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AVIATION AND CLIMATE: THE STATE-OF-THE-ART

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ABSTRACT

As a human activity, the aviation sector is a contributor to climate change due the CO_2 emissions and also non-CO_2 effects which result from the interactions of the engine effluents with the atmosphere. The understanding and quantification of the impact of the aviation sector on climate is an intricate topic, whose evaluation largely depends on the scope considered. Furthermore, identifying the possible and efficient levers to mitigate such impact is of interest. This paper proposes a short review of the scientific literature regarding aviation and climate. Furthermore, it proposes an analysis of prospective decarbonisation scenarios for the sector in the context of the Paris Agreement. The results indicate that the ability of the aviation sector to reduce its CO_2 emissions by 2050 thanks to technological levers (including progresses in aerodynamics and propulsion) alone depends on the objective for the limitation of temperature increase by 2100. For an objective of +1.5 °C, if air traffic grows at the rate predicted by the aviation industry, it will consume a larger share of the carbon budget than its current share of CO_2 emissions. Also, the results are compelling in regard of the low-carbon energy availability for the aviation sector.

1. INTRODUCTION

In its sixth assessment report published in 2021 [18], the Intergovernmental Panel on Climate Change (IPCC) concluded that human activities have had an unequivocal influence on the warming of the atmosphere, oceans and land. Between the periods 1850–1900 and 2011–2020, the average temperature has increased by 1.09 °C, of which 1.07 °C is due to human activities. Anthropogenic emissions of greenhouse gas (GHG), in particular CO_2, are the main cause of the increase in effective radiative forcing (ERF), which is the indicator used to quantify the climate impact of human activities. In addition to necessary measures for adaptation to this warming, mitigation strategies, including GHG reduction, must be settled to limit the temperature increase and its consequences. In this context, the Paris Agreement aims to hold “the increase in the global average temperature to well below +2 °C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5 °C”[1]. To achieve the latter goal, CO_2 emissions must change radically and the IPCC scenarios describe a decrease in CO_2 emissions of around 7 % per year to limit warming to 1.5 °C [19], whereas they grew at a rate of 1.2 % per year between 2010 and 2019.

As the consequences of global warming become more pressing, the debate is becoming increasingly polarised around the future of the aviation sector. Based on the ISAE-SUPAERO Référentiel Aviation et Climat [4], this paper provides a state-of-the-art of the scientific literature on the climate impact of aviation (§2) and on the technological levers considered to reduce it (§3), before analysing prospective transition scenarios for the aviation sector in compliance with the Paris Agreement using a specific methodology (§4). Finally, section §5 offers concluding remarks.

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[1] Paris Agreement, UNFCCC, 2015.

2. AVIATION CLIMATE IMPACT

The aviation sector contributes to the increase in global warming through multiple mechanisms illustrated in Figure 1 and classified into two categories. On the one hand, the CO_2 effects correspond to the enhancement of the greenhouse effect induced by CO_2 emissions, mainly from the combustion and production of kerosene. On the other hand, the five non-CO_2 effects include all other climate impacts of aviation. Some of these effects are warming and some are cooling: in total they generate a positive ERF. They include the effects of non-CO_2 engine effluents (including NO_x, soot and water vapour) and contrail-induced cirrus effects [16].

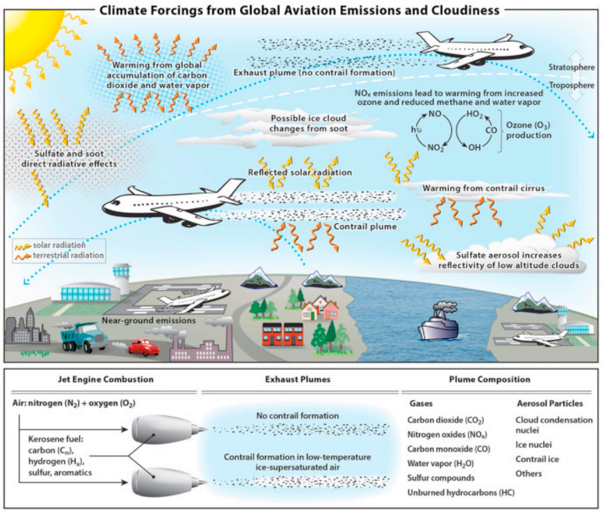

Figure 1: Schematic view of the CO_2 and non-CO_2 effects of aviation (Lee *et al.* [16]).

