ISAE–SUPAERO

AVIATION AND CLIMATE
A LITERATURE REVIEW

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Foreword

We would like to express our thanks to the members of the school board, especially Director General Olivier Lesbre and the vice-director at the time, Marie-Hélène Baroux, for their support and trust throughout this project. Marie-Hélène Baroux enthusiastically welcomed our proposal to write this document during a meeting in summer 2020, which enabled us to begin this collective bibliographical work.

We would also like to thank Grégoire Casalis and Laurent Joly, director and vice-director of research and educational resources respectively, for having led the editorial committee set up to ensure the scientific integrity of this document. This document thus went through a specific three-phase peer review process, during which the document was submitted to ISAE-SUPAERO colleagues and to independent researchers for critical review.

A very early version of this document was proofread by our colleagues at ISAE-SUPAERO Sandrine Berger, Pierre-Marie Guineheuc, Florent Grotto and Aleksandar Joksimovic at the beginning of 2021. Their feedback enabled us to finalise a more complete first version, which was then read by our other colleagues Nicolas Binder, Valérie Budinger–Pommier, Grégoire Casalis, Alain Haït, Joël Jézégou, Frédéric Lachaud, Olivier Lesbre, Jean-Marc Moschetta and Angélique Rissons. We were then able to improve the document structure and its readability, and to send a completed version to seven independent peer reviewers with skills covering the range of subjects addressed. The reviewers were Olivier Boucher (IPSL), Philippe Novelli (ONERA), David Salas (CNRM), Bruno Savard (Polytechnique Montréal), Laurent Terray (CERFACS), Étienne Terrenoire (ONERA) and Xavier Vancassel (ONERA). Despite the extensive reviews, any remaining errors are the full responsibility of the authors.

Our sincere thanks go out to all the reviewers, both internal and independent, for their constructive comments which made it possible to significantly improve the overall quality of the document, in both substance and form. We extend our special thanks to Laurent Terray for having provided us with the sources for figure 2.10 from the IPCC Group I Sixth Assessment Report, which we used in chapter 2 to discuss the climate impact of aviation in detail. We also thank Xavier Vancassel for his help in clarifying the process of contrail formation in section 2.1.2.

Acronyms

ACARE	Advisory Council for Aviation Research and Innovation in Europe
AEA	All Electric Aircraft
AFOLU	Agriculture, Forestry and Land Use
AJF	Alternative Jet Fuel
ATAG	Air Transport Action Group
ATM	Air Traffic Management
BECCS	Bioenergy with Carbon Capture and Storage
BLI	Boundary Layer Ingestion
BtL	Biomass-to-Liquid
CAST	Climate and Aviation - Sustainable Trajectories
CEF	CORSIA Eligible Fuels
COP	Conference Of Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CROR	Contra-Rotating Open Rotor
DAC	Direct Air Capture
DLUC	Direct Land Use Change
EASA	European Union Aviation Safety Agency
EEA	European Economic Area
EGTS	Electric Green Taxiing System
EMC	ElectroMagnetic Compatibility
ERF	Effective Radiative Forcing
EU-ETS	European Union - Emissions Trading System
EWIS	Electrical Wiring Interconnection System
FOLU	Forestry and Land Use
FRL	Fuel Readiness Level
FT	Fischer–Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEFA	Hydroprocessed Esters and Fatty Acids
HVO	Hydrotreated Vegetable Oils
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization

ICCT	International Council on Clean Transportation
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
LHV	Lower Heating Value
LULUCF	Land Use, Land-Use Change and Forestry
MEA	More Electric Aircraft
NDC	Nationally Determined Contributions
PtL	Power-to-Liquid
RF	Radiative Forcing
SAF	Sustainable Aviation Fuels
TRL	Technology Readiness Level
UHBR	Ultra-High Bypass Ratio
UN	United Nations

Contents

Part I

Introduction

Positioning of the report

A polarisation of the debate around the air sector...

As of 2021, the six years between 2015 and 2020 were the warmest six years on record, 2020 being one of the three warmest along with 2016 and 2019[a]. It is not a random coincidence, but an obvious sign of global warming. The decade ending in 2020 was 1.2 °C warmer than the period 1850–1900. Whereas the reality of climate change and its anthropogenic origin[b] are gradually impressing on civil society, the public debate is becoming increasingly polarised around the aviation sector.

On the one hand, aviation is coming under fire from increasingly sharp criticism. In France, we can for example mention the march on the airports organised on the 3rd of October 2020, the first public demonstration specifically targeting airports; or the opposition of part of civil society to airport construction or extension projects, which the Citizens Convention for Climate has proposed to ban[c]. Criticism also stems from the aeronautical sector directly, as evidenced by the recent creation of two employee collectives, Aéro-Décarbo[d] and ICARE, which both aim to contribute to the debate on aeronautics and aviation in the context of climate change. This movement is not specific to France, such as the opposition to the extension of Heathrow airport or the *flygskam* movement born in Sweden and which quickly spread to the rest of the world. One constant criticism is to point out the responsibility of the aviation sector in global warming and to demand that the traffic it generates be controlled so as to make it compatible with the Paris Agreement.

On the other hand, the aeronautical industry spotlights the positive ecological impact of aircraft where they prevent the construction of heavy infrastruc-

[a] 2020 Was One of Three Warmest Years on Record, UNCC, 14th of January 2021.

[b] The adjective anthropogenic qualifies any phenomenon likely to be a consequence of the presence or action of human beings.

[c] One can think of the airport project at Notre-Dame-des-Landes, but also to the recent decision by the Government of France to abandon the extension project of Roissy airport: Jugé "obsolète", le projet de nouveau terminal à l'aéroport de Roissy abandonné par le gouvernement, Le Monde, 11th of February 2021.

[d] This collective of ISAE-SUPAERO alumni and employees from the aeronautical sector was founded under the name Supaéro-Décarbo before it took its current name. In 2020 they published a report together with the think tank The Shift Project on the future of aviation.

tures (especially tunnels) or decrease the footprint, thus protecting biodiversity, along with the important contribution of the aviation sector to global peace and global economy. The aviation sector admits its impact on climate change but promises technological solutions which can be used to make air traffic sustainable. Alexandre de Juniac, Director General of the IATA[a], confirms that "[stopping or significantly reducing flights] would have serious consequences for people, jobs and economies around the world. It would be a step back towards an isolated, smaller, poorer and more restricted society. Let us work together to make aviation sustainable. The problem is the CO_2. We can do something significant to reduce it and we are doing it."[b] This ambition can be seen through numerous industrial programmes, sometimes in partnership with the public authorities, aiming to develop low-carbon aviation. At European level, the partnership Clean Aviation aims to define a road map to achieve zero net emissions by 2050[c]. In the same way, 2021 saw the implementation, under the aegis of the ICAO,[d] of CORSIA, a carbon offsetting and reduction scheme for international aviation. Numerous technological and operational innovations are also planned to attenuate the climate impact of the aviation sector. At the end of 2020, Airbus unveiled its ZEROe plan which aims to develop hydrogen-powered aircraft by 2030–2035[e], while Boeing aims to operate its commercial flights using 100 % renewable fuels[f].

. . . which concerns ISAE-SUPAERO

ISAE-SUPAERO is deeply concerned by these debates which call the Institute to declare its position for several reasons. First of all, the Institute has demonstrated its long-standing ambition to provide technological solutions to the major challenges of aviation. Since its creation, students from the 1910 and 1913 year group at the École Supérieure d'Aéronautique (forefather of ISAE-SUPAERO) thus contributed to the development of the Coanda turbine and the Éclair propeller of Bloch–Dassault. This culture has been maintained to this day, ISAE-SUPAERO having recently participated in a number of innovative aerospace programmes such as the Caravelle, Concorde, Ariane, Rafale and A380 programmes, . . . Responding to challenges is thus part of the culture of the institution, which is currently contributing to researching technological solutions to the global warming problem. One can mention for example the Mermoz Drone project[g] which aims to participate in the development of disruptive technologies for low-carbon aviation via hydrogen technology, or even the three

[a] The International Air Transport Association, IATA, founded in 1945, is an international commercial organisation of airline companies and a lobby. In 2016, it counted 290 companies representing around 82 % of global passenger traffic (source: Wikipedia, article IATA, consulted on the 17th of February 2022).

[b] Working Towards Ambitious Targets, IATA, consulted on the 21st of February 2021.

[c] Clean Aviation, consulted on the 10th of May 2021.

[d] The International Civil Aviation Organization, ICAO, is a UN agency created in 1944 by the Chicago Convention and which participates in the development of policies and standards that enable the standardisation of international air transport.

[e] ZEROe – Towards the world's first zero-emission commercial aircraft, Airbus, consulted on the 3rd of March 2021.

[f] Boeing opte pour le carburant 100 % renouvelable, IE portal, the 26th of January 2021.

[g] More details about the Mermoz Drone project can be found on the web page dedicated to the project.

industrial chairs with Airbus, Daher and Safran oriented towards innovative aircraft architectures and propulsion systems[a].

Furthermore, the current institutional, industrial and social context is driving the development of research aiming to reduce the climate impact of aviation. The European Commission has launched a new research funding programme, Horizon Europe, one of the four pillars of which is to help "answer global concerns, including sustainable development objectives"[b] (which include the climate). It has also set up several public-private partnerships, especially the Clean Sky programme which aims to reduce the environmental impact of aviation, meet society's needs and ensure aeronautical leadership in Europe[c], the fuel and hydrogen cells programme whose objective is to facilitate the introduction of these technologies on the European market[d] or even the SESAR programme which aims at improving air traffic management[e].

Finally, a growing proportion of ISAE-SUPAERO staff and students feel the need to fully commit on these issues. Numerous initiatives are therefore emerging. Within the research scientist community, there is Labos 1.5 initiative, a collective created in March 2019 and which comprises now more than 500 members. Its aim is "to bring the entire French research community towards a transformation process based on the reduction of its environmental footprint"[f]. Among the students, 700 students from the aeronautical sector, 335 of which from ISAE-SUPAERO, wrote a column in the newspaper Le Monde in May 2020 to plead in favour of a reduction in air traffic[g]. This reflects a rise in ecological awareness, particularly among the younger generations who are worried about their future, and is part of wider student movement, illustrated for instance by the student COP[h], the student manifesto for ecological awakening[i] or the recent open letter from HEC students for a "green" dean[j], which aims to make environmental issues a core subject in training programmes. To be able to continue to attract excellent students therefore requires taking these considerations into account, and the training courses within our Institute have indeed started to evolve in this direction.

