The non-CO_2 impacts of planes are a key reason to reduce aviation demand

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Summary

Aviation has effects on the climate in addition to those generated by its CO_2 emissions. To date, all estimates of these non-CO_2 impacts suggest that they are substantial and, overall, increase aviation's warming effect. They are increasingly recognised in policy documents, but specific measures to address them are rare. Policy makers have been reluctant to address them for various reasons – notably, compared to CO_2, there is greater uncertainty about them, they are relatively short-term, and 'average' estimates of impact mask significant differences between flights. However, these reasons become far less important if policy decisions are about the desirable scale of the sector as a whole, or about limiting particular types of flights, rather than trying to calculate the specific environmental impact of an individual flight, or to trade off CO_2 and non-CO_2 impacts against each other. Latest understanding of global warming highlights the urgency of near-term action, not least to avoid indirect feedback effects or reaching climatic 'tipping points'. Existing technological solutions proposed by the industry have generated concerns about their large-scale viability, the speed with which they can be deployed, and whether they will address these non-CO_2 impacts. In contrast, demand management measures – including managing airport capacity, new taxes or charges or restricting the most environmentally-damaging types of flights – could cut both CO_2 and non-CO_2, are likely to receive public support and could be implemented relatively quickly.

Introduction

Aviation's contribution to rising carbon dioxide levels in the atmosphere is well documented. However, less attention is given to the contribution of aviation's non-CO2 emissions to climate change. These pollutants add substantially to the overall climate impact of aviation, but are rarely explicitly factored into aviation policy. It is vital that they receive more attention, not least because they make the case for demand reduction more compelling.

Aviation's non-CO_2 impacts:

As well as carbon dioxide, planes emit a variety of other pollutants including soot and sulphate particles, nitrogen oxides and water vapour. These have effects on atmospheric composition and on cloud formation.

C R E D S

How significant are aviation's non-CO_2 impacts?

The idea that the non-CO_2 emissions from planes have an important effect on climate is absolutely not new – although the number put on 'how bad' they are, compared with CO_2 emissions, varies considerably, not least depending on the question asked, the metric used1 and the time period of interest. Adding extra CO_2 is like adding semi-permanent insulation around the earth, given its long atmospheric lifetime. In contrast, some of the non-CO_2 impacts are more like temporary insulation, which dissipate relatively quickly (compared to CO_2 effects) if not 'topped up' by further flights.

Consequently, as the Fifth Annual Report of the IPCC highlighted, there is no ideal metric for comparing CO_2 and non-CO_2 impacts, not least because: "No single metric can accurately compare all consequences… All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time" (Stocker et al, 2013). Annex 1 of this briefing attempts to illustrate this with a simple example, showing how trajectories of activity, and the time period of interest, affect the value to be placed on the relative impact of non-CO_2 compared to CO_2. There is also greater uncertainty about non-CO_2 effects, compared to CO_2 effects, as discussed in a later section of this paper.

In 2021, the latest major overview study on the topic was published (Lee et al, 2021), updating and drawing together work that dates back over 20 years, including a major report by the IPCC in 1999 (IPCC, 1999). Lee et al provide a range of estimations of aviation's climate impacts, including its contribution to date, and its likely impacts in the future.

Looking back, Lee et al estimate that, by 2018, the amount of effective radiative forcing2 (i.e. a measure of the cumulative warming effect from the birth of the aviation industry up to 2018) that was due to aviation was 2.9 times as great as the amount due to aviation CO_2 emissions alone. Meanwhile, in estimating future effects, in terms of the warming effects likely to occur over the next 20 years due to the aviation activities that took place in 20183, the non-CO_2 effects could be 4 times as great as those from the CO_2 alone4.

1 For example, metrics include Radiative Forcing and Effective Radiative Forcing; Global Warming Potential and GWP*; Global Temperature change Potential etc.

2 Lee et al (2021) argue that the ERF metric is a better measure for looking at aviation impacts than radiative forcing (a metric used in previous studies), because of the closer correlation with equilibrium global-mean surface temperatures for some forcing agents. Compared with using the RF measure, use of the ERF leads to a lower estimate of aviation's contribution to total anthropogenic global warming. The IPCC started using this metric in 2013. Like RF, it measures the atmospheric effects from aviation at a point in time, based on the accumulated effects at that time from the sector since its inception. Myhre et al (2013) define it as "the change in net top-of-the-atmosphere downward radiative flux after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged". It is measured in (m)Wm-2.

