variables such as the origin and destination airport and type of aircraft.

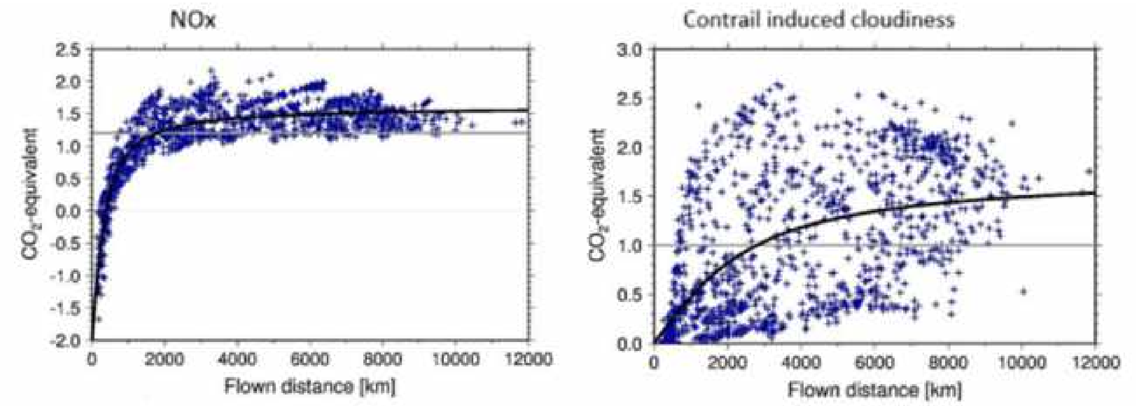
AirClim

To arrive at climate impacts of emissions, ANCO incorporates the AEOLUS forecasts and the CO_2eEstimator developed by DLR. DLR uses the climate response model AirClim to derive these impacts. This enables ANCO to estimate the non-CO_2 impacts. These non-CO_2 effects are calculated using regression formulas incorporated in the tool, which vary based on the flight's characteristics (e.g., aircraft type, route, latitude and longitude). By also including weather and spatial dependent factors, emission weighting factors become more accurate but also harder to calculate (CE Delft, 2023a). The ANCO tool, however, does not include weather and detailed spatial factors of individual flights.

Dahlmann et al. (2023) and Thor et al. (2023) offer further insights into the CO_2eEstimator. In short, the climate response model (AirClim) uses the emission levels and location (longitude, latitude, altitude) in combination with a set of precomputed atmospheric responses to calculate the temporal development of the global near-surface temperature change (Dahlmann et al., 2023). The study shows how aviation emissions' climate impact differs depending on location factors.

Figure 2.2 shows how much non-CO_2 emissions such as nitrogen oxides (NO_X) and contrail induced cloudiness differ depending on the flown distance. The grey line in both graphs shows the constant factor, which barely manages to capture the actual climate impact of these emissions. The blue crosses depict the climate impact in CO_2-equivalent factor per distance. For nitrogen oxides, the constant factor would overestimate the impact at short distances and underestimate the impact at long distances. In contrast, the black line, is the distance-dependent function used by Dahlmann et al. (2023), which manages to capture the impact of the emissions more precisely. Note that these functions do not yet include latitudinal dependency (which is calculated later as well).

Figure 2.2 Different climate impacts of non-CO2 emissions due to distance



Source: Excerpt from Dahlmann et al. (2023, p. 34)

Insights obtained via the ANCO tool

The ANCO tool makes it possible to determine the climate impacts of all flights departing from Dutch airports in a certain year. In addition, climate effects for individual flights can be calculated as well. The origin and destination airport of interest can be filled in, the seat category and a climate metric can be selected. The climate impacts include CO_2 and non-CO_2 emissions, nitrogen oxides (NO_X), water vapor (H_2O) and contrail induced cloudiness. ANCO determines the climate effects of individual non-CO_2 components at the flight level as well. In the ANCO tool, non-CO_2 impacts are aggregated, and emission weighting factors are estimated in the ATR100 and GWP100 metrics. They consider the total additional warming effect by these non-CO_2 metrics.

Table 2.1 shows the results obtained by the ANCO tool for WLO Low and WLO High scenarios in different years and for the metrics ATR100 and GWP100. Except for 2050, the CO_2e factors are rather similar when the two metrics are compared. The factors are subject to a time horizon of 100 years. In general, the ANCO tool results show that the CO_2e factor increases with decreasing levels of CO_2. The CO_2 impact of departing flights is estimated to decrease mainly due to incorporating increasing sustainable aviation fuel (SAF) blending obligations. This is also one of the reasons behind differences in outcomes for WLO scenarios where, for example, different assumptions are made on annual efficiency improvements reducing fuel consumption. CE Delft (2023a) stipulates that the CO_2e factor can be determined for individual flights (route aircraft combinations) and that these individual factors can vary greatly.

Table 2.1 The ANCO tool predicts an equivalent factor varying between 3.7 and 9.2 for departing flights

			WLO Low			WLO High		
		2017	2030	2040	2050	2030	2040	2050
CO_2	Estimated tank-to-wing CO_2 (million tons)	10.2	10.3	7.1	3.6	8.6	5.1	2.2
ATR100	CO_2e factor	4.0	4.1	5.0	7.8	4.1	5.0	8.0
GWP100	CO_2e factor	3.7	3.8	4.7	7.4	4.0	5.1	9.2

Source: Excerpt from CE Delft (2023a, p. 18)

The calculation methodology for the effects of non-CO_2 emissions is distance and latitude dependent. Thus, the climate impact at different locations on Earth is taken into account. The CO_2e Estimator, which is incorporated into ANCO, estimates the effects of *average* atmospheric conditions (CE Delft, 2023a). Thus, ANCO does not make a distinction between the impacts of individual flights on the same route that arise due to atmospheric conditions. It is not possible to include weather, seasonal differences and detailed spatial dependent factors, as they are not known for future flights (CE Delft, 2023a). For instance, winter flights have a bigger climate impact due to a higher probability of forming contrails (CE Delft, 2023a).

As with any climate metric, uncertainties persist in estimating the climate impacts of individual non-CO_2 emissions (see Lee et al., 2021). Uncertainties in ANCO are hard to quantify since they exist across the different sets of climate response functions and the AirClim model. The study by CE Delft (2023a) is fully transparent in acknowledging the uncertainties, differences with previous studies and potential shortcomings of the applied model – see, for example, textbox 1 in their study.[4] The authors further note that revision of the AirClim model is currently in progress. The estimates provided by ANCO depend on the chosen time horizon and the chosen metric. As confirmed by literature and interviews, GWP100 and ATR100 outcomes approach each other as the time horizon gets longer. Still, the factors given in Table 2.1 would be smaller if a longer time horizon was chosen.

2.3 Key takeaways on accounting for non-CO_2 emissions

- Jet engines emit primarily through the combustion of jet fuel during flight. This yields both CO_2 emissions and non-CO_2 emissions such as nitrogen oxides (NO_X) and methane (CH_4). Together, these emissions have a (net) global warming impact.
- Different greenhouse gases/emissions have different lifetimes. The climate impact of CO_2 is relatively certain and persistent over time, whereas most of the non-CO_2 greenhouse gases have less certain impacts.
- CO_2 equivalents are popular for assessing the impact of different greenhouse gases relative to CO_2. This is true in particular in the context of certain economic activities, for example in social cost benefit analysis. Emission weighting factors are multipliers to represent the additional climate impact of aviation's non-CO_2 emissions. They are the ratio of total CO_2 equivalent emissions to CO_2 emissions and follow from climate metrics and their time horizons. Well-known metrics include GWP and ATR.
- From the perspective of climate and atmospheric science, there is no unique and objectively correct (way of applying an) emissions weighting factor. In general, a metric applying a shorter time horizon will yield a higher non-CO_2 to CO_2 ratio, and hence gives a higher weight to non-CO_2. Although largely arbitrary, the choice of metric and time horizon highly likely leads to different economic outcomes in SCBA. Apart from the choice itself, the literature acknowledges the high uncertainty surrounding estimates of the non-CO_2 climate impacts. This uncertainty implies a large bandwidth in emissions weighting factors.
- Based on the characteristics of (forecast) flights departing from the Netherlands in 2017, 2030, 2040 and 2050, the recently developed ANCO tool derives the accompanying emissions weighting factor of non-CO_2 to CO_2 for GWP and ATR utilizing a 100-year time horizon.
- When using a single-value metric such as derived in the ANCO tool, it is important to pay attention to how its underlying assumptions and valuations relate to the use of the metric, for example in SCBA. Despite the shortcomings of a single-value metric or factor, using metrics helps to account for non-CO_2 emissions and to create awareness of climate impacts. The desk research and discussions with the interviewees show that there is no consensus yet on the relative size of the CO_2 and the non-CO_2 impacts. This discussion is still ongoing.

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4 The underlying analysis of the ANCO tool, for example, considers present and future emissions, disregarding the emissions of historic aviation. The climate impact of CO_2 is affected more greatly by historical emissions than short-lived non-CO_2 effects. The result is that the ratio between non-CO_2 and CO_2 emissions is higher in the ANCO tool than other ratios known in the literature.

3 Monetary valuation of emissions

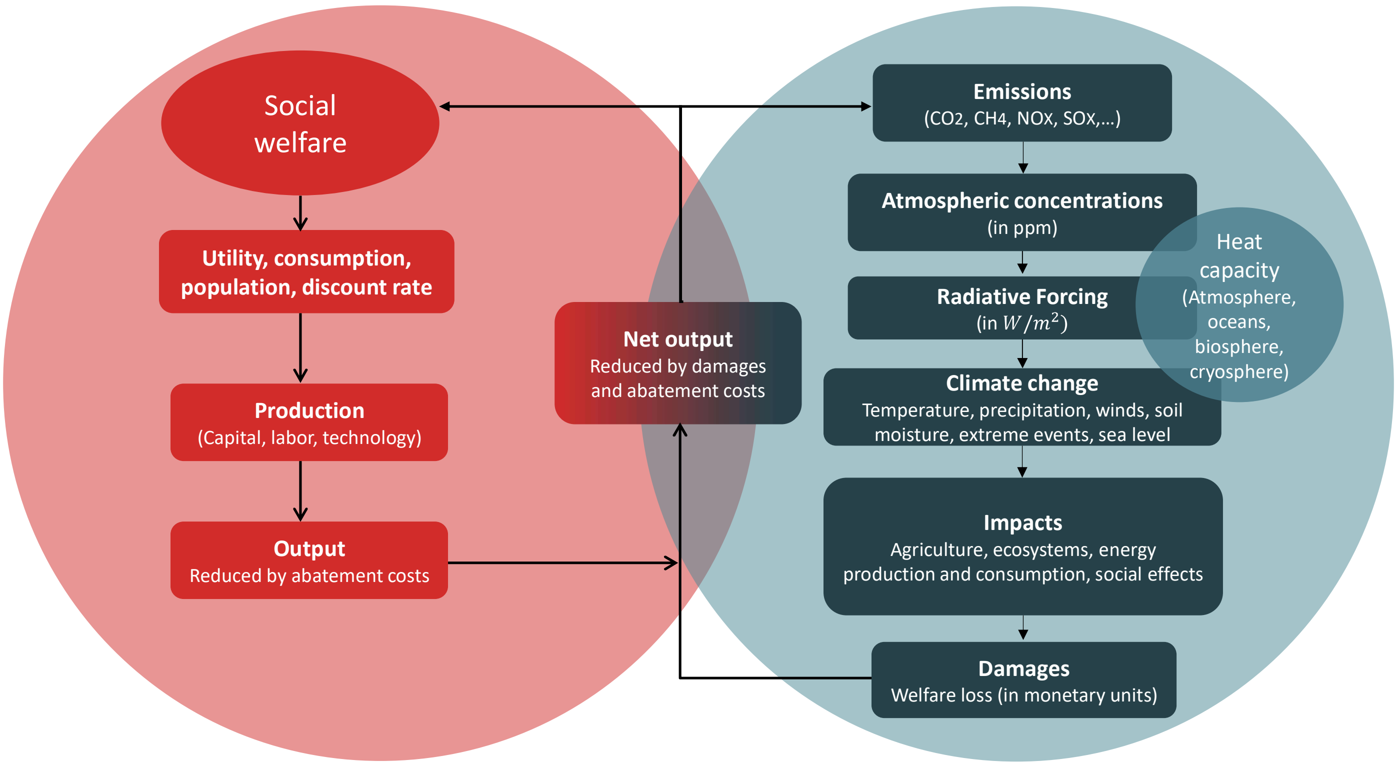
The damage cost approach and the abatement cost approach are two distinct ways to derive the price for emissions. In the Netherlands, the abatement cost approach is used. In this approach it is inconsistent to apply separate prices for non-CO_2 emissions.

