ISAE–SUPAERO

AVIATION AND CLIMATE

A LITERATURE REVIEW

SUMMARY

September 2022

Scott Delbecq, Jérôme Fontane, Nicolas Gourdain,
Hugo Mugnier, Thomas Planès and Florian Simatos

Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

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This document has been published by ISAE-SUPAERO, a French engineering school specialised in the aeronautics and space sector. This is a summary of a more comprehensive report entitled Aviation and Climate: a literature review, which aims to provide scientific elements useful for the understanding of aviation and climate issues. This summary presents the main results and conclusions.

The work is based on the scientific literature and the most recent data available, most of whose time series end in 2018. References are omitted in this summary, except for figures taken directly from other works. The interested reader is invited to consult the full version of the document, as well as the spreadsheet containing the data and calculations made for this report. The sections of the report corresponding to the different parts of this summary are indicated in square brackets in the different subheadings.

This review is the result of the collective work by six authors: Scott Delbecq, Jérôme Fontane, Nicolas Gourdain, Hugo Mugnier, Thomas Planès and Florian Simatos. It was coordinated by Florian Simatos and has been subject to a specific review process, including both ISAE-SUPAERO staff and independent researchers from different institutes. It is available under Creative Commons CC-BY-SA licence. This document is subject to updates, in order to make corrections or add any missing elements. You can send your comments at contact-referentiel@isae-supaero.fr.

ISAE-SUPAERO Aviation and Climate: a literature review.
S. Delbecq, J. Fontane, N. Gourdain, H. Mugnier, T. Planès and F. Simatos, 2022.
https://doi.org/10.34849/a66a-vv58

KEY MESSAGES

Climate impact of aviation: estimations depend on the scope

Aviation contributes to global warming through its CO_2 emissions and several non-CO_2 effects such as contrails. The assessment of the impact of the aviation sector can be limited to CO_2 emissions alone, or it can consider all effects together. In the first case, commercial aviation was responsible for 2.6% of global anthropogenic CO_2 emissions in 2018. If we consider all effects (CO_2 and non-CO_2), commercial aviation accounted for 5.1% of the climate impact over the period 2000-2018.

Non-CO_2 effects: promising strategies

Specific strategies to reduce non-CO_2 effects represent a major lever for limiting the climate impact of aviation. Because of the short lifetime of non-CO_2 effects, these strategies can be effective quickly. Although more research is needed to reduce uncertainties, these strategies may be deployable in the near future. Nevertheless, these measures cannot substitute for efforts to reduce CO_2 emissions from the sector.

CO_2 effects: limited technological opportunities in the short term

By 2050, breakthrough solutions make it possible to envisage a low-carbon aircraft. In the shorter term, the only mature levers for reducing CO_2 emissions within the time frame set by the climate emergency are incremental improvements in aircraft efficiency and the use of biofuels. However, incremental improvements are reaching their technological limits, while the constraints of energy availability, production capacity and competition on uses are likely to limit the availability of biofuels.

A necessary trade-off between the level of traffic and the share of the global carbon budget allocated to the aviation sector

Apart from technological and operational levers, the level of traffic and the share of the global carbon budget allocated to aviation are the two parameters that determine the sustainability of a trajectory for the aviation sector. Their value must be set by policy decisions. The limited ability of the aviation sector to rapidly reduce its CO_2 emissions implies that, if traffic grows at the rate foreseen by the aviation industry, it will consume a larger share of the carbon budget than its current share of emissions, thus requiring other sectors to reduce their emissions faster than the average.

Uncertainties on energy availability

The decarbonisation of aviation fuels could be limited by the availability of low-carbon energy resources. Their massive use could then lead to a displacement of environmental problems, notably related to land use. More generally, it is necessary to think about the transition of the aviation sector with a systemic view within the framework of planetary boundaries.

CONTEXT

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Positioning of the report

As the consequences of global warming become more pressing, the debate is becoming increasingly polarised around the future of the aviation sector. While many institutional and private reports have recently addressed the issue, the objective of the ISAE-SUPAERO Aviation and Climate literature review is to provide everyone, from our scientific position, with the elements necessary to build informed opinions on this subject, as objectively as possible. This document therefore provides a state-of-the-art of the scientific literature on the climate impact of aviation and on the levers envisaged to reduce it, and analyses transition scenarios for the aviation sector in compliance with the Paris Agreement.