3 I.e. the estimated warming effects due to 2018 aviation likely to occur between 2018 and 2037.

4 GWP20 figure taken from Table 5 of Lee et al (2021). Use of the GTP metric that provides a measure of direct temperature effects in a particular future year, or the metrics covering a longer time period, would give a lower figure.

Using another method (GWP*), Lee et al estimate that "aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone".

Conversely, since non-CO_2 effects dissipate relatively quickly, Lee et al highlight that "a steadily falling rate of emission of (positive) short-lived climate forcers has the same effect on global temperature as active removal of CO_2 from the atmosphere".

A different indicator of the scale of aviation's non-CO_2 impacts is given by changes during the pandemic. According to the IPCC's Sixth report (Szopa et al, 2021), the reduction in CO_2 that occurred as a result of changes to every human activity (fewer cars being driven; industry, retail and businesses shutting etc.5) resulted in a reduction in the amount of Effective Radiative Forcing that occurred in 2020 of 0.01Wm^{-2} compared to what was expected. The reduction due to the change in aviation contrails only was 4 times greater – at 0.04Wm^{-2} – even though aviation is, in relative terms, a minority activity. (Only 2-4% of the world's population were estimated to fly in 2018, Gossling & Humpe, 2020.) The benefits of the CO_2 reduction will continue, whereas the benefit from the contrail reduction is, effectively, a one-off gain, meaning that, over time, the CO_2 reduction becomes more important. However, this still demonstrates the enormous potential scale of the 'quick win' that could result from cutting air travel.

How are aviation's non-CO_2 impacts currently considered by policy makers?

There are a few long-standing examples of factoring aviation's non-CO_2 effects into decision making. The Department for Business, Energy and Industrial Strategy's advice to companies about how to compare the emissions of aviation with other modes of transport on a per kilometre basis has included an uplift for non-CO_2 effects for many years (BEIS, 2022), and some carbon offset calculators also do so6.

Non-CO_2 effects are also being given increasing emphasis in policy documents. The Government's latest 'Jet Zero' strategy recognises that "aviation has non-CO_2 climate impacts, which need to be addressed" (DfT, 2022), and, as part of the Sixth Carbon Budget, the Climate Change Committee recommends that aviation's non-CO_2 impacts need to be monitored and reduced to zero by 2050 (CCC, 2020).

And yet existing policy mostly just focuses on CO_2 emissions. Although both the EU and UK have considered including additional aviation effects within their Emissions Trading Schemes, at the moment, they only include CO_2 [7].

5 This would also include the reduction in aviation CO_2 that occurred.

6 See, for example, www.atmosfair.de

7 As a result of the EU Emissions Trading System Directive 2023/958, in the EU, monitoring and reporting of non-CO_2 emissions from aviation will be required from 2025 (Donceel, 2023).

The International Civil Aviation Organisation's carbon calculator which supports offsetting for passengers only deals with CO_2 [8]. The international offsetting scheme for aviation – CORSIA – only includes CO_2. In 2020, the Supreme Court overturned the Court of Appeal's ruling that the Airports National Policy Statement was unlawful (which it had partly made on the basis that the document failed to consider non-CO_2 impacts).

So why is non-CO_2 not factored into decision making more routinely? This briefing identifies three principal reasons. However, these reasons become far less important if the policy decisions are about the desirable scale of the sector as a whole, or about limiting particular types of flights, rather than trying to calculate the specific environmental impact of an individual flight, or to trade off CO_2 and non-CO_2 impacts against each other.

Why have policy makers been reluctant to tackle aviation's non-CO_2 impacts?

1. There is uncertainty about the climate impact of non-CO_2 emissions

Planes emit a diverse mix of pollutants and the ways in which these interact with atmospheric chemistry are complex, geographically specific, difficult to assess and model, and variable in terms of their impacts over time9. Several new effects are now being discussed, which could have either a cooling or warming effect, but substantial uncertainties mean these can't yet be included in overall calculations (Lee, 2018). Even for more established effects, non-CO_2 impacts are about eight times more uncertain than CO_2 impacts (Lee et al, 2021).