3.1 Monetary valuation approaches and SCBA

Linkage between the climate and economic system

What is the price of emissions? To make social investment or policy decisions regarding different alternatives to address the climate impact of aviation, data on costs and benefits in the same unit is needed. A monetary valuation of the emissions, and the related climate impact, offers such a metric. The underlying premise of the economic valuation of emissions is that these emissions harm the potential present and future economy and society. Figure 3.1 shows a simplified representation of how the climate and the economic system are linked.

Figure 3.1 The climate and economic system are linked through the damage of increasing emissions



Source: SEO (2024), adapted from integrated assessment models such as DICE (Nordhaus, 2017).

Starting from (social) welfare in the top left corner, the economic activities resulting in emissions (top right corner) cause damage to society (lower right corner) via the climate system. From an economic perspective, the damage can be interpreted as a lower ability to create welfare (net output) to sustain the consumption and production needed for social welfare. Social welfare itself is often characterized as the sum of utility of all individuals. The simplified linkage in this figure does not explicitly show the temporal and spatial variation involved in social welfare, emissions and climate damages. Clearly, the social welfare of future generations will be affected by emissions produced today (temporal variation). In the same way, avoiding these emissions would lower current social welfare in favour of future social welfare.

Damage cost and abatement cost approach are two alternatives to derive efficient prices

To determine the price or valuation of climate emissions, the literature mentions two main approaches: the damage (social) cost approach and the abatement cost approach. Both approaches are used by practitioners in SCBA. The damage cost approach aims to value the emissions in such a way that their negative impact on social welfare is directly reflected, whereas the abatement cost approach focusses on the (marginal) costs of avoiding or mitigating the negative climate impact of the emissions. The two approaches are explained in greater detail in Section 3.2 and Section 3.3.

In the context of a social welfare analysis, both approaches aim to arrive at a proxy of the (social) efficient price of the emissions. The efficient price here refers to the true marginal social costs of the emissions. Welfare economics dictates that only when the true marginal social costs equal the true marginal social benefits, a welfare-optimal equilibrium exists.

In both approaches, the efficient price is a proxy for the true marginal social costs of the emissions. Finding this proxy is sometimes also referred to as the shadow price method. In case of market failures, i.e. when external effects of production are not reflected in the market prices, the shadow price is a hypothetical price, that internalizes this market failure (Perman et al. 2011). A shadow price emerges as part of the solution to an optimisation problem, for instance obtaining emission reduction at minimum cost.

Dutch aviation-specific SCBA guideline

The Netherlands maintains a guideline on how to carry out an aviation-specific social cost benefit analysis (SCBA), see SEO et al. (2021). The guideline stipulates that changes in climate impact, notably to CO_2 and non-CO_2 emissions should be addressed by using efficient prices.

From an economic perspective, the efficient prices for CO_2 and non-CO_2 emissions may vary by economic scenarios, time horizons and countries. For example, when productivity levels are very high, the marginal costs of not being able to produce due to climate damage are higher, ceteris paribus, than in economic scenarios with low productivity levels. In the Netherlands, the efficient price of CO_2 emissions is determined by PBL Netherlands Environmental Assessment Agency and CPB Netherlands Bureau for Economic Policy Analysis. According to the aviation-specific SCBA guideline, the efficient price for CO_2 determined by PBL and CPB must be used in the SCBA.[5]

PBL and CPB do not provide aviation-specific efficient prices for non-CO_2 emissions. The aviation-specific SCBA guideline therefore strongly suggests "*to derive the non-CO_2 effect from the CO_2 effect by converting to CO_2 equivalents, as long as it is not possible to accurately determine the climate effects of individual non-CO_2 components at the flight level*" (SEO et al., 2021, p. vii). The climate effects are typically estimated based on applying a multiplier or an emission weighting factor to the CO_2 effects. The suggested emission weighting factor to be used for non-

5 The aviation-specific SCBA guideline refers to policies, scenarios, aviation forecasts, defined key figures, and discount rates. The guideline dates back to 2021 and hence represents the knowledge and state-of-affairs at that time. While conducting aviation-related SCBAs in the present or future, it is the responsibility of the researchers and practitioners to investigate whether new insights or information warrant different approaches or choices (SEO et al., 2021, p. i).

CO_2 emissions is two. This means that the non-CO_2 effect is just as large as the CO_2 effect. Overall, the guideline therefore recommends using twice the CO_2 effect as a proxy for the total climate effect related to the emissions of greenhouse gases by aviation. The total of CO_2-equivalent emissions should subsequently be valued at the efficient CO_2 price [6] The guideline further specifies that this approach should be followed if more specific knowledge about the climate impact of non-CO_2 emissions of aviation, differentiated by distance, height or location, is not available. If more information becomes available that better reflects the Dutch aviation context, the guideline recommends using these insights.

For our study and the current discussion on how to assess the alternative approaches for the valuation of non-CO_2 climate impacts of aviation, it is crucial to understand how PBL and CPB derive the efficient CO_2 price. They do so by making use of the abatement cost approach. They apply the CO_2 price to certain greenhouse gases, "following the general convention of converting emissions of various greenhouse gases to CO_2 equivalents based on their greenhouse effect" (CPB & PBL, 2016, p.6), e.g. methane (CH_4), nitrous oxide (N_2O) and halogenated hydrocarbons. The efficient price is equal to the minimum marginal abatement costs (in Dutch: preventiekosten), which are the costs that the polluter makes to avoid (the CO_2 equivalent) emissions (CPB & PBL, 2016; CE Delft, 2023b).

The CO_2 equivalent price is based on two distinct economic scenarios regarding the future of the global and Dutch economy, the so-called WLO-High and WLO-Low scenarios. These scenarios are paired to a given CO_2 budget for the remaining century.[7] In WLO High, emissions grow faster than in WLO Low. Therefore, the emission reduction needs to be higher in WLO High to reach the CO_2 target. In addition, there is also a scenario exploring the objective of limiting global warming to no more than two degrees Celsius above pre-industrial levels. In each scenario, the cumulative emission reduction is realized at the lowest possible costs, referred to as the efficient CO_2 price.

The WLO scenarios are from 2016 and have not been updated since. Currently, PBL and CPB are developing new scenarios, including a climate module. From the discussions with the interviewees, we conjecture that the underlying approach to value emissions – i.e. the abatement cost approach – will remain the same. The new scenarios are expected to be published in 2025.

3.2 The damage cost approach in more detail

The social costs of CO_2

The social cost of any emission can be seen as the monetary value of the net harm to society associated with adding a small amount of that greenhouse gas to the atmosphere in a given year (White House, 2021). The social cost of carbon can be calculated using an integrated assessment model that optimizes a social welfare function (the

[6] Please note this only refers to the emissions that are not accounted for via other economic pricing mechanisms, hence only the emissions that are regarded as (still) being an externality. If the negative impact of emissions is already incorporated in ticket prices or airline costs, double counting these CO_2 costs must be avoided. If these costs are internalized, for example by the EU ETS trading scheme, these integrated costs must be subtracted from the cost valuation. In theory, with a fully well-functioning trading scheme including all departing flights, the external costs of CO_2 emissions should be equal to zero. Non-CO_2 emissions are not yet incorporated in any existing economic pricing mechanism in aviation. Hence, these effects are fully considered externalities.

[7] "The CO_2 emission budget indicates how much CO_2 may still be released into the atmosphere to remain within the climate target set per scenario for this century. [CPB & PBL] set the limit to this century since they take into account that a backstop technology will become available at a later time that they do not yet know about" (CPB & PBL, 2016, p.4).

discounted sum of population-weighted utility per capita consumption).[8] In literature, and throughout this study, this approach is referred to as the damage cost approach.

Integrated assessment models are economic models in which the population offers labour to produce goods and services. Output is then divided between consumption and investment; a certain output is saved and reinvested into the economy, contributing to future capital accumulation (Nordhaus, 2017). At the same time, production contributes to CO_2 emissions. These enter the carbon cycle, where some of the CO_2 contributes to an increase of atmospheric concentrations while some is stored in reservoirs, such as the ocean or the biosphere. Feedback mechanisms often involve exchanges between different reservoirs and can amplify or dampen climate change effects. An increasing atmospheric concentration affects radiative forcing, which alters the climate by a change of temperature. This climate change has several impacts that lead to damage, in terms of lost welfare. The damage function links the warming climate to net economic output (Marten & Newbold; 2012). Net economic output is reduced by damage and abatement measures, designed to mitigate this damage. As a result, consumption decreases.

The economic impacts are converted into their present-day value using a discount rate. This discount rate reflects the time preference of individuals to receive benefits now rather than in the future. A high discount rate puts less value on future benefits (e.g. reduced emissions) and more value on present consumption. Box 3.1 discusses the discount rates in the Dutch context of aviation policies. The discount rate is affected by how one extra unit of consumption diminishes as a person becomes wealthier (the elasticity of marginal utility of consumption) and the growth rate of per capita consumption (Pindyck, 2013). The social cost of CO_2 is the value that minimizes the discounted present value of damage balanced against abatement costs. Estimating the social cost of emissions is very sensitive to the discount rate, the growth rate and the marginal utility of consumption. Discounting raises ethical questions about the fairness of discounting the welfare of future generations in comparison to our own (Pindyck, 2013). It is hard to pin down rates of time preference and the elasticity of marginal utility of consumption.

Box 3.1 The discount rate in Dutch aviation-related SCBA varies between 1.6 and 2.9 per cent

The aviation-specific SCBA guideline recommends to use the currently valid discount rates as determined for the whole economy by the Werkgroep discontovoet. The last update was made in 2020. The current discount rates to apply boil down to:

- 2.9 per cent for capacity-related travel time gains;
- 1.6 per cent for (costs of) investments in infrastructure;
- 2.25 per cent for all other costs and benefits.

Furthermore, the guideline recommends conducting sensitivity analyses using a 0.4 per cent point higher discount rate in economic scenarios with higher growth and a 0.4 lower discount rate in scenarios with lower economic growth.