Global warming *[chapter 1]*

In its sixth assessment report published in 2021, 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, 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.

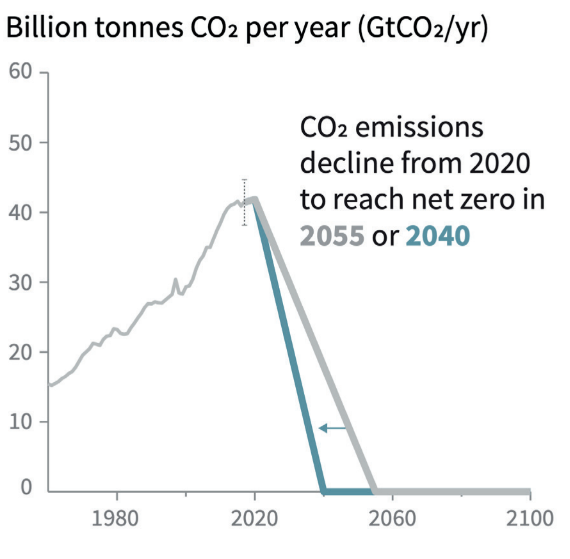

Figure 1: Schematic trajectories of the CO_2 emissions reduction needed to limit global warming to +1.5°C, with the blue trajectory increasing the chances of success (IPCC Special Report 1.5°C).

In addition to necessary measures for adaptation to this warming, mitigation strategies, including reduction of greenhouse gas emissions, 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. To achieve the latter goal, CO_2 emissions must change radically as illustrated in *figure 1*. The IPCC scenarios describe a decrease in CO_2 emissions of around 7% per year to limit warming to 1.5°C, whereas they grew at a rate of 1.2% per year between 2010 and 2019.

CO_2 and non-CO_2 effects *[section 2.1]*

The aviation sector contributes to the increase in global warming through multiple mechanisms illustrated in *figure 2* and classified into two categories.

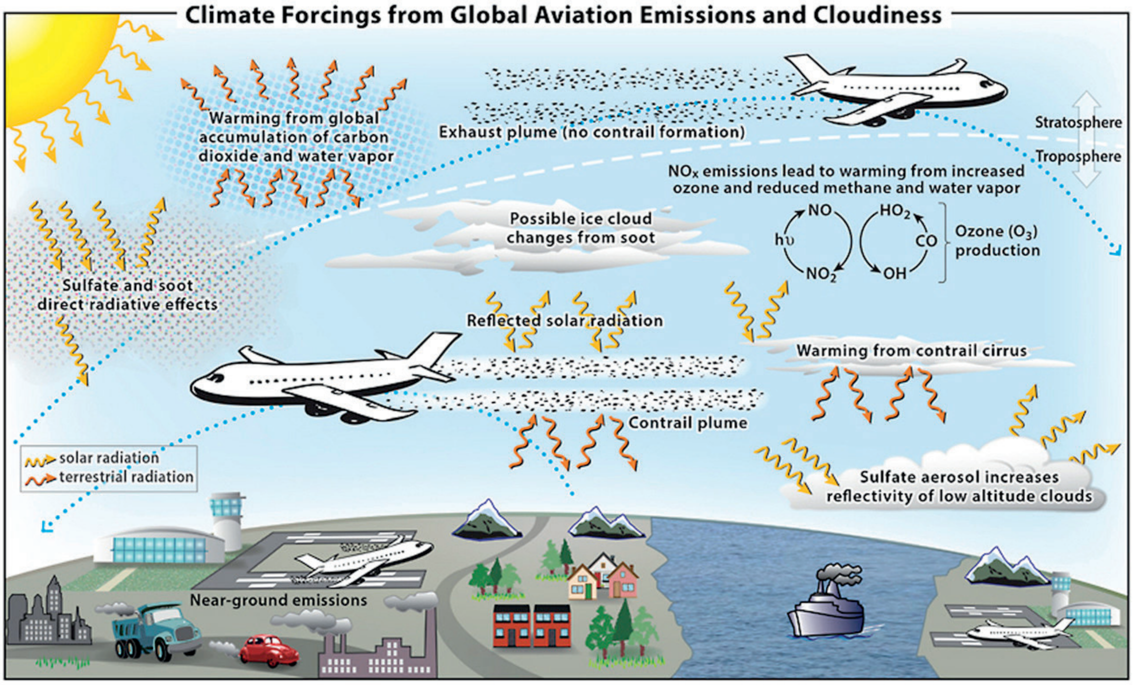

Figure 2: Schematic view of the CO_2 and non-CO_2 effects of aviation (Lee et al.).