However, scientific understanding has increased over the last 20 years – for example, in relation to the effects from 'contrail cirrus' (one of the largest potential causes of warming) – and, for the established effects, the consistent scientific consensus has been that overall, the non-CO_2 emissions from planes make the climate impacts of flying worse (Lee et al, 2021). Application of the precautionary principle would dictate that the relatively well-understood non-CO_2 impacts need to be a formal part of decisions about the sector.

8 ICAO Carbon Emissions Calculator (ICEC)

9 For example, emissions of NO_X have effects on atmospheric levels of ozone, methane and water vapour – with these effects playing out over different timescales – but with the general consensus being that, at present, these effects lead to an overall warming effect over a 100-year period.

2. It is difficult to calculate the impacts of the non-CO_2 emissions of a particular flight.

Research demonstrates that many of the effects of an individual flight vary considerably depending on when and where it takes place, both individually and across different regions of the world (Lund et al, 2017). For example, one of the biggest potential non-CO_2 impacts from flying comes from the contrails that form in the wake of planes – trailing clouds of ice crystals that both deflect incoming sunlight, but also reflect heat back to the earth – and their associated effects on cirrus cloud formation. Their likelihood of forming, and the impacts they have, are affected by factors including location, temperature, time of day, season, altitude and the level of moisture in the air that they are flying through. For example, flying at night– or at typical long-haul cruise altitudes – typically generates greater warming effects from contrails than flying during the day, or at lower altitudes (Stuber & Forster, 2007; Dahlmann et al 2016, Teoh et al 2023). This is problematic if trying to give a non-CO_2 value to a particular flight.

Given that non-CO_2 effects are often localised, that future growth in aviation will be geographically uneven, and that there may be a range of changes to engine technologies, flight altitudes and atmospheric saturation effects, this also means that the magnitude of the non-CO_2 effects of aviation in the future may not be the same as in the past. However, for assessing the average effects of the sector as a whole over the next few decades, this issue is less important.

3. CO_2 and non-CO_2 emissions affect the climate over different timescales

The third and potentially most important reason why policy makers have found non-CO_2 impacts problematic is the issue of timescales. Some of the direct effects from the non-CO_2 emissions of a flight may be gone in a matter of hours, albeit that 'thermal inertia' may mean that there is a longer timescale for these effects to feed through into temperature change[10]. In contrast, CO_2 remains in the atmosphere for an extremely long time, creating problems for hundreds of years. Any solutions to non-CO_2 emissions which risk increasing CO_2 – such as engines which produce less NO_X but are also less efficient – or longer or lower flight patterns that reduce contrail-cirrus formation at the expense of fuel burn – need very serious consideration to ensure that short-term gains do not increase longer term problems.

However, consideration of trade-offs becomes unimportant if policymaking is focused on considering the overall scale of the sector, or restricting certain categories of flight, since this will affect both CO_2 and non-CO_2 impacts.

10 The global temperature impacts of contrails are thought to peak at about five years after their existence, whilst the temperature impacts of all aviation non-CO2 impacts are thought to peak about 30 years after emissions, due to the complex feedbacks and lag effects inherent in the earth-climate system (source: personal correspondence with P Forster, July 2020).

Why focusing on aviation's non-CO_2 impacts is of increasing importance

Rapid action is needed

In their Sixth report, the IPCC highlight the need for 'deep and rapid reductions' in both CO_2 and non-CO_2 emissions and that "the choices and actions implemented in this decade will have impacts now and for thousands of years (high confidence)" (IPCC, 2023).

The need to address CO_2 is undeniable, given its long-term accumulation in the atmosphere. However, the shorter term gains achieved by cutting short-lived climate forcers could be key to reducing the risks of extreme weather and damage to ecological systems in the immediate future and 'buy time' for developing solutions. This is particularly the case given the indirect effects created by 'earth system feedbacks', some of which could, in turn, lead to additional CO_2 (Fu et al, 2020). For example, the forests recently damaged by wildfires across the world this summer will not be soaking up the same amount of CO_2 in the next few years.