Source: SEO et al. (2021, p. xi)

The social cost of non-CO_2 emissions

While in the damage cost approach radiative forcing pathways of other gases are mostly entered exogenously and the focus is on CO_2, more scientific research has started to include non-CO_2 emissions and their respective cycles, impact and damage functions as well. Many of these attempts focus on methane (CH_4) and nitrous oxide (N_2O),

[8] Well-known examples of integrated assessment models are the Dynamic Integrated Climate-Economy Model (DICE) developed by Nobel laureate William Nordhaus, the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model developed by Richard Tol (as an author of IPCC shared winner of the Nobel Peace Prize for 2007) or the Policy Analysis of the Greenhouse Effect (PAGE) by Chris Hope.

which are the most considered greenhouse gases in climate policy analysis (Fankhauser, 1994; Marten & Newbold, 2012; Shindell et al., 2017; Mallapragada & Mignone, 2020; Azar et al., 2023).

While a great range of studies on the social cost of carbon have been published since the 1990s and an increasing amount of work is being done on the social cost of methane and nitrous oxide, the social costs of aviation-related emissions has been studied to a lesser extent. Often when social costs of aviation-related emissions are studied, the focus is on air quality rather than climate aspects. Furthermore, many studies concern themselves with the physical climate impacts of aviation only and do not translate these climate impacts into economic metrics. Some studies address the social costs of non-CO_2 climate species, but focus on other sectors (Lintunen & Rautiainen, 2021).

Only a few studies address the social cost of aviation-related emissions. Examples are Grobler et al. (2019), Shindell (2015), Azar & Johansson (2012) and Dorbian et al. (2011). Grobler et al. (2019) use DICE and other tools to compute estimates of aviation's climate impacts to derive speciated emission cost metrics for both climate and air quality per unit of aviation emissions considering CO_2, nitrogen oxides (NO_X), contrail-cirrus, black carbon and water (H_2O). The largest uncertainty in this approach is associated with the equilibrium climate sensitivity and the climate damage function (Grobler et al., 2019). The global aggregate total cost of all aviation-related emissions is $200 per metric ton emission in 2015 USD, with an uncertainty range of $30-$530 per metric ton emission. The climate impacts of nitrogen oxides emissions reported by Shindell (2015) are between ten to twenty times smaller than the estimates by Grobler et al. (2019), the difference likely being due to the estimation of net radiative forcing by nitrogen oxides. Much of the challenge also depends on how well the (physical) climate impacts of aviation-related gases and aerosols can be estimated. Factors such as feedback mechanisms, the impact of differing temperature responses due to different climate forcers, interaction with other gases and aerosols, spatial and temporal patterns, engine efficiency and aircraft size play a role (Grobler et al., 2019).

3.3 The abatement cost approach in more detail

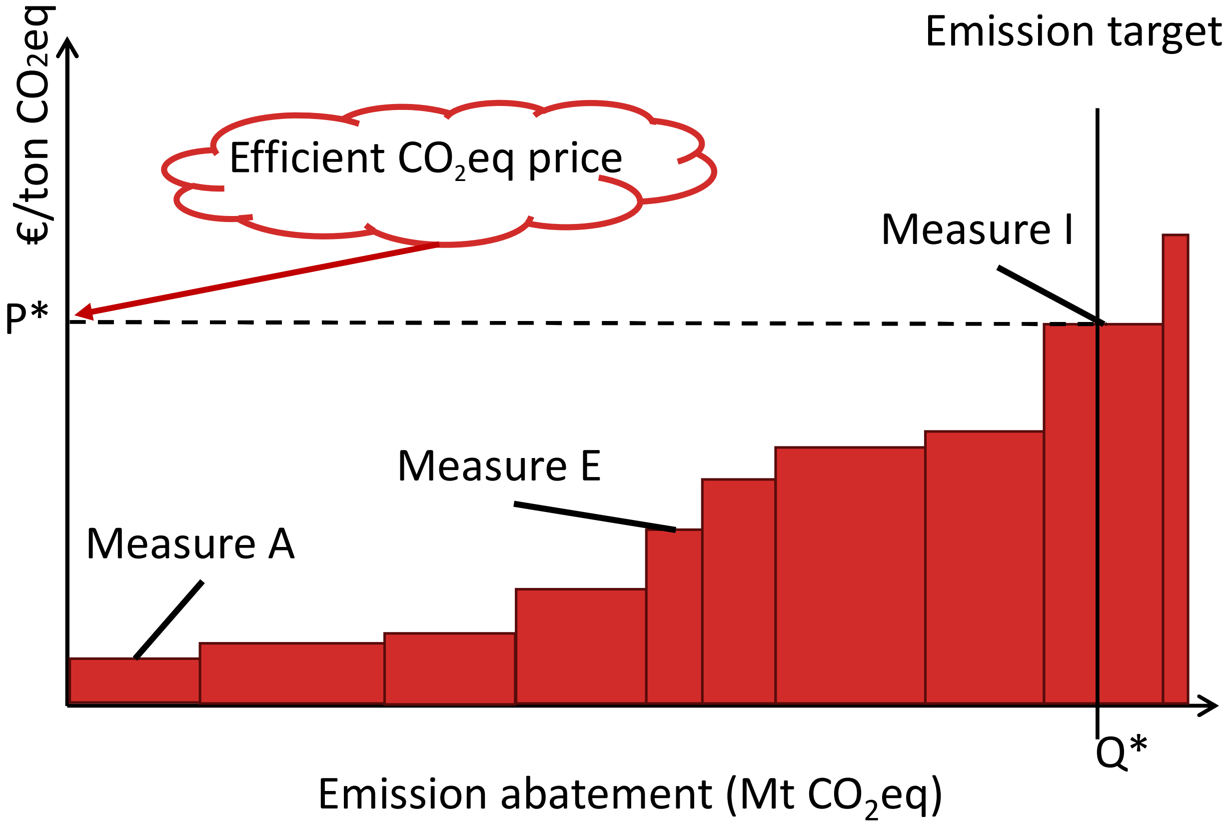
Abatement cost curve

The essence of the abatement cost approach is the cost-effectiveness criterion stating that the (social) marginal costs of reducing the potential of an economic bad (good) should be minimized and, hence, should be equal across sectors, time and space (Baumol & Oates, 1988). The first applications of the abatement cost approach in environmental economics date back to the early 1980s (Kesicki & Strachan, 2011). The abatement cost approach focusses on the (marginal) costs of avoiding or mitigating the negative climate impact of the emission. By ranking all alternatives according to their (marginal) costs, the aim is to find the minimum (marginal) social costs of avoiding or mitigating. These minimum (marginal) social costs serve as the proxy for the shadow price, i.e. the efficient price of CO_2 in the context of our study.

To determine the abatement costs, all possible (technologically available) measures and/or technologies to reduce/prevent emissions and their respective costs are identified. These measures are then ranked according to their marginal costs per unit of reduced emission (the abatement costs). The efficient price is determined as the marginal abatement costs of the last measure that is needed to reach the overall emission reduction goal. The overall emission reduction goal is predetermined and follows, for example, directly from the WLO scenario under investigation.

Figure 3.2 provides an intuitive illustration of abatement cost curves. In this illustration, eleven distinct measures are available to abate emissions. Each measure has different associated costs of abatement per ton CO_2 (equivalent) and has a different potential total amount of abatement. The measures are ranked according to their costs. In this case, measure A has lower costs than measure E, and measure E has lower costs than measure I. To minimize the accompanying social costs of abatement, any strategy/policy should prioritize making full use of measure A, then B and so forth. To arrive at the efficient CO_2 price, one needs to consider the ranked measures and find the last measure needed to reach the emission target (Q^*). In our case, the last measure to take is measure I. The efficient CO_2 price, the one to consider in the SCBA, equals the social marginal costs of this last measure (P^*).

Figure 3.2 The marginal costs of the last abatement measure to meet the target determine the price



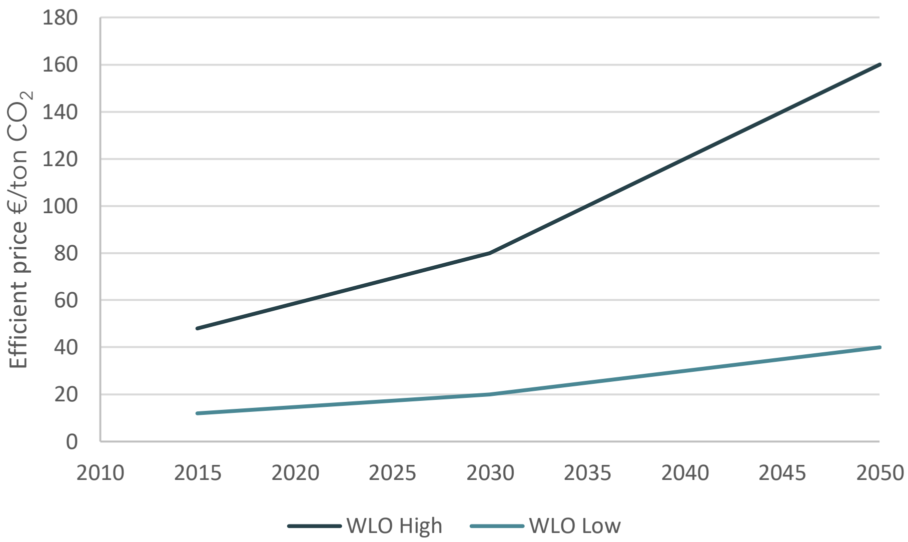
Source: SEO (2024) based on Kesicki & Strachan (2011)

Marginal abatement cost curves can be created for all sectors of the economy or specified for one particular sector. An alternative is ranked first if it has a better marginal benefit/cost ratio (e.g. lower marginal abatement costs) than other alternatives. A 'true' global optimum has been reached if the marginal abatement cost is the same across all sectors and countries. If not, a trade of emissions (or abatement) from one sector to another would raise social welfare. After equalizing marginal costs across sectors (or across all measures within a specific sector), the total cost of achieving the emission target by reallocating resources cannot be further reduced. Using economy-wide marginal abatement cost curves, ensures that no efficient abatement option is overlooked and all resources are allocated to the cheapest abatement opportunity first. A sector-specific marginal abatement cost curve combined with sectoral goals would likely not include the most cost-efficient emission reductions and therefore lead to a suboptimal situation.

Application of abatement cost curves in the Dutch policy context

For the current efficient price paths, PBL and CPB use MERGE (Model for Exploring Regional and Global Effects of Energy Policy) as applied in Blanford et al. (2014) to derive a global marginal abatement cost curve for all sectors of the economy. MERGE optimizes global energy and climate systems with regional and technological details for the long term. Figure 3.3 shows the derived efficient price path for a ton CO_2. The MERGE model estimates the efficient price in both the WLO High and WLO Low scenario in 2050. Subsequently, the price path is determined by applying a Hotelling discount rate of 3.5 per cent.[9]

Figure 3.3 The efficient price path leads to €160 per ton CO_2 in 2050 in WLO High and to €40 in WLO Low



Source: Adapted from CPB & PBL (2016)

The original MERGE climate submodel includes three of the most important anthropogenic greenhouse gases: CO_2, methane (CH_4) and nitrous oxide (N_2O).[10] Interactions between these gases, such as co-benefits of reducing gases, are accounted for in MERGE. This also holds true for the application of the model by PBL and CPB. The interviewees confirm this notion. This implies that if an abatement option reduces CH_4 as well as CO_2, both effects are included to derive the global marginal abatement cost curve (via the interactions in the climate submodel). Consequently, if the current CO_2 price is applied, no corrections for potential co-benefits are needed.[11]

In line with MERGE, a quick scan of alternative available integrated assessment climate models confirms that the coverage of non-CO_2 emissions mainly consists of CH_4, N_2O and F gases (hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride).[12] Contrails, NO_x, or CO are not mentioned in these studies and neither seem to be

9 The Hotelling discount rate is a concept in economics used to identify how the value of non-renewable resources changes and increases over time taking into account their increasing scarcity and hence increasing opportunity costs.