[a] Les chaires – Fondation ISAE-SUPAERO, consulted on the 10th of May 2021.

[b] Présentation du programme Horizon Europe, consulted on the 8th of February 2021.

[c] History | Clean Sky, consulted on the 10th of May 2021.

[d] Mission & Objectives, consulted on 10th of May 2021.

[e] SESAR Joint Undertaking, consulted on 10th of May 2021.

[f] Labos 1.5, consulted on 8th of February 2021.

[g] Aéronautique: « La transition écologique impose une profonde transformation de notre industrie », Le Monde, 29th of May 2020.

[h] Convention pour la Transition Écologique des Établissements du Supérieur, accessed on the 4th of March 2022.

[i] Manifeste étudiant pour un réveil écologique, consulted on the 4th of March 2022.

[j] Pascal Galinier, Les étudiants de HEC veulent un patron « vert » pour leur école, Le Monde, 13th of January 2021.

Report content

Objectives

Will technological innovations be sufficient to make aviation sustainable? Will we have enough energy resources to enable the transition for the entire fleet? What would be a sustainable level of air traffic in the future? These questions are carried through the public debates and their answers underpin the positioning of the various stakeholders on this subject: Alexandre de Juniac claims for decarbonisation of planes while Stay Grounded[a] retorts that planes should stay on the ground.

While these questions have motivated the writing of this report, its objective is not to take sides or to answer them, as the answers largely depend on societal choices and technological and on economic developments that cannot be predicted with certainty. However, **the aim of this report is to provide each individual, from our scientific standpoint, with the elements to build informed opinions on those issues, as objectively as possible**. Through this report, we also hope to stimulate debates within ISAE-SUPAERO and thus contribute to the emergence of a collective position on these crucial issues.

Methodology

To produce a document as objective as possible, we chose to rely almost exclusively on the available scientific literature. We used other sources only when the information we were looking for was not available. These other sources are numerous: indeed the links between aviation and climate have recently been discussed in many reports, from institutional actors (European Union or the ICAO for example), industry (especially IATA and ATAG[b]), private actors (especially consulting firms (McKinsey, Roland Berger or BL Evolution, to name but a few) and also from associations or members of civil society (for example Öko–Institut, ICCT, Transport & Environment, The Shift Project, Aero Decarbo, Biofuelwatch or Stay Grounded). These reports turned out to be precious sources of information which often enabled us to trace back to the un-

[a] Stay Grounded is an association campaigning for the reduction of airline transport and its negative impacts .

[b] The Air Transport Action Group, ATAG, is a coalition of industries, companies and organisations from the aviation sector. The IATA is actually one of its members.

derlying academic source. As a last resort, and where that was not possible, we cited these reports directly.

Working on the climate requires using figures which may vary from one source to another, as for example evaluation of greenhouse gas (GHG) emissions, and which are subject to more or less significant uncertainties. Concerning the sources, we chose to use as much as possible data cited in the Intergovernmental Panel on Climate Change (IPPC) reports. IPCC is an intergovernmental body open to all UN member countries and which today gathers 195 members. It aims to "provide policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options"[a]. We used the IPCC Special Report 1.5 °C as basis to define which path would be compatible with the objective of the Paris Agreement in chapter 9. Concerning uncertainties, those related to the climate impact of aviation are given in chapter 2, but more general uncertainties (for example on greenhouse gas emissions or radiative forcing values) are not systematically stated for sake of clarity.

The IPCC does not publish new scientific results per se, but it rather summarises the knowledge available in the scientific literature, and provides assessment on the level of confidence. The IPCC's reports are divided into two categories:

- **assessment reports**: we specifically use the data from the fifth and sixth assessment reports (AR5 and AR6) published in 2013 and 2021 respectively;
- **special reports** focusing on more specific topics. In particular we took data from the Special Report on the impacts of global warming of 1.5 °C (referred to as Special Report 1.5 °C) published in 2018, which aims to describe possible paths limiting global warming to +1.5 °C and to analyse the differences between warming of +1.5 °C and +2 °C.

Scope

This document describes the climate impact of aviation, which is composed of CO_2 and non-CO_2 effects, both described in detail in chapter 2. It allows to study and evaluate the levers that can be activated to decrease this impact. Even if non-CO_2 effects currently dominate CO_2 effects, the focus is made essentially on CO_2 effects in this report as they have a long-term effect on the climate and the associated uncertainties are much weaker. The methodologies for studying them are also more robust. We can for example relate them to the notion of carbon budget in order to determine air traffic trajectories in line with the objectives of the Paris Agreement.

Global aviation is classically divided into three main sectors: commercial aviation (passenger and freight), military aviation and general or private aviation (business or leisure aviation, emergency aviation. . .). In the remainder of the report, we will mainly consider commercial aviation since it represents the major contribution to the climate impact of global aviation, see figure 1. In 2018, commercial aviation accounted for 88 % of CO_2 emissions from global aviation,

[a] GIEC, consulted on the 3rd of March 2021.

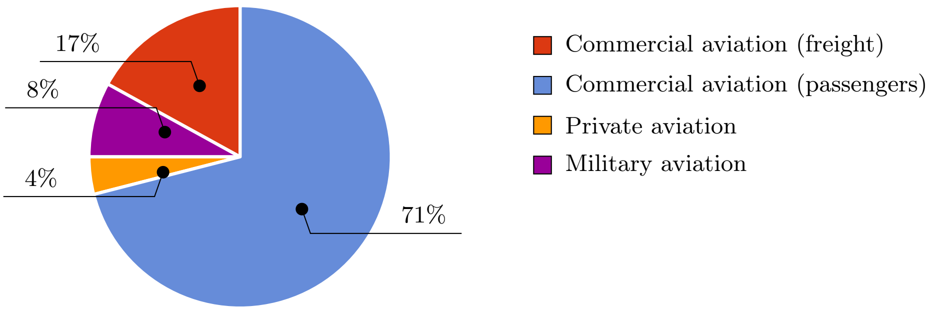

Figure 1: Distribution of CO_2 emissions from global aviation in 2018 according to the type of aviation. After figure 1 of Gössling and Humpe[1].

compared to 8% and 4% for military and private aviation, respectively[1]. Chapter 2 details the contribution of global aviation whereas the rest of the report focuses on commercial aviation. Commercial aviation includes planes following FAR25/CS25 standards, ranging from regional planes to long-haul planes. As a result, only the technical characteristics of these aircraft are discussed in this report. Therefore the different levers for improving efficiency discussed in section III are specific to this category of aircraft. To simplify, in the rest of the report and unless otherwise specified (mostly in chapter 2), "aviation" refers to commercial aviation. Moreover, we stress that we focus on the largest possible scope for commercial aviation, i.e., world traffic including domestic and international aviation, while other studies only consider restricted geographic scopes or only part of the total traffic, for instance the ICAO that typically focuses on international aviation.

This report mainly focuses on the technical aspects of the link between aviation and climate, and which partly constitute the core business of ISAE-SUPAERO. In particular, the technological levers specific to aviation that can be activated to reduce its CO_2 impacts are discussed together with their limits. In part III, the technical innovations considered to improve the efficiency of an aircraft, the new potential energy carriers to decarbonise aviation fuels and the possibilities for the mitigation of non-CO_2 effects are specifically detailed. Part IV will focus on the analysis of prospective scenarios compatible with the Paris Agreement.

Important subjects are however not very detailed or left out. Operational aspects are only rapidly addressed in chapter 7 where we discuss the levers considered for reducing non-CO_2 effects. This is a limitation to this report, which we plan to remedy in subsequent versions by discussing subjects such as trajectory optimisation, air traffic management, formation flights or the use of airport infrastructure energy. However, the impact of the improvement in operations is taken into account in the prospective scenarios analysis in chapter 9 by considering usual orders of magnitude. Furthermore, despite the importance of these issues for the transition of the aviation sector, we do not address the economic aspects (e.g., the impact of new energy vectors on the cost of a flight or the importance of aviation in the global economy), sociological aspects (e.g., who flies and why, which needs does aviation meet) or regulation aspects (e.g., the role of governance in the aviation sector in the fight against climate impacts).

Organisation

The document is organised into five main parts, the first of which ends here. The second part (chapters 1 to 3) provides an environmental assessment of the current situation. Chapter 1 first explains the main mechanisms of climate change. Chapter 2 then focuses more specifically on the climate impact of aviation and chapter 3 introduces a Kaya decomposition specific to aviation, the terms of which represent the relevant action levers for modelling the past and future evolution of its climate impact.

The third part (chapters 4 to 7) presents the technological levers that can be activated to reduce the climate impact of aviation. After an introduction into how an aircraft works in chapter 4, different technological levers are described in detail: efficiency improvement (chapter 5), fuel decarbonisation using new energy carriers (chapter 6) and measures to mitigate non-CO_2 effects (chapter 7).

The fourth part (chapters 8 and 9) offers and analyses different prospective scenarios for aviation by 2050. In chapter 8 we present general background information on the future trajectories for aviation, especially a specific methodology for evaluating the sustainability of the scenarios based on the carbon budget concept. Chapter 9 presents a state of the art of academic studies on future scenarios for aviation along with the trajectory analysis results using CAST, a tool developed at ISAE-SUPAERO.

The fifth part of the report concludes with an assessment of the situation and a presentation of broader discussions aiming to widen the debate beyond the energy/climate issues addressed in the report, while the sixth part includes all the appendices.

Part II

Environmental impact of aviation

This part aims to explain the climate impact of the aviation sector. Chapter 1 presents the main mechanisms of climate change and concludes with an introduction to the notion of planetary boundaries which is discussed further in the last part of the report. In chapter 2, a review of the scientific knowledge on the climate impact of aviation is presented. Finally, chapter 3 introduces a Kaya decomposition specific to aviation, each term of the decomposition representing a relevant action lever for modelling the past and future evolution of its climate impact.