Moreover "the likelihood and impacts of abrupt and/or irreversible changes in the climate system, including changes triggered when tipping points are reached, increase with further global warming (high confidence)" (IPCC 2023). A recent Nature article highlighted nine potentially irreversible 'tipping points', which are "too close for comfort" (Lenton et al, 2019). From this perspective, reducing every source of warming as early as possible is a priority.

Existing plans are inadequate

The aviation industry was particularly badly hit by the pandemic. Since then, for both industry and Government, the aim seems to be to return to 'business as usual' – even though, before the Covid-19 crisis, researchers were working on the assumption that the global distance travelled by air could increase four-fold between 2006 and 2050 – with major increases in both CO_2 and non-CO_2 impacts likely, even if dramatic improvements in fuel efficiency were achieved (Bock & Burkhardt 2019).

Offsets, and technological changes, such as planes powered by hydrogen or electricity, 'sustainable aviation fuels' and improvements in aircraft efficiency are currently relied upon to provide the solution. However, many commentators are highlighting the numerous problems with these approaches – including the timescales over which new technologies could become available and scaled up, the difficulties with scaling up (in terms of available clean energy or sustainable feedstocks, not least given the needs of other sectors), and the availability of meaningful offset schemes – see, for example, Royal Society (2023), Quiggin (2023), Becken et al (2023), AEF (2023) and Mackey (2023). Several commentators also highlight that these solutions may not reduce non-CO_2 impacts (Lee 2023, Dray et al 2022).

Demand reduction offers a more sustainable future

Demand reduction offers a way of cutting both CO_2 and non-CO_2 at the same time – and, in practice, could be achieved by curbing airport expansion, new taxes or charges, and/or introducing restrictions on the most environmentally-damaging flights.

A priority recommendation of the Climate Change Committee (2023) is that "No airport expansions should proceed until a UK-wide capacity management framework is in place to annually assess and, if required, control sector GHG emissions and non-CO_2 effects… After a framework is developed, there should be no net airport expansion unless the carbon-intensity of aviation is outperforming the Government's emissions reduction pathway and can accommodate the additional demand." For any Government serious about tackling aviation's climate impact, avoiding unmanaged expansion would seem like a minimum sensible requirement.

Meanwhile, new or additional taxes or charges could also be used to manage demand, and to address the current anomaly that the tax that airlines pay (air passenger duty) does not adequately compensate for the fact that they do not pay fuel duty or VAT (Sewill 2005, Cairns & Newson 2006, Murphy 2019, T&E et al 2021). New taxes are likely to have public support and to be socially progressive. In the UK Climate Assembly, 80% of assembly members 'strongly agreed' or 'agreed' that taxes that increase as people fly more often and further, and should be part of how the UK gets to net-zero (Climate Assembly UK 2020). Subsequently, various large-scale polls have shown support for this approach (Beaver 2021, BEIS/Defra 2021, Phillips & Seaford 2021). Analysis of the distributional impacts of potential new taxes also finds them to be distributionally neutral or progressive (i.e. poorest people would be affected least), with the proviso that recent migrants on lower incomes may need special consideration (Buchs & Mattioli, 2022, Fouquet & O'Garra, 2022).

It is relevant that some people fly much more than others (Gossling & Humpe 2020, Hopkinson & Cairns 2021), since it means that a relatively large difference could be made by policies that only affect a minority of people. For example, recent work by Quiggin (2023) has suggested that it would be possible to achieve a 36% reduction in UK aviation demand simply by requiring the 23% of people who take multiple flights each year to reduce by one return flight (and to take no more than four in total each year).

It would also be interesting to explore whether limiting certain categories of flight might be a way of addressing non-CO_2 issues without increasing CO_2. In a recent analysis of contrail formation over the Atlantic, Teoh et al highlight that 12% of transatlantic flights account for 80% of warming due to contrails and that "an unsophisticated approach might minimise the number of flights at selected times of the day (i.e. dusk) or season (i.e. winter) when the risk of forming strongly warming contrails is greatest". Although 'unsophisticated', given the challenges involved in generating individual flight values, such an approach might be precisely what is needed to break the deadlock of non-CO_2 always being seen as 'too difficult' to deal with.