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 induce 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, contrails being represented in *figure 2* by *Contrail plume*.

Assessment of the climate impact of aviation *[section 2.2]*

The assessment of the climate impact of aviation depends on the scope considered:

- whether non-CO_2 effects are taken into account;
- the restriction to commercial aviation (responsible for approximately 90% 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.

Period	CO_2		Anthropogenic ERF	
	$GtCO_2$	% of emissions	mW m^{-2}	% of anthro-pogenic ERF
Global aviation, combustion only				
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.

CO_2 effects are quantified by the amount of CO_2 emitted. In 2018, emissions from the combustion of kerosene used by global aviation accounted for 2.4% of the global anthropogenic emissions, and full life cycle emissions from commercial aviation accounted for 2.6% of the total.

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, on the one hand extended to include the CO_2 emissions over the full life cycle (including manufacturing), and on the other hand restricted to commercial aviation (instead of global aviation), its share in the increase in anthropogenic ERF amounts to 5.1% between 2000 and 2018. In contrast to the estimate of CO_2 effects, recent annual values of aviation's share of the increase in anthropogenic ERF exhibit large variations. These values are therefore not very representative, which explains the absence of this figure for the single year 2018.

Comparison of CO_2 and non-CO_2 effects *[section 2.3]*

Although the CO_2 effects are 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, the increase in ERF induced by non-CO_2 effects over the period 1750-2018 is estimated at 66 mW m^{-2} while it amounts to 34 mW m^{-2} for CO_2 effects. The contrail-induced cirrus are the dominant non-CO_2 effect and their contribution to the ERF increase is evaluated to 57 mW m^{-2}.

The estimation of non-CO_2 effects is still subject to significant uncertainties. This is particularly the case for contrails, which are estimated to have an impact of 57 mW m^{-2}, but have a 90% chance of being in the range 17 to 98 mW m^{-2}. 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 anthropogenic ERF.

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KAYA IDENTITY

Kaya identity *[chapter 3]*

The Kaya identity provides a useful conceptual framework for identifying the different levers available to a given sector of activity to reduce its CO_2 emissions. Adapted to the aviation sector, it can be written:

$$\underbrace{CO_2}_{\substack{CO_2 \\ \text{Emissions}}} = \underbrace{\frac{CO_2}{E}}_{\substack{\text{Carbone} \\ \text{intensity}}} \text{ x } \underbrace{\frac{E}{\text{Traffic}}}_{\substack{\text{Energy} \\ \text{intensity}}} \text{ x } \underbrace{\text{Traffic}}_{\text{Traffic}}$$

The CO_2 emissions of the aviation result from a combination of three terms:

- the carbon intensity which represents the amount of CO_2 released per unit of energy (E) used to power an airplane;
- the energy intensity which corresponds to the amount of energy (E) 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).

Figure 3 shows the evolution of these different terms over the period 1973-2018. Since 1973, the fuel used to power aircraft 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 passenger-kilometre 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.

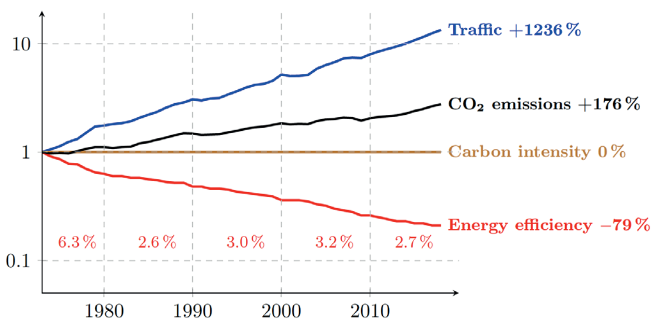

Figure 3 : Evolution of the different terms of the Kaya identity between 1973 and 2018, starting with a unitary value in 1973. The red figures at the bottom indicate the energy efficiency annual variations averaged over each decade while the figures on the right the global evolution over the whole period.

Each term of the Kaya identity corresponds to a lever that can be activated to reduce 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.

The two technological levers (decarbonation and efficiency) are detailed in the report whereas the lever of the traffic level is considered as a variable whose influence is analysed in several scenarios for commercial aviation.