Chapter 1

Global warming

1.1 A double scientific consensus

Concerning the climate, there is from now on a firmly established double scientific consensus. On the one hand the earth's climate is warming, and on the other hand, it is of anthropogenic origin.

1.1.1 The reality of global warming

Global warming is confirmed by numerous data: rise in the world's surface temperature as shown in figure 1.1 (+1.09 °C over the decade 2011-2020 compared to the period 1850-1900), rise in the average sea level (+20 cm between 1901 and 2018), acidification of oceans (drop in pH of 0.08 between 1950 and 2015) or even melting of the ice caps (40% decrease in the Arctic sea ice coverage level in September between 1979-1988 and 2010-2019), are examples of the average trends (in space and time) which point to global warming[MDZP+21]. Together, they leave no room for doubt and make the IPCC state that "global warming is unequivocal"[IPC14]. These observations are all the more convincing in that they are supported by a mechanistic explanation. Not only are scientists observing global warming, they are also able to explain the main underlying mechanisms. These mechanistic explanations have been validated using numerical models which simulate changes in past temperatures compatible with the observations[FMA+13], as in figure 1.1.

Between the periods 1850–1900 and 2011–2020, the average global temperature at the Earth's surface therefore increased by 1.09 °C. This value corresponds to a geographic average and conceals significant disparities since temperatures are warming almost twice as fast above land areas. Therefore the average temperature above land has increased by 1.59 °C within the same period, compared to an increase of 0.88 °C above the oceans[MDZP+21].

1.1.2 The anthropogenic cause of warming

The average global temperature is the result of an energy balance between the energy received from the Sun and the energy re-emitted by the Earth (see section 1.2). Numerous factors govern this balance. Some are not of human origin,

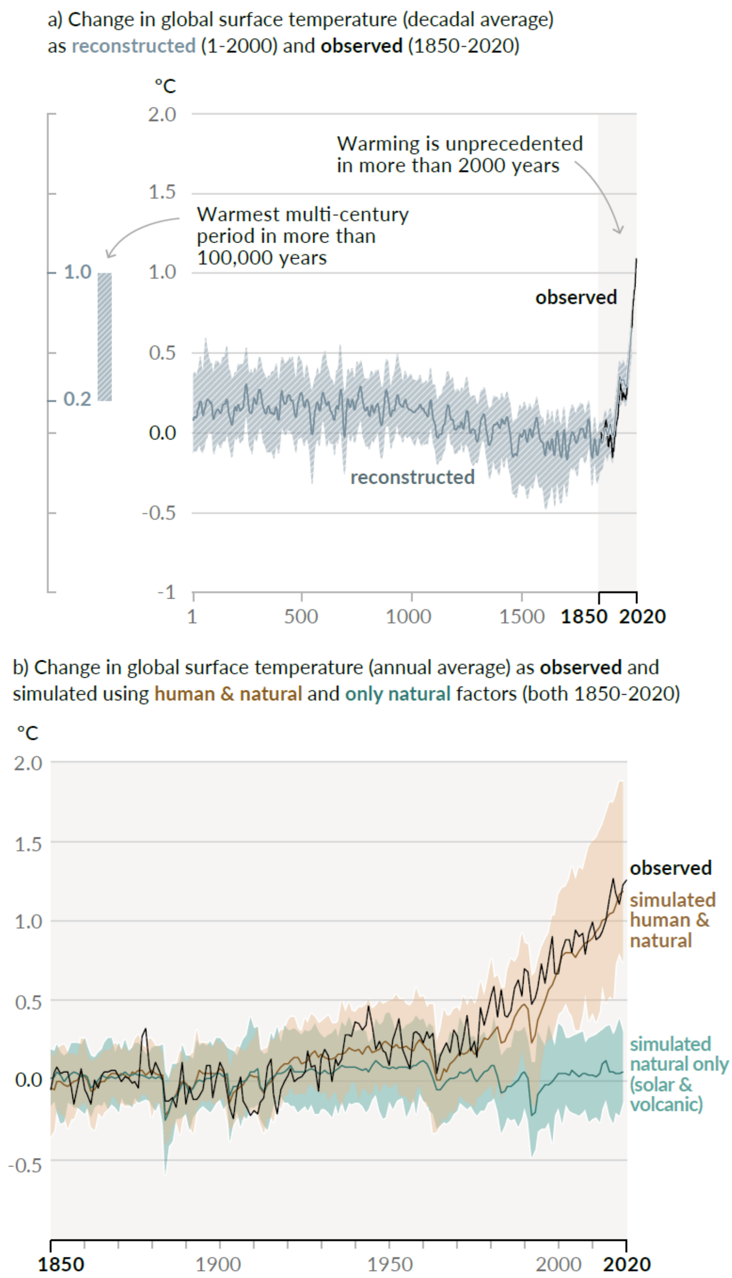

Figure 1.1: Rise in the world's surface temperature compared to the period 1850–1900. At the top, the global rise observed since 1850 (in black) and reconstructed from year 1 (in blue). At the bottom, the comparison with models, with or without anthropogenic effects. According to figure SPM.1 *Changes in global surface temperature relative to 1850-1900* on page 7 of the Summary for Policymakers of the IPCC Working Group I Sixth Assessment Report[MDZP+21].

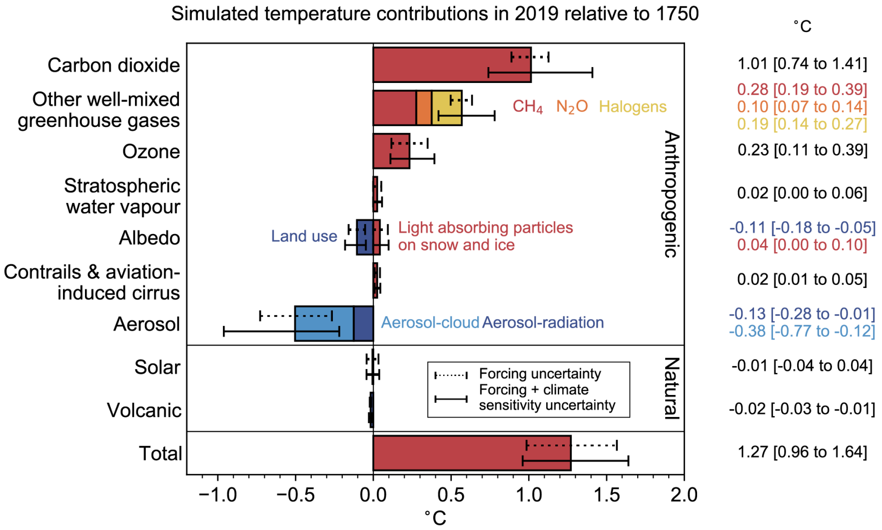

Figure 1.2: Contribution of various factors in terms of temperature simulated between 1750 and 2019. The anthropogenic contribution results in particular from greenhouse gases which increase temperatures, a rise partly compensated by other anthropogenic effects, mainly aerosols, which have an overall cooling effect. The other causes, especially natural causes, represent an insignificant contribution. According to figure 7.7 in chapter 7 of the IPCC Working Group I Sixth Assessment Report[FSA+21].

such as solar activity, volcanic eruptions or even changes in the Earth's orbit, while others are, such as fossil CO_2 emissions and anthropogenic aerosols or even deforestation and land use change.

Until the early 2000s, the debate was still ongoing among the scientific community on the relative importance of each of these contributing factors, and therefore of the human or non-human origin of global warming. For this reason, in its first assessment report published in 1990, the IPCC cautiously stated that "emissions resulting from human activity are substantially increasing atmospheric greenhouse gas concentrations", without directly making a link with past warming, and studied "how human activity was likely to change the global climate"[IPC10]. The question is now settled, the IPCC considering since its Third Assessment Report in 2001 that "most of the warming observed during the last 50 years is attributable to human activity"[IPC01]. In France, a debate took place at the Academy of Sciences in 2010 which concluded that the "increase [in global warming] is mainly due to the increase in CO_2 concentration in the atmosphere", in turn "unquestionably due to human activity"[PBSC10]. More recently, with the issue of its sixth assessment report in 2021, the IPCC concluded on an unequivocal influence of human activity on warming of the air, oceans and lands[MDZP+21], just like the correspondence between the observations and simulations in figure 1.1. Thus, human activity has increased the average surface temperature by +1.07 °C between the periods 1850–1900 and 2011–2020, against a measured increase of +1.09 °C. Figure 1.2 illustrates the contributions of the various natural and human factors to the warming observed and clearly shows that human factors are largely predominant.

1.2 The climate, the result of an energy balance subject to feedback effects

1.2.1 Radiative balance

The Sun, like any hot body, emits energy in the form of electromagnetic waves which travel through space and part of which reach the Earth, thus providing it with energy stored in the form of heat. The Earth, thus becoming a hot body, also re-emits energy, still in the form of electromagnetic waves. When the climate is in balance, the Earth's energy balance is null. The energy reaching Earth from the Sun is equal to the energy it re-emits, and this is what is called **radiation balance**. Today the Earth is in **radiation imbalance**: it is re-emitting less energy than it is receiving. The surplus energy is stored in the oceans for more than 90%. The remainder of this energy surplus contributes to warming the surfaces of the continents ($\sim 3\%$), melting the ice caps, sea ice and glaciers ($\sim 3\%$) and warming the atmosphere ($\sim 1\%$). The high inertia of the oceans in returning the effect of this accumulation of energy on the climate explains the long-term effects of radiation imbalance.