Meanwhile, as part of considering aviation demand reduction, there also need to be discussions about transition strategies for those who work in aviation (Chapman & Wheatley 2020, Stay Grounded 2021) and ways of improving alternatives to air travel, potentially including support for digital communications, investment in domestic tourism and lower cost rail travel.

Action to stabilise the climate needs to be taken now. Reducing aviation demand would achieve reductions in both CO_2 and non-CO_2 impacts – and the non-CO_2 impacts of aviation are sufficiently large that they are worth addressing.

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Annex 1: Why timescales and demand trajectories matter

To understand the balance between the CO_2 and non-CO_2 impacts of aviation – and why different studies appear to produce dramatically different values – imagine a considerably simplified scenario – illustrated in Figure 1. This assumes that, **in year 1**, there is a **one-off** activity (like a flight) which emits 'one warming unit' of Gas A (shown in dark blue), and other emissions (collectively called 'Gas B') whose effects are equivalent to '10 warming units' of Gas A. (Gas B impacts are shown in red). In this scenario, 'warming units' are defined to mean units that cause the atmosphere to trap a greater amount of heat energy than it otherwise would.

By year 2, all of the direct impacts of Gas B on the atmosphere have gone, whilst the effects of Gas A continue (shown in light blue), with no change over the following 9 years. Gas A can be thought of as similar to CO_2 (which only decays very slowly), whilst Gas B can be thought of as similar to contrail-cirrus, whose effects are relatively short-term. By year 10, 'end state' metrics would suggest that no multiplier (or rather a multiplier of '**1**') should be used if trying to estimate the total impacts of Gas A and Gas B, because, by year 10, the direct effects of Gas B on the atmosphere have gone.

However, over the course of 10 years, in this illustrative scenario, there will have been a cumulative total of 10 warming units from Gas A and 10 from Gas B. On the basis that changes in atmospheric composition in every year matter (since changes in a particular year may lead to indirect effects – such as ice melt – which then has climatic consequences), other metrics add together the effects in every year. Using this sort of approach, the total impact would be calculated using a multiplier of 2 (i.e. the Gas A effects would be multiplied by two to get the full effects of the activity over the ten year period).

The figures for these calculations are given in Table 1.

Then suppose that rather than a one-off activity, there is a **steady level** of activity, (Figure 2) which emits the equivalent of one warming unit of Gas A every year, and 10 warming units of Gas B. In this scenario, the warming units of Gas B are the same every year, whilst the impacts of Gas A mount up over time. In this scenario, by year 10, the multiplier would be two (since the accumulation of Gas A in the atmosphere would match the impacts of Gas B emitted in that year). However, considering the effects over the whole 10-year period, the balance between the warming effects of Gas A and Gas B would imply a multiplier of **2.8**.

Then suppose that activity levels **increase** by 10% a year (Figure 3). This time, the year 10 multiplier would be 2.5, whilst over the 10 years, the warming effects of Gas B are increased relative to Gas A, with an implied multiplier of **3.1**.

Alternatively suppose that activity levels **decrease** by 10% a year (Figure 4). Over the 10 year period, the warming effects of Gas B reduce relative to Gas A, and the year 10 multiplier becomes 1.6 whilst the 10-year-period multiplier drops to **2.6**.

All figures also show that, if looking over shorter time periods than 10 years, the relative contribution of Gas B during those years is greater. For example, over a three year period, with a steady level of activity, the total Gas B effects are six times greater than the Gas A effects. Hence, the choice of time period, the assumed trajectory of the activity (growth, steady state or decline) and whether the focus is on warming at an 'end year', or for the whole time period, all lead to different multiplier values.

Finally consider the scenario where activity increases by 10% per year to year 5, then **reduces by 50%** (perhaps due a pandemic) in year 6, then increases by 10% per year again (Figure 5). Comparing this with the data for Figure 3 (which assumes an uninterrupted growth of 10% per year), it is notable that, whilst total warming due to Gas A over 10 years is reduced by 20% (from 75.3 to 60.2 units), total warming due to Gas B is reduced by 34% (from 159.4 to 105.7 units). Moreover, in this scenario, compare year 6 with year 5 – for Gas A (because it is long-lasting) the effect is simply a smaller increase in warming, but for Gas A and B combined, the overall amount of warming falls.