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IMPROVING AIRCRAFT EFFICIENCY

Numerous efficiency levers *[chapitre 4]*

Since the beginning of commercial aviation, aircraft have always kept a standard tube-and-wing architecture, consisting of a fuselage, a wing and tailplanes. 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 thus have a limited speed compared to turbofans.

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. These operational levers are not detailed in the report but are taken into account in the analysis of scenarios for commercial aviation.

Finally, the speed of an aircraft cannot be directly considered as a lever for improving efficiency. Indeed, for an existing aircraft, reducing its flight speed does not a priori reduce its consumption. On the other hand, using an aircraft equipped with turboprop engines instead of an aircraft equipped with turbofans (and therefore flying slower) would result in fuel consumption gains of around 20%.

Incremental improvements *[sections 5.1 to 5.5]*

Historically, gains of efficiency have been achieved incrementally by the different actors of the aviation industry: engine, aircraft and systems manufacturers. They 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 (*figure 4*).

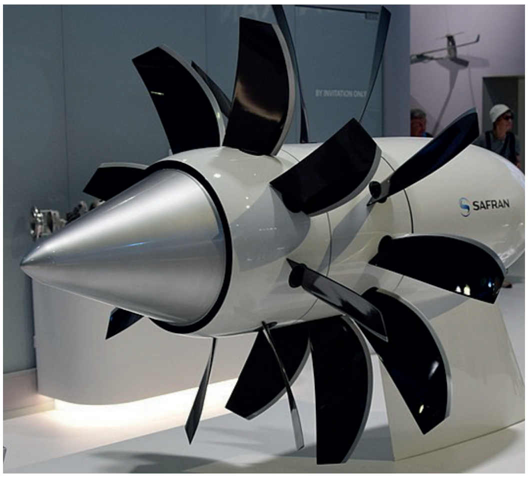

Figure 4 : Example of an Open Rotor engine (Wikimedia Commons).

The improvement of aircraft aerodynamics represents also an important lever to reduce the three main sources of the aircraft drag:

- the skin friction drag: design of laminar wings;
- the induced drag: increase of wingspan and form modification of wingtips;
- the parasite drag: optimisation of the components integration within the aircraft.

Reducing the weight of an aircraft reduces its fuel consumption. The main part of the weight reduction of the airplane structure stems from the replacement of metal structures by composite materials. Further reduction can be achieved through new additive manufacturing processes based on 3D printing.

The improvement of aircraft systems, which currently account for 5 to 10% of fuel consumption, will be achieved mainly through their electrification. 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, particularly 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.

Technological breakthroughs *[section 5.6]*

These foreseeable yearly rates of efficiency improvement are lower than the historical rates of 3.5% given in *figure 3*, suggesting 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, like the Blended-Wing Body illustrated in *figure 5*. This type of architecture could improve fuel efficiency by up to 25%. Important architectural transformations are also considered for propulsion systems, such as the distributed or buried architectures which are based on the boundary layer ingestion (*figure 5*). However, the associated efficiency gains are expected to be less than 5%. 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.

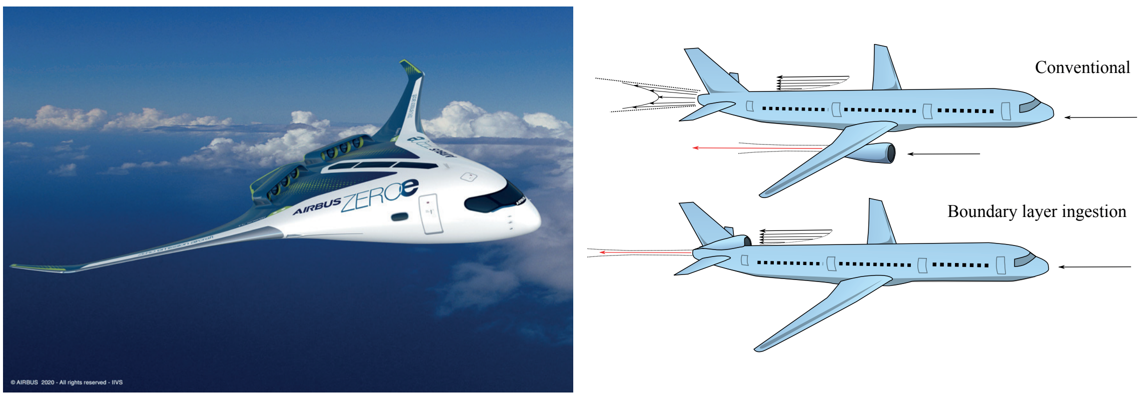

Figure 5: Examples of breakthrough architectures. On the left, a Blended-Wing Body concept (Airbus). On the right, the principle of boundary layer ingestion (Binder).

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.

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DECARBONISING FUEL

The fossil kerosene has always been used to power aircraft and its carbon intensity, including its production, is evaluated about 88 gCO_2-eq/MJ. The decarbonisation of aviation fuels consists in replacing the fossil kerosene with another potentially low-carbon energy vector. Four alternative energy carriers are currently considered.

Electricity stored in batteries *[section 6.1]*
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 MJ/kg, an all-electric short-haul aircraft (180 passengers, 1000 km range) would require densities of around 3 MJ/kg, which are not expected before several decades.

Hydrogen *[section 6.2]*
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 architectures.

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.

Electrofuels *[section 6.3.3]*
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. Therefore, their production only requires electricity. 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.

Biofuels *[section 6.3.2]*
Biofuels are alternative jet 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 fuel consumption of the aviation sector. 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.

Developing low-carbon production chains *[sections 6.1, 6.3.2, 6.4]*
Like electricity, hydrogen and electrofuels are not yet mature alternative fuels for large commercial aircraft. Their production generates also potentially significant CO_2 emissions. For example, the

carbon intensity of current liquid hydrogen production methods is 153 gCO_2-eq/MJ and the one of the global production of electricity is currently around 132 gCO_2-eq/MJ. Since the fossil kerosene carbon intensity is lower (88 gCO_2-eq/MJ), 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 leads to 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, rendering the assessment of corresponding CO_2 emissions very difficult. *Figure 6* provides estimates of life cycle emission factors for various biofuels. Those produced from cellulosic material are the most effective from a climate point of view and they enable to forecast biofuels which would reduce CO_2 emissions over the full life cycle by 75% compared to fossil kerosene.

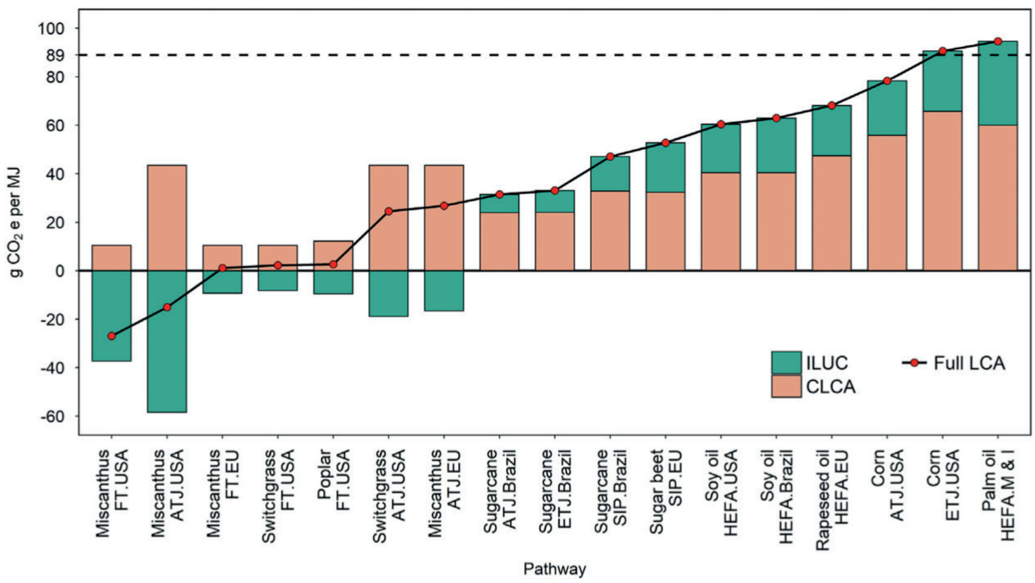

Figure 6: Full life cycle CO_2 emissions of different biofuels (Zhao et al.). Green bars corresponds to the emissions related to the indirect land use change and orange bars to the emissions over the rest of the life cycle (biomass cultivation, synthetic fuel production...).

In any case, the comparison between the current situation and the use of new energy vectors requires considering the full life cycle, and therefore taking into account the CO_2 emissions due to the production of the fuel when assessing the climate impact of aviation.

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SUSTAINABLE SCENARIOS: TRADE-OFF BETWEEN TRAFFIC AND CARBON BUDGET

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

Methodology and carbon budget for aviation *[sections 1.3.3, 8.1, 8.3]*

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 humankind 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. in order to comply 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 (cf. *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.

Analysis of sustainable scenarios for aviation *[section 9.2]*

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

Three illustrative technological scenarios are considered: a trend scenario without decarbonisation (A), a trend scenario with partial fleet decarbonisation (B) and a scenario with technological breakthrough and complete fleet decarbonisation (C). 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 to 89 gCO_2-eq/RPK. These values can be compared to the carbon intensity of the 2019 world fleet which is 131 gCO_2-eq/RPK or to that of the latest generation of aircraft which is less than 100 gCO_2-eq/RPK.

Scenario	A	B	C
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 %
Share of the fleet that will use 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.

Once these technological 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 7 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 C. To limit warming to +2°C, the results are more nuanced: in the case of the 2.6% reference share, the most pessimistic scenario A would require an annual decrease in air traffic of 1.8% while the most optimistic scenario C would allow an annual growth of 2.9%.

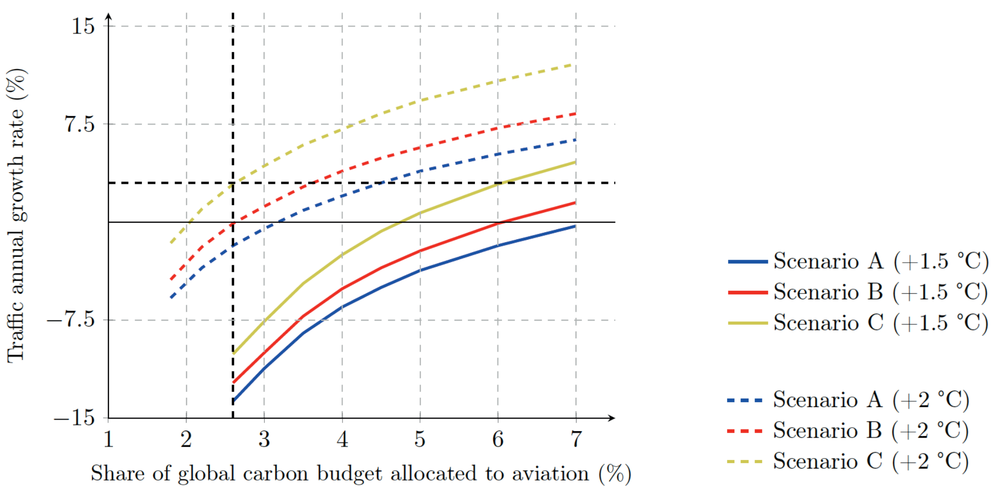

Figure 7 : Maximum sustainable annual traffic growth rate as a function of the global carbon budget share allocated to commercial aviation for the scenarios A, B and C. Reading: if 3% of the global carbon budget for +1.5°C is allocated to commercial aviation, then the maximum sustainable traffic annual growth rate is -7.5% for scenario C.

This study can be extended to other global carbon budgets. *Figure 8* shows the results of a parametric analysis for different global carbon budgets for the scenarios B and C. 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.

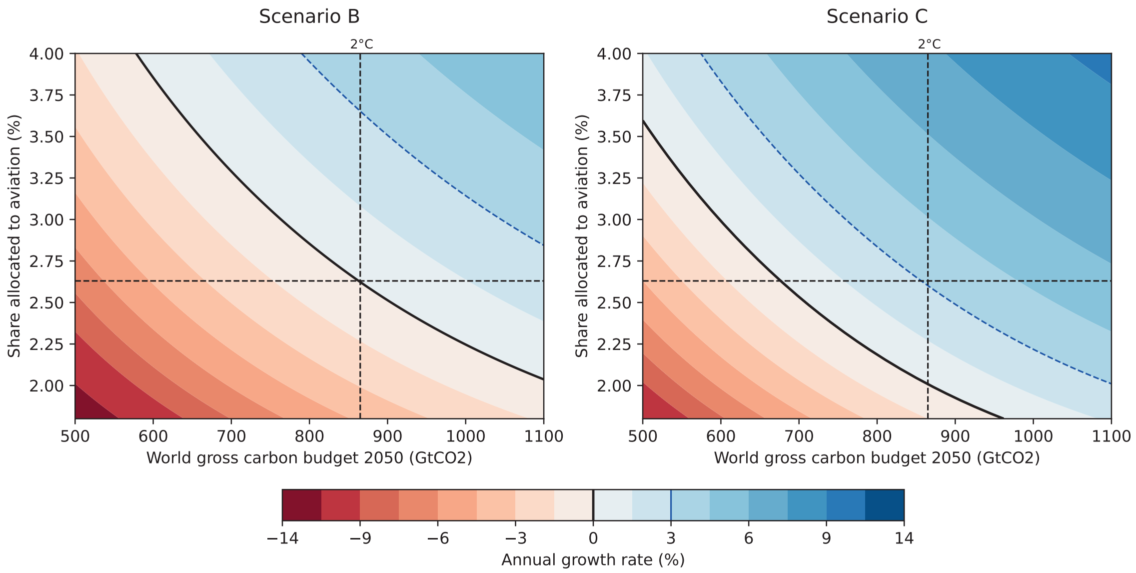

Figure 8: Maximum sustainable air traffic growth rates for the scenario B (left) and C (right) for different carbon budget allocations. Reading (right plot): for scenario C, a global carbon budget of 860 $GtCO_2$ corresponding to climate target of +2°C and a share allocated to aviation of 2.6%, the maximum sustainable air traffic growth rate is 3%.

Limitations on deployment speed and energy availability *[sections 6.4, 9.4.1, 9.4.3]*

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 start 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.

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. 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.

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Short-term effects *[section 2.3]*

Non-CO_2 effects mitigation is possible in the short-term because they are short-lived, a characteristic noticeable in *figure 9*: 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 this is the case in 2009, the climate impact of aviation also decreases, while the impact due to CO_2 effects does not decrease but increases less rapidly.

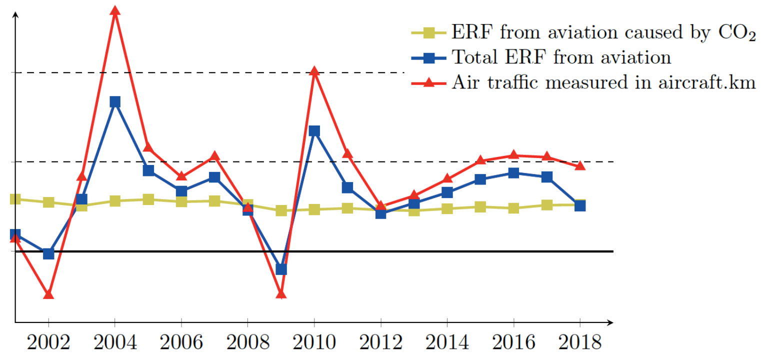

Figure 9 : Annual variation rate of ERF from aviation and air traffic. Reading: in 2010, the total ERF from aviation increased by 6.7%, the ERF from aviation due to CO_2 effects only by 2.3% and the air traffic (measured in aircraft-kilometre) by 10%.

Levers to mitigate non-CO_2 effects *[chapitre 7]*

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 jet fuels are different from those of fossil kerosene. Thus, these alternative jet 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%. This assessment needs to be further investigated and consolidated, especially for the contrails.

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 flights. Indeed, only a small fraction of flights are responsible for the majority of contrail formation and recent studies suggest that between 2% and 12% of flights are responsible for 80% of the radiative forcing induced by contrails. 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%.

Promising strategies *[section 9.4.2]*

Presently, these strategies seem promising for significantly and rapidly reducing non-CO_2 effects. Their widespread use would rapidly limit or even reduce (compared to 2018) the global warming caused by aviation. They therefore represent a major lever for achieving the objectives of the Paris Agreement in terms of temperature. Nevertheless, more investigations are needed to confirm these recent scientific results and to develop deployment scenarios. However, these solutions cannot replace measures to reduce CO_2 emissions, which have the greatest long-term impact on climate change.

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ISAE-SUPAERO

10, avenue E. Belin - BP 54032
31055 Toulouse CEDEX 4 - France

33 (0)5 61 33 80 80

www.isae-supaero.fr

Institut Supérieur de l'Aéronautique et de l'Espace