The quantity of energy reaching the Earth is described by the mean surface power density, given in watts per square metre, and written $\mathrm{W\,m^{-2}}$. This mean surface power density is $340\,\mathrm{W\,m^{-2}}$ which means that every second, three hundred and forty joules of energy reach each surface area of one square metre on average at the top of the Earth's atmosphere. This is both a temporal and spatial mean. At a given time, the surfaces not lit by the Sun do not receive any and even during daytime, the differences in the angle of incidence of the Sun's rays lead to differences according to latitude. Figure 1.3 describes what happens to those $340\,\mathrm{W\,m^{-2}}$ denoted by the incoming yellow arrow. Adding the two outgoing yellow and orange arrows suggests that less energy is leaving ($100+239=339\,\mathrm{W\,m^{-2}}$) than is arriving ($340\,\mathrm{W\,m^{-2}}$). Even if uncertainties weigh on each of the individual flux, it is certain that radiation imbalance (the *imbalance* part on the figure) is positive, *i.e.* the Earth is emitting less energy than it is receiving. This radiation imbalance is currently estimated at $0.7\,\mathrm{W\,m^{-2}}$[FSA+21]. To understand this imbalance, two main mechanisms come into play[a]: reflection of the Sun's rays (quantified by the **albedo**) and the **greenhouse effect**. We will also discuss **aerosols** which play an important role both on the albedo and the greenhouse effect.

1.2.2 Albedo

Out of the $340\,\mathrm{W\,m^{-2}}$ incident radiation, $100\,\mathrm{W\,m^{-2}}$ are directly reflected into space by the clouds, the atmosphere and the ground. This property of a surface to reflect is measured by a coefficient called the **albedo**. It is a dimensionless number between 0 and 1 which quantifies the proportion of energy reflected: the Earth's mean albedo is therefore around $100/340 \approx 0.3$. An albedo of 0 corresponds to a surface that lets through or absorbs all solar radiation reaching it, and an albedo of 1 to a surface that fully reflects it. Low clouds (cumulus or stratus) therefore have a relatively high albedo, potentially reaching 0.9 for

[a] It should be noted that the heat given off directly by human activity (*i.e.* by heating) is insignificant in this imbalance.

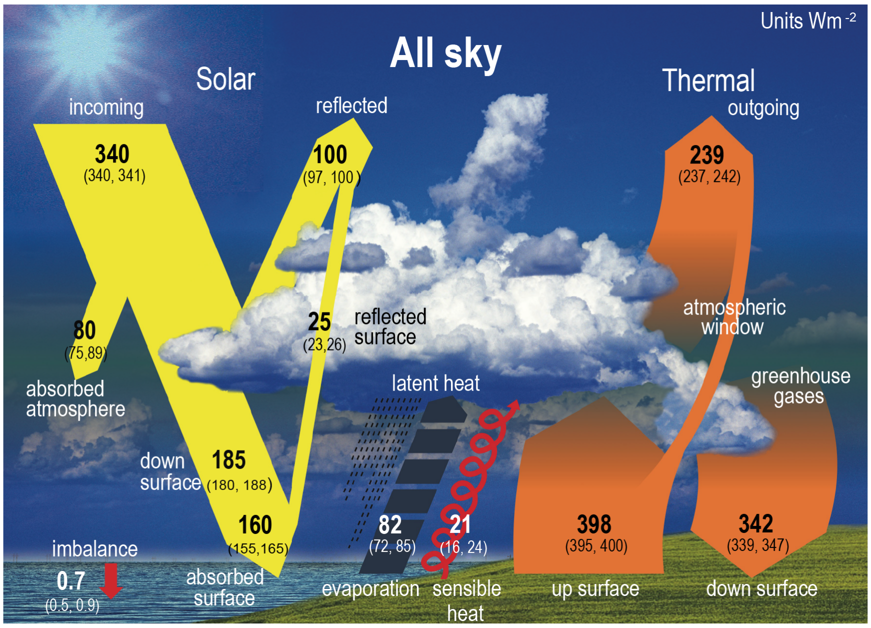

Figure 1.3: Earth's radiation balance: out of the 340 W m^{-2} which reach the Earth through solar radiation, 100 W m^{-2} are reflected directly (albedo), 239 W m^{-2} are re-emitted by the Earth in a different spectrum (thermal radiation) and 0.7 W m^{-2} are absorbed by the Earth, leading to its warming. The numbers in brackets in relation to the energy flow cover the range of values induced by the observation constraints. According to figure 7.7 in chapter 7 of the IPCC Working Group I Sixth Assessment Report[FSA+21].

Cumulonimbus (which effectively stop us seeing the Sun) whereas high altitude clouds (such as the cirrus induced by aircraft contrails) have a much lower albedo, typically between 0.2 and 0.4. Different elements of the Earth's surface have very different albedoes, for example fresh snow has an albedo of over 0.8 and water has an albedo of less than 0.1.

1.2.3 Greenhouse effect

The remaining quantity of energy, *i.e.* $340 - 100 = 240\,\mathrm{W\,m^{-2}}$, is therefore absorbed by the Earth (in the oceans, the biosphere, the cryosphere, the lithosphere and the atmosphere) in the form of heat, in turn dissipated in the form of electromagnetic waves. The emission spectrum of a hot body is governed by its temperature via Planck's law. The waves emitted by the Sun have wavelengths lying in between 0.2 µm and 3 µm, whereas the waves emitted by the Earth, a much cooler body, are found within the infra-red spectrum, with wavelengths between 3 µm and 70 µm.

However, certain gases of the atmosphere react to terrestrial but not solar wavelengths. They therefore "let through" incoming energy but absorb part of the energy re-emitted by the Earth which they convert into heat. These are **greenhouse gases**. Only gases made up of more than three atoms can absorb the waves emitted by the Earth in the infra-red spectrum. Therefore, nitrogen (N_2), oxygen (O_2) and argon (Ar), which constitute more than 99.9% of the Earth's atmosphere, are not greenhouse gases. Among the less than 0.1% remaining gases, we find water vapour especially (H_2O) which is the main natural greenhouse gas, ozone (O_3), carbon dioxide (CO_2) which is the main greenhouse gas of anthropogenic origin, as well as methane (CH_4) and nitrous oxide (N_2O).

In order to maintain the Earth system's temperature balance, the stronger the greenhouse gas effect, the higher the Earth's temperature must be to enable the greenhouse gases to "let through" enough outgoing energy to compensate the incoming energy. This explanation is a good description of what happens, especially for water vapour. Nevertheless, for carbon dioxide, there are a few finer details. In effect, absorption of infra-red radiation over the entire height of the atmosphere by carbon dioxide is almost maximum. Therefore, this absorption only slightly depends on a variation in CO_2 concentration, we say that *absorptivity is saturated*. In fact, a rise in CO_2 concentration only increases the greenhouse effect indirectly by increasing the*emission altitude*, see the highly educational article by Dufresne and Treiner for further details[2].

Different greenhouse gases have a more or less significant effect on the greenhouse effect and have different lifetimes. To compare them we usually use the concept of GWP (which stands for *global warming potential*) which converts greenhouse gas emissions into CO_2 equivalent by taking two factors into account, power and duration. This is referred to as CO_2 equivalent, written CO_2-eq. To convert greenhouse gas emissions into CO_2 equivalent, the GWP method determines the equivalence between the climate impact of an emission pulse of a ton of the gas considered and en emission pulse of a ton of CO_2. This calculation requires to specify a time horizon over which the climate impact is evaluated, and it is generally set at 100 years (see annex A for further details).

The greenhouse effect is therefore a natural phenomenon, essential to the Earth's habitability. If there were no greenhouse effect, the Earth's average temperature would be around -18 °C[a] compared to +15 °C today[2]. The problem is therefore not the greenhouse effect, but its reinforcement caused by greenhouse gas emissions of anthropogenic origin. Figure 1.4 illustrates the change in greenhouse gas emissions of anthropogenic origin which rose from 29 $GtCO_2$-eq in 1970 to 57 $GtCO_2$-eq in 2019. These emissions led to a rise in the atmospheric concentration of the three most important greenhouse gases of anthropogenic origin which are carbon dioxide, methane and nitrous oxide. Thus, carbon dioxide represented 0.028% of the atmospheric composition in 1750 and 0.040%[4b] in 2018, and it is this rise, which appears minor, which is the main cause of current global warming as we will see below.

[a]This value of −18 °C is obtained using the Earth's current albedo (0.3). However, removing the greenhouse effect implies removing water vapour at the origin of clouds which contribute to the albedo. If we calculate the Earth's temperature without greenhouse effect and without clouds (therefore with a lower albedo, of around 0.1), we would obtain an Earth temperature balance point of -2 °C.

[b]These low concentrations are usually given in parts per million, ppm: 1 ppm = 0.0001%. Expressed in this unit, atmospheric CO_2 concentration was estimated at 277 ppm in 1750 and 410 ppm in 2019[MDZP+21].

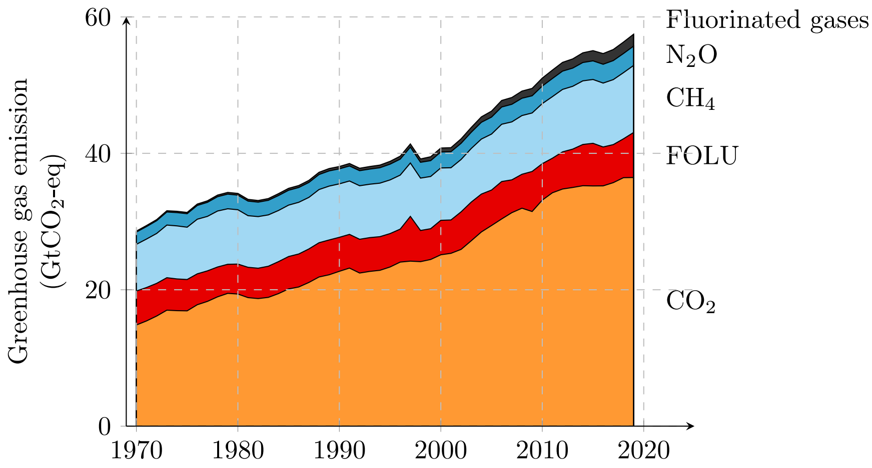

Figure 1.4: Change in greenhouse gas emissions between 1970 and 2019. FOLU is the acronym for *Forestry and Land Use*, and the values reported here correspond to the associated CO_2 emissions. Methane and nitrous oxide FOLU emissions are included in the categories CH_4 and N_2O. The data for CO_2 are taken from the Global Carbon Budget 2020[3] and the data for other greenhouse gases are courtesy of Olivier and Peters[OP20].