Although the CO_2 effect is the most straightforward to evaluate, it is nevertheless the non-CO_2 effects that are predominant, with a twofold climate impact compared to CO_2 emissions. Indeed, Lee *et al.* [16] evaluated the increase in ERF induced by non-CO_2 effects over the period 1750–2018 to $66\,\mathrm{mW\,m^{-2}}$ [21-121][2] while it amounts to $34\,\mathrm{mW\,m^{-2}}$ [28-40] for CO_2 effects[3]. The contrail-induced cirrus are the dominant non-CO_2 effect and their contribution to the ERF increase is evaluated to $57\,\mathrm{mW\,m^{-2}}$ [17-98] [16]. The estimation of non-CO_2 effects is still subject to significant uncertainties and a recent study [2] provided a slightly lower estimation of the non-CO_2 effects contribution to aviation-induced ERF around 63 % rather than 66 %. Furthermore, the effect of NO_x may be underestimated, while the uncertainties in estimating the climate impact of aerosol-cloud interactions are so large that they are generally excluded from the assessment of aviation-induced ERF. Finally, the CO_2 and non-CO_2 effects are of a fundamentally different nature: the CO_2 effects are cumulative and long-lived, and therefore depend on the cumulative value of CO_2 emissions, whereas non-CO_2 effects are instantaneous and short-lived. This difference has important consequences on their respective impacts on ERF as can be seen on Figure 2: there is a strong correlation between traffic variation and variation in the climate impact of aviation, while the variation in the climate impact due to CO_2 effects is very stable. This illustrates both the preponderance of non-CO_2 effects and the cumulative and short-term characteristics of CO_2 and non-CO_2 effects, respectively. When air traffic decreases, as in 2009, the climate impact of aviation also decreases, while the impact due to CO_2 effects does not decrease but increases less rapidly.

Various scopes can be thus considered to evaluate the climate impact of the aviation sector, depending on:

- whether non-CO_2 effects are taken into account;
- the restriction to commercial aviation (responsible for approximately 88 % of kerosene consumption) or the extension to global aviation, including military and private aviation;
- accounting for CO_2 emitted only during the flight (combustion) or that attributable to the entire life cycle of the sector, including the production of kerosene (which accounts for around 20 % of combustion-related emissions), aircraft and airport infrastructures;
- the choice of the time window over which the impact is measured, for example since the beginning of the industrial period in 1750 or over a more recent period.

Table 1 shows the assessment of the climate impact of the aviation sector for several scopes, each resulting from a different combination of these choices. CO_2 effects are quantified by the amount of CO_2 emitted. In 2018, emissions from the combustion of kerosene used by the entire aviation sector accounted for 2.4 % of the anthropogenic total, and full life-cycle emissions from commercial aviation accounted for 2.6 % of the total [4].

When non-CO_2 effects are taken into account, the assessment of the impact is then measured by estimating the value of the anthropogenic ERF induced by the sector. Between 1750 and 2018, the period usually considered in the scientific literature, global aviation, considering only combustion-related CO_2 emissions, was responsible for 3.8 % of the anthropogenic ERF. Considering the same perimeter but over a more recent period of time from 2000 to 2018, the aviation is responsible for 4.8 % of the increase in anthropogenic ERF. If the scope is extended to include the CO_2 emissions over the entire lifecycle (including manufacturing), its share in the increase in anthropogenic ERF amounts to 5.1 % between 2000

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[2] This range corresponds to the 90 % confidence interval around the median value of $66\,\mathrm{mW\,m^{-2}}$, indicating that the true figure lies in between $21\,\mathrm{mW\,m^{-2}}$ and $121\,\mathrm{mW\,m^{-2}}$ with a 90 % probability.

[3] This figure only accounts for CO_2 emissions due to combustion.

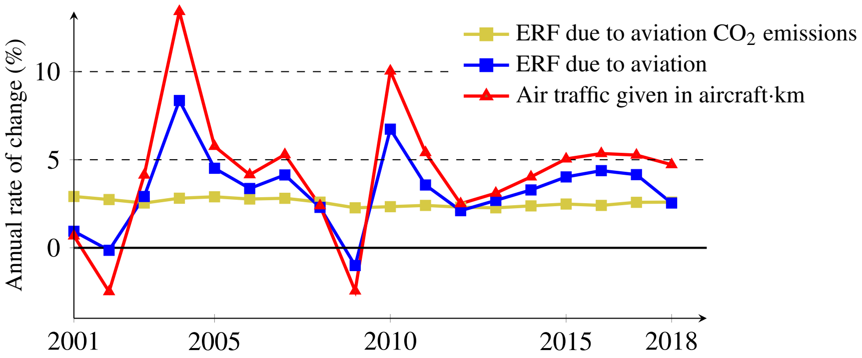

Figure 2: Annual rate of change of ERF due to aviation, ERF due to aviation CO_2 emissions and air traffic. Data taken from Lee *et al.* [16] and ICAO.

Period	CO_2		Anthropogenic ERF	
	$GtCO_2$	% of emissions	$mW\,m^{-2}$	% of anthropogenic ERF
Global aviation, only combustion				
1750–2018	32,9	1.4 %	100,9	3.8 %
2000–2018	15,1	2.1 %	44,2	4.8 %
2018	1,0	2.4 %	2,5	—
Commercial aviation, full life-cycle				
2000–2018	16,0	2.3 %	47,6	5.1 %
2018	1,1	2.6 %	4,2	—

Table 1: Assessment of the climate impact of aviation for various scopes [4].

and 2018. In contrast to the estimate of CO_2 effects, recent annual values of aviation's share of the increase in anthropogenic ERF show large variations. These values are therefore not very representative, which explains the absence of this figure for the year 2018 [4].