10 Aerosol emissions are not included in the original climate submodel. CPB (2015) indicates that in its application, aerosol emissions are calculated based on exogenous assumptions about air pollution policies and fossil emission rates.

11 Interviewees indicate that a different climate model may be used for the update of the WLO scenarios. This model would still include CH_4, N_2O and F gases.

12 See USEPA (2014) and Yan et al. (2024) for details.

included in the integrated assessment models. Most likely, aviation-specific emissions are out of scope (Yan et al., 2024). Therefore, reduction measures and the marginal costs of non-CO_2 aviation-related emissions are not yet accounted for in the marginal abatement cost curve of currently used models. This also holds true for MERGE. However, this does not invalidate the models as long as the volume of aviation-specific emissions, such as contrails, is small in comparison to that of the total global and sector-wide emissions. The fact that there is no analysis available of the marginal abatement costs of aviation-specific emissions implies that a sector-specific marginal abatement cost analysis is not available either.

Marginal abatement costs of non-CO_2 emissions in aviation

What are the consequences of not accounting for aviation-specific non-CO_2 emissions? If the marginal abatement potential and costs of non-CO_2 emissions would be included in currently used marginal abatement cost curves, they could have an effect on the current efficient CO_2 equivalent price, depending on whether they are cheaper to implement or not.[13] Interviews with economists and climate scientists have revealed that abating contrails could be relatively cheap. For instance, start-ups, airlines and tech companies are using artificial intelligence and atmospheric and climate science to develop contrail forecast maps and identify routes that would not cause contrails. Costs could be competitive with other forms of abatement (The Guardian, 2023). This suggests that the efficient CO_2 price could be lower than it is at the moment. However, the share of (non-CO_2) emissions from aviation in total global warming is fairly small at about 4 per cent (Klöwer et al., 2021). Therefore, the impact of including these emissions in global abatement curves is likely to be fairly small as well. When accounting for the marginal abatement costs of certain emissions, the benefits (costs) of simultaneously reducing (increasing) other emissions should be taken into account. For instance, while flying at lower altitudes reduces contrail formation, the fuel burn is higher, which will lead to higher CO_2 emissions. In principle, these co-benefits are accounted for in MERGE. However, they are not specifically targeted at the aviation sector.

A few attempts have been made to identify aviation-specific marginal abatement cost curves, for example in the United Kingdom, see Department for Transport (2011). This approach is most useful when considering different policy alternatives within a sector. In a recent working paper, Salgas et al. (2024) aim to develop aviation-specific marginal abatement cost curves as well. In both studies, the non-CO_2 climate effects of aviation are part of the climate model but not explicitly accounted for in developing the measures to derive the marginal abatement cost curves.

3.4 Methods and guidelines in other countries

The United Kingdom

The UK government provides specific guidance on transport analysis to evaluate aviation, rail or highway interventions, called Transport Analysis Guidelines (TAG). One chapter is dedicated to environmental impact appraisal. Another chapter of TAG is dedicated to aviation. For the quantification of greenhouse gas emissions, all emissions from departing and arriving flights in the UK are converted to CO_2 equivalents. Wider impacts, such as

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[13] Ideally, marginal abatement costs of all specific emissions are known and included in the analysis. The marginal abatement costs of reducing non-CO_2 emissions such as NO_X or contrails might differ from the marginal abatement costs of reducing CO_2 emissions. Hence, the measure with a better marginal benefit/cost ratio (for example NO_X) would be taken first and ranked first on the marginal abatement cost curve. Excluding NO_X or contrails might therefore in theory lead to an upward bias of the total abatement cost curve (and hence the efficient price path). However, as long as the share of these specific emissions in the total global and sector-wide emissions IS LOWS, the effect on the global abatement cost curve would be small.

displaced emissions from other geographies, are also considered. The document acknowledges the most recent insights of Lee et al. (2021) about the climate effects of non-CO_2 emissions, the use of Global Warming Potential (GWP) factors to quantify them and their uncertainty (GOV.UK, 2024). Due to the high uncertainty surrounding these factors, TAG recommends to either conduct a qualitative assessment of non-CO_2 impacts or a quantitative assessment as a sensitivity test, using the latest guidance on GWP factors and the Department for Energy Security & Net Zero (DESNZ) guidelines for monetary valuation. Monetary valuation is based on the general governmental guidelines on the valuation of greenhouse gas emissions for policy appraisal by the DESNZ. To this aim, the DESNZ uses the estimated abatement costs per ton of CO_2 equivalent. The marginal abatement costs are global and derived from publicly available IAMs from the Integrated Assessment Consortium (IAMC) and International Institute for Applied Systems Analysis (IIASA) (GOV.UK, 2021). The carbon price should be adjusted for internalized carbon pricing such as the EU ETS.

As a platform for broader discussion, the Department for Transport of the UK government has developed a technical report with marginal abatement cost curves for the UK aviation sector. For different demand scenarios, the necessary emission saving targets and measures were determined. The extent of emission savings associated with the measures were quantified from 2010 to 2050. The way in which these measures interact with one another and secondary impacts such as noise, local air quality and non-CO_2 emissions were considered. Measures such as airport capacity adjustments, operational incentives and mandatory biofuels proved to be both emission reductive and cost effective (Department for Transport, 2011).

Germany

The German Environment Agency (Umweltbundesamt) is part of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection (BMUV) (Umweltbundesamt, 2024). As a scientific agency, it advises policy makers contributing to drafting legislation, but also enforces environmental laws. In its Methodological Convention 3.2 for the Calculation of Environmental Costs it recommends using the damage cost approach. The resulting social cost of carbon is 880 euro per ton CO_2 in 2024 when weighting the welfare of current and future generations equally and it has a value factor of 300 euro (in 2024) when placing a higher weight on the welfare of the current generation (discounting for pure rate of time preference). The costs are derived from the open-source Greenhouse Gas Impact Value Estimator (GIVE) integrated assessment model. The climate costs of CO_2, CH_4 and N_2O are modelled. To express costs for other greenhouse gases, the agency recommends using the GWP for a time horizon of 100 years. In order to transfer the value factors to greenhouse gas (GHG) emissions in the aviation sector and if no precise value for the emission weighting factor for individual flights is available, the German Environment Agency recommends using an average emission weighting factor of 3 (Umweltbundesamt, 2024).

United States

The Federal Aviation Administration provides guidelines for the US to conduct project-level SCBA for capacity-related airport projects and investments (FAA, 2020). The guidelines do not provide specifics on the value of CO_2 or non-CO_2. According to the guideline, "investments or actions intended primarily to alleviate environmental problems associated with pre-existing facilities at the airport should be subjected to BCA [Benefit-Cost Analysis] requirements" (FAA, 2020, p. 56, p. 39). They have to comply with certain environmental requirements under the National Environmental Policy Act (NEPA) and be accomplished in the most cost-effective manner possible that is acceptable to the FAA (FAA, 2020, p. 39). If benefits of environmental projects were to be measured in a Cost-Benefit Analysis, they could encompass willingness to pay to prevent environmental degradation (FAA, 2020, p.39). To deal with uncertainty in general, the FAA recommends a sensitivity analysis, which can encompass probability distributions or the one or two variable test (FAA, 2020).

In order to incorporate the social benefits of emission reduction in a uniform way, the Obama administration formed an Interagency Working Group (IWG) that was later continued by the Biden administrations. The IWG uses the integrated assessment models DICE, PAGE and FUND and a weighting of their results to create estimates for the social cost of carbon, methane and nitrous dioxide with a discount rate of 2,5, 3 and 5 per cent respectively. As is common when using the damage cost approach, the values are highly dependent on the discount rate. The social cost for CH_4 in 2020 ranges from $670 to $2,000 per metric ton, for N_2O from $5,800 to $27,000 per metric ton and for CO_2 from $14 to $76 per metric ton (The White House, 2021). Aviation-specific emissions are not mentioned. To capture uncertainty, the estimates for all discount rates and the 95th percentile of estimates based on a 3 per cent discount rate should be considered. The technical documentation provides a frequency distribution for social cost values for emissions in 2020, which reflects uncertainties in key model parameters, such as the equilibrium climate sensitivity. When an agency deems it appropriate to conduct an additional quantitative uncertainty analysis, it should adhere to best practices for probabilistic analysis (The White House, 2021, see p. 6, footnote 4). Although disputed, these numbers have also been used in programmes under the NEPA for environmental impact assessments (Öko-institut, 2023).

Sweden

The Swedish Transport Administration (Travikverket) has provided recommendations for the valuation of climate-related effects. Greenhouse gases other than CO_2 should be converted to CO_2 equivalents according to GWP100. They then should be valued at a shadow price, which is based on the cost of the climate action required to achieve long-term climate goals in Sweden. The administration also waives estimating climate damage due to significant uncertainty and calls its approach the "cost of action" approach, which equals the abatement cost approach in this study. However, this approach assumes that the shadow price is already embedded in fuel prices (for example by the EU ETS) and that no explicit valuation of climate-related effects is necessary. It is assumed that climate externalities arising from aviation are already internalized due to the inclusion of intra-EU flights in the EU ETS (Trafikverket, 2023). According to the guidelines of Travikverket, emissions from air traffic should be multiplied by a high-altitude factor of 1.9 for international flights at about 10,000 meters altitude and 1.3 for domestic flights at a lower altitude (Trafikverket, 2024, p. 176). The altitude effects are not covered by EU ETS. Uncertainty in these factors is not addressed explicitly. SCBA in general should be treated with sensitivity analysis, the more diverse, the better. The challenge often lies in a lack of resources, though. One form of sensitivity analysis that is suggested is scenario analysis, for example by creating maximum and minimum calculations, where all variables are assigned either a best or worst outcome (Travikverket, 2024).

In a cost-benefit analysis for electric airplanes, Travikverket (2023) first separates high altitude emissions and then derives a relationship ratio between high-altitude CO_2 and total CO_2. After CO_2 emissions have been corrected for high altitude with this ratio, a factor of 1.7 is used, based on Lee et al. (2021) and Azar & Johansson (2012), to estimate CO_2 equivalents accounting for high-altitude effects on a global scale.