1.2.4 Aerosols

Aerosols are fine liquid or solid particles found in the atmosphere: soot, organic compounds, inorganic compounds (sulphates, ammonium compounds), salt crystals, terrigeneous dust[a], volcanic ash, etc.[5] It is of both natural origin (volcanic eruptions, sand storms) and anthropogenic origin (particles released during the incomplete combustion of hydrocarbons, mainly in the transport, industry and electricity production sectors), and it generally has a short lifetime. It has multiple climate impacts. On the one hand it reacts with solar radiation which it can disperse or absorb. Dispersion has a cooling effect since it helps increase the Earth's albedo, whereas absorption has a warming effect similar to the greenhouse effect. Among the aerosols of anthropogenic origin, there are for example sulphates and nitrates which have a purely dispersive effect, or even black carbon (soot) which absorbs solar radiation. As we will see below, aerosols have a globally cooling effect on the climate. Nevertheless, they also have harmful effects, on health especially[6–8]. Aerosols also interact in a complex manner with clouds[9]: they can change their chemical and physical composition and thus influence their radiative properties or even precipitations. Understanding aerosol-cloud interactions (especially via cloud water droplet size) is currently an important research topic and one which is not addressed in this report.

1.2.5 Feedback effects

Predicting the climate is an extremely difficult task due to **feedback effects** by which a cause leads to a consequence which in turn acts on the cause, either

[a] A terrigeneous compound derives from the erosion of land areas. Terrigeneous dust mainly comes from desert areas and is often called desert dust.

amplifying it (in this case it is called positive feedback) or attenuating it (in this case it is called negative feedback). Let us take the example of ice-albedo feedback. An increase in temperature (for example via the increase in greenhouse gas concentration) leads to melting of the ice caps and therefore a decrease in ice coverage which is then replaced by vegetation or water. However, the ice's albedo (*i.e.* its reflective property) is higher than that of vegetation and water. This reduced ice coverage therefore leads to a drop in the albedo which, as explained earlier, decreases the energy re-emitted by the Earth. Starting with warming, we end up with a phenomenon which accentuates it by adding to the radiation imbalance. Ice-albedo feedback is therefore an example of positive feedback. Numerous other feedback effects participate in determining the Earth's climate[10], in particular due to interactions between ocean and atmosphere, and make the consequences of a radiation imbalance extremely difficult to predict. It is precisely for this reason that we hear so much about the +1.5 °C or +2 °C threshold which we will discuss below. It is the threshold from which certain positive feedback effects may reach significant magnitude and therefore significantly increase uncertainty regarding the level of climate disruption. Beyond around +2 °C, the feedback loops induce very great uncertainty in climate disruption.

1.2.6 Radiative forcing

The elements presented above can be used to understand the main mechanisms at stake in the Earth's radiation balance. The instantaneous balance is governed by the albedo and the greenhouse effect, and the dynamics to explain the way in which the terrestrial climate system recovers from radiation imbalance is complex, due to feedback loops which involve phenomena occurring on different time scales.

As mentioned previously, the Earth's current radiation imbalance is $0.7\,\mathrm{W\,m^{-2}}$. A notion complementary to radiation imbalance is the notion of **radiative forcing**. Radiative forcing is the radiation imbalance which would exist if, all other things being equal, the Earth's surface (land + sea) and the troposphere were not adjusted to changes in forcing (greenhouse gas, albedo, aerosols, etc.). So radiation imbalance and radiative forcing differ in that, following a change in forcing, the former takes all adjustments of the climate system into account and the latter, none. In practice, it is an intermediate notion, called effective radiative forcing (ERF), which is calculated. Effective radiative forcing is calculated after having left atmospheric temperatures, water vapour and clouds to adjust, but leaving surface temperature or part of the surface conditions unchanged[a]. In the rest of this report and unless otherwise explicitly stated, the radiative forcing values reported are those of effective radiative forcing.

Figure 1.5 illustrates the change in ERF since 1750, year of reference considered to be the start of the industrial era and from which the Earth's climate system began to come out of its state of radiation balance. It considers all the terms which participate in radiative forcing, both the anthropogenic terms (especially greenhouse gases and aerosols) and natural terms (solar and volcanic activity). Certain effects increase radiative forcing, such as greenhouse gases or

[a]In the past, ERF was put forward to improve RF (*Radiative Forcing*) which was calculated taking fewer atmospheric adjustments into account, see box 8.1 in chapter 8 of the IPCC's fifth report[MSB+13].

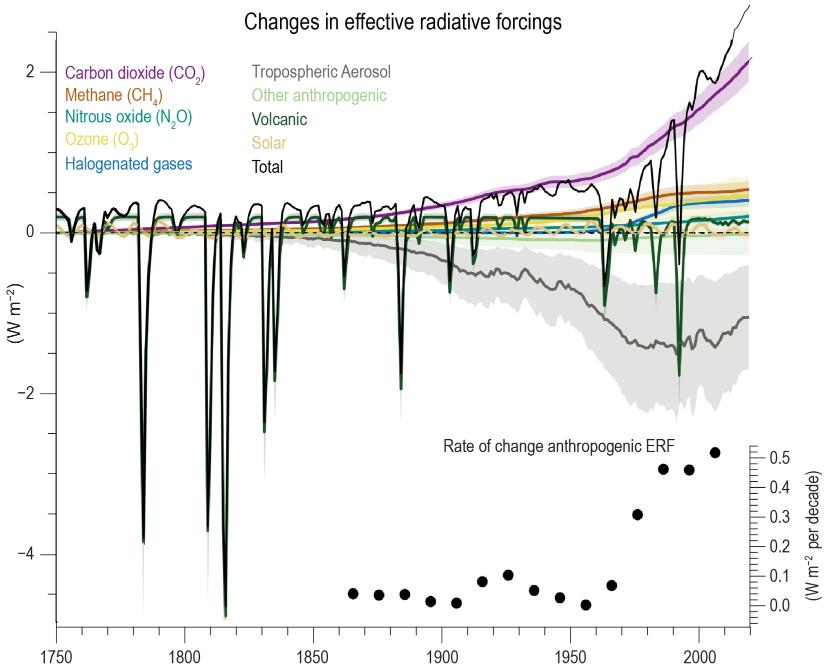

Figure 1.5: Change in radiative forcing between 1750 and 2019 according to the various mechanisms of the climate system. The shaded areas represent the uncertainties (90% confidence intervals), and show that aerosols represent the greatest source of uncertainty. According to figure 2.10 in chapter 2 of the IPCC Working Group I Sixth Assessment Report[GTA+21].

the tropospheric ozone, whereas others decrease it, such as aerosols, the increase in albedo following land use change or the stratospheric ozone.

Figure 1.6 illustrates the situation in 2019: this figure is therefore the counterpart of figure 1.2 but in terms of radiative forcing and not temperature. One can see that in 2019, radiative forcing had a global value of 2.72 $W\,m^{-2}$ and that CO_2 emissions are the main cause. In an informal manner, we can interpret this figure as follows: if all human activity which took place between 1750 and 2019 had taken place in an instant in 1750, then the Earth's climate system would have gone from a state of radiation balance to a state of radiation imbalance, whose value is 2.72 $W\,m^{-2}$.

However, we previously saw that terrestrial radiation imbalance is 0.7 $W\,m^{-2}$. This means that since 1750, the climate system has already adjusted to the 2.72 $W\,m^{-2}$ radiative forcing. The Earth has been in radiation imbalance since at least 1970 and between 1971 and 2018 accumulated around 434 900 EJ of energy. A small part (1%) of this surplus energy was stored in the atmosphere and led to part of the rise in the temperature of the planet's surface. The vast majority of this surplus energy (91%) accumulated in the oceans, effectively illustrating their importance in the Earth's climate system[GTA+21]. The slow rate of diffusion of heat from the upper ocean layers to the deep layers partly explains the inertia of the terrestrial climate system.

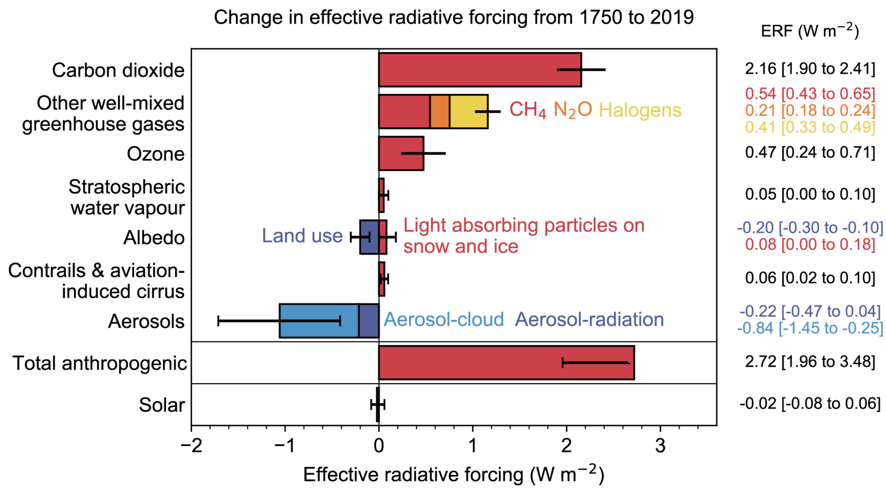

Figure 1.6: Change in ERF from 1750 and 2019. The net anthropogenic effect on radiative forcing takes a value of $2.72\,\mathrm{W\,m^{-2}}$. This positive radiative forcing is especially due to greenhouse gases such as CO_2, partly counterbalanced by negative radiative forcing generated by aerosols. According to figure 7.6 in chapter 7 of the IPCC Working Group I Sixth Assessment Report[FSA+21].