In practice, scientists look at longer time horizons, such as 20, 50 or 100-years; in year 1, the difference between CO_2 and non-CO_2 impacts is larger than 1:10; there are time delays between changes to the atmosphere and impacts on temperature; and the non-CO_2 emissions are both gaseous and particulate; including a range of effects, which play out over somewhat different timescales and in more complex ways. For example, NOx generates both cooling and warming impacts.

However, the general implications are likely to be valid – for example, if the focus is on assessing climate impacts over a shorter time period, non-CO_2 impacts are relatively more important than if assessing effects over longer time periods, and in a scenario where aviation is reduced, there is likely to be a greater reduction in warming effects from aviation than a consideration of CO_2 alone would imply.

The one complicating factor which alters the calculations is that the average effect of each additional flight may not be the same over time. For example, one study of contrail-cirrus suggested that a four-fold increase in flight distance was likely to be accompanied by a lower increase in contrail effects, because of improvements in fuel efficiency; because of changes to flight altitude; because the locations where flights will increase most were expected to be different to those where most flying was currently taking place; and because of atmospheric 'saturation' effects. Nonetheless, it still found that, by 2050, the radiative forcing due to contrails was likely to have increased by between 2.8 and 3.3 times (Bock & Burkhardt 2019)

Table 1: Relative impacts of two gases over a 10 year period

Figure number:		Warming units of Gas A	Warming units of Gas B	Implied multiplier *over 10 years*	Implied multiplier *over 3 years*	Multiplier in year 10
1	One-off activity	10	10	2	4.3	1
2	Steady level of activity	55	100	2.8	6	2
3	10% increase in activity p.a.	75.3	159.4	3.1	6.2	2.5
4	10% decrease in activity p.a.	41.4	65.1	2.6	5.8	1.6
5	10% p.a. increase; 50% drop in year 6	60.2	105.7	2.8	n/a	2

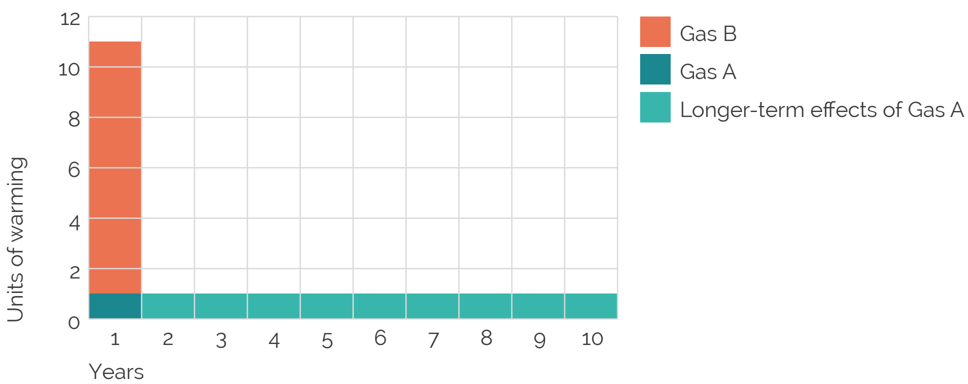

Figure 1: One-off activity

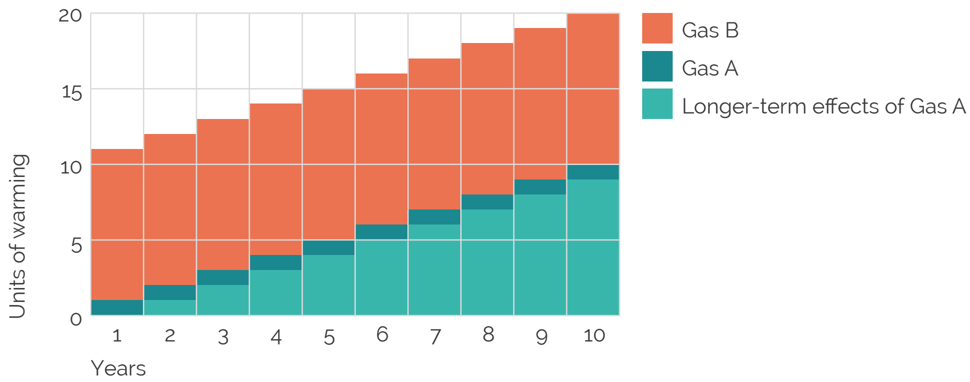

Figure 2: Steady level of activity

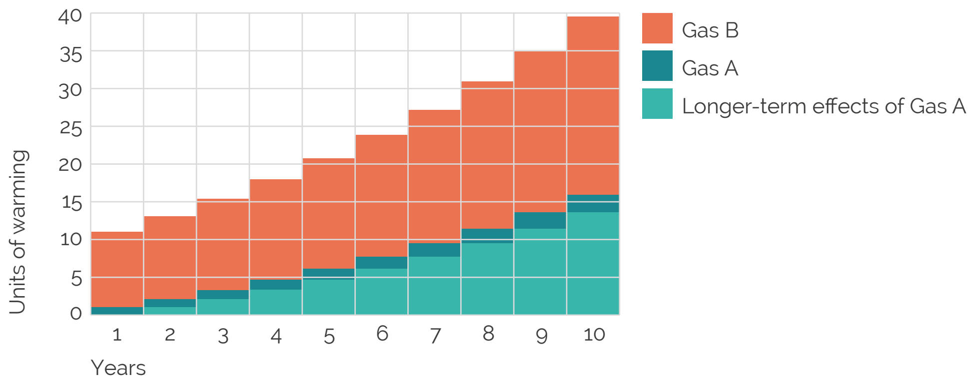

Figure 3: Increase in activity of 10% p.a.

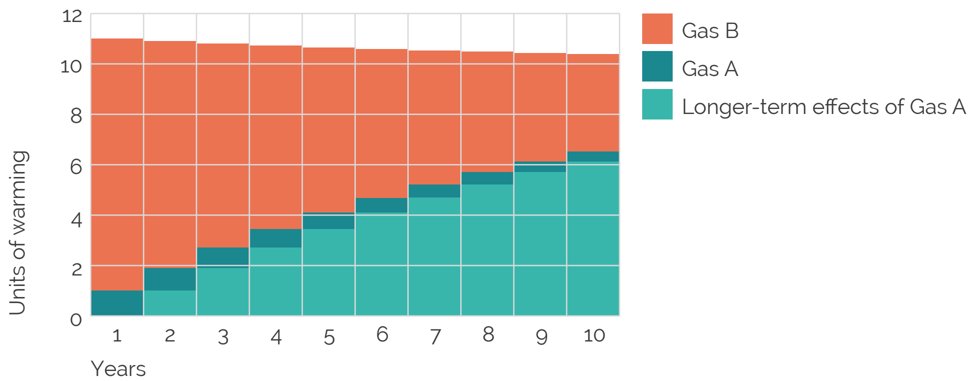

Figure 4: Reduction in activity of 10% p.a.

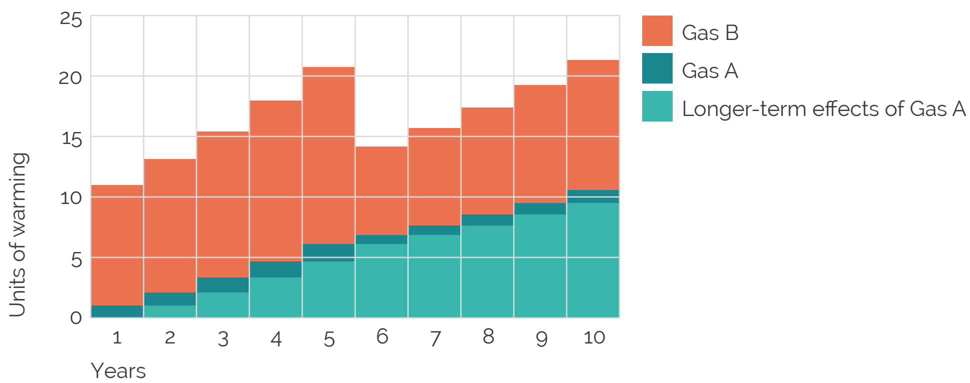

Figure 5: Activity drops by 50% in year 6, then resumes growth of 10% p.a.

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