France

The French guidelines on how to conduct socio-economic evaluations of public investments are described by France Stratégie, a government policy analysis body that is also known as the Commissariat general à la stratégie et à la prospective (CGSP). Similar to the UK and the Netherlands, it does not use the damage cost approach but identifies a carbon value aligning with the goal of net zero greenhouse gas emissions by 2050 (France Stratégie, 2019). This document does not treat how to quantify aviation-specific emissions. For this, the Agence de la transition écologique (ADEME), which falls under the Ministry of Ecology, has developed a separate methodology. It specifies that all emissions must be in CO_2 equivalents using GWP100 and must include CO_2, N_2O, CH_4 and F gases. For the calculation of aviation-related emissions it recommends using the website of the French Civil Aviation Authority

(DGAC), which provides access to aviation related emissions excluding the effect of aircraft condensation trails. Due to lack of better information on the climate impact of non-CO_2 emissions, ADEME proposes to use a multiplier factor of 2. for each kilogram of CO_2 equivalent due to the combustion of CO_2, one kilogram of CO_2 equivalent is added to account for non-CO_2 components (Ministère de la Transition Écologique, 2022). Uncertainty regarding this factor is not addressed.

3.5 Key takeaways on monetary valuation emissions

- To make investment or policy decisions regarding different alternatives addressing the climate impact of aviation, data on costs and benefits in the same unit is needed. Monetary valuation offers such a metric.
- There are two main alternative approaches to determine the price of climate emissions: the damage (social) cost approach and the abatement cost approach. The damage cost approach aims to value the emissions in such a way that they reflect the negative impact on social welfare directly, whereas the abatement cost approach focusses on the (marginal) costs of avoiding or mitigating the negative climate impact of the emissions.
- The Dutch guideline on aviation-specific SCBA recommends using the efficient price of CO_2 emissions. The efficient price is determined by PBL and CPB based on the abatement cost approach, applying the integrated assessment model MERGE.
- Separate efficient prices based on the abatement cost curve for non-CO_2 emissions are not available in these types of integrated assessment models. The climate impact of non-CO_2 emissions and their interaction with the other greenhouse gases, however, are accounted for in these models. The coverage of non-CO_2 emissions mainly consists of CH_4, N_2O and F gases and does not include the more aviation-specific non-CO_2 emissions. In deriving the efficient price for CO_2 emissions, PBL and CPB follow the general convention of converting emissions of various greenhouse gases to CO_2 equivalents.
- For the damage cost approach, a few studies are available that identify separate efficient prices for CO_2 and non-CO_2 emissions to address the social cost of aviation-related emissions, including CO_2, NO_X, contrail-cirrus, black carbon and H_2O.
- Looking at the practices in other countries – the United Kingdom, Germany, the United States, Sweden and France – shows a mixed picture. In the UK, Sweden and France, the abatement cost approach is recommended in applied research, such as SCBA, whereas in the US and Germany predominantly the damage cost approach is advocated. The countries applying the abatement cost approach all use conversion to CO_2 equivalents and then multiplying the result by the efficient CO_2 (equivalent) price to monetize the climate impacts. The suggested emission weighting factor differs slightly for the reviewed countries, but often lies between 2 and 3.

4 Monetary valuation of non-CO_2 in SCBA

The social damage cost approach is often considered preferable to the abatement cost approach. However, in practice it is less feasible. The use of the abatement cost approach requires converting non-CO_2 emissions into CO_2 equivalents. The SCBA practitioner may address the uncertainties via sensitivity analyses, as recommended in the guideline.

4.1 Comparison of the two main valuation approaches

There is an ongoing debate on whether the social damage cost approach or the abatement cost approach is the preferred method to derive the shadow price of emissions. Based on the literature and discussions with the experts for this study, we summarize this debate below.

A study from Marten and Newbold (2012) suggests that the damage cost approach is a better approach, since multiplying the CO_2 price with a CO_2 equivalent (often GWP100) when following the abatement cost approach can lead to substantial errors for the abatement benefits of individual gases (and lower errors for multi-gas policies). This is mainly due to the equivalents' arbitrary time horizon and constant level of concentration. The GWP ratio does not capture further connections in the chain that lead to economic damage. For the social cost to straightforwardly align with a GWP unit, however, many simplifying and often unrealistic assumptions would have to be made. Marten and Newbold (2012) argue that when estimates for the marginal social cost of each individual gas are unavailable, it is up to the decision maker to determine whether the error of multiplying the CO_2 equivalents with the social cost of CO_2 is acceptable.

Pindyck (2013) argues that the integrated assessment models on which this approach are based allow for a great deal of freedom in inputs and assumptions, especially when it comes to estimating how higher CO_2 concentrations lead to increased temperatures and translate into reductions in GDP and consumption (the marginal damage). Because of their sensitivity to the chosen discount rate and risk aversion rate (essential to estimate consumption and welfare), emission prices can have a wide range of values (Tol, 2009; Pindyck, 2013).

Mallapragada and Mignone (2020) derive a theoretical relationship between GWP and the economic damage ratio between two gases, relaxing some of the simplifying assumptions from Marten and Newbold (2012): the discount rate is not zero and economic losses do not scale linearly with temperature. They find that their theoretical assumptions generally agree well with numerical approaches to test this relationship. Using an economic growth rate of two per cent, a time horizon of 100 years would be roughly consistent with a discount rate of three per cent, and a time horizon of 20 years would be roughly consistent with a discount rate of seven per cent. The relationship between the time horizon and the discount rate becomes more restrictive as discounting includes the marginal utility of consumption as well. Furthermore, the relationship is sensitive to the decay rates of different emissions, feedback mechanisms of the climate systems given their current state, as well as temperature changes and future economic growth rates. For aviation emissions, the assumptions for time horizons to agree with the discount rate would have to be extended under more restrictive conditions (Mallapragada & Mignone, 2020, p.114).

General cost-benefit analysis (CBA) guidelines encourage the damage cost approach. This includes, for instance, the guidelines in the Handbook of Environmental Prices by CE Delft (2023b) and the general guidelines for social cost-benefit analysis by CPB and PBL (2013).[14] In an ideal case, this approach would adequately reflect society's willingness to pay for/trade off emission reduction and account for the social costs and benefits (CPB & PBL, 2016; CE Delft, 2023b). The willingness to pay can be seen as the marginal benefits of emission reduction, or in other words the avoided damage by emissions.

However, marginal benefits of emission reduction are hard to estimate, especially over a long period of time (CPB & PBL, 2016). This issue is also addressed in CE Delft's Handbook and recognized by the interviewees of the present study. Valuation based on revealed and stated preferences can lead to an inaccurate estimate of the willingness to pay if people are not well informed about the actual damage of environmental pollution (CE Delft, 2023b).[15] Hence, the willingness to pay is not known and only the abatement cost curve is often considered in practice. Furthermore, the social cost of carbon equals the willingness to pay at the optimum level of emission reduction. The optimum/target level of emission reduction depends on the policy goals.

4.2 Application to SCBA

The main objective of SCBA is to identify and quantify the relevant social costs and benefits of certain policy alternatives. From this perspective, the monetary valuation of externalities – in our study CO_2 and non-CO_2 emissions – boils down to identifying the efficient price of these externalities. Since there is no (efficient) market price available, several shadow cost approaches can be applied. Figure 4.1 presents a flowchart with the relevant choices for these approaches. The three main dimensions are: 1) choice of underlying valuation method, 2) assessment per species or by a climate metric, 3) choice of climate metric and time horizon.

The choices regarding these dimensions ultimately determine whether separate efficient prices per species are plausible to use in the SCBA. Box 4.1 provides the most typical use of calculating climate effects in aviation-specific SCBA. The example shows that discounting of the monetary valuation is based on the moment of emission. Hence, when considering the welfare impact of a reduction in flights in 2030, both the positive and negative impacts are measured in 2030 and subsequently translated into a net present value.

Box 4.1 discusses how to account for the CO_2 emissions. Looking at non-CO_2 emissions may differ depending on the available information. Only when information about the unit (damage) change in separate greenhouse gas emissions is known, for example the unit change in the damage of contrails, in combination with the shadow price of this damage, the same logic as with CO_2 emissions can be applied: define the change in damage in units, multiply it by the shadow price for the year(s) under consideration and apply standard discounting to calculate the present value. In the flowchart shown in Figure 4.1, this would be the approach if the valuation of climate impacts follows from a damage costs analysis. If information – units and prices – is not available (or reliable) for individual gases, a climate metric is used to arrive at the unit change in non-CO_2 emissions based on the change in CO_2 emissions in combination with the efficient price of CO_2.

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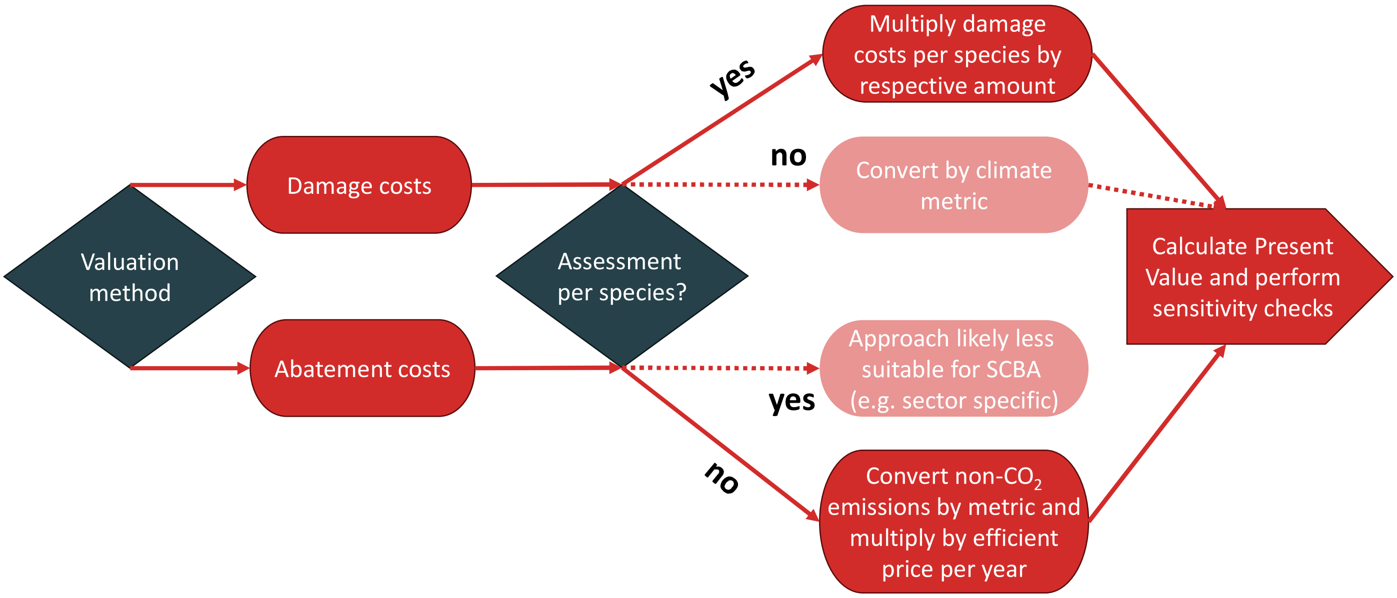
14 Appendix B briefly discusses damage ratios and cost-effective ratios as alternative valuation approaches.

15 WTP can be derived based on revealed or stated preferences. Through observed market behaviour in an existing complementary market, revealed preferences can indirectly determine WTP in a missing market (CE Delft, 2023b). Stated preferences are obtained via questionnaires, interviews or other techniques.

Figure 4.1 Flowchart incorporating economic valuation of non-CO_2 climate impacts in SCBA



Source: SEO (2024)

Box 4.1 Illustration of calculating the change in climate impact of aviation in a typical SCBA

Assume, for illustration purposes only, that one needs to identify the impact of a hypothetical capacity restriction. Due to this capacity restriction, it is anticipated that in 2030, 2040 and 2050 the total number of departing flights from Dutch airports would be 1,000 flights lower. Suppose that these 1,000 flights per year translate to a decrease of 1,000*40 ton CO_2 well-to-wing per year.[16] The calculation of the welfare climate impact of this restriction follows from the guideline and is relatively straightforward. It equals the efficient price times the unit change in Mton discounted back to the current date. For example, for WLO High the net present value of the change in 2040 in 2025 would be equal to (€160 * 1,000*40 ton CO_2)/(1+0.0225)^15. To get the total impact over the chosen time horizon (typically 100 years), one needs to calculate the present value for each year and sum these values.

Source: SEO (2024)

In all available abatement cost approach integrated assessment models, both CO_2 and non-CO_2 emissions are considered in the underlying climate models.[17] The abatement cost approach defines the efficient price of the emission as the minimum (social) marginal costs of reducing the emissions to the pre-defined target level. In the abatement cost approach, identifying different efficient prices is inconsistent with using the abatement curve to find the single minimum cost of reducing the emissions. In fact, if there are two minimum prices – i.e. efficient prices – at least one of them fails to be efficient after all. Given the same impact on the climate target, one would utilize the cheaper alternative (with the lower efficient price) first, until its marginal costs of reducing the emissions increase and become equal to the efficient price that was originally the highest.

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16 The number of flights at Dutch airports in 2017 was about 555,000. Therefore, there were about 277,500 departing flights. The total estimated tank-to-wing CO_2 emissions of departing flights in 2017 equal 10.2 million ton. Hence, the average departing flight would yield a total of 40 ton tank-to-wing CO_2 emissions.

17 As discussed in Section 3.3, the current model used to derive the Dutch efficient CO_2-equivalent prices includes CH_4 and N_2O. Non-CO_2 emissions specific to aviation are not included to derive the abatement costs.

The flowchart in Figure 4.1 also indicates that mixing both valuation methods is not advisable. Given that in the Dutch context the abatement cost approach has been followed to identify and quantify the efficient price of CO_2, there is no need to derive or use a separate price for individual non-CO_2 greenhouse gases. This implies the need for converting non-CO_2 emissions using a metric, and hence the need to choose a metric, in the Dutch SCBA context.

To provide practical guidance, the aviation-specific SCBA guideline recommends using twice the CO_2 effect as a proxy for the total climate effect. This recommendation follows from taking the average weighting factor reported in the literature. If more estimates of weighting factors become available in the future, it is important that the applied time horizon of the underlying climate metric – in particular for the commonly used GWP metric – matches the time horizon of the SCBA. The time horizon of the Dutch SCBA is 100 years. This would support the use of GWP100 to remain consistent across all potential effects: both positive and negative welfare effects beyond 100 years are ignored.

Some experts in the interviews highlighted the advantages of using a separate price for non-CO_2 emissions instead. Sector-specific marginal abatement cost curves could be a motivation for the aviation sector to pursue its sustainability goals. Pricing non-CO_2 emissions separately might stimulate mitigation strategies, such as flying at lower altitudes to avoid contrail emissions. Merely diverting a small part of a fleet could reduce contrails significantly while only leading to a small increase in CO_2 (Teoh et al., 2020; Schumann et al., 2011). An SCBA evaluating the mitigation of aircraft contrails could, therefore, potentially present a positive case for contrail mitigation.

Other experts, however, argue that calculating a separate price for non-CO_2 emissions would come with more uncertainties and complexities. There are great uncertainties surrounding emission reduction trade-offs between certain gases and there are methodological challenges to determine abatement costs for each gas individually. Furthermore, these experts stipulate that from a scientific perspective these climate science uncertainties should be addressed by climate science and cannot be solved by applying different monetary valuations.

As a final word of caution, some experts warn for underestimating the persisting climate effects of CO_2. Any policy targeted at a trade-off between CO_2 and non-CO_2 emissions should be handled with extreme care. Interviewees warn that abating non-CO_2 emissions at the cost of additional CO_2 emissions might not improve welfare because of the persistent (more than 100 year-long) impact of CO_2 emissions. The practical use of the aviation-related SCBA guideline does not focus on these kinds of trade-offs as policy alternatives. Given the 100-year time horizon of the SCBA, the SCBA does not seem to be the most appropriate tool to evaluate these kind of policy alternatives.

4.3 Discounting and uncertainty

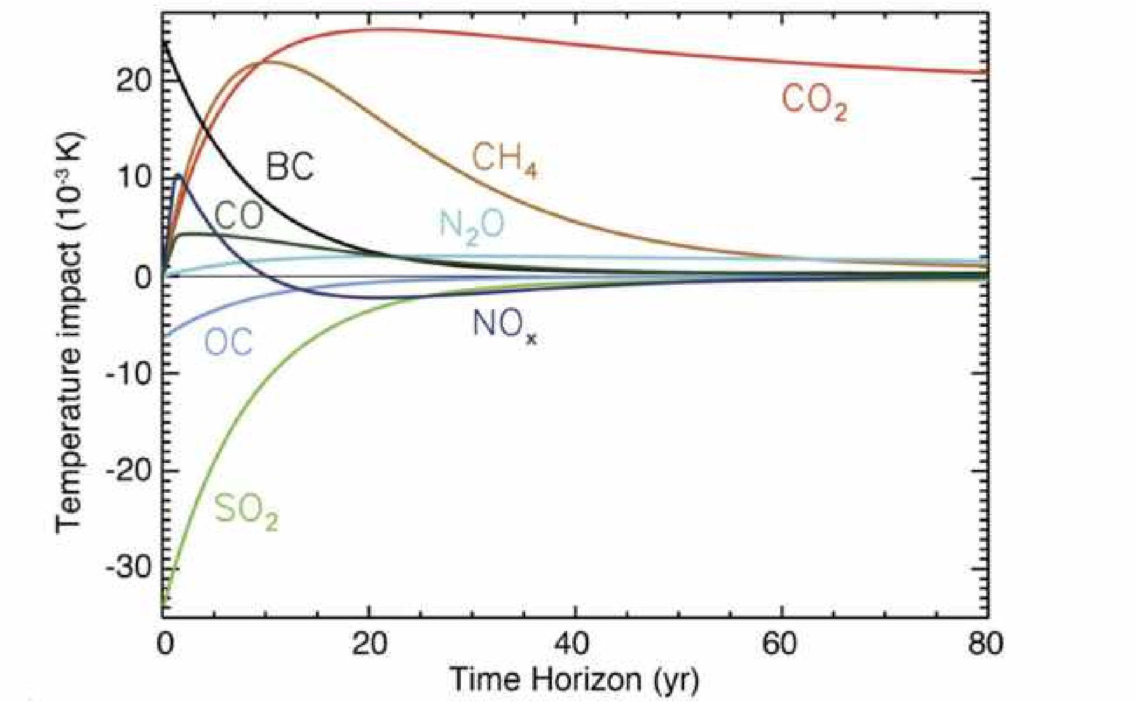
As argued above, applying separate prices for CO_2 and non-CO_2 emissions as an outcome of the abatement cost approach would be inconsistent. Hence, the main responsibility of the SCBA practitioner is to be aware of the choice of climate metric – and hence the implied weighting factors – translating non-CO_2 emissions into CO_2-equivalence units. From an economic perspective, discounting and uncertainty are two dimensions to consider with respect to identifying the non-CO_2 climate effects of aviation.

Discounting

Physical metrics should be as transparent as possible and ideally avoid value judgements, for example by choosing a time horizon. The only value judgment should rest with the SCBA practitioner in applying the appropriate discount rate to determine the net present value of future benefits and costs.

Providing physical metrics as transparent as possible is within the realm of climate science. IPCC (2023) investigates whether looking at emissions separately is a way forward. To do so, the emissions are examined by using their temperature responses to one pulse per year. Rather than using a cumulative average, it is more precise to consider the emission for each year, with a large impact from short-lived emissions in the beginning. There are temperature response functions, for example, in terms of absolute GTP (AGTP) that show the temporal development per species of the emissions of annual global aviation, see Figure 4.2.

Figure 4.2 Temperature responses for total anthropogenic one-year emissions



Source: IPCC (2023)
Note: OC denotes Organic Carbon, SO_2 sulphur dioxide, CO carbon monoxide, BC black carbon, N_2O nitrous oxide

Figure 4.2 shows that temporal response functions for aviation-related emissions might be available. However, they might vary with regard to emission species they consider, which year the emissions occur (important for discounting and pricing) and where they occur. The current available functions do not distinguish between emissions at the flight level. Therefore, it is not feasible to compute a total temporal response function for all these emissions together. Using the climate metrics ATR100 and GWP100 as given by the ANCO tool is the next best option. In that approach, the accumulated effect over 100 years is taken and multiplied with the efficient price of the year in which the emission takes place. The result is then discounted to arrive at the current year's value. If the annual increase in the CO_2 price is equal to the discount factor, then the effects of annual price increases and of discounting level each other out. In that case, the current cost-efficient price can be used without discounting.

In the Netherlands, however, the efficient price path is determined using the Hotelling rule. Using a climate metric with a time horizon of 100 years is in line with the general time horizon of SCBA and together with applying the current CO_2 price path fits best within the SCBA methods applied in the Netherlands.[18]

Uncertainty about non-CO_2 climate effects of aviation

The uncertainties about the methods used (damage vs abatement approach) stand on their own, no matter if non-CO_2 emissions are included or not. Furthermore, economic trade-off ratios (instead of CO_2 equivalent factors) do not reduce these uncertainties. So, uncertainties surrounding non-CO_2 emissions are mostly reflected in the physical metrics and should be addressed in these metrics as well.

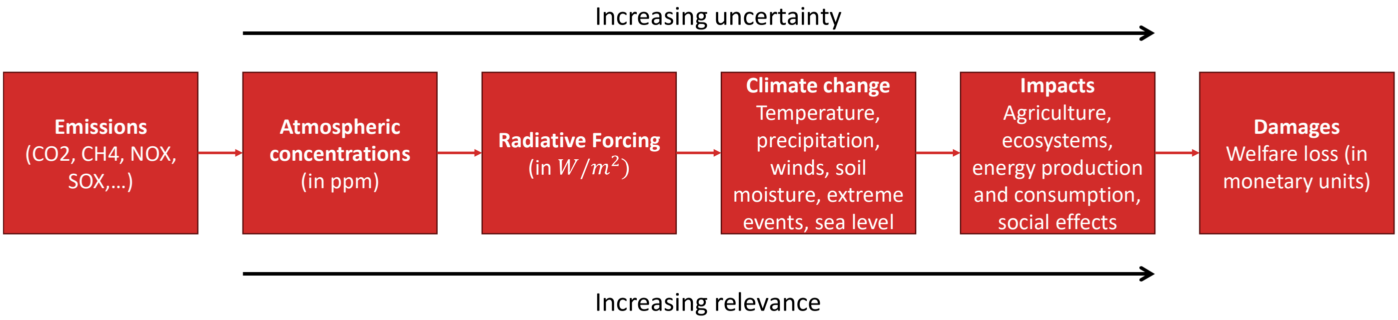
Regarding the physical climate metrics, Fuglestvedt et al. (2010) distinguish between two types of uncertainty: structural and parametric uncertainty. Structural uncertainty refers to the policy context, such as the choice of time horizon or the choice of the metric itself. Parametric uncertainty refers to the scientific knowledge about the emission's impact. In general, physical metrics incorporate the great uncertainty of the emission's effect on the energy balance of the Earth.

For aviation-related non-CO_2 emissions in particular, the chemical processes and the interaction with other aerosols and gases is very complex to measure, leading to parametric uncertainty. For aviation related gases and aerosols, the link between atmospheric concentration and radiative forcing may differ from that of gases typically considered in integrated assessment models and climate policies (Mallapragada & Mignone, 2020). Additionally, as reported by Grobler et al. (2019), estimating the impacts of climate system feedback and temperature responses due to different climate forcers remains challenging. Radiative forcing and the lifetime of emissions are two primary sources of uncertainty (Dahlmann et al., 2016). This is also reflected in the large uncertainties regarding the radiative forcing of contrails and NO_X emissions in the study by Lee et al. (2021). In contrast, CO_2 emission has relatively few uncertainties and its effect is relatively permanent. Structural uncertainty influences how we weigh parametric uncertainty. Choosing a shorter time horizon gives more weight to non-CO_2 emissions and therefore also to the corresponding uncertainties. Therefore, as insights from interviews reveal, when dealing with structural uncertainty, it is important to not neglect CO_2's predictable and long-term impact, as it exhibits less parametric uncertainty than non-CO_2.

Linking climate change to economic damage comes with additional uncertainties, apart from the uncertainties already related to the physical-based parameters. Figure 4.3 illustrates how uncertainties increase as the parameters become more economic and relevant to society (Fuglestvedt et al., 2010). The chain in the figure links the causes of climate change via impacts to damage. As argued by Pindyck (2013), estimates about climate sensitivities rely at least on scientific results, whereas damage functions rely on many assumptions. For instance, little is known about the damage to be expected with larger temperature increases and potential catastrophic outcomes that could push up the price of emissions significantly.

18 We note that at present (2024), the CO_2 valuations used in SCBA show a yearly price increase of 3.5 per cent, which is based on a discount rate used in 2016. Since 2020, the discount rate used in SCBA itself was updated to 2.25 per cent, without changing CO_2 price path accordingly. This will hopefully be solved in 2025, as in that year new CO_2-prices price paths from new WLO scenarios are anticipated to be published.

Figure 4.3 Uncertainties in the chain that links causes to climate effects of emissions



Source: Excerpt from Fuglestvedt et al. (2010)

Uncertainty and the Dutch guideline for aviation-specific SCBA

Following the general Dutch guidelines for SCBA, the guideline for aviation-specific SCBA distinguishes between three types of uncertainty: knowledge uncertainty, policy uncertainty and uncertainty about future developments. The uncertainty of the non-CO_2 climate effects of aviation as discussed in our study is knowledge uncertainty. Besides these climate effects, other aviation-specific examples of knowledge uncertainty in the context of SCBA include the non-linear impact of airport capacity restrictions on the hub performance of a hub airport (e.g. Schiphol), the monetary valuation of (reliability in) access and egress travel time, the monetary valuation of noise, and the monetary valuation of the health impact of ultrafine particles.

The aviation-specific guideline already recommends certain analyses to address the uncertainty of the climate effects of aviation, most notably:

- to perform a sensitivity analysis on the WLO High scenario with efficient prices belonging to the 2-degree climate uncertainty forecast;
- to perform a sensitivity analysis with the equivalent factors 1 and 4 (in addition to the standard recommended weighting factor of 2).

The first recommendation addresses the uncertainty regarding the true efficient price of CO_2. The recommendation suggests a sensitivity analysis with the highest approximation of the efficient price available (at the time of publication of the guideline) within a set of realistic policy and economic scenarios.

The second recommendation deals with the uncertainty of the non-CO_2 climate effects of aviation. The use of a range of equivalent factors is recommended because of the many uncertainties regarding non-CO_2 climate effects and the non-linear relationship between CO_2 and non-CO_2 effects. The chosen range of equivalent factors 1 and 4 is based on the study by Lee et al. (2021) and basically takes the minimum and maximum value of the equivalent factor based on the choice of climate metric: GWP20, GWP50, GWP100, GTP20, GTP50 and GTP100. The upper limit of 4 is based on GWP20 and the lower limit of 1 is based on GTP20, see Appendix B in SEO et al. (2021).

In our interviews, the experts have indicated that recommending a bandwidth is an appropriate way to address the non-CO_2 climate effects of aviation in the SCBA context. Box 4.2 discusses min-max or min-max regret decision rules as an alternative methodology of addressing the incomplete scientific understanding of climate as proposed by Manski et al. (2021). These rules, however, are less suitable for SCBA because the SCBA aims for a neutral evaluation of the costs and benefits, whereas the min-max or min-max regret decision rules take a conservative approach.

Box 4.2 Min-max or min-max regret decision rules take a more conservative approach to climate uncertainty

The study by Manski et al. (2021) provides numerical examples of min-max and min-max regret decision rules in the context of a dynamic economic trade-off between emissions abatement and reduced damage from emissions-caused temperature increases in SCBA. The min-max decision rule chooses the policy alternative that minimizes the total cost of abatement and damage under the most pessimistic assumption(s) regarding the climate model. This rule is conservative by design. The min-max regret decision rule is to choose the policy alternative that minimizes the maximum regret across the various choices to make in applying the integrated climate assessment models. The maximum regret is equal to the largest degree of suboptimality in the analysis.

Source: SEO Amsterdam Economics (2024)

The bandwidth ideally should reflect the whole range of potential realistic values of, in this case, equivalent factors. The base equivalent factor should obviously lie within the bandwidth. The base equivalent factor does not necessarily have to be the midpoint of the bandwidth because the potential equivalent factors may not be uniformly distributed. In the current aviation-specific SCBA guideline, this full range of values includes different measures and time horizons. The chosen GWP20, for example, only considers the emissions in the first twenty years, which seems to violate the main assumption of applying a time horizon of 100 years in Dutch SCBA. The (structural) uncertainty in the valuation of non-CO_2 emissions may be reduced by using a standard time horizon of 100 years, instead of a mix of time horizons. A period of 100 years is equal to the time horizon over which other costs and benefits are computed in social-cost benefit analysis in the Netherlands.

Sensitivity analyses applying a lower and upper limit of the weighting factor are appropriate to address parametric uncertainty. However, this bandwidth should not reflect variation in weighting factors due to the choice of climate metric, time horizon or other observed factors. Furthermore, when differentiated factors become available, a single lower and upper limit will most likely not be sufficient. Differentiated factors such as the ones available in the ACNO-tool, hence, should come with differentiated lower and upper limits to reflect the underlying parametric uncertainty.

4.4 Key takeaways on monetary valuation of non-CO_2 in SCBA

- There is an ongoing debate on whether the social damage cost approach or the abatement cost approach is the preferred method to derive the shadow price of emissions. General cost-benefit analysis guidelines encourage the damage cost approach. However, the marginal benefits of emission reduction are hard to estimate, especially over a long period of time. This prevents the application of the social damage cost approach in the aviation-specific Dutch SCBA context.
- The monetary valuation of CO_2 and non-CO_2 emissions boils down to identifying the shadow price of these externalities. There are three main dimensions to consider: 1) choice of the underlying valuation method (damage cost of abatement cost approach, 2) assessment per species/type of emission or by a climate metric, 3) choice of a climate metric and a time horizon.
- In the abatement cost approach, differentiation of prices between greenhouse gases would be inconsistent. The abatement cost approach defines the efficient price of the emission as the minimum (social) marginal costs of reducing the emissions to a pre-defined target level. Identifying different efficient prices is inconsistent with using the abatement curve to find the single minimum cost of reducing the emissions.
- Using the efficient price in SCBA hence implies using CO_2 equivalents, the need for weighting factors and the use of a single price for the climate-related greenhouse gas emissions.
- We conclude that there is no objectively superior approach readily available to address the non-CO_2 effects in SCBA. Therefore, the guideline's recommendations to use the constant emission weighting factor, or to use

differentiated factors when identification of individual non-CO_2 components at flight level becomes available, and to apply one efficient CO_2 (equivalent) price remain valid.

- The recommendation of using sensitivity analyses applying a lower and upper limit of the weighting factor also remains valid. However, this bandwidth should not reflect variation in weighting factors due to the choice of climate metric, time horizon or other observed factors. Furthermore, when differentiated factors become available, a single lower and upper limit will most likely not be sufficient. Differentiated factors, hence, should come with differentiated lower and upper limits to reflect the underlying parametric uncertainty.
- The (structural) uncertainty in the valuation of non-CO_2 emissions may be reduced by using a standard time horizon of 100 years, instead of a mix of time horizons. A period of 100 years is equal to the time horizon over which other costs and benefits are computed in social-cost benefit analysis in the Netherlands.

5 Conclusion and recommendations

There is no single objectively correct way to approximate the ratio between CO_2 and non-CO_2 emissions. Given the abatement cost approach, one price for CO_2-equivalent emissions applies. Using a constant emission weighting factor remains valid. In a sensitivity analysis the lower and upper limits should reflect parametric uncertainty.

Recommendations in aviation-specific SCBA guideline remain valid

Before turning to the separate sub questions, we first discuss whether the aviation-specific Dutch SCBA guideline needs to be updated in line with developing insights from (predominantly) climate science. We conclude that the latest scientific insights do not provide consensus about any objectively superior approach that is readily available to address the non-CO_2 effects in SCBA. Hence the guideline's recommendation to use a constant emission weighting factor and to apply one efficient CO_2 (equivalent) price remains valid. This approach is recommended until more precise identification of individual non-CO_2 components at flight level becomes available and can be applied. This also holds true for addressing the uncertainty via a sensitivity analysis using a lower and upper limit of a set of realistic emission weighting factors.

Although this study looks only at the underlying methods and assumptions and does not assess the numerical values of the weighting factors, we recommend to periodically evaluate these values. The anticipated update of the efficient price path of CO_2 emissions for the Netherlands would be an opportune moment to evaluate the recommended emission weighting factors, including lower and upper limits. Any updates of these figures should be made available to SCBA practitioners.

When considering a coherent set of realistic weighting factors, it is important to explicitly define what type of variation one wants to address. The current lower and upper limits of the bandwidth recommendation in the guideline provide a mix of different climate metrics and time horizons. Hence, in this way mainly addressing the structural uncertainty without covering parametric uncertainty. The structural uncertainty in the valuation of non-CO_2 emissions may be reduced by using a standard time horizon of 100 years only. A period of 100 years is equal to the time horizon over which other costs and benefits are computed in social-cost benefit analysis in the Netherlands.

Conversion of non-CO_2 emissions to CO_2 equivalents

In what way does the conversion of non-CO_2 emissions into CO_2 equivalents consider the differences in climate effects between CO_2 emissions and non-CO_2 emissions, both in general and in the tool developed by CE Delft and DLR?

The metrics for conversion of non-CO_2 emissions into CO_2 equivalents cannot fully account for all climate effects of CO_2 and non-CO_2 emissions. How climate effects are reflected is influenced by the gases' lifetime in the atmosphere, their radiative efficiency, regional sensitivities and feedback mechanisms. Different climate metrics highlight different aspects of climate effects, depending on whether they are based on radiative forcing or temperature increase and which time horizon they use. In the tool developed by CE Delft and DLR, climate effects of individual flights are represented on a climatological basis with average conditions. Due to their complexity, weather and spatial dependencies are not taken into account. The metrics used are GWP100 and ATR100. GWP emphasizes contrail cirrus while ATR highlights the warming effect of NO_x induced ozone. In general, the metrics do not account for the persisting climate effects of CO_2 after more than 100 years. Furthermore, there is parametric uncertainty regarding estimating the climate effects of non-CO_2 emissions.

A separate monetary valuation?

Can the conversion of non-CO_2 emissions to CO_2 equivalents exist alongside a potential separate monetary valuation of the non-CO_2 climate effects? What implicit assumptions about the trade-off between CO_2 and non-CO_2 emissions are then applied from the perspective of the SCBA, and under what conditions is this economically consistent (i.e., does this not lead to the application of two different valuations for ultimately the same (climate) effect)?

The conversion of non-CO_2 emissions to CO_2 equivalents cannot exist alongside a potential separate monetary valuation of the non-CO_2 climate effects. This would lead to the application of two different valuations quantifying the same climate effect. Given that, in the Dutch context the abatement cost approach has been followed to identify and quantify the efficient price of CO_2, there is no need to derive or use a separate price for individual non-CO_2 greenhouse gases.

Literature and country-case study about the valuation of non-CO_2 emissions

What information is available in existing (scientific) studies on the economic/monetary valuation of non-CO_2 emissions, or the climate effects of non-CO_2 emissions? And, is this information applicable to the valuation of non-CO_2 emissions in SCBAs concerning aviation?

While a great range of academic literature on the social cost of carbon has been published since the 1990's and an increasing amount of work is being done on the social cost of methane (CH_4) and nitrous oxide (N_2O), the economic valuation of aviation-related emissions has been studied to a lesser extent. A key challenge in valuing non-CO_2 emissions from aviation is to accurately estimate the physical climate impacts of aviation-related gases and aerosols. While numerous studies have been done and significant progress in climate science has been made, these assessments still contain uncertainties, particularly with regard to estimating radiative forcing and climate sensitivity. Additionally, factors such as interactions with other gases and aerosols, variations over time and space, climate feedback mechanisms, engine efficiency and aircraft size further complicate these assessments. Linking these physical impacts to economic damage increases the uncertainty. In view of the challenges of estimating marginal damage, the guidelines on SCBA of several countries (including the Netherlands) recommend the abatement cost approach and the use of an emission weighting factor. Countries applying the abatement cost approach all use CO_2 equivalents followed by multiplication by the efficient CO_2 (equivalent) price to monetize the climate impacts. The suggested emission weighting factor differs across the reviewed countries, but often lies between 2 and 3.

Methods for the valuation of climate effects of non-CO_2 emissions

What are suitable methods to derive such figures, and what is the expected impact of using accurate/alternative figures on the qualitative conclusions of existing SCBAs (in other words: does it matter)?

Suitable methods to price emissions are either derived from the damage cost approach or the abatement cost approach. The valuation of non-CO_2 emissions can then take place per species or by converting emissions into CO_2 equivalents. Only when information about the unit (damage) change in separate greenhouse gas emissions is known on a year-by-year basis, for example the unit change in the damage of contrails, in combination with the shadow price of this damage, one can define the change in damage in units per species, multiply it by the shadow price valid for the year(s) under consideration and apply standard discounting to calculate the present value. Since this information is not available in the Dutch context, the abatement cost approach remains the only viable method. In the abatement cost approach, using different efficient prices is inconsistent with its goal of minimizing overall costs to meet a predefined target. Instead, an emission weighting factor derived from a climate metric is used to convert non-CO_2 emissions into CO_2 equivalents, paired with an efficient CO_2 price. The ANCO tool offers a method for more accurate weighting by accounting for geographic flight regions. ANCO's factors are higher than those in current SCBA guidelines and applying them would place greater emphasis on non-CO_2 emissions and would yield larger estimates of CO_2 equivalent emissions.

Incorporating uncertainty

In what way should the uncertainty surrounding non-CO_2 effects be incorporated in the SCBA, and does this depend on how non-CO_2 effects are (monetarily) valued?

The uncertainties regarding the methods used (damage cost vs abatement cost approach) stand on their own, no matter if non-CO_2 emissions are included or not. Furthermore, uncertainties increase as the metrics capture more economic and socially pertinent impacts. Uncertainties should therefore be first addressed in physical metrics. In contrast to non-CO_2 emissions, CO_2 emission has relatively few uncertainties and its effect is relatively permanent. Choosing a shorter time horizon gives more weight to non-CO_2 emissions but comes with greater uncertainty. Therefore, it is useful to consider the results in the SCBA when using a time horizon that emphasizes the permanent impact of CO_2 (e.g. a time horizon larger than 100 years).

A common approach to address parametric uncertainty is to report not only a point estimate but also a bandwidth around the point estimate of anticipated impacts from changes in economic activity (e.g. the number of flights departing from the Netherlands) across policy scenarios. The Dutch guideline already recommends using such ranges. This is considered an appropriate way to address the non-CO_2 climate effects of aviation in the SCBA context. However, this bandwidth should reflect parametric uncertainty and not reflect variation in weighting factors due to the choice of climate metric, time horizon or other observed factors. Furthermore, when differentiated factors become available, a single lower and upper limit will most likely not be sufficient. Differentiated factors, hence, should come with differentiated lower and upper limits to reflect the underlying parametric uncertainty.

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Appendix A Interviewees

Table A.1 List of interviewees

Name	Affiliation
Rob Aalbers	CPB
Lynette Dray	University College London, Energy Institute
Bram Peerlings	NLR
David Engler	NLR
Rick van der Ploeg	University of Oxford
Feijia Yin	TU Delft
Stefan Grebe	CE Delft
Katrin Dahlmann	German Aerospace Center (DLR)
Maria Borjesson	Linkoping University
Marianne Tronstad Lund	CICERO (Center for International Climate Research, Norway)
Jan Fuglestvedt	CICERO (Center for International Climate Research, Norway)

Appendix B Alternative valuation approaches

A cost-benefit analysis may use the social cost of carbon and, for greater precision, a separate valuation with a social cost per emission. Likewise, the CO_2 equivalent factor could then be determined using an economic trade-off ratio. Economic trade-off ratios would use separate pricing for emissions, which would defeat the purpose of climate metrics. The damage cost approach uses impulse response functions to estimate how concentrations will change in response to emissions, how long these emissions remain in the atmosphere, and how they subsequently translate into temperature changes over time. When calculating the temporal development of the global near-surface temperature change, longitude, latitude and altitude should ideally be taken into account. Without integrating non-CO_2 climate impacts through metrics like GWP100 or ATR100, the only value judgment rests on the choice of the discount rate and time horizon, which are used to determine the net present value of future damage.

Damage ratios

CO_2 equivalents and equivalent factors incorporate an implicit choice about the importance of emissions in the short or long term. Thus, the metrics are already embedding value judgement, even before the discounting in the cost-benefit analysis takes place. From an ideal economic perspective, an index that indicates the trade-off among gases "should be an outcome of an analysis that minimizes the discounted present value of damages and mitigation costs" (Manne & Richels, 2001, p.675). This refers to the damage cost approach. Therefore, some studies, such as Azar & Johansson (2012), Marten & Newbold (2012) and Mallapragada & Mignone (2020), and interviewed experts have described a trade-off ratio between emissions that depends on the economic damage of these emissions. Azar and Johansson (2012, p.565) refer to this as "the net present value of the economic damage from the global average surface temperature change following a unit pulse emission of gas X in relation to the net present value of the economic damage from the temperature change from a unit pulse emission of CO_2". This is also referred to as the global damage potential, see Box B.1.

Despite the difficulty of estimating these parameters – as briefly explained in Box B.1 – the main difference between a greenhouse gas and CO_2 can be approximated, if the decay rate and radiative efficiency are known (Mallapragada & Mignone, 2020).[19] When these are identified, it is possible to calculate the warming effect of one greenhouse gas relative to CO_2 and sum that over the relevant time period of the cost-benefit analysis. Still, for aviation this would come with more complexities. The decay rates of short-lived aviation-related emissions can be measured per days or weeks, while the decay rate of CO_2 can be measured per centuries. Also, as indicated by Dahlmann et al. (2023) and Thor et al. (2023), the warming effects of non-CO_2 emissions depend on the geographic flight region.

[19] An increase in concentration due to an increase in emission depends on the decay rate of the emitted gas.

Box B.1 Economic damages as a function of temperature change by a unit pulse emission

In the expression for the global damage potential below denotes $G(t)$ the total economic output, $\frac{\partial D(t)}{\partial E_0}$ denotes the damage in output and changes in current's year emissions multiplied with the discount factor, where *r* is the discount rate and *t* the time in the future. The integral sums up the discounted damages values over an infinite time horizon. This equation (extracted from Mallapragada & Mignone, 2020) can be divided by the social cost of carbon, to obtain a damage ratio between two gases.

$$SCX = \int_0^{\infty} G(t) \frac{\partial D(t)}{\partial E_0} e^{-r} \, dt$$

To estimate $\frac{\partial D(t)}{\partial E_0}$, knowledge is necessary on the quantity of emissions and how they affect atmospheric concentrations, the forcing-concentration relationship, its impact on temperature (and climate) change and lastly, its impact on damage. This effect can also be described by the following formula:

$$\frac{\partial D(t)}{\partial E_0} = \frac{\partial D(t)}{\partial T(t)} \frac{\partial T(t)}{\partial F(t)} \frac{\partial F(t)}{\partial C(t)} \frac{\partial C(t)}{\partial E_0}$$

Each ratio describes how much the numerator increases or decreases due to a one-unit change in the denominator.

Mallapragada & Mignone (2020), Marten & Newbold (2012) and Tol et al. (2008) argue that if certain simplifications and assumptions are made, the global damage potential can be viewed as the global warming potential. Thus, when the pulse emission damage is unavailable or unknown, GWP can provide an alternative, using the same time horizon as in the social cost benefit analysis.

Cost-effective ratios

A different economic approach is presented by Manne & Richels (2001) and is based on the abatement cost approach. In this approach, the trade-offs between gases are based on the relative prices of all gases that ensure reaching an emission target at the lowest possible cost. To do so, they use MERGE to identify the economically efficient strategy to stay below a certain temperature ceiling. The temperature trajectories include the cooling effects of sulphate aerosols as well (Manne & Richels, 2001). Unlike the GWP unit, this method takes into consideration that the relative prices of gases depend on both the specific target and the proximity to achieving that target, similar to GTP. In the early years, short-lived gases will only have a small effect on temperature in the late twenty-first century. However, the closer one gets to the temperature ceiling, the more worthwhile it becomes to reduce short-lived gases compared to long-lived gases (Manne & Richels, 2001).

Azar & Johansson (2012) derive a cost-effective trade-off ratio for aviation. In doing so, they use an average mass of NO_X emissions related to the mass of CO_2 emissions (normalized pulse emissions, assuming the pulse lasts one year). This relationship remains unchanged over time, assuming a proportional change of NO_X as the amount of CO_2 emissions change. Therefore, technological changes and fuel efficiency improvements would not be included. In their discussion, Azar & Johansson (2012) also raise the concern that a constant multiplier that makes no distinction with regard to altitude or geographical conditions would not create incentives for airlines to minimize their overall climate impact efficiently.