1.3 Attenuating global warming

1.3.1 Consequences of global warming

The energy received, the albedo and greenhouse gas concentration therefore determine the Earth's balance via complex interactions. If, all other things being equal, greenhouse gas concentration increases as is currently the case, then the Earth's temperature must also increase mechanically to restore the radiation balance. This equilibrium can take centuries to set in especially due to the high thermal inertia of the oceans. The climate data recorded since the middle of the 20$^{\mathrm{th}}$ century can be used to precisely determine the quantity of greenhouse gas emitted into the atmosphere (see figure 1.4) or even the past change in temperatures (see figure 1.7). If the current path is maintained (scenario often called a trend or *business-as-usual* scenario), especially if the rate of increase in emissions remains constant, climate models predict an average rise in global temperatures up to +3.3 °C to +5.7 °C by 2100 (median value of +4.4 °C). This scenario and four others, from the IPCC Sixth Assessment Report[MDZP+21], are presented in figure 1.7.

The human specie has never known such a hot climate. One needs to go back several million years to find comparable climate conditions whereas Homo sapiens only appeared around 300 000 years. The current atmospheric CO_2 concentration (410 ppm in 2019[MDZP+21]) has not been seen for 3 million years.

This rise in temperatures could have different major consequences, depending on its intensity. Figure 1.8 summarises the risks on the main areas of concern such as the threat to ecosystems or extreme weather events. The greater the rise in temperature, the higher the risks, and major consequences can be already

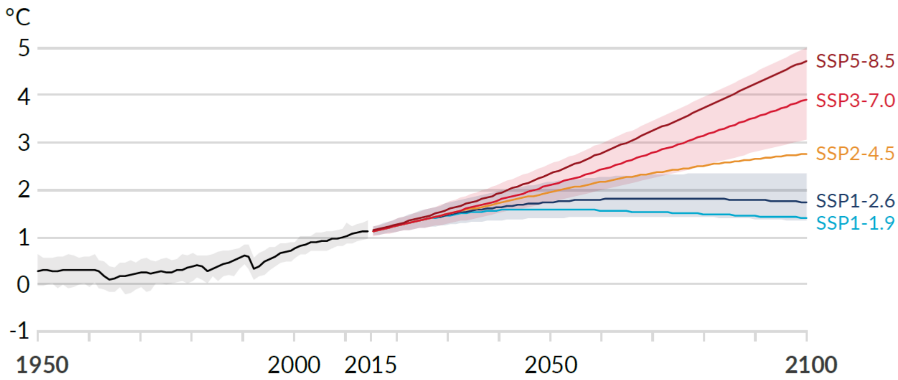

Figure 1.7: Change in the world's average temperature compared to the period 1850–1900. From 1950 to 2015, the figure shows the observed temperature (black curve) with its range of uncertainties (grey area). From 2015 to 2100, this curve continues for a selection of five of the IPCC's latest scenarios. For scenarios SSP1-2.6 and SSP3-7.0, the *very likely* brackets are shown. According to figure SPM.8 *Human activities affect all the major climate system components, with some responding over decades and others over centuries* on page 29 of the summary for policymakers of the IPCC Working Group I Sixth Assessment Report[MDZP+21].

seen from +1.5 °C. The consequences of global warming are many and varied. For example, one can mention melting of the ice caps, disappearance of the coral reef from warm waters, rise in sea levels, decrease in agricultural yields, water stress, heat waves, changes in ecosystems and impacts on biodiversity. For example, at +4 °C recurrent heat waves associated with very high levels of humidity could make large part of the Earth inhabitable for humankind[11].

Finally, it is interesting to mention certain specific features. The non-linearity of the Earth's climate system implies for instance that the consequences may be a lot more severe at +2 °C than at +1.5 °C[IPC18], and even more so for temperatures higher than +2 °C. In addition, the +2 °C threshold is generally taken as the threshold from which runaway effects may take hold, and thus cause the Earth's climate system to leave its historical equilibrium state[12] (see section 1.2.5).

1.3.2 The Paris Agreement

This alarming scientific finding is at the centre of the Paris Agreement, signed in 2015 by 196 countries at the COP21 in order to contend with the threat of climate change. The undertaking from the signing parties of this agreement is set out in article 2 to[a]

> "[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 above pre-industrial levels."

The objective of the Paris Agreement is therefore to attempt to limit global warming to +1.5 °C. The Paris Agreement also specifies that the efforts of all

[a] Paris Agreement, UNFCCC, 2015.

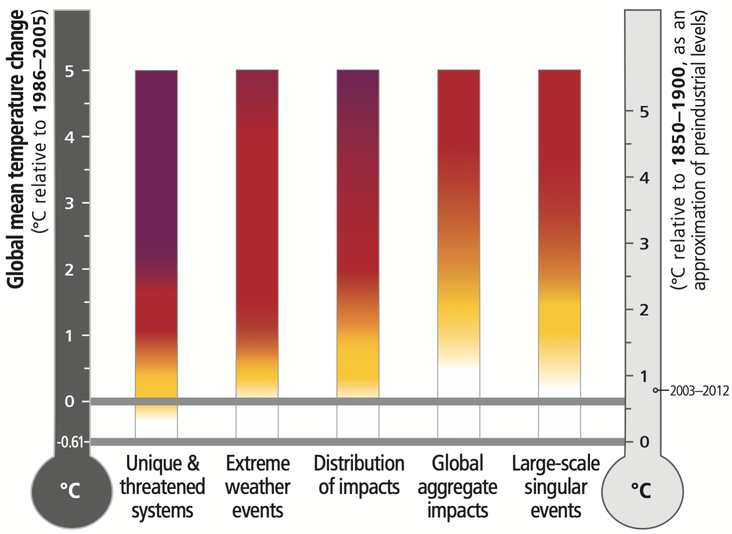

Figure 1.8: Presentation of the main risks related to global warming for the five main areas of concern: threat to ecological and human systems, extreme weather events, disproportionate distribution of impacts, global aggregate impacts and large scale singular events. The more the temperature rises, the greater the risks. The risk scale is shown under the graph. According to figure 1 from Assessment Box SPM.1 from the summary for policymakers of the IPCC Working Group II Fifth Assessment Report[FBD+14].

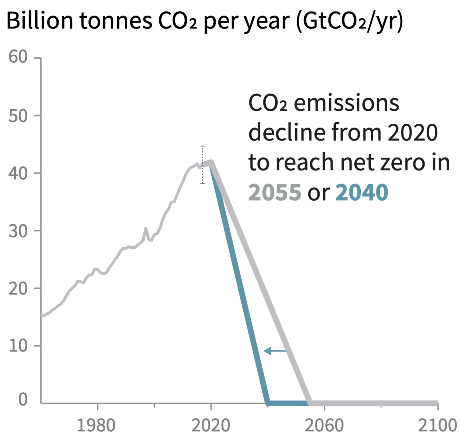

Figure 1.9: Schematic pathway of net CO_2 emissions for reducing warming to +1.5 °C, with a higher probability of success for the blue curve than for the grey curve. To date, global CO_2 emissions have not yet begun to decrease. According to figure SPM.1 from the summary for policymakers of the IPCC Special Report 1.5 °C[IPC18].

countries will be assessed every five years, and that they must achieve zero net emissions in the second half of the 21st century. To do that, CO_2 emissions must be massively reduced from now on as shown in figure 1.9, to reach net zero, *i.e.* a balance between anthropogenic CO_2 emissions and sinks. Article 4 of the Paris Agreement also explicitly aims to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". To reach such a goal, CO_2 emissions will have to continue to decrease at a pace comparable to the drop in emissions in 2020 following the Covid-19 crisis[a], see section 8.1 for more details.

Despite the enthusiasm that this historic agreement brought about, several studies have shown that the efforts made so far remain insufficient. On the one hand, the undertakings correspond to a path of 3 °C to 4 °C[13, 14, UNE20] and on the other hand, these undertakings are not always upheld by the States[b]. Therefore, whereas emissions should have to decrease massively from now on in order to comply with the objective of the Paris Agreement as illustrated in the diagram in figure 1.9, CO_2 emissions had still not begun to decrease before the health crisis, increasing from 41.4 $GtCO_2$ in 2015 to 43.0 $GtCO_2$ in 2019[3].

Limiting global warming to +1.5 °C remains physically possible. If all greenhouse gas and aerosol emissions would stop today, temperatures, after having continued to increase for at most a few years (especially due to the disappearance of aerosols and therefore cessation of their cooling effect), would eventually rapidly decrease before stabilising[ADS+18]. Even if this scenario is physically possible, immediately and completely stopping greenhouse gas emissions is of course unrealistic: there is a socio-economic structural inertia in implementing attenuation measures. For this reason, in all the more realistic scenarios studied by the IPCC, the temperatures in the next 10 to 20 years are already largely determined regardless of the path taken[KPA+13], as it can be seen in figure 1.7. In other words, the actions taken today will only begin to have a significant effect in at least two decades[c].

1.3.3 Carbon budget

The carbon budget is a useful concept for the fight against global warming. It is the maximum cumulative quantity of CO_2 which can be emitted into the atmosphere before reaching zero net emissions[d] while reducing global warming to below a given temperature. The emissions are calculated net, therefore minus anthropogenic carbon sinks (see chapter 8), and compared to the pre-industrial era. CO_2 concentration and temperature are, to a large extent, linked by an almost linear relationship. It is estimated that were atmospheric CO_2 concentration to double, there would be a temperature increase of between +2.3 °C and +4.7 °C[15] (90% confidence interval). The IPCC considers that, from 2020, no more than 500 $GtCO_2$ should be emitted to limit warming to +1.5 °C[MDZP+21]. This value is the median value corresponding to the current state of knowledge

[a]This does not mean that emissions have to be reduced in a similar manner.

[b]On this subject, see how the French State was convicted on the 14th of January 2021 and ordered to pay a symbolic one Euro fine, during the "Affair of the Century" trial, for climate inaction.

[c]See also for example the TFE.8 of the technical summary to the IPCC Fifth Assessment Report[SQP+13].

[d]Zero net emissions means that the quantity of CO_2 emitted by human activity is equal to the quantity of CO_2 captured by anthropogenic carbon sinks.

about uncertainties on the climate system, and it is often interpreted and presented as the budget with a fifty percent chance of limiting warming to +1.5 °C. In other words, to have a fifty percent chance of limiting warming to +1.5 °C, humanity must not emit more than 500 $GtCO_2$ before reaching net zero emissions. As an indication, this budget corresponds to 12 years of emissions at the current pace (*i.e.* 43.0 $GtCO_2$ in 2019[4]).