3. TECHNOLOGICAL LEVERS

Limiting the climate impact of aviation requires reducing both CO_2 and non-CO_2 effects. In this section, we present the main technological levers currently being considered. Focusing on commercial aviation only, we discuss levers to reduce non-CO_2 effects before providing an overview of measures to improve aircraft efficiency and decarbonise aviation fuels.

3.1 Non-CO_2 effects: promising strategies

Since non-CO_2 effects are short-lived, their short-term mitigation is possible. Several recent studies suggest that it is possible to significantly reduce the climatic impact of non-CO_2 effects, including contrails.

On the one hand, the non-CO_2 emissions of alternative fuels are different from those of fossil kerosene. Thus, these alternative fuels could have a beneficial role in mitigating non-CO_2 effects. For example, several recent studies suggest that the use of biofuels at a 50 % incorporation rate could reduce the aviation-induced ERF by 10 to 25 % [3, 14, 13, 20, 25]. On the other hand, one of the most promising measure to reduce non-CO_2 effects concerns operational strategies that rely on the trajectory modification for a minority of aircraft. Indeed, only a small fraction of flights are responsible for the majority of contrail formation and a recent study in Japanese airspace concluded that 2 % of flights are responsible for 80 % of the energy forcing induced by contrails [29]. This yields the prospect of effective mitigation strategies based on trajectory modification for a small number of flights at the cost of very low fuel extra consumption, less than 1 %.

Presently, these strategies seem promising for significantly and rapidly reducing non-CO_2 effects. Nevertheless, more work and investigations are needed to confirm these recent scientific results, in particular to improve the efficiency of aviation weather models to confidently forecast the development, the persistence and the physical properties (e.g. the optical depth) of contrails [6]. However, these solutions cannot replace measures to reduce CO_2 emissions, which have the greatest long-term impact on climate change.

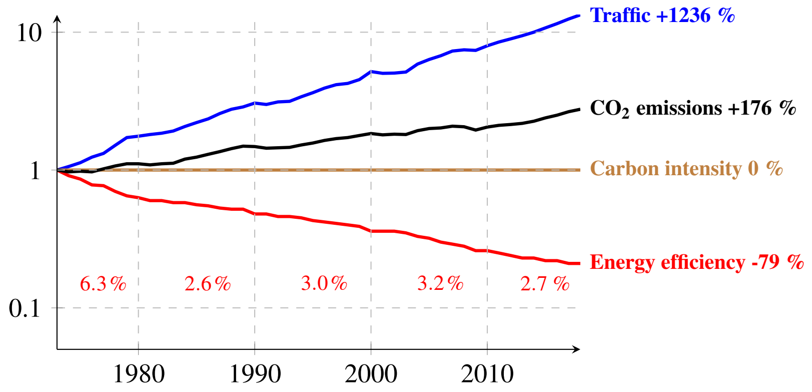

Figure 3: Evolution of the different terms of the Kaya identity (1) between 1973 and 2018, starting with a unitary value in 1973. The red figures at the bottom indicate the energy efficiency annual variations averaged over each decade while the figures on the right denote the global evolution over the whole period. Data taken from IEA and ICAO.

3.2 CO_2 effects: efficiency and decarbonisation

3.2.1 Kaya identity

In order to reduce the CO_2 emissions of the aviation sector, it is convenient to consider the so-called Kaya identity specifically derived for the aviation sector:

$$\underbrace{CO_2}_{\substack{CO_2\\ \text{emissions}}} = \underbrace{\frac{CO_2}{E}}_{\substack{\text{Carbon}\\ \text{intensity}}} \times \underbrace{\frac{E}{\text{Traffic}}}_{\substack{\text{Energy}\\ \text{intensity}}} \times \underbrace{\text{Traffic}}_{\text{Traffic}} \tag{1}$$

This approach offers a comprehensive but simplified framework to understand the origin of the CO_2 emissions as the interdependence of the right-hand side terms is neglected. The CO_2 emissions of the aviation sector result from a combination of three terms:

- the carbon intensity which represents the amount of CO_2 released per unit of energy used to power an aeroplane;
- the energy intensity which corresponds to the amount of energy required for one passenger to travel one kilometre;
- the traffic level which is given by the total number of kilometres travelled by all passengers, measured in revenue passenger kilometres (RPK).

While the first two terms rely on technological grounds, the last one is driven by societal, political, economic and cultural developments. Each term of this identity corresponds to a lever that can be activated to change the aviation CO_2 emissions:

- the reduction of the carbon intensity is a decarbonation lever associated with the use of low-carbon fuels;
- the reduction of the energy intensity is a technological lever associated with the improvement of the overall aircraft efficiency;
- the reduction of the traffic level is a sobriety lever.

Before discussing the technological and decarbonation levers, it is interesting to have a brief historical view on the evolution of these three levers over the last five decades as illustrated in Figure 3, by using public data provided by IEA and ICAO.

Since 1973, the fuel used to power aeroplanes has remained essentially the same, therefore the carbon intensity has not changed yet. On the other hand, the energy intensity has decreased by almost 80 % in 45 years, corresponding to an average improvement of 3.5 % per year. This illustrates the very significant technological progress made by the aviation sector. In the meantime, this five-fold decrease in aircraft energy consumption per RPK has been largely offset by a thirteen-fold increase in traffic level over the same period, leading to a near tripling of the aviation CO_2 emissions.

3.2.2 Improving energy efficiency

Since the beginning of commercial aviation, aircraft have always kept a standard tube-and-wing architecture, consisting of a fuselage, a wing and tail planes. Regarding the propulsion system, two types of engines are mainly used: most of the commercial aircraft are equipped with turbofans, while some regional aircraft use turboprops. The latter are more efficient but less powerful and are thus restricted to regional aviation with a limited maximum take-off weight.

The energy efficiency of aircraft can be improved in two ways: either incrementally without fundamental modification of both the aircraft architecture and its propulsion system or through breakthrough innovations that reinvent the aircraft architecture. Regardless of the innovation type, replacing the oldest aircraft in the fleet with these new and more efficient ones will reduce the energy intensity of the aviation. The aircraft energy consumption can also be reduced by resorting to operational levers such as the increase of the seat-occupancy rate of the aircraft, or the optimisation of ground and flight operations thanks to air traffic management (ATM).

Historically, gains of efficiency have been achieved incrementally by the different actors of the aviation industry (engine, aircraft and systems manufacturers) and also by improvements on operations. The industry actors generally work separately on four disciplines: propulsion, aerodynamics, structure and aircraft systems, the latter providing non-propulsive functions such as air conditioning or flight controls.

Improving engines is a major lever for reducing aircraft fuel consumption. In addition to the improvement of the gas turbine thermodynamic cycle, the increase of the bypass ratio is the most promising outcome for new engine architectures, with the near-term advent of Ultra High Bypass Ratio and Open Rotor engines [7]. The improvement of aircraft aerodynamics represents also an important lever to reduce the three main sources of the aircraft drag: the design of laminar wings to reduce the skin friction drag [9], the increase of wingspan and the design wingtips to reduce the induced drag [8] and the optimisation of the components integration within the aircraft to reduce the parasite drag. Reducing the weight of the aircraft also reduces its fuel consumption. Most of the recent weight reduction comes from the replacement of metal-based structures by composite materials. Further reduction can be achieved through new additive manufacturing processes based on 3D printing [10]. The improvement of aircraft systems, which currently account for 5 to 10 % of fuel consumption, will be achieved mainly through their electrification [17]. This evolution, readily observable in some sub-systems of the latest aircraft generations, will enable to increase the components efficiency by replacing pneumatic and hydraulic systems. However, some technological limitations on power electronics have still to be resolved regarding thermal management, power density and reliability.

The renewal of the fleet integrating all these incremental improvements as well as the improvement of operations, would yield efficiency gains of at most 2 % per year in the next decades [4]. These foreseen yearly rates of efficiency improvement are lower than the historical rates of 3.5 %, illustrating that technological limits are about to be reached. In order to achieve greater efficiency gains, it is thus necessary to design novel aircraft architectures, integrating the four disciplines mentioned previously.

The shape of the aircraft can be completely redesigned, e.g. by considering a blended-wing body architecture. This type of architecture could improve fuel efficiency by up to 25 % [1]. Important architectural transformations are also considered for propulsion systems, such as the distributed or buried architectures which are based on the boundary layer ingestion. However, the corresponding efficiency improvements are expected to be less than 5 % [22]. Finally, the aircraft propulsion system could also be rethought with, for example, the advent of hybrid-electric propulsion, which would allow a more efficient energy use. However, there are still many limitations for implementing these promising technological breakthroughs. Their development will face technical and certification issues and they will not be mature before 2030 at best. Moreover, these new architectures will require reinforced synergies between the various actors of the sector.

3.2.3 Decarbonisation

The fossil kerosene has always been used to power aircraft and its carbon intensity, including its production, is evaluated about $89\,\mathrm{gCO_2\text{-}eq/MJ}$[4] [30]. The decarbonisation of aviation fuels consists in replacing the fossil kerosene with another potentially low-carbon energy vector. Three alternative energy carriers are considered in this paper: electricity stored in batteries, liquid hydrogen and synthetic fuels (electro- and biofuels).

The advantage of an all-electric aircraft lies in the removal of all direct emissions, including CO_2, NO_x, soot and water vapour, thus reducing the climate impact of the flight phase close to zero. Therefore, the CO_2 emissions are only due to the production of electricity. Presently, the development of large all-electric aircraft is limited by the mass energy density of electric batteries. While small all-electric aircraft (up to 19 passengers, 1000 km range) can be envisaged in the short term with current densities of $1\,\mathrm{MJ\,kg^{-1}}$, an all-electric short-haul aircraft (180 passengers, 1000 km range) would require densities of around $3\,\mathrm{MJ\,kg^{-1}}$, which are not expected before several decades [5, 15]. Beyond this technical limitation, the emission factor of the global production of electricity is currently around $132\,\mathrm{gCO_2\text{-}eq/MJ}$, which is 48 % higher than that of fossil kerosene. As a consequence, the decarbonisation of the electricity production stands as a prerequisite before being considered as a potential solution for commercial aviation.

To power aircraft, hydrogen is likely to be stored in liquid form to minimise the volume occupied, which requires a storage at −253 °C. For the same amount of energy, liquid hydrogen is three times lighter but takes up four times more space than conventional kerosene. This larger volume requires a redesign of aircraft architecture. Hydrogen can either be used in a fuel cell, but power densities are limited, or burned in a gas turbine. Focusing on the latter case, the combustion of hydrogen does not emit CO_2 but its production may. This combustion also emits NO_x and water vapour, but no soot. The non-CO_2 effects would therefore not be eliminated, but they would a priori be reduced compared to a conventional aircraft [23].

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[4] This is a representative value of the kerosene current carbon intensity, which can vary depending on several factors like the production place.

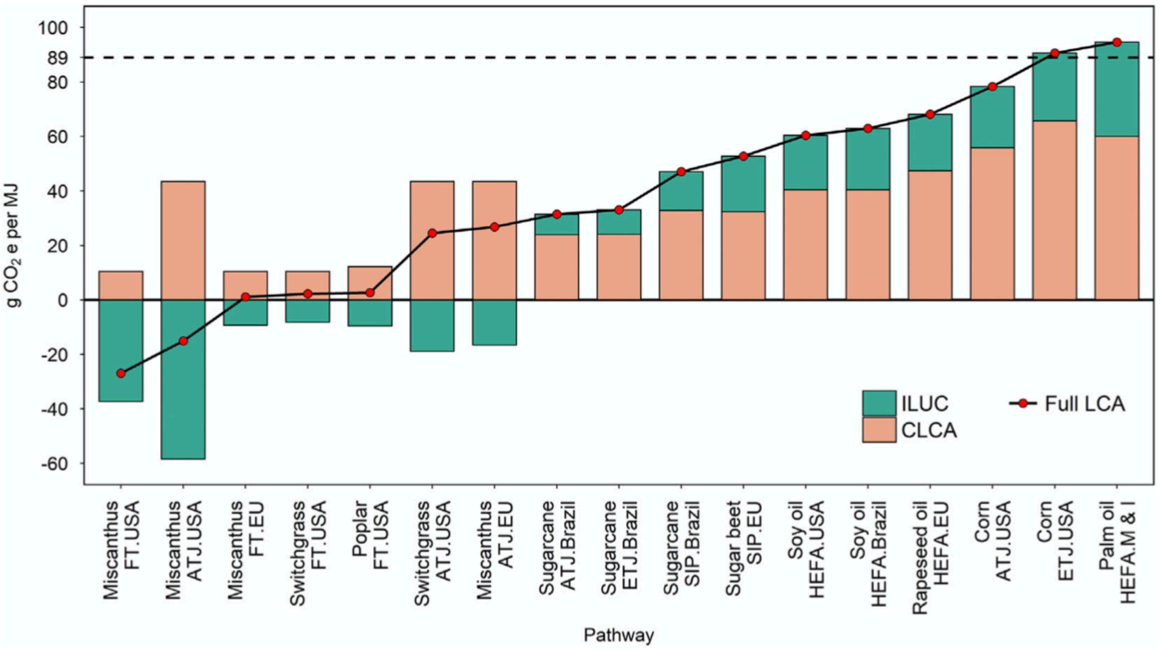

Figure 4: Full life cycle emissions of different biofuels (Zhao *et al.* [30]). Green bars corresponds to the emissions related to the indirect land use change (ILUC) and orange bars to the emissions over the rest of the life cycle (biomass cultivation, synthetic fuel production. . .)

Electrofuels are synthetic fuels produced from the combination of hydrogen obtained by electrolysis of water, and CO_2 which comes either from the atmosphere or from industrial sources. The corresponding efficiency varies between 40 and 50 % depending on the CO_2 concentration of the source used. The concentration of atmospheric CO_2 is 0.04 %, whereas the concentration at the output of industrial processes can be much higher, around 35 % in the smoke produced by steelworks, and even up to 100 % for some thermochemical processes such as the production of ammonia [26]. Biofuels are synthetic fuels produced from biomass: dedicated bioenergy crops, agricultural and forestry residues, algae, used cooking oil or municipal waste. These feedstocks can be converted into synthetic fuel through different production processes. To date, the biofuels used by aviation are produced from lipidic raw materials (vegetable oils) via the HEFA process which is the only one to be developed at an industrial scale. In 2018, the production amounts to 15 million litres of biofuels which represented 0.004 % of the energy consumption of the aviation sector [11]. Other production processes, including the Fischer–Tropsch process which exploits lignocellulosic resources or the alcohol-to-jet process from a wide variety of resources, are being considered for the future but are at lower stages of development.

Like electricity, hydrogen and electrofuels are not yet mature alternative fuels for large commercial aviation. Their production generates also potentially significant CO_2 emissions. For example, the carbon intensity of current liquid hydrogen production methods is 153 $gCO_2\text{-eq}/MJ$. Since the fossil kerosene carbon intensity is lower, using these alternative fuels in their current production conditions would increase CO_2 emissions. Before these energy vectors become beneficial from a climate point of view, it is therefore essential to develop low-carbon electricity production from renewable energies or nuclear energy.

Biofuels are currently the most technologically mature decarbonisation solution. Their combustion emits approximately as much CO_2 as the combustion of fossil kerosene, but as this CO_2 does not come from fossil reserves but from the atmosphere where it has been captured during the growth of the biomass, it enables CO_2 emissions reduction when considering the full life cycle. Furthermore, the biomass cultivation also generates emissions related to land use, which depend on many physical and socio-economic factors, which renders the assessment of corresponding CO_2 emissions difficult. Figure 4 provides estimates of life-cycle emission factors for various biofuels [30]. Those produced from cellulosic material are the most effective since they enable overall negative emissions, leading to a potential CO_2 emissions reduction over the full life-cycle greater than 100 % compared to fossil kerosene.

Scenario	T	TD	BD
Annual energy efficiency improvement between 2020 and 2050	1 %	1 %	1.5 %
Average load factor in 2050	89 %	89 %	92 %
Reduction in consumption via operations in 2050 compared to 2020	0 %	8 %	12 %
Fleet share using low-carbon fuels in 2050	0 %	50 %	100 %
Emission factor in 2050 (gCO_2-eq/RPK)	89	52	17

Table 2: Main technological assumptions for the three illustrative scenarios considered [4].

4. SCENARIO ANALYSIS

Several recent scientific works have proposed methodologies to assess the sustainability of scenarios for commercial aviation. The objective of this section is to present a specific methodology developed at ISAE-SUPAERO [21] and to apply it to some illustrative scenarios.

4.1 Methodology

The analysis of the scenarios is based on the concept of carbon budget. Its definition depends on the concept of carbon neutrality, which corresponds to an exact balance between the quantity of CO_2 emitted by human activities and the quantity of CO_2 captured by anthropogenic carbon sinks. The carbon budget represents the maximum cumulative amount of CO_2 that humanity can emit into the atmosphere before reaching carbon neutrality while limiting global warming below a given temperature.

We mainly consider median global carbon budgets for +1.5 °C and +2 °C, as extreme values of the Paris Agreement, and we consider scenarios up to 2050. These carbon budgets can be corrected by integrating possible anthropogenic carbon sinks, in which case they are qualified as *gross*. The share of the global carbon budget allocated to the aviation sector results from political, economic and societal choices. Therefore, ranges of possible values are considered. The sustainability of a scenario is assessed through the comparison of the cumulative emissions from aviation to the allocated carbon budget, i.e. to be aligned with the climate commitments, cumulative emissions have to be lower than the allocated carbon budget.

Regarding the share of the global carbon budget allocated to aviation, a reference value corresponds to the recent share of commercial aviation in global CO_2 emissions, which amounts to 2.6 % in 2018 (see Table 1). This value corresponds to the share that would be allocated to the aviation sector in a non-differentiated approach where all sectors of activity would reduce their emissions from 2018 at the same annual rate. Allocations below or above this value can also be considered and a larger allocation to aviation would mechanically require other sectors to reduce their emissions faster than the average.

4.2 Results

The analysis of sustainable scenarios for aviation is conducted using the tool CAST, developed at ISAE-SUPAERO, which enable to simulate transition scenarios for aviation and assess their climate impact [21].

Three illustrative technological scenarios are considered: a trend scenario without decarbonisation (T), a trend scenario with partial fleet decarbonisation (TD) and a scenario with technological breakthrough and complete fleet decarbonisation (BD). The main characteristics of these scenarios are provided in Table 2. It is assumed that low-carbon fuels will reduce CO_2 emissions over their full life cycle by an average of 75 % compared to fossil kerosene. These different assumptions lead to emission factors per RPK in 2050 ranging from 17 gCO_2-eq/pass.km to 89 gCO_2-eq/pass.km. These values can be compared to the carbon intensity of the 2019 world fleet which is 131 gCO_2-eq/pass.km or to that of the latest generation of aircraft which is less than 100 gCO_2-eq/pass.km.

Once these technology assumptions have been defined, a parametric analysis can be performed by considering different global carbon budgets and different shares allocated to commercial aviation. The traffic growth rate is then adjusted so that the cumulative emissions of the scenario equal the carbon budget allocated to aviation. In this sense, the resulting growth rate is a maximum sustainable growth rate.

Figure 5 represents the evolution of the maximum sustainable annual traffic growth rate for the three illustrative scenarios with respect to the global carbon budget share allocated to commercial aviation, considering median carbon budgets for +1.5 °C and +2 °C. For +1.5 °C, an allocation of 2.6 % of the global carbon budget to the aviation sector (dotted vertical line) implies a strong decrease in traffic whatever the scenario. To reach the trend growth rate of air traffic of 3 % (dotted horizontal line), it would be necessary to allocate 6 % of the global carbon budget to the aviation sector in the case of the most ambitious scenario BD. To limit warming to +2 °C, the results are more nuanced: in the case of the 2.6 % reference share, the most pessimistic scenario T would require an annual decrease in air traffic of 1.8 % while the most optimistic scenario BD would allow an annual growth of 2.9 %.

This study can be extended to other global carbon bud-

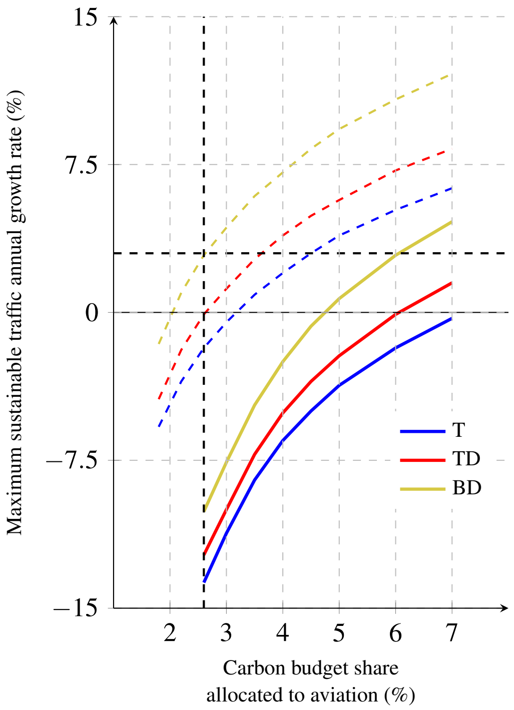

Figure 5: Maximum sustainable annual traffic growth rate as a function of the global carbon budget share allocated to commercial aviation for the T, TD and BD scenarios. Solid and dashed lines correspond to a limitation of temperature increase to +1.5 °C and +2 °C, respectively.

gets. Figure 6 shows the results of a parametric analysis for different global carbon budgets under the TD and BD scenarios. The vertical and horizontal dotted lines represent the median carbon budget for +2 °C and the reference share of 2.6 %, respectively. This figure allows for a more comprehensive analysis and also sheds light on the trade-offs to be made between air traffic growth rate and the share of the global carbon budget allocated to aviation for a given climate target.

4.3 Limitations on deployment speed and energy availability

This analysis of different scenarios highlights two limitations that are likely to impact significantly the ability of the aviation sector to rapidly and efficiently reduce its CO_2 emissions.

First, there are limitations regarding the speed of deployment of technological solutions in the fleet. Indeed, since the sustainability of a scenario is driven by the cumulative CO_2 emissions of the sector, the reduction of emissions must occur early to be effective. However, incremental and operational improvements in energy efficiency, with gains of no more than 2 % per year, will not allow for a sufficiently rapid decrease of CO_2 emissions, and disruptive innovations (e.g. flying wings or hydrogen-powered aircraft) are not expected before 2030 at best. Furthermore, solutions relying on electricity will be worth to be deployed only when the global electricity mix has become low-carbon, which may take several decades [12].

The second limitation is related to the energy availability, which applies to any alternative fuels considered for replacing fossil kerosene. The scientific studies available to date show that, in the event of strong traffic growth, biofuels are unlikely to account for more than 20 % of global aviation energy consumption in 2050 [27]. The demand for low-carbon electricity could also face availability limitations, with some scenarios for aviation in 2050 predicting that the aviation sector would need more than 30 % of the total low-carbon electricity generated worldwide [4].

5. CONCLUSIONS

Like all human activities, the aviation sector is facing a challenge to reduce drastically its climate impact in the next thirty years in order to comply with the objectives of the Paris Agreement on climate change mitigation. Aviation contributes to global warming through its CO_2 emissions and five non-CO_2 effects such as contrails-induced cirrus. CO_2 effects are cumulative and long-lived, and therefore depend on the cumulative value of CO_2 emissions, whereas non-CO_2 are instantaneous and short-lived. This difference has important consequences on their respective impact on anthropogenic effective radiative forcing (ERF). The assessment of aviation climate impact can be limited to CO_2 emissions only, or it can account for all effects. In the first case, commercial aviation was responsible for 2.6 % of global anthropogenic CO_2 emissions in 2018. When all effects (CO_2 and non-CO_2) are considered, the contribution of commercial aviation to the anthropogenic ERF is estimated to be 5.1 % over the period 2000–2018.

In order to mitigate the climate impact of aviation, specific strategies to reduce non-CO_2 effects represent a major lever. Due to the short lifetime of these effects, strategies such as trajectory modifications to avoid contrail formation and replacement of fossil kerosene by biofuels could be effective rapidly. Although more research is needed to reduce the uncertainties, these strategies could be activated in the short term. Nevertheless, these measures to mitigate non-CO_2 effects cannot substitute to efforts to reduce CO_2 emissions from the sector. By 2050, disruptive technological solutions could contribute to the advent of a low-carbon aircraft. The limitation of global temperature rise in 2100 to +1.5 °C imposes a rapid decrease of CO_2 emissions and therefore, only mature levers can be used for reducing CO_2 emissions in the short term, namely incremental improvements in

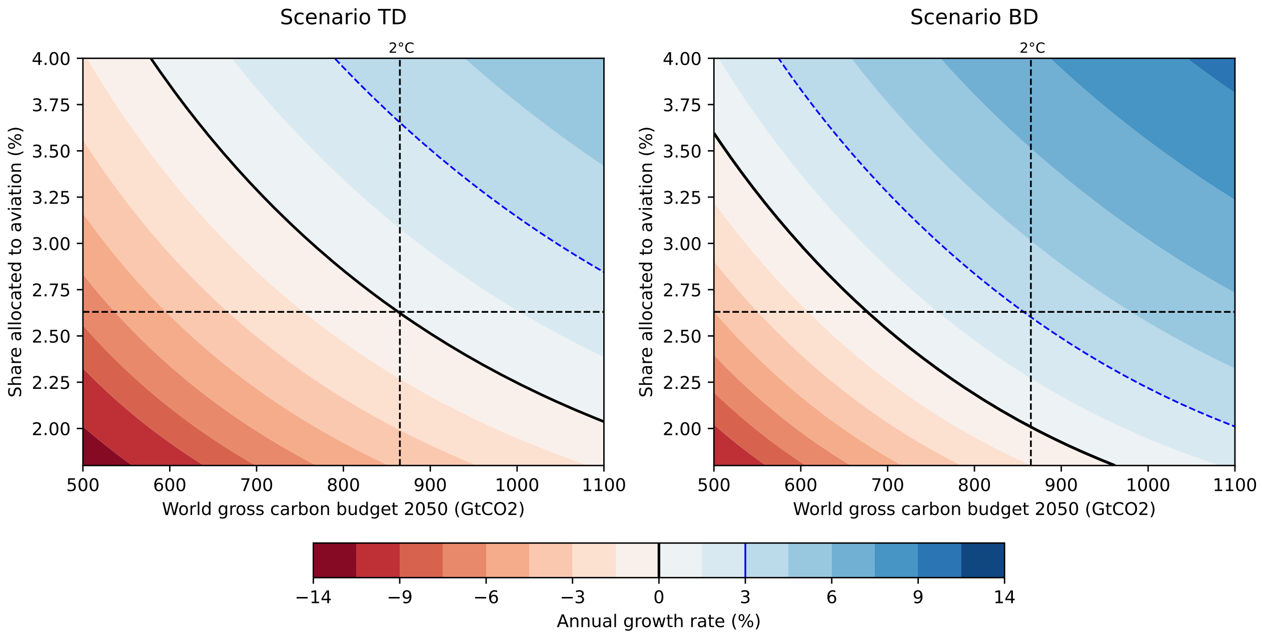

Figure 6: Maximum sustainable air traffic growth rates in the TD (left) and BD (right) scenarios for different carbon budget allocations.

aircraft efficiency and the use of biofuels. However, incremental improvements are reaching their technological limits, while the constraints on energy availability, production capacity and competition with other sectors are likely to limit the availability of biofuels.

Apart from technological and operational levers, the level of air traffic and the share of the global carbon budget allocated to aviation are the two remaining parameters that determine the sustainability of a trajectory for the aviation sector. Their value must be set by political decisions. The difficulty of the aviation sector to reduce sufficiently its CO_2 emissions by 2050 thanks to technological levers, implies that, if air traffic grows at the rate predicted by the aviation industry, the limitation of global temperature rise to +1.5 °C will require the aviation sector to consume a larger share of the carbon budget than its current share of CO_2 emissions, thus requiring other sectors to reduce their emissions faster than the average pace. However, for an objective of +2 °C, an allocation of 2.6 % of the carbon budget to aviation is compatible with industrial air traffic growth perspectives.

Finally, the decarbonisation of aviation fuels could be limited by the availability of low-carbon energy resources, namely biomass and electricity. Their massive use could then lead to a displacement of environmental problems, notably related to land use. In general, it is necessary to think about the transition of the aviation sector in a systemic way within the framework of planetary boundaries [24, 28].

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