Journal of
*Risk and Financial Management*

*Article*

# Towards True Climate Neutrality for Global Aviation: A Negative Emissions Fund for Airlines

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**Abstract:** What would it take for aviation to become climate-neutral by 2050? We develop and model a trajectory for aviation to reduce its $CO_2$ emissions by 90% by 2050, down to a level where all residual emissions can be removed from the atmosphere without crowding out other sectors that also need negative emissions. To make emitters pay for the carbon removal, we propose and model a negative emissions fund for airlines (NEFA). We show that it can pay for the removal of all $CO_2$ emitted by aviation from 2030 onwards, for a contribution to the fund of USD 200–250 per ton $CO_2$ emitted. In our baseline simulation, USD 3.3 trillion is invested by the fund over 40 years in high-quality carbon removal projects designed for biodiversity and societal co-benefits. While we do propose a number of governance principles and concrete solutions, our main goal is to start a societal dialogue to ensure aviation becomes both responsible and broadly beneficial.

**Keywords:** climate-neutral aviation; funding negative emissions



**Citation:** Nick, Sascha, and Philippe Thalmann. 2022. Towards True Climate Neutrality for Global Aviation: A Negative Emissions Fund for Airlines. *Journal of Risk and Financial Management* 15: 505. https://doi.org/10.3390/jrfm15110505

Academic Editors: Ştefan Cristian Gherghina and Shigeyuki Hamori

Received: 5 August 2022
Accepted: 27 October 2022
Published: 1 November 2022



## 1. Introduction

### 1.1. The Urgency of Making Aviation Climate Neutral

To remain within the critical 1.5 °C warming limit defined by the Intergovernmental Panel on Climate Change (IPCC 2018) and avoid the much more dangerous 2 °C warming, IPCC's 2021 Assessment Report 6, Working Group 1 estimates the remaining carbon budget at 300–400 Gt $CO_2$ (IPCC 2021). This requires rapid and far-reaching action in all sectors, in order to reduce emissions by half by the year 2030 and by around 90% by 2050, for all pathways with no or limited overshoot. Even more urgently, IPCC Assessment Report 6, Working Group 3 states that immediate action is required and global GHG emissions must peak "at the latest before 2025" (IPCC 2022). As climate scenarios are generally modeled in 5-year increments, this means that 2025 global GHG emissions must be lower than 2019 in all 1.5 °C, and even 2 °C, scenarios, as illustrated in Figure SPM.4 (IPCC 2022). As a consequence, global emissions must start falling immediately.

The aviation sector itself clearly aims for net zero by 2050. This goal is a central message carried by its two main organizations: International Air Transport Association (IATA), which prominently displays "*Our Commitment to Fly Net Zero by 2050*" (IATA 2021), and the International Civil Aviation Organization (ICAO), which declared in July 2022 "*Countries support global 'Net-zero 2050' emissions target to achieve sustainable aviation*" (ICAO 2022), later adopted as "global aspirational goal" at the 41st ICAO Assembly. As we will elaborate, this is a significant challenge, particularly given the past track record of aviation.

### 1.2. Hypotheses and Methodology

In this paper, we will examine the action necessary for aviation to reach its own target, based on the most realistic assessment of the $CO_2$ and non-$CO_2$ climate impact of aviation, a perspective of alternative fuels, which includes their whole life-cycle and impact on society and biodiversity, as well as expected improvements in aircraft efficiency and load factors.

We postulate that the aviation sector reduces its $CO_2$ emissions in the same proportion as is required from all human activity to stay within a safe carbon budget, i.e., by 50% by 2030 and by 90% by 2050 compared to 2019. How this could be possible will be shown in the following. It still requires carbon removal of at least 10% of 2019's emissions. For non-$CO_2$ short-lived impacts, sufficient and sustained reductions will neutralize their effect. We shall analyze the impact of reduction pathways, alternative fuels, and possible routing changes on such short-lived climate impacts.

A major challenge of carbon removal is who is going to pay for it. Removal of current emissions can be paid for by current emitters, but if past emissions also need to be removed, as we shall show is necessary on a decarbonization pathway, then a polluter-pays rule requires that current polluters contribute to a fund that will pay for later removal. We describe how such a fund could work and provide estimates of its financial flows, based on a series of simulations with a broad range of initial conditions, using a simple financial model of the fund. We shall also examine the robustness of our proposal and identify input conditions leading to undesirable or unrealistic outcomes.

Finally, we shall address governance issues, for example, can the aviation sector be trusted to organize the transition to net-zero climate impact or is another organization called for? We propose and discuss a governance approach led by the aviation sector and supervised by participating countries to ensure compliance. We also discuss what level of country participation is required, and how to ensure it.

Technical terms such as "climate forcing" will be used when needed for precision, and defined when first used.

An analysis of ethical considerations, effects on inequality, the "optimal" level of globalization, moral hazard, and the purpose of aviation from the societal perspective is beyond the scope of this paper and will be published separately. Here, these topics will be mentioned only when useful for understanding.

## 2. Literature Review

### *2.1. Large and Growing Climate Impact of Aviation*

The considerable contribution of $CO_2$ emissions of aviation reached 1.034 Gt in 2019 (Lee et al. 2021). This includes commercial passenger flights (71% of emissions), private passenger flights (4%), freight (17%), and military flights (8%) (Gössling and Humpe 2020). Domestic flights represent 39.6% of fuel and emissions, and international flights 60.4% (Gössling and Humpe 2020). Aviation's climate impact could actually be three times larger than measured by $CO_2$ emissions alone, due to the multiple effects of burning kerosene at high altitudes (Lee et al. 2021). Its climate impact is further increased by embodied emissions in the production of fuel, airplanes, infrastructure, maintenance, etc.

For the period 1940–2018, two-thirds of aviation's climate impact is based on non-$CO_2$ radiative forcing, often called climate forcing (Lee et al. 2021), with direct $CO_2$ emissions accounting for the remaining third. Radiative forcing represents the imbalance of energy entering and leaving the atmosphere, affecting the climate. It can be decomposed into contributing factors such as $CO_2$ or contrails, and is measured in Watt/$m^2$. This finding is essential and will be discussed in detail in the next section.

Growth of passenger air travel has been extraordinary by any measure (Figure 1, Table S2). Past revenue passenger-km (RPK) of global aviation peaked in 2019 at $8.7 \times 10^{12}$ RPK, before declining in 2020 due to COVID-19 and slightly recovering in 2021 (Ritchie et al. 2020; Airlines for America 2022). $CO_2$ emissions followed the same pattern (Sausen and Schumann 2000; Lee et al. 2021), growing more slowly due to efficiency improvements, which we cover in Section 3. For comparison, future net-zero compatible projections for RPK and $CO_2$ are shown on the same graph and analyzed in Section 3.

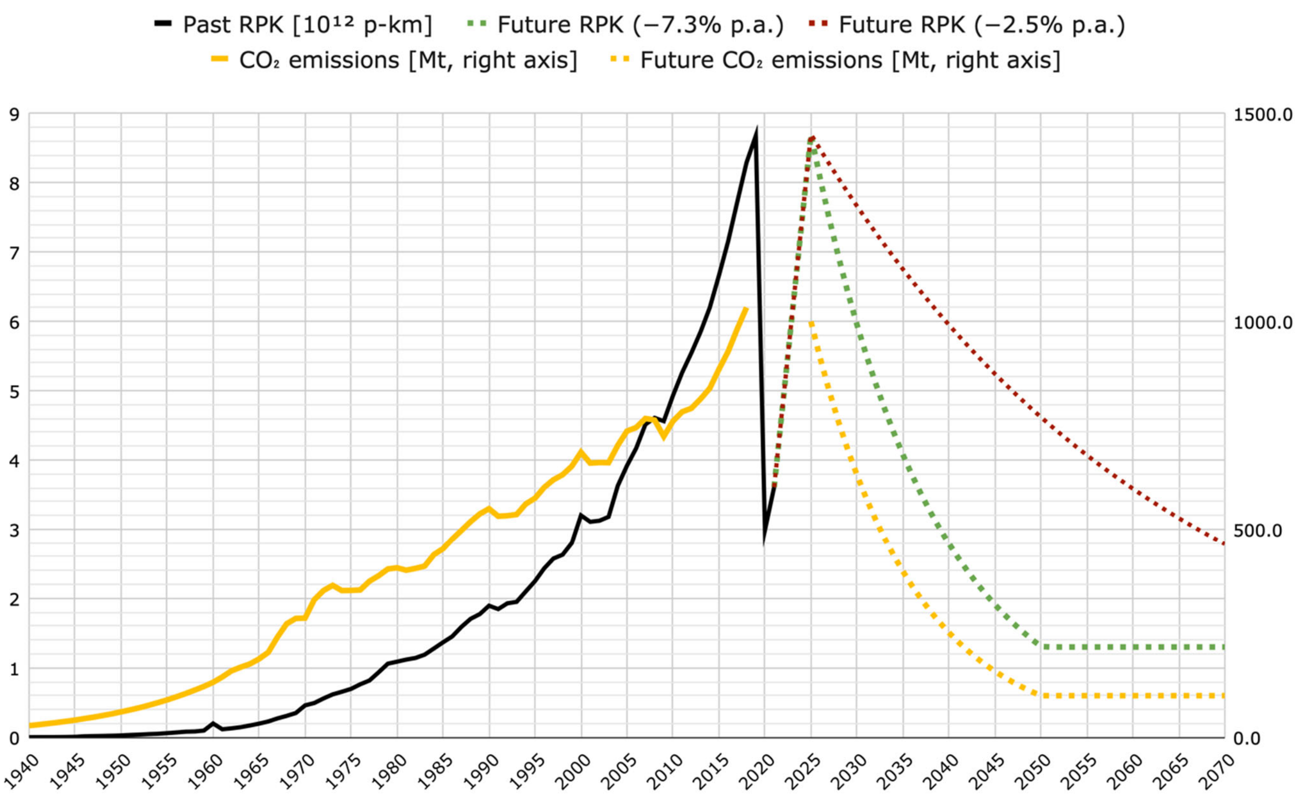


**Figure 1.** Revenue passenger-km (Ritchie et al. 2020; Airlines for America 2022) (black) and $CO_2$ emissions (Sausen and Schumann 2000; Lee et al. 2021) (yellow, right axis); future developments of RPK and $CO_2$ are discussed in Section 3 (dotted lines).

Pre-COVID projections for 2050 reach even more extraordinary levels of up to $34 \times 10^{12}$ RPK (Gössling and Humpe 2020), i.e., +292% from 2019, although this has been revised more recently to $22 \times 10^{12}$ RPK (ATAG 2021), corresponding to 3.1% p.a., or +153% increase from the 2019 value, in the "central" forecast.

Clearly, aviation is not yet on a path to net-zero climate impact. In this paper, we draft such a path, with special emphasis on the necessary emissions and activity reductions and on the role and funding of negative emissions. We also propose a two-level (airline and global) governance approach.

*2.2. Long-Term and Short-Term Climate Impacts*

The combined non-$CO_2$ climate impacts of aviation, especially from contrails, $NO_x$, and short-term ozone increase, are much greater than the impact of $CO_2$ alone (Lee et al. 2021; Neu 2021). However, they are mostly short-lived, i.e., they do not accumulate in the atmosphere like $CO_2$. This combination of short- and long-term effects complicates proper accounting and makes commonly used calculations (like those based on $GWP_{100}$ factors—the global warming potential over 100 years) highly inaccurate and of limited help as a basis for the long-term climate neutrality of aviation.

The ratio of the total climate impact compared to that of $CO_2$ alone depends on the development of aviation. Based on the current growth rates, technical parameters (fuel composition and resulting gases and soot), and flight parameters (humidity, temperature, altitude), this ratio is around three (Lee et al. 2021). These conditions will continue if aviation continues to develop on a trajectory similar to the past, in particular with continued growth and fossil fuels use. The non-$CO_2$ climate impact is projected to be so significant with continued aviation growth, that even if zero-$CO_2$ fuels magically replaced all kerosene overnight, aviation alone would still contribute up to 0.4 °C additional warming globally by 2100 (Brazzola et al. 2022).

On the other hand, if aviation growth stopped, $CO_2$ would continue accumulating in the atmosphere, whereas the component related to short-lived climate impacts would eventually become constant (i.e., causing no *further* warming), more specifically, $NO_x$ levels would stabilize after ~40 years and $CH_4$ after 60–70 years (Lee et al. 2021) (methane's steady-state 8–12 year lifetime in the atmosphere is extended via positive feedback from other trace elements). This means that the ratio of the total climate impact compared to that of $CO_2$ alone would shrink. For the relevant time-scale to stabilize the climate by 1.5 °C by 2050, the recommendation by the Swiss Academy of Natural Science, based on an extensive review of international scientific literature (Neu 2021) is to use a factor of three, corresponding to the current conditions described above. We will follow this recommendation in our paper.

It is important to note that, strictly speaking, a sustained reduction in total short-lived climate impacts such as contrails will cool the climate (analogous to reducing the power of an additional heater, leading to temperature stabilizing at a lower level), and at a sufficient reduction level, could temporarily cancel the effect of continued, but annually reduced $CO_2$ emissions. Based on various post-COVID recovery scenarios (Klöwer et al. 2021), an annual reduction in air traffic emissions of just 2.5% is sufficient to balance the cooling effect of reducing short-lived climate impacts with the progressively falling warming effect of remaining $CO_2$ emissions, which reach about 50% of the 2019 level in 2050 under this scenario. This model stops in 2050 and does not address how long aviation should continue shrinking by 2.5% p.a., or how to remove the accumulated $CO_2$.

### *2.3. The Possible Contribution of Alternative Fuels*

Getting global aviation to net zero climate impact is an enormous challenge and we have not seen anything close to a credible plan to achieve it. Plans by airlines and their organizations such as IATA could be seen as wishful thinking (Beevor and Alexander 2022) given their reliance on "sustainable" fuels. Scientific literature quantifies in detail aviation's past and current impact (Lee et al. 2021; Gössling and Humpe 2020) and makes projections about possible futures (Klöwer et al. 2021), without suggesting how net zero impact could be achieved. Country long-term climate plans, even well-written plans (Swiss Federal Council 2021), may simply suggest that climate-neutral fuels would solve the problem, without much further analysis.

Could better fuels help, and if so, how much? Here, we examine alternative fuels, which include liquid fuels designed to be burned as a replacement for kerosene, such as synthetic aviation fuels and biofuels, which the industry refers to as "Sustainable Aviation Fuel" (SAF). It does not include hydrogen, which is still in early development and facing significant challenges for use in aviation, or batteries.

In 2019, global aviation burned 341 Mt of kerosene (2018 emissions (Lee et al. 2021), adjusted for 2019 growth: 1034 Mt $CO_2$, +4.2%, 3.16 kg $CO_2$ per kg kerosene). How much of this could be replaced by alternative fuels, and what would be the climate impact? Given the centrality of alternative fuels in all existing aviation initiatives, answering this question is key.

Proponents of SAF in their optimistic assessments (ATAG 2021; World Economic Forum 2021) estimate that 30–195 Mt of alternative fuels could be available by 2050. In 2020, 0.05 Mt were available and, if extending current growth and planned production facilities, assuming no delays and that current growth can be maintained at scale, in 2050 about 30 Mt might be available. This is optimistic, as it assumes a disproportionate share of available bio-feedstocks, which is estimated at 200 Mt (ATAG 2021), is used for aviation. Indeed, today, most of the identified potential feedstock sources are not used for various technical or cost reasons; instead palm oil is the main feedstock used, with often very large social and environmental impacts.

Given the very high energy requirements for synthetic fuels and their current low technology readiness, such fuels will likely play a very limited role in the next three climate-critical decades. Theoretically, the potential of power-to-liquids is very high and constrained only by available clean electricity (assuming technology readiness and capacity are developed). However, available clean energy is likely to be a serious constraint in the coming few decades, as we analyzed in our previous work (Nick and Thalmann 2021). Exploring "Energy limits and alternative uses", we concluded that 15 GJ of clean energy, which is sufficient for all annual energy needs for one person, could instead be used to produce 6 GJ or 130 kg of aviation fuel, sufficient for one passenger flying 4400 km.

Now that we have an estimate of the quantity of alternative fuels, what could be their climate impact?

The findings of the previous section on short-term climate forcing of aviation are essential to effectively estimate the total impact of aviation and, thus, the impact of possible mitigation. Furthermore, any alternative fuel, when burned, will produce a similar quantity of $NO_x$ and possibly contrails, still causing two-thirds of the direct warming effect of kerosene, even if the fuel itself is completely $CO_2$-neutral. Additionally, achieving full carbon neutrality over the whole lifecycle of SAF is almost impossible, as shown in a meta-analysis of 613 biofuel life-cycle assessment studies, including first-, second-, and third-generation biofuels (Jeswani et al. 2020).

Recent empirical evidence (Voigt et al. 2021), consistent with climate modeling of soot particles from burning fuel and contrail formation (Burkhardt et al. 2018), indicates that alternative fuels with lower aromatic content, especially naphthalene, can reduce soot by possibly 50–70%, as well as the associated ice crystal development, and contrail formation (aromatic rings are highly stable and are the last component of jet fuel to burn). If validated at large scale, the resulting lower contrail formation could reduce the total climate effect of aviation relative to $CO_2$ alone from three- to approximately two-fold, based on the central estimates for the effect of contrails (Lee et al. 2021) and a reduction of 60% of ice particle formation. There remains uncertainty to the applicability of these conclusions, as the measurements were based on two sets of flights with a single highly advanced experimental version of the Airbus A320, namely the D-ATRA of the Deutsches Zentrum für Luft- und Raumfahrt.

Additionally, the climate conditions and flight altitude significantly affect (modeled) contrail formation, with differences of two orders of magnitude, and 2.2% of flights forming 80% of all contrails, in a model (Teoh et al. 2020) based on actual flights in Japan for six weeks in 2012–2013. Re-routing these flights could reduce contrails by 59%, or by 20% if limited to re-routing without using more fuel and emitting more $CO_2$. However, this may not work in other climates.

In this paper, which focuses on policy proposals in the climate-critical period of 2022–2050, we will assume that synthetic or biofuels only emit 25% of the $CO_2$ of kerosene over their entire lifecycle, and that the total climate impact of synthetic or biofuels is 75% of kerosene's climate impact: the two-thirds of non-$CO_2$ impacts unchanged plus the one-third of $CO_2$ impact divided by four.

This is much better than the lifecycle impact of today's biofuels and assumes significant technological and sourcing progress. Palm-oil based commercial aviation biofuels, the only sort available in any usable quantity today, can have lifecycle emissions well over 100% of kerosene, in addition to significant biodiversity destruction. If, as is often the case, the palm oil comes from converted peat swamps (Cooper et al. 2020), then the climate impact averages 90 t $CO_2$e/ha/yr, for 3–4 t of palm oil, which is an order of magnitude higher than burning kerosene. There is almost no transparency in the biofuel industry, especially in regard to feedstock sourcing (Biofuelwatch 2018), and any reported information, often denied by the concerned companies, is very hard to verify independently. It is however well established that palm oil accounts for around 40% of all vegetable oil worldwide, with by far the highest growth rate, and is a significant driver of forest loss (Ritchie and Roser 2021). In a large commodity market, it is hard to separate good from bad practices; any demand drives pressure to produce more, and in the case of palm oil this ultimately also drives deforestation.

On the other hand, our estimates do not consider the effect of cleaner burning with less soot. As a mini-sensitivity analysis, assuming 50% $CO_2$ over the full lifecycle and a total climate impact of two instead of three times that of the $CO_2$ emissions alone for synthetic or biofuels, the total climate impact of these fuels is 50% compared to kerosene. The two-thirds of non-$CO_2$ impacts divided by two, plus the one-third of $CO_2$ impact divided by two. In this paper, we shall retain the first estimate of 75%.

In summary, recent literature published in the last two years provides a very detailed analysis of the climate impacts of aviation, especially of the non-$CO_2$ elements accounting for two-thirds of the total impact. Additionally, most key elements needed to estimate the potential and contribution of alternative fuels are well documented. What is missing are proposals, models, financing and governance mechanisms detailing how aviation could actually reach net-zero climate impact. We aim to address these gaps and to start a broader societal dialogue.

## 3. Reducing the Climate Impact of Aviation

In the past, fuel and $CO_2$ efficiency of air travel have improved significantly, from 2.5 kg $CO_2$ per revenue passenger kilometer (RPK) in 1950, to 1 kg $CO_2$/RPK in 1960, to 0.125 kg $CO_2$/RPK in 2018, a twenty-fold improvement (Ritchie et al. 2020). This led to lower fuel costs and, following deregulation, much lower prices (−90% over 70 years), which caused a major rebound effect ("Jevons paradox"). Consequently, total fuel consumption and emissions have increased 6.8 times over 58 years.

Future efficiency improvements are expected to continue at a much lower rate. The high energy demand of flying is a physical limitation of airplane design, which needs to generate sufficient lift to stay airborne and overcome air resistance. Airplanes are already almost as energy efficient as they possibly could be (MacKay 2011). Small improvements are still possible, mainly based on better air traffic management and fuller airplanes. They were on average 82.4% full in 2019, up from around 60% in 1960 (Lee et al. 2021). COVID-19 has since significantly reduced load factors (IATA 2022b), but this will recover. Engine improvement might contribute a few percent to energy and climate efficiency, and perhaps another 7 to 9% each can be obtained by blended wing-body design, and laminar flow control (MacKay 2011). None of this is even remotely sufficient to overcome the effect of expected growth of air traffic, or decarbonize today's volume of air traffic in line with the climate emergency described in the introduction. The only technology known today to potentially deliver an order of magnitude or more efficiency improvement are airships. If they are designed to be as fast and as long as trains (22 m/s and 400 m, respectively), then train-like efficiencies could be reached (MacKay 2011). This is not seriously on the books, though.

The prospect of reducing flights could lead to overcapacity. As a result, buying new airplanes might be limited, but given the large differences between airline fleets (Thalmann et al. 2021), simply using the most efficient existing airplanes could yield a significant improvement. By doing this and returning to previously reached load factors above 82%, a further 10% efficiency improvement could likely be achieved by 2030, relative to 2019.

In 2030, alternative fuels are likely to remain marginal. Therefore, to reduce the 2018 total aviation impact by half, given a 10% assumed total efficiency improvement, passenger-kilometers need to be reduced by around 44% (1–0.5/0.9) from 2018, or 47% (1–0.5/0.9/1.042) from 2019, based on 4.2% growth in 2019. We obtain an activity level of $4.6 \times 10^{12}$ passenger-km in 2030, estimated to be compatible with 1.5 °C. This is slightly more than the activity level in 2021 ($4.1 \times 10^{12}$ RPK, IATA 2022a) and close to its level in 2005.

Estimating the aviation size in 2050 compatible with climate neutrality is trickier. We exclude possible developments in all-electric aircraft (battery, fuel cell, or other) or massive deployment of airships, simply because we have no basis for making such an estimate. All-electric aircraft and airships would allow for additional capacity, provided they are powered by clean electricity and do not burn any fuel, i.e., do not produce $CO_2$, $NO_x$, or contrails, and assuming they can be made climate neutral over their lifecycle. In the absence of such technological break-throughs, an ambitious estimate of possible efficiency improvement by 2050 relative to 2019 is 30%, which requires that all aircraft are better than best-in-class in 2019 and that the average load factor exceeds 90%.

As shown in the literature review, a reduction in climate impact by the middle of the century is expected from alternative fuels. In the "official" aviation growth scenarios, 30 Mt of biomass-based aviation fuels would be available in 2050 (ATAG 2021; World Economic Forum 2021). This limit is practical, not absolute, given a sufficient large-scale change in diet, agriculture, land use, cooking and heating practices around the world, a bigger portion of the current 25 Gt of (totally unsustainable) human appropriation of biomass could be used for energy conversion. This, however, is a matter of time and sectoral priorities. Given feedstock limitations and alternative uses and postulating that benefits for biodiversity and society are to be safeguarded, we assume biofuels to cover only 12 Mt of aviation fuels in 2050. We argued earlier that biofuels have a lower climate impact by 25% compared to kerosene, so that these 12 Mt of biofuels will have a climate impact comparable to reducing kerosene use by 3 Mt, or 1% of pre-COVID use.

With 30% fuel efficiency improvement and 3 Mt of kerosene's impact saved through fuel substitution, the reduction in aviation's climate impact in 2050 is only about 31% relative to 2019. The remaining 236 Mt of kerosene still account for 715 Mt $CO_2$ emissions, ignoring the short-lived climate effects of aviation, which will be neutralized by flight reductions. It is not impossible that this quantity of $CO_2$ could be extracted from the atmosphere every year by the middle of the century, but it is hardly acceptable that aviation monopolizes nearly all negative emissions, crowding out other sectors that also need them to become climate-neutral, in particular food production. In the absence of a general prescription for what an optimal or fair share of negative emissions for aviation would be, we postulate that this sector has to reduce its emissions in the same proportion as is needed by all sectors to remain within the critical 1.5 °C warming limit, i.e., by 90% (see our introduction).

To go from the 31% reduction obtained through fuel efficiency and partial substitution to the necessary 90%, the only actionable lever left is the number of flights by 85%. This may seem extreme when 31% are already obtained through technological measures, but that is because the efficiency improvement applies only to the significantly reduced level of activity in 2050. As a result, and if we assume that all types of air transportation decrease by the same proportion, the passenger transport activity must decrease to 1.32 trillion passenger-km by 2050. This is 15.2% of the activity level of 2019, or about the activity level of 1984. If the adjustment happens over 25 years, assuming full post-COVID recovery by 2025, the required annual reduction in passenger-km would be around 7.3%, allowing stabilization by around 2050 (Figure 1). When implemented, depending on the actual reduction pathway reached, the precise climate effect of non-$CO_2$ emissions can be recalculated, and the required stable size of aviation adjusted.

Looking well beyond 2050, once the global climate has hopefully been stabilized not far from the 1.5 °C warming limit with minimal overshoot, very different assumptions are possible, especially using a lower factor for long-term non-$CO_2$ climate forcing, technologies not yet in development today, long-distance high-speed rail, or a culture and societal organization demanding minimal travel. Our paper focuses on policy proposals to reach the required decarbonization and pay for negative emissions to remove the last 10% of 2019 emissions by 2050.

## 4. Paying for Negative Emissions

### *4.1. From a Country to an International Air Transport Perspective*

In our proposal for a Swiss Negative Emissions Fund (Nick and Thalmann 2021, 2022), we describe and model a public fund to finance the removal of all Swiss territorial GHG emissions from 2030, based on the "polluter pays" principle. It would start in 2025 by setting aside funds for the removal of 5% of all territorial emissions, increasing this proportion by 5% each quarter until 100% is reached in 2030. Each emitter would either immediately reduce or remove their emissions or pay into the fund each quarter. The fund would develop a diversified portfolio of suitable biological and geological projects. The negative emissions fee would replace all existing $CO_2$ taxes and the Swiss Emissions Trading System, which is linked to the EU ETS. Our model estimates that the necessary fee per ton of $CO_2$e to pay for future removal is CHF 240–290, depending on the speed and ambition of decarbonization, with faster decarbonization leading to a lower $CO_2$ price.

International aviation is of course very different from a country and a number of factors have to be considered:

- Growth rate: aviation is projected to continue increasing emissions for decades unless the whole model changes, most likely as a result of change being imposed from outside. Rich countries' territorial emissions have been falling since at least 2005 and some since 1990, and other countries are expected to peak soon and then start decreasing.
- Non-$CO_2$ climate effects of aviation, on average, triple the climate impact. For countries, this impact is much smaller, a fraction of the impact of $CO_2$, mainly due to methane and nitrous oxide. However, due to their short-lived nature, these non-$CO_2$ effects will have a much lower impact if air travel starts declining, and a disproportionately large impact if current growth continues.
- Territoriality: it is unclear who is responsible for emissions in international airspace or when briefly flying over a third country.
- High-risk business/high default rate: due to high fixed costs, deregulation, cyclicality, and highly variable fuel costs, airlines are a very risky business. Additionally, due to the difficulty of getting creditors to pay across jurisdictions, any payment to a future negative emissions fund would need to happen almost immediately, possibly even as a pre-payment before flights.

### *4.2. Proposed Concept*

Despite these differences, we also propose the creation of a Negative Emissions Fund for Airlines (NEFA). The governance issues will be addressed in the next chapter. Here, we shall examine the operations of NEFA.

Each airline or flight operator of an international flight declares a flight route, time, aircraft, and fuel consumption (using IATA's existing Airline Handbook on CORSIA (IATA 2019)) to NEFA. The flight authorities of each participating country also report flights to NEFA, validating the airline declarations. Discrepancies are examined. At the end of each quarter, the calculated $CO_2$ emissions are invoiced to the airline. We distinguish two phases:

- The contraction phase: airlines must contract flights by at least 2.5% p.a. until 2050, as a condition for continued participation in NEFA. The 2.5% figure is the minimum to ensure the short-lived non-$CO_2$ effects balance the $CO_2$ emitted (Klöwer et al. 2021). However, when the contraction phase ends, this effect stops and the long-lived $CO_2$ must still be removed, which is the purpose of the payment into the fund.
- The steady-state phase: after a period of stabilization (which we do not model here), the short-lived non-$CO_2$ effects will stop affecting the climate; only long-lived GHG (in our model only $CO_2$) must be removed.

This allows NEFA to account for $CO_2$ removal only. Even if every airline reduces its flights by 2.5% every year, this eliminates climate warming for the year due to dynamic effects of short-lived climate forcing, but $CO_2$ still accumulates in the atmosphere and will stay there for thousands of years, unless removed. While the funding may be assured by payment to NEFA, the overall volume will exceed aviation's fair share of future available $CO_2$ removal capacity. Therefore, additional mechanisms are required to contract global aviation to a "fair" level in order to decarbonize by 90%, just as is necessary in other sectors of society, as we established above. An aggregate reduction in flights of 7.3% p.a. until 2050 is needed, as shown above.

NEFA will only pay for negative emissions in eligible countries (see below), with the right biodiversity and societal co-benefits, and an appropriate governance in place prior to investing. The suitable $CO_2$ price would be set at the start of the fund, which we here assume to be the year 2025. Airlines would have a 5-year transition period, where only part of their emissions would be subject to a NEFA payment, namely 5% in the first quarter, 10% in the second, until 100% is attained after 5 years in 2030. Given the large volume of aviation emissions, and the very low availability of good quality negative emissions projects today, there will inevitably be a time lag between each flight and the removal of corresponding emissions. This time lag contributes to the dangerous "overshoot", where global warming temporarily exceeds 1.5 °C, and should be minimized.

A NEFA based on such mechanisms could truly neutralize all direct climate impacts of global aviation. Given the strong levers proposed and the financial resources of frequent flyers, broadly coinciding with the world's richest 1%, NEFA could by 2030 mobilize resources to initially crowd out other sectors' negative emissions projects. However, this would only be a short-lived problem considering the 7.3% contraction mechanism, since every decade aviation would contract by more than half until a steady state in 2050 is reached. On the other hand, rapid mobilization of funds could significantly accelerate the development of negative emissions in many countries, probably on balance helping other sectors by making negative emissions capacity available. To avoid crowding out other sectors, we proposed capping negative emissions used for aviation to 400 Mt p.a., which is four times the stable level.

### *4.3. Model and Assumptions*

To test the financial feasibility of the proposed Negative Emissions Fund for Airlines, we built a simple model, with the following assumptions:

- Fund launch 2025.
- 2025 $CO_2$ aviation emissions: 1000 Mt.
- Flights (i.e., RPK) reduction of 7.3% p.a. from 2025 until 2050.
- Flight $CO_2$ emissions reduction of 8.8% p.a. from 2025 until 2050, including efficiency gains of 1.5% p.a.
- Emissions stabilization in 2050 at 100 Mt $CO_2$.
- $CO_2$ payments increase by 5% per quarter from 2025 to 100% in 2030.
- First year of negative emissions: 1 Mt in 2026.
- Annual growth of negative emissions for 10 years: +50%.
- Annual growth of negative emissions after 10 years: +25%.
- Max annual negative emissions available for aviation (cap): 400 Mt.
- Negative emissions cost: $400/t $CO_2$ including project governance, in 2025.
- Negative emissions cost: $250/t $CO_2$ including project governance, from 2050.
- Interest rate: 2.00%.
- All prices and costs are adjusted for inflation (our model uses constant 2021 US dollars).

Our simulation assumes full participation of all countries and inclusion of both domestic and international aviation. In the real world, implementation in climate clubs is more likely, as we discuss below. Only $CO_2$ is removed; short-lived climate effects of aviation will be neutralized by the flight reductions required for effective $CO_2$ removal.

### *4.4. Results*

Our simulation (Figures 2 and 3, Table S1) shows the feasibility of a fair, effective and affordable pathway towards climate neutrality for global aviation. While the model is simplified, we successfully tested it over a wide range of variations for the basic parameters, which we detail in the sensitivity analysis below, suggesting the proposed approach is sound.

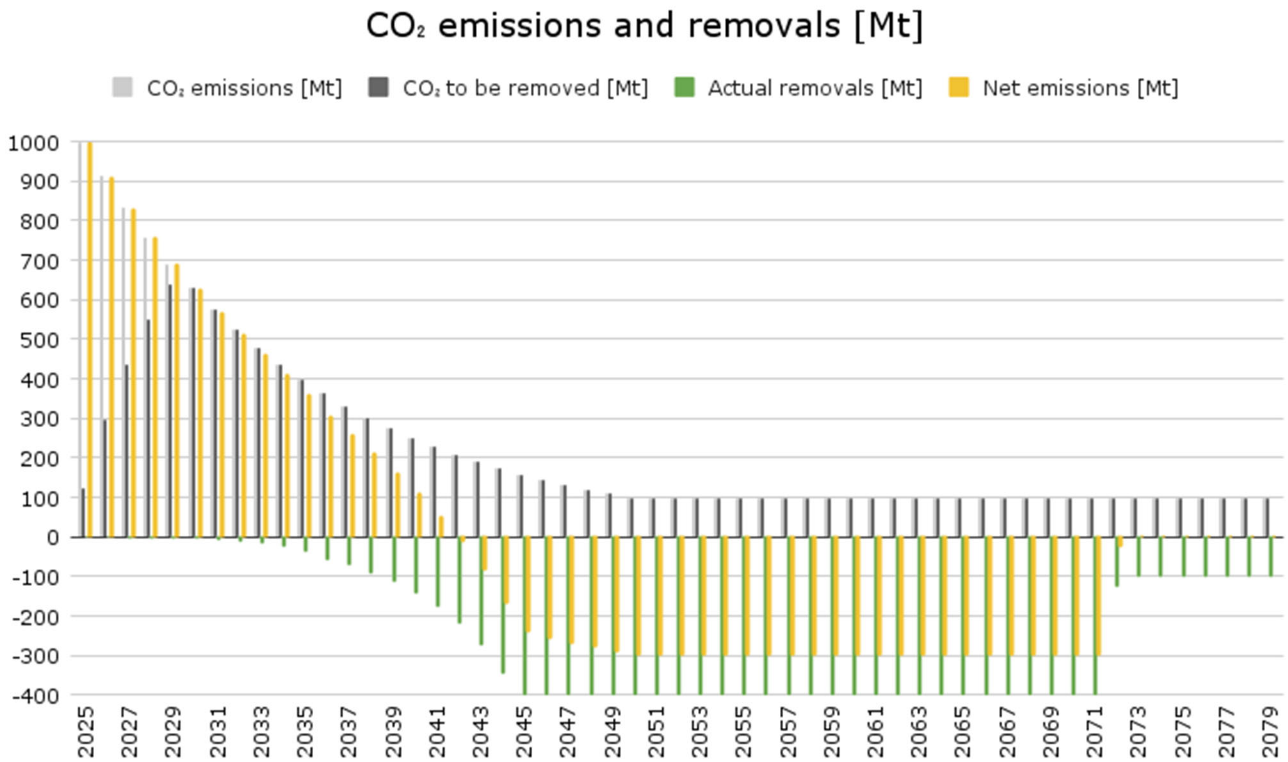


**Figure 2.** Simulated $CO_2$ flows showing global aviation reaching net zero in 2042 on an annual basis, and all aviation $CO_2$ from 2030 removed by 2072.

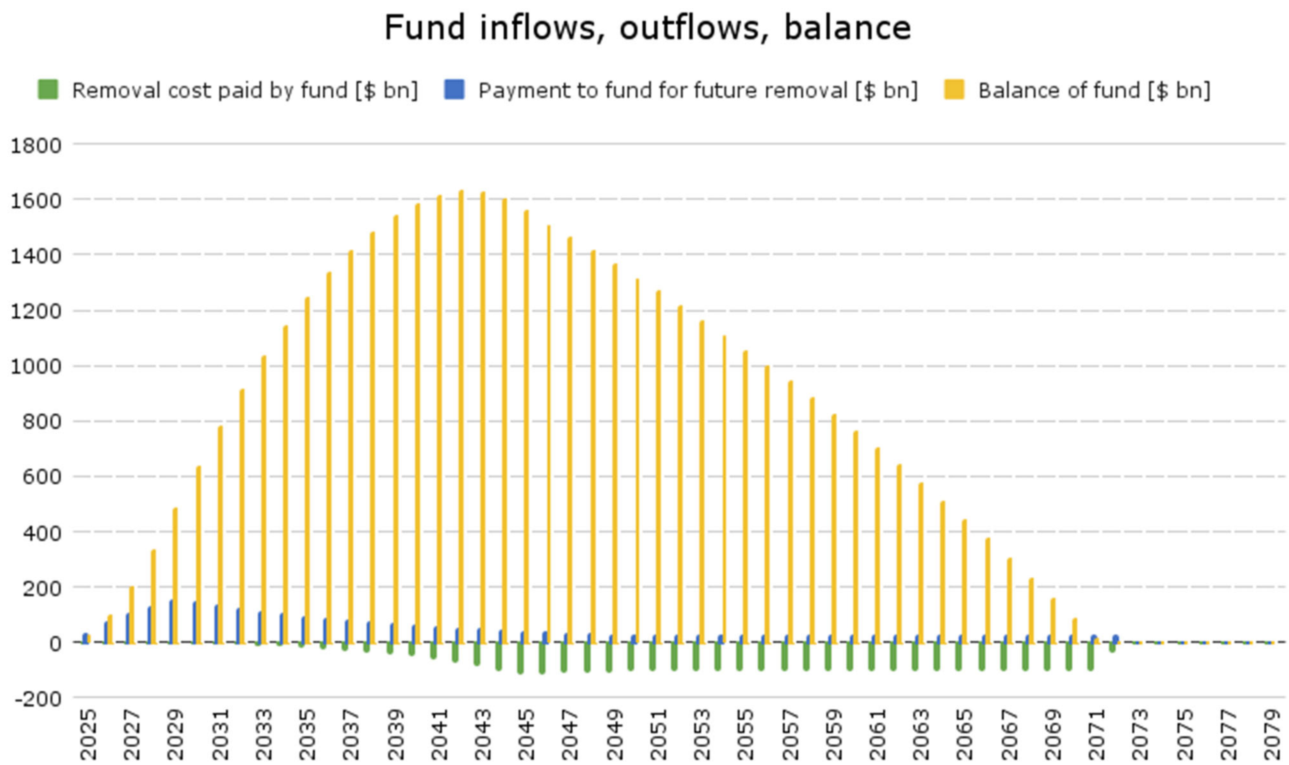


**Figure 3.** The baseline simulation of financial flows showing differentiated timing of early inflows (high emissions now) and payments for $CO_2$ removals, which need time to develop.

The baseline simulation of $CO_2$ flows (Figure 2) shows the 2025–2030 ramp-up of emissions to be removed, the aggregate decarbonization of global aviation reaches its stable fair share along a 1.5 °C pathway by 2050 (dark gray), the 2025–2045 development of negative emission projects capped at aviation's share (green), and the resulting net emissions becoming negative from 2042 (yellow), until all $CO_2$ derived from aviation from 2030 has been removed by 2072; thereafter annual removals equal annual emissions.

In detail, the approach is fair and effective on several levels, since aviation contributes its fair share of global decarbonization efforts by reaching net zero $CO_2$ in 2042, eventually removes all excess $CO_2$ emitted from 2030, and is climate neutral from 2025 onwards based on the dynamic effects of sustained reductions in short-lived climate forcing. Negative emissions for aviation are capped, which avoids crowding out other sectors that will need their own negative emissions (e.g., food production). Additionally, NEFA helps to kick-start the development of negative emissions solutions, including governance, monitoring, and helping participating countries clearly separate their own decarbonization from NEFA aviation projects.

The resulting $CO_2$ modeled price of USD 230, or USD 200–250 over a broad range of parameters, is entirely affordable for typical frequent flyers, largely overlapping with the global richest 1% of people. In fact, this $CO_2$ price is far too low to reduce demand to sustainable levels, which we estimate at an annual 7.3% reduction in flights. For example, a recent simulation for Switzerland (Thalmann et al. 2021, scenario "$CO_2$ Act with Growth") suggests that a similar or slightly higher tax would reduce $CO_2$ emissions by 29–43% by 2050; whereas fairness requires at least a 90% reduction. This also means regulation and other public policy instruments are required (we propose flying rights auctions), in addition to pricing $CO_2$, if the $CO_2$ price is designed to exactly cover the costs of negative emissions.

The baseline simulation of financial flows shows annual payments to the fund peaking in 2030 at $145 bn, before declining to USD 23 bn in 2050 (blue bars in Figure 3); $CO_2$ removal needs time to develop and only peaks in 2045 at a cost of USD 112 bn, before stabilizing at USD 100 bn in 2050 (green); this delay allows NEFA to build reserves peaking at USD 1.63 trillion in 2042, before declining to zero in 2072 (yellow), when all $CO_2$ emitted by aviation from 2030 onwards has been removed.

### *4.5. Sensitivity Analysis and Robustness*

We also performed a comprehensive sensitivity analysis of how changes in all parameters affect the baseline $CO_2$ price of USD 230, total payment and completion year, as summarized in Table 1. The level of initial emissions is unchanged at 1000 Mt.

The model is clearly non-linear, as its main building blocks are exponential functions: rate of $CO_2$ reductions, interest rate, annual growth rate of negative emissions projects. The only linear relationship is between removal costs as input, and $CO_2$ price and the sum of payments for $CO_2$ removals as outputs. Within the parameter range defined in Table 1, all three outputs are "well-behaved" in the sense that they are defined everywhere, continuous, differentiable, and monotonic.

The two main "problematic" outputs highlighted in Table 1 in red either lead to an excessive contribution to overshooting the 1.5 °C warming limit and very high costs (USD 9.7 tn vs. USD 3.3 tn for the baseline), and/or simply take too long to remove the excessive $CO_2$ (around a century).

In summary, our sensitivity analysis shows a range for the final $CO_2$ price of USD 160–314, based on a broad range of parameter changes. If limited to "reasonable" parameter values, the $CO_2$ price remains fairly stable between USD 200 and USD 250, with a central estimate of USD 230 per ton $CO_2$. In most cases, the total cost of removal is between USD 2.9 and USD 3.8 trillion, with a central value of USD 3.3 trillion. All $CO_2$ emissions deriving from aviation are removed by a year in the range 2069–2080 (central value: 2072), ensuring effective carbon neutrality from 2030, with limited overshoot (short-lived non-$CO_2$ effects would be neutralized from 2025, based on the sustained contraction of flights).

**Table 1.** Sensitivity analysis using one-at-a-time variation of baseline parameters (green), affecting the three main outputs (yellow); "problematic" outputs and associated inputs (red) are discussed below.

| **Sensitivity Analysis** | | **Range of Parameter** | | **$CO_2$ Price [USD/t]** | | **Σ $CO_2$ Removal Payments [USD bn]** | | **Removed All Excess $CO_2$ by Year** | |
|---|---|---|---|---|---|---|---|---|---|
| Simulation parameters | Baseline | Min. | Max. | Min. param. | Max. param. | Min. param. | Max. param. | Min. param. | Max. param. |
| Emission reductions p.a. | 8.8% | 2.5% | 10.0% | 160 | 239 | 9651 | 2953 | 2136 | 2069 |
| Reductions, narrower range, p.a. | | 5.0% | 7.3% | 196 | 218 | 5177 | 3772 | 2091 | 2077 |
| Final emissions [Mt/p.a.] | 100 | 50 | 150 | 231 | 227 | 2979 | 3717 | 2069 | 2076 |
| NE growth 2027-36 | 50.0% | 33% | 60% | 203 | 246 | 3326 | 3217 | 2078 | 2068 |
| NE growth 2037+ | 25.0% | 10% | 50% | 204 | 243 | 3401 | 3228 | 2080 | 2069 |
| Max removals [Mt p.a.] | 400 | 200 | 800 | 186 | 249 | 4629 | 2897 | 2128 | 2057 |
| Removal cost in 2025 [USD/t] | 400 | 300 | 600 | 222 | 245 | 3173 | 3422 | 2072 | 2072 |
| Removal cost from 2050 [USD/t] | 250 | 200 | 300 | 190 | 270 | 2671 | 3841 | 2072 | 2072 |
| Interest rate p.a. | 2% | 1% | 3% | 269 | 196 | 3256 | 3256 | 2072 | 2072 |
| Interest rate, extreme range | | 0% | 4% | 314 | 168 | 3256 | 3256 | 2072 | 2072 |
| Simulation results-baseline | | | | 230 | | 3256 | | 2072 | |

## 5. Governance

### *5.1. Country vs. Airline Perspective, Nature of Risks, Role of Markets*

Who should be responsible for reaching the climate-related objectives of aviation? Countries, aviation organizations, airlines, or some combination of the three? What is best decided at which level? While net zero $CO_2$ is relatively easy to define and monitor, climate neutrality is less straightforward as it can be defined in different ways, depending on which baseline is chosen (Brazzola et al. 2022), as sustained reductions in short-lived climate forcing will have a *cooling* effect. Additionally, how can an intermediate goal, such as a 50% reduction in $CO_2$ by 2030 be governed? Which baseline year is perceived as most favorable, when considering nationally determined contributions (NDCs)? How can companies gaming the system be prevented, such as buying failed airlines to access their past emission rights, or going bankrupt to avoid paying for accumulated negative emission liabilities?

There is no single good answer, but any good solution must include a number of elements.

First, all flight emissions must be accounted for in the United Nations Framework Convention on Climate Change (UNFCCC) process and included in NDCs. Aviation emissions could be included in national accounting and national NDCs. The easiest way to achieve this would be for each country to count all domestic flights (already included in country accounts) and all outbound international flights. However, this may generate significant resistance from countries and could become ungovernable if airlines move to avoid regulation. We therefore propose an intergovernmental management of the flying rights of international aviation (domestic flights remain within country climate commitments and their respective NDCs). This governance could be attached to ICAO (International Civil Aviation Organization, headquartered in Montreal) or possibly to the NEFA itself. Under UNFCCC, international aviation thus governed would be treated as another country with its own NDC.

Second, to limit the default risk of airlines, a payment for future negative emissions must be made to NEFA almost immediately for each flight. To limit the country default risk, NEFA could be made international and backed by suitable institutions such as the World Bank, ECB and multiple national central banks.

Third, to ensure that a smaller global aviation still delivers its main benefits, especially the essential components of globalization including knowledge transfer, connectivity, resilience and capacity building, and disaster response, suitable national and international regulation is required, since the highest-benefit use of limited aviation capacity is not necessarily the most profitable one, and might not be served under a pure market governance system. In practice, commercial airlines might buy flying rights at an auction and sell most available seats, with the remaining portion being set aside for priorities chosen democratically in the airline's country. Humanitarian or disaster-relief organizations operating their own flights might obtain their flying rights before the general auction of the remaining rights, with proper governance of flight use. Either way, more research and experimentation are needed to find the best allocation mechanisms.

Finally, for airlines, rapidly reaching net zero must become both the basis of their regulatory and moral "license to operate", and hopefully their market acceptance. Unless market acceptance is conditional on credible action to remain within the 1.5 °C warming limit, the market itself would be of limited use in the societal transition to a world respecting this limit, and will need to be regulated or restricted.

### *5.2. Failure of CORSIA*

From today's perspective, global aviation is not on track to reach climate neutrality anytime soon, certainly not by 2050, and is definitely not on track to reduce emissions by half by 2030. The main industry initiative, Carbon Offsetting and Reduction Scheme for International Aviation or CORSIA (ICAO-CORSIA 2022), adopted in October 2016 by the 191 country members of the International Civil Aviation Organization (ICAO), is a very timid political compromise, which is likely to have an extremely limited climate impact, if any. Indeed, the stated goal of CORSIA is to ensure that *growth* of aviation after 2020 is carbon-neutral (not climate-neutral), making no mention of the Paris Agreement or the need to decarbonize, nor demonstrating why this is a scientifically valid goal. Furthermore, emissions below the 2019 baseline level are grandfathered, rewarding historical polluters and creating an incentive to buy failed airlines with past emissions. The many exceptions and loopholes, such as for Least Developed Countries, Small Island Developing States and Landlocked Developing Countries, create an incentive to base airlines or hubs there. Participation is voluntary until 2026, and then compulsory from 2027 to 2035, with major countries such as China, India, Russia, or Brazil not yet participating, and showing no sign that they might join by 2027. Another weakness of CORSIA is that the main reduction mechanisms are carbon credits to offset emissions, which will become largely unavailable as countries need to meet their own ambitious NDCs under the Paris Agreement. Furthermore, there is no universally accepted standard for the quality of offsets accepted by all CORSIA participants and no mechanism to ensure the quality of offsets. Even if offsets could be maintained at an adequate quality standard, the host country projects could be crowded out by CORSIA offsets, if their price is higher.

A further limitation of CORSIA is that it completely ignores non-$CO_2$ climate impacts, which represent two thirds of the total impact, as well as the dynamic effects of change in short-lived climate impacts. When promoting "sustainable aviation fuels", meaning biofuels, in all its communications to date, CORSIA claims that they are climate-neutral, which is impossible due to non-$CO_2$ impact and biofuel lifecycle emissions.

Worse, CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels (ICAO 2021) allow palm oil-based fuels from Malaysia and Indonesia to generate 76.5–99.1 $gCO_2e/MJ$. As kerosene contains 43.1 MJ/kg (net, i.e., lower heating value) or 73.3 $gCO_2e/MJ$, the palm oil-based SAR is allowed under CORSIA to generate 104–135% of kerosene emissions. If kerosene refining and other lifecycle emissions are included, kerosene reaches 85–95 $gCO_2e/MJ$, with a central value of 89 $gCO_2e/MJ$ (UK Department for Transport 2021), meaning CORSIA accepts "sustainable aviation fuels" emitting 86–111% of kerosene.

Based on all of this, it is no surprise that, as of May 2022, Climate Action Tracker rates aviation's carbon-neutral growth goal as "critically insufficient" and considers CORSIA "extremely unlikely" to reach this goal (Climate Action Tracker 2022).

### *5.3. History of Broken or Forgotten Promises*

Historically, airlines have set relative targets (emissions per passenger-km) that, mainly due to better aircraft technology and higher load rates, have delivered impressive savings, but that are still dwarfed by much faster growth, as shown in Figure 1. This practice continues today with, for example, EasyJet—a major airline very vocal about its sustainability credentials—declaring a 35% $CO_2$ emissions intensity reduction target from 2020 to 2035 (EasyJet 2022). No mention is made of how much the airline plans to grow, but it doubled in the decade pre-COVID. At a similar future rate, absolute emissions would actually increase by 84% during this period. Beyond $CO_2$, airlines refuse to take any responsibility. For example, EasyJet states (EasyJet 2021): "*We know that aviation also contributes to non-carbon dioxide climate effects in the atmosphere and despite recent studies highlighting these effects, more robust research is required to provide further guidance on how best to tackle these impacts*", straight out of the 1950s "Merchants of doubt" playbook (Oreskes and Conway 2011).

Beyond refusing to act on non-$CO_2$ climate effects and using relative targets, the airline sector, including IATA, has an almost perfect track record of missing or conveniently "forgetting" its own targets. In an impressive piece of detective work Beevor and Alexander (2022) covering the period 2000–2021, analyzed mostly deleted web pages with the Wayback Machine, for the UK-based NGO Possible. The authors found that all but one target have been missed, changed (usually set back a decade or so), or abandoned. In detail, efficiency targets, directly aligned with fuel cost reduction, were most frequently set but largely missed. Alternative fuel targets were *all* missed, often by a factor of 10 or more. This is despite alternative fuel targets being reduced and pushed back several times, from originally 10% for 2017 to 6% for 2020, then 4.5%, then 3% and finally to currently 2% for the year 2025.

No targets were linked to reducing the number of flights, or even the absolute level of emissions.

### *5.4. NEFA Governance and Participation Enforcement*

We have developed and modeled a pathway leading to true climate neutrality for global aviation. Even if it works on paper, is there any realistic chance of reducing air transport and of NEFA ever being implemented?

To reach emission reduction goals, we propose annual auctions of flying rights, following a 7.3% p.a. flight reduction pathway until 2050. The proceeds of the auctions are invested in NEFA, enabling reducing the $CO_2$ price paid by airlines for removal, and allowing airlines to avoid paying twice. A small fraction of flying rights might be attributed to outside auctions, for priority missions, as suggested above.

As airlines could be based in any of the 200 countries of the world, the only way to ensure that they will buy flying rights and pay for their $CO_2$ emissions is to link payment to flight destinations. We propose that "climate clubs" of climate-conscious countries define an airline's adherence to NEFA as a condition to gain access to their airports. Any two of the EU, China, Japan, and the US would be a good starting point and would send a strong signal. This lever is strongest for main flight destinations. Participation in such clubs could be encouraged by funding negative emissions projects by NEFA in member countries only, bringing them jobs, investments, biodiversity and societal co-benefits. This lever significantly expands the destination approach above. Each recipient country would need to show a credible net-zero action plan, as NEFA projects are additional to the country achieving its own net zero, and should not "crowd out" emission abatement projects. NEFA projects must ensure biodiversity and societal co-benefits, and proper governance must be in place before funds can be transferred.

NEFA might be much more acceptable to all aviation stakeholders if they could self-manage the system and its main components: cap and trade reducing available passenger-km by 7.3% p.a. including annual rights auctions; airline-level reporting rules, payments, and set a minimum target of 2.5% p.a. for flight reductions; reporting, regulation, and perhaps even a reward for airlines for avoiding contrail-forming zones; and finally access to airports only for those airlines participating in NEFA, and negative emissions funding access only for countries participating in NEFA to access its airports. Like CORSIA, this could be managed by ICAO with support from IATA and the Air Transport Action Group, which would limit the role of national states to setting the rules and objectives, and auditing the process and accounts (Figure 4).

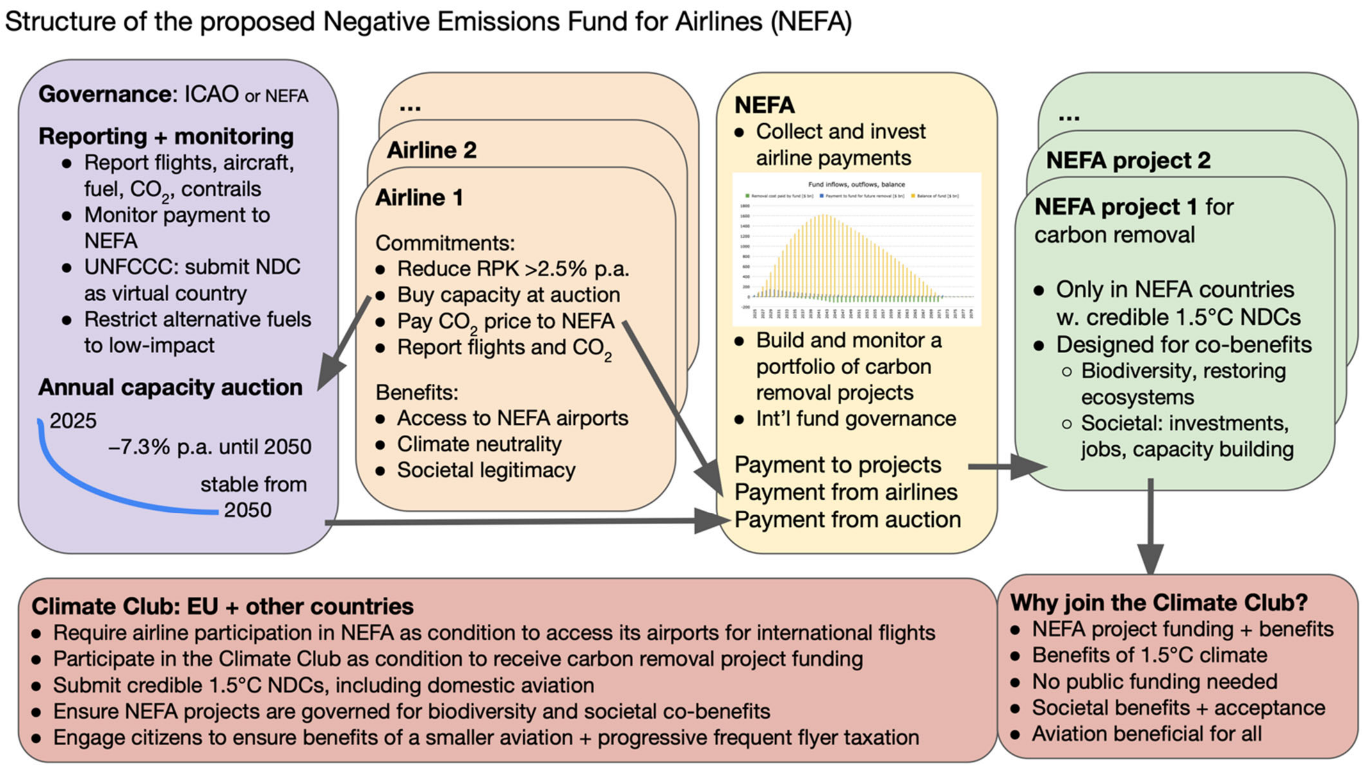


**Figure 4.** Links between the proposed governance structure, role of the fund, carbon removal projects, and benefits for countries, with arrows showing financial flows.

## 6. Discussion and Conclusions

### *6.1. Can NEFA Be Implemented in the Real World?*

Despite numerous challenges coming especially from the extraterritorial character of international aviation, the proposed approach is very likely to work once a critical mass of countries can agree to jointly act. Obviously, a single country, even a large one, cannot achieve much alone; there is simply too much scope for airlines to avoid any regulation or constraint. What would be a critical mass to get started? Fully answering this question would require different modeling, which is beyond the scope of our paper, but we can provide some elements. A group of countries acting together ("climate club") can impose regulation on extraterritorial airlines, if access to its airports is sufficiently important and is conditional on participating in NEFA. Europe accounts for more than half of all international tourist arrivals worldwide, and would be costly for any large international airline to avoid. This gives the EU extraordinary leverage to single-handedly implement NEFA, although together with one additional large partner, the action would be much more effective: US or China would be ideal, but Japan or Mexico would be very helpful.

Other than the EU itself, in many areas including climate action, there are several initiatives aiming to enhance joint international environmental action, including the recent proposal (German Federal Government 2022) by Olaf Scholz, German Chancellor, of a G7-led Climate Club to decarbonize the industry, or the Responsible Minerals Initiative, started in 2008, covering almost all electronics players worldwide, and ensuring responsible sourcing of tin, tantalum, tungsten, cobalt, and gold. Enforcement is led by major consumer electronics companies, participating to protect their own reputation, and requiring compliance by their suppliers.

Countries could join the EU climate club later, allowing for the flexibility needed to acquire domestic political alignment and parliamentary support. Fundamentally, the proposal is very attractive for many countries because: (1) it solves the problem of decarbonizing aviation, one of the most difficult sectors to decarbonize, without any initial investment other than regulation and monitoring, and (2) it opens the door to access well-funded investments into high-quality negative emission projects with significant biodiversity and societal co-benefits, creating jobs and potentially generating broad support within the country.

The immense role played by the EU also means that without its participation, another coalition would need to be very broad to succeed. From the EU's perspective, implementing NEFA would actually be relatively simple, and could be achieved by removing domestic aviation from the EU ETS and integrating it in NEFA or a similar EU fund. It would not affect the planned Carbon Border Adjustment Mechanism.

Any successful implementation must ensure accurate reporting, monitoring, payment collection, and fund governance. To increase its credibility, NEFA could be backed by suitable multilateral institutions such as the ECB, the World Bank, and possible national banks of main participating countries. Equally obvious, project quality must be ensured, to deliver verifiable and genuine negative emissions, persistent over time, and to avoid double-counting or crowding out of each host country's carbon removal projects, already part of that country's net zero plan and NDC.

Finally, a number of aviation stakeholders, especially investors and equipment manufacturers, may welcome and support a credible plan to reduce uncertainty, giving the aviation sector an assured future, even one with fewer flights, and positioning it as part of the solution instead of being a big driver of the problem.

### *6.2. Conclusions—A New Vision for Aviation*

A combination of rapid technology development, deregulation and partial exemption from responsibility by governments, airlines and investors playing the extraterritorial game of avoiding remaining regulation, rising inequalities, low-cost business models with culturally embedded (and purposefully designed) hypermobility, together with only recently understood non-$CO_2$ climate forcing—have together made aviation the intractable climate problem that it is today, risking nullifying any credible climate action in all other sectors of society. Yet, COVID-19 has shown the extraordinary fragility of today's aviation, and the rapidly worsening climate crisis adds significant uncertainty to any plans related to aviation, hindering investment and making almost any part of aviation excessively risky.

As identified by Donella Meadows (1999) and repeatedly validated in various sectors, growth is indeed a key leverage point, but counter-intuitively for many, a negative one: less growth is needed to solve many problems, or in the case of global aviation, a significant reduction in flights to its size in the early 1980s, followed by a stable state. Once this main insight has been accepted, all the moving parts start falling into place, and responsible global aviation becomes possible, fairly contributing its part to solve the climate crisis, based on evolutionary low-risk technology and today's best practices, using resources well within the planetary boundaries.

Our NEFA proposal, validated using a simple financial model, indicates a fair, effective, and affordable way to make aviation truly climate neutral, which could rapidly be implemented with little public funding. For both rich and poor countries, it liberates public resources to focus on other sectors, which serve a much larger part of their population and for much more essential needs, and delivers a much-needed quick win for the climate. It also mobilizes significant private resources, as illustrated in our baseline simulation, a value of $3.3 trillion over 40 years that is mobilized to invest in high-quality carbon removal projects designed for biodiversity and societal co-benefits.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jrfm15110505/s1, Table S1: Simplified model of NEFA, Table S2: Aviation Key Metrics 1929-2070.

**Author Contributions:** Conceptualization, methodology, software, validation, formal analysis, investigation, resources: S.N. and P.T.; data curation, writing—original draft preparation: S.N.; writing—review and editing, visualization: S.N. and P.T.; supervision, project administration, funding acquisition: P.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** See supplementary material.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

Airlines for America. 2022. World Airlines Traffic and Capacity, March 2022. Airlines For America. March. Available online: https://www.airlines.org/dataset/world-airlines-traffic-and-capacity/ (accessed on 23 October 2022).

Air Transport Action Group—ATAG. 2021. "Waypoint 2050". Air Transport Action Group—ATAG. Available online: https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/ (accessed on 23 October 2022).

Beevor, Jamie, and Keith Alexander. 2022. Missed Targets: A Brief History of Aviation Climate Change Targets. UK: Possible. Available online: www.wearepossible.org/latest-news/for-20-years-the-aviation-has-missed-all-but-one-of-their-sustainability-targets (accessed on 23 October 2022).

Biofuelwatch. 2018. Neste: The Finnish Company Preparing to Put Palm Oil in Aircraft Fuel Tanks—Biofuelwatch. Available online: https://www.biofuelwatch.org.uk/2019/neste-aviation-biofuels/ (accessed on 23 October 2022).

Brazzola, Nicoletta, Anthony Patt, and Jan Wohland. 2022. Definitions and Implications of Climate-Neutral Aviation. *Nature Climate Change* 12: 761–67. [CrossRef]

Burkhardt, Ulrike, Lisa Bock, and Andreas Bier. 2018. Mitigating the Contrail Cirrus Climate Impact by Reducing Aircraft Soot Number Emissions. *Npj Climate and Atmospheric Science* 1: 1–7. [CrossRef]

Climate Action Tracker. 2022. Climate Action Tracker: International Aviation. Available online: https://climateactiontracker.org/sectors/aviation/ (accessed on 23 October 2022).

Cooper, Hannah V., Stephanie Evers, Paul Aplin, Neil Crout, Mohd Puat Bin Dahalan, and Sofie Sjogersten. 2020. Greenhouse Gas Emissions Resulting from Conversion of Peat Swamp Forest to Oil Palm Plantation. *Nature Communications* 11: 407. [CrossRef] [PubMed]

EasyJet. 2021. EasyJet 2021 Annual Report and Accounts 'Fast Track—The Recovery'. EasyJet plc. Available online: https://corporate.easyjet.com/~{}/media/Files/E/Easyjet/documents/easyjet-2021-annual-report-and-accounts.pdf (accessed on 23 October 2022).

EasyJet. 2022. EasyJet Signs up to Support Breakthrough Carbon Removal Solutions. Available online: https://mediacentre.easyjet.com/story/15528/easyjet-signs-up-to-support-breakthrough-carbon-removal-solutions (accessed on 23 October 2022).

German Federal Government. 2022. Speech by Olaf Scholz, Chancellor of the Federal Republic of Germany and Member of the German Bundestag, at the 13th Petersberg Climate Dialogue. Website of the Federal Government | Home Page. Available online: https://www.bundesregierung.de/breg-en/news/speech-by-olaf-scholz-chancellor-of-the-federal-republic-of-germany-and-member-of-the-german-bundestag-at-the-13th-petersberg-climate-dialogue-2064056 (accessed on 23 October 2022).

Gössling, Stefan, and Andreas Humpe. 2020. The Global Scale, Distribution and Growth of Aviation: Implications for Climate Change. *Global Environmental Change* 65: 102194. [CrossRef]

IATA. 2019. IATA—An Airline Handbook on CORSIA. IATA. Available online: https://www.iata.org/contentassets/fb745460050c48089597a3ef1b9fe7a8/corsia-handbook.pdf (accessed on 23 October 2022).

IATA. 2021. IATA 77th AGM: Net-Zero Carbon Emissions by 2050. October 4. Available online: https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/ (accessed on 23 October 2022).

IATA. 2022a. IATA—Air Passenger Numbers to Recover in 2024. Available online: https://www.iata.org/en/pressroom/2022-releases/2022-03-01-01/ (accessed on 23 October 2022).

IATA. 2022b. IATA—Passenger Demand Recovery Continued in 2021 But Omicron Having Impact. Available online: https://www.iata.org/en/pressroom/2022-releases/2022-01-25-02/ (accessed on 23 October 2022).

ICAO. 2021. CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. Available online: https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202021.pdf (accessed on 23 October 2022).

ICAO. 2022. ICAO: Countries' Support Global 'Net-Zero 2050′ Emissions Target to Achieve Sustainable Aviation. July 25. Available online: https://www.icao.int/Newsroom/Pages/Countries-highlevel-ICAO-emissions-talks-support-netzero.aspx (accessed on 23 October 2022).

ICAO-CORSIA. 2022. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Available online: https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx (accessed on 23 October 2022).

IPCC. 2018. *Global Warming of 1.5° C: An IPCC Special Report on the Impacts of Global Warming of 1.5° C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge and New York: Cambridge University Press.

IPCC. 2021. *IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.

IPCC. 2022. *IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.

Jeswani, Harish K., Andrew Chilvers, and Adisa Azapagic. 2020. Environmental Sustainability of Biofuels: A Review. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 476: 20200351. [CrossRef] [PubMed]

Klöwer, Milan, Myles Allen, David Lee, Simon Proud, Leo Gallagher, and Agnieszka Skowron. 2021. Quantifying Aviation's Contribution to Global Warming. *Environmental Research Letters* 16: 104027. [CrossRef]

Lee, David S., David W. Fahey, Agnieszka Skowron, Myles R. Allen, Ulrike Burkhardt, Qi Chen, Sarah J. Doherty, S. Freeman, P. M. Forster, J. Fuglestvedt, and et al. 2021. The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018. *Atmospheric Environment* 244: 117834. [CrossRef] [PubMed]

MacKay, David J. C. 2011. *Sustainable Energy—Without the Hot Air*. Repr. Cambridge: UIT Cambridge.

Meadows, Donella H. 1999. Leverage Points: Places to Intervene in a System. *The Academy for Systems Change (blog)*. Available online: http://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/ (accessed on 23 October 2022).

Neu, Urs. 2021. The Impact of Emissions from Aviation on the Climate. *Swiss Academies Communications* 16. Available online: https://scnat.ch/en/id/cSx4y (accessed on 23 October 2022).

Nick, Sascha, and Philippe Thalmann. 2021. Carbon Removal, Net Zero, and Implications for Switzerland. E4S Enterprise for Society. Available online: https://e4s.center/document/carbon-removal-net-zero-and-implications-for-switzerland (accessed on 23 October 2022).

Nick, Sascha, and Philippe Thalmann. 2022. Swiss Negative Emissions Fund—Paying for Net Zero. E4S Enterprise for Society. Available online: https://e4s.center/document/swiss-negative-emissions-fund-paying-for-net-zero (accessed on 23 October 2022).

Oreskes, Naomi, and Erik M. Conway. 2011. *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*, Paperback ed. New York: Bloomsbury Press.

Ritchie, Hannah, and Max Roser. 2021. Forests and Deforestation: Palm Oil. Our World in Data. Available online: https://ourworldindata.org/palm-oil (accessed on 23 October 2022).

Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. $CO_2$ Emissions from Aviation. Our World in Data. November 28. Available online: https://ourworldindata.org/co2-emissions-from-aviation (accessed on 23 October 2022).

Sausen, Robert, and Ulrich Schumann. 2000. Estimates of the climate response to aircraft $CO_2$ and NOx emissions scenarios. *Climatic Change* 44: 27–58. [CrossRef]

Swiss Federal Council. 2021. Switzerland's Long-Term Climate Strategy Long-Term Low Greenhouse Gas Emission Development Strategies (LT-LEDS) The Federal Council. Available online: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target/climate-strategy-2050.html (accessed on 23 October 2022).

Teoh, Roger, Ulrich Schumann, Arnab Majumdar, and Marc E. J. Stettler. 2020. Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. *Environmental Science & Technology* 54: 2941–50. [CrossRef]

Thalmann, Philippe, Fleance Cocker, Pallivathukkal Cherian Abraham, Marius Brülhart, Nikolai Orgland, Dominic Rohner, and Michael Yaziji. 2021. *Introducing an Air Ticket Tax in Switzerland: Estimated Effects on Demand*. Ecublens: E4S Enterprise for Society. Available online: https://infoscience.epfl.ch/record/285985/files/WP_aviation_en.pdf (accessed on 23 October 2022).

UK Department for Transport. 2021. *UK Department for Transport—Sustainable Aviation Fuels Mandate—Summary of Consultation Responses and Government Response*; London: UK Department for Transport. Available online: https://www.gov.uk/government/consultations/mandating-the-use-of-sustainable-aviation-fuels-in-the-uk (accessed on 23 October 2022).

Voigt, Christiane, Jonas Kleine, Daniel Sauer, Richard H. Moore, Tiziana Bräuer, Patrick Le Clercq, Stefan Kaufmann, Monika Scheibe, Tina Jurkat-Witschas, Manfred Aigner, and et al. 2021. Cleaner Burning Aviation Fuels Can Reduce Contrail Cloudiness. *Communications Earth & Environment* 2: 1–10. [CrossRef]

World Economic Forum. 2021. Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe. Available online: https://www.weforum.org/reports/guidelines-for-a-sustainable-aviation-fuel-blending-mandate-in-europe/ (accessed on 23 October 2022).