The notion of carbon budget is essential since it shows that cumulative emissions matter. It is not just a question of reaching net zero, the trajectory that leads to a potential net zero situation matters and needs to respect a certain total carbon budget. The +1.5 °C carbon budget is very low and indicates to many scientists that it is a climate target that will be very hard to reach. For example, the budget will be fully consumed by existing infrastructures alone (power plants, cars, etc.) if they are used normally until their expected end of life[16]. The carbon budget for +2 °C amounts to 1350 $GtCO_2$[MDZP+21], which offers more room for manoeuvre as it will be illustrated in chapter 9.

1.4 Climate and energy

1.4.1 Energy transition

As it can be seen in figure 1.4, CO_2 emissions represent 65% of anthropogenic greenhouse gas emissions in 2019. These emissions are caused by various industrial processes (especially steel mills and cement works) but also and above all by the combustion of fossil fuels (petrol, coal and natural gas), which represented almost 90% of CO_2 emissions[MGS+18]. Complying with the carbon budget to limit warming to +1.5 °C or +2 °C is therefore mainly a question of reducing energy-related emissions. There are three levers which can be activated to this end:

- **efficiency**, where a given usage is performed using less energy;
- **decarbonisation**, where an energy vector is replaced by another one, less CO_2-emitting;
- **sobriety**, where usage is reduced.

Doing without fossil fuels is an enormous challenge which a quick look back over history can help us understand. Indeed, in figure 1.10 shows that in the past, one energy source came after the next and that each energy source was increasingly exploited. In particular a clear acceleration from the middle of the 20^{th} century is observed, a phenomenon which the scientific community calls the "great acceleration"[17].

According to the International Energy Agency (IEA), in 2019, global energy production reached 598 EJ, 81.3% of which was of fossil origin[IEA20c]. These 598 EJ primary energy are rarely usable as is. It is usually necessary to extract the energy or produce it, or even convert it (for example, refine it in the case of petroleum or liquefy it in the case of hydrogen produced in gaseous form) and then transport it to be able to use it on a daily basis as final energy. These steps require energy and induce losses, for example during transport (gas leaks in pipelines or Joule effect in electric cables) or due to conversion efficiencies.

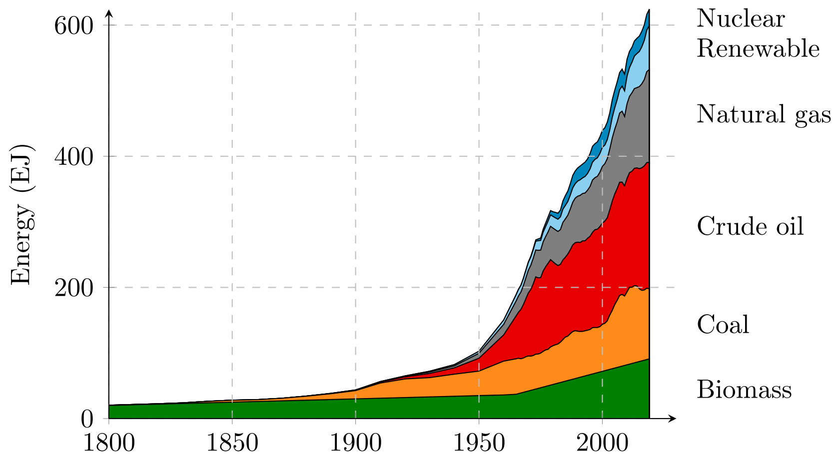

Figure 1.10: Evolution in the global energy mix between 1800 and 2019. Data courtesy of Our World in Data.

These losses mean that the available final energy deposit is about 416 EJ per year, which represents 69% of the primary energy.

One can see in figure 1.10 that replacing all fossil energies by low-carbon ones (nuclear, renewable or biomass) represents a monumental challenge since it involves both drastically reversing trends for fossil energies and at the same time considerably stepping up the renewable and nuclear energies trend which in 2019 only represented around 15% of global primary energy.

Within the global final energy deposit, part of it (6.9 EJ, *i.e.* 19,3%), is present in the form of electricity, which is often seen as a low-carbon energy. Even if that is true in France where 70.6% of electricity is produced by nuclear power and only 7.9% from fossil fuels, the situation is not the same around the world, where 10.2% of the electricity is produced from nuclear power and 64.2% from fossil fuels[IEA20c]. This impacts the carbon intensity of electricity, at a value of 9.9 gCO_2-eq/MJ in France and 132 gCO_2-eq/MJ worldwide[a]. Therefore, electrification only helps reduce greenhouse gases emissions when electricity production is low-carbon, therefore from biomass, renewable energies or nuclear.

1.4.2 Energy limits. . .

This example of electricity illustrates an important point. In a sustainable low-carbon world, final energy can no longer be produced mainly from extraction of natural stocks as it is today with fossil fuels, but will need to be produced essentially from renewable sources (hydraulic, wind, solar, biomass, . . .) and nuclear. This remark applies in particular to the energy carriers which will be considered in chapter 6. Hydrogen and alternative jet fuels are energy carriers that need to be produced.

[a]We used the value stated by the AIE for worldwide electricity carbon intensity. For the carbon intensity of electricity in France, we used the values provided by the Réseau de Transport d'Électricité (global production and CO_2 emissions) which points to production of 1.9 EJ for 19.2 $MtCO_2$-eq emissions.

To be more precise, since we cannot create energy according to the first law of thermodynamics, it involves the conversion of available energies which are essentially unlimited over the time scales in question (renewable energies, namely wind and solar energy, and, to a lesser extent, tidal and geothermal energy, to which we can add biomass, where it is managed sustainably, especially without over forestation) into other energy carriers the most capable of meeting certain needs (energy carriers that can be used when required, which provide stable power, . . .)

In principle, this energy deposit is colossal. As much energy reaches the Earth through solar radiation in an hour than all the energy used by humanity in a year. Nevertheless, only a small fraction of this energy can be recovered. For example, the photosynthesis efficiency is around 1% and that of solar panels around 20%. Limits also exist on the surface that we can dedicate to these energy "production" activities. For instance, land areas represent only 29% of the Earth's surface. Knowing whether it is possible to have as much energy as today in a sustainable world remains an open question[18].

1.4.3 . . . and planetary boundaries

More broadly speaking, a sustainable world must respect the planetary boundaries, of which the energy availability mentioned above is only an example. Other planetary boundaries include for example biodiversity or even mining resources, both at the forefront of the energy transition. Indeed, the destruction of habitats is today the first cause of biodiversity decline of terrestrial animals. Protecting biodiversity requires maintaining (or even restoring) lands free of human influence, which therefore restricts surface area available for energy production. In the same way, the renewable electricity production infrastructure (wind farms or solar farms) requires an increased quantity of mining resources, copper for example, some of which may come to lack especially due to the rise in extraction costs caused by the drop in concentrations. In this report, we will focus on the energy/climate aspects related to aviation. Nevertheless, thinking the aviation sector transition, and that of all business sectors faced with the same constraints, requires taking the various planetary boundaries into account, to avoid simply "shifting the problem", for example resolving the climate problem by causing the extinction of biodiversity or the rarefaction of mining resources. These important questions will be discussed in the conclusion to this report.

Chapter 2

Aviation and climate

2.1 CO_2 and non-CO_2 effects

The impacts of aviation on the climate, shown on figure 2.1, are of two types: CO_2 effects and non-CO_2 effects. This section begins with the presentation of these two types of effects before giving the various ways of evaluating them in the next section.

2.1.1 CO_2 effects

CO_2 effects correspond to CO_2 emissions from aviation, the direct climate impact of which is reinforcement of the greenhouse effect. There are essentially two types of emissions: emissions related to kerosene combustion and emissions over its entire life cycle, *i.e.* emissions related to its production, refining and transport. We can also consider emissions occurring throughout the aircraft's life cycle, related to its construction, maintenance and end of life and related to airport infrastructures. Nevertheless, these emissions are low, around 2% of all emissions from aviation[19]. These emissions are not taken into account for global aviation in this report, but they are when the scope is narrowed to commercial aviation.

2.1.2 Non-CO_2

The impact of aviation on the climate is not only limited to CO_2 emissions, as kerosene combustion releases other products, especially water vapour and aerosols (soot and sulphate) which lead to contrail formation. Depending on the flight phase, kerosene combustion may also emit nitrous oxide (N_2O) and methane (CH_4) but these emissions overall represent less than 1% of CO_2-eq emissions[a] and are therefore usually left out. In addition to the effects of these gases, at least five non-CO_2[9] effects are also contributing: cirrus formation caused by condensation trails (*contrail cirrus*), the effect of NO_x and water vapour on greenhouse gas concentrations, aerosol-radiation interactions

[a]See note FCCC/SBST A/2005/INF.2 by the SBSTA for example or the base carbone by the ADEME.

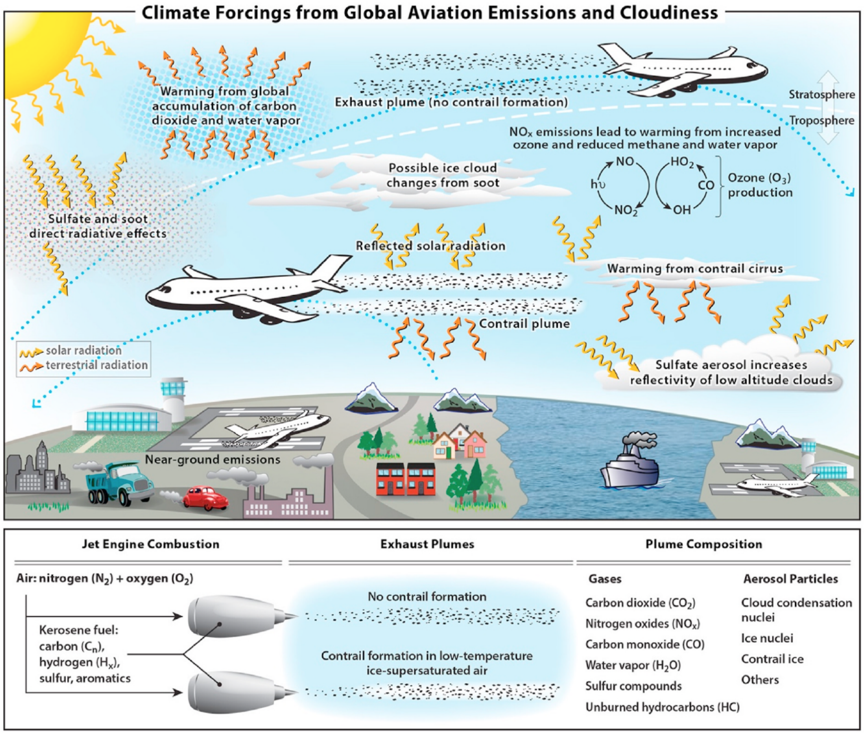

Figure 2.1: Schematic overview of the processes by which aviation emissions and increased cirrus cloudiness affect the climate system. Net positive RF (warming) contributions arise from CO_2, water vapour, NO_x, and soot emissions, and from contrail cirrus (consisting of linear contrails and the cirrus cloudiness arising from them). Negative RF (cooling) contributions arise from sulfate aerosol production. Net warming from NO_x emissions is a sum over warming (short-term ozone increase) and cooling (decreases in methane and stratospheric water vapour, and a long-term decrease in ozone) terms. Net warming from contrail cirrus is a sum over the day/night cycle. These contributions involve a large number of chemical, microphysical, transport and radiative processes in the global atmosphere. The radiative forcing quantitative values associated with these processes are shown on figure 2.7 for 2018. According to figure 1 (and its caption) by Lee *et al.*[9].

and aerosol-cloud interactions. We describe in detail the non-CO_2 effects induced by contrails, and other effects more briefly (see Lee *et al.*[9] for further details).

Contrails

A cloud is made up of water droplets or sometimes ice crystals in suspension in the atmosphere. In pure air without any aerosols or ions, these droplets form when the water vapour is largely supersaturated with respect to liquid water, its relative humidity having to be effectively higher than 100% (around 500%)[20,21]. This especially depends on saturated vapour temperature and pressure conditions and therefore indirectly on altitude. In these conditions, the water vapour contained in the air condenses to form droplets. This condensation can nevertheless occur for low levels of supersaturation found in the atmosphere (of around 1%) as it is largely facilitated by the presence of aerosols serving as condensation nuclei. Clouds can have a cooling albedo effect, but they contribute to the greenhouse effect and therefore also have a warming effect. The net impact depends on many cloud parameters such as their microphysical characteristics, optical depth, altitude, life time or even the time of day at which they form.

Contrails are thin, linear clouds of ice particles which can be seen behind flying aircraft[22]. They form for thermodynamic reasons similar to that of fog formation caused by people breathing in cold and humid air: cold, moist ambient air mixes with warm air expelled by breathing (or, for an aircraft, by the engines), potentially creating conditions of supersaturation relative to liquid water in which droplets are formed by condensation[a]. For a contrail to form, the water vapour in the plume must therefore be supersaturated with respect to liquid water. In the case of conventional, kerosene-fuelled engine effluents, this condensation is greatly enhanced by the presence of combustion and ambient aerosols entrained in the plume, which act as condensation nuclei. Soot particles emitted in large quantities thus play an important role. This is reinforced by the concomitant emissions of particle precursors: sulphur in the fuel, unburnt organic compounds, as well as electrical charges produced by the high temperatures reached in the combustion chamber. Some of the droplets formed then freeze almost instantly, depending on their size, to form ice crystals.

Figure 2.2 shows that the formation and persistence of contrails depend on the one hand on the ambient atmospheric conditions (temperature and relative humidity) and on the other hand on the mixing line of the plume air, defined by the revised Schmidt–Appleman criterion[23] which allows to establish the threshold temperatures of contrail formation.

Depending on the values of the ambient temperature and humidity at the flight level, several cases can occur, as shown in figure 2.2, depending on two criteria:

- the relative position of these ambient conditions (marked by the solid and hollow circles) regarding the two saturation lines of water vapour with respect to liquid water and ice (solid and dotted line, respectively);
- whether or not the mixing line of the plume air (marked by the dash-dotted lines) passes through the saturation zone of the water vapour with respect to liquid water.

If the atmospheric water vapour is supersaturated with respect to liquid water (and therefore supersaturated with respect to ice), then the aircraft is probably flying in a liquid water cloud to which the water droplets will be added. If the atmosphere is subsaturated with respect to ice (and therefore subsaturated with respect to liquid water), a contrail may form if the mixing line of the plume air passes through the area of supersaturation with respect to liquid water (cases 1 and 3), but in any case it will not persist beyond a few minutes. However, if the mixing line of plume air does not pass through the region of supersaturation with respect to liquid water, no contrails will form (case 4). Therefore, for contrails to form and persist, the mixing line of plume air must pass through the region of supersaturation with respect to liquid water and the ambient atmospheric water vapour must be both subsaturated with respect to

[a]In the case of natural clouds, this condensation is triggered not by external forcings as with breathing or aircraft, but by upward movement of air caused by buoyancy forces.

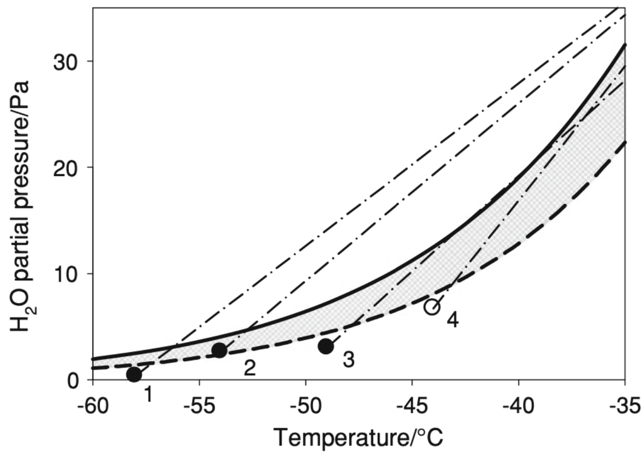

Figure 2.2: This figure explains the thermodynamic conditions related to the formation and persistence of contrails. The solid line is the saturation line of the water vapour with respect to liquid water, and the dotted line with respect to ice. Thus, the grey area corresponds to the area of subsaturation with respect liquid water and supersaturation with respect to ice. The straight lines represent the evolution of the exhaust mixing line, with hot air and high partial pressure at the engine outlet (starting in the upper-right corner), which dries and cools down progressively (moving down and left). In case 1, condensation trails are formed because the exhaust plume mixing line is transiently in a supersaturated zone with respect to liquid water, which allows the formation of water droplets and their subsequent freezing into crystals. This trail does not persist because at the aircraft's flight altitude (the point of arrival of the mixing line), the air is subsaturated with respect to ice. The crystals therefore evaporate quite quickly. In case 2, a trail is created and persists because, after passing through a phase of supersaturation with respect to liquid water, the plume is finally dispersed in an atmosphere supersaturated with respect to ice and thus the ice crystals persist. In case 4, although the mixing line has passed through a phase of supersaturation with respect to ice, no trail is created because it does not pass through a phase of supersaturation with respect to liquid water. According to figure 15.3 of Gierens *et al.*[21].

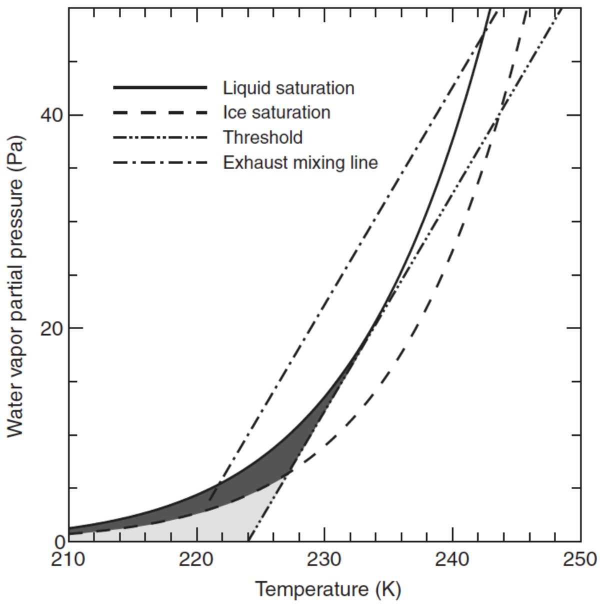

Figure 2.3: Identification of the regions of contrails formation and persistence as a function of the partial pressure of water vapour and the temperature at the flight level. The light grey area corresponds to the formation region of non-persistent contrails. The dark grey area corresponds to the formation region of persistent contrails. According to figure 9 of Vancassel *et al.*[22].

liquid water and supersaturated with respect to ice (case 2). Thus, as shown in figure 2.3, one can identify a zone in which contrails form but do not persist (light grey) and a zone where they form and persist (dark grey).

In dry air with a low relative humidity relative to ice, a contrail does not survive for more than a few minutes. But in ice supersaturated regions, the ice particles of the contrail grow by deposition of ambient water molecules and the contrail can persist, or even develop into induced cirrus clouds difficult to distinguish from natural cirrus clouds (the *contrail cirrus* of figures 2.1 and 2.7). Aircraft spend 10 to 15% of their cruising time in such regions[21,24,25], and about 5% of the kerosene burned is burned in these regions[26].

Furthermore, the trailing vortices which develop in the wake of the aircraft play an important role in the initial phase of development of condensation trails at flight altitude as they capture and trap in their core a large part of the engine effluents (mainly water vapour)[25,27]. The lifetime of these vortices, of around a few minutes over a distance which can reach up to 30 km downstream on the largest aircraft, mainly depends on the aerodynamic load distribution on the wing and on the horizontal tail, and increases with the aircraft's size and weight[28]. The evolution of these trailing vortices is shown in figure 2.4 according to the distance downstream x normalised by the aircraft's wing span b. In the near field ($x/b < 1$), the wake takes the shape of a multipolar vortex system, each single vortex being generated at a surface discontinuity. It depends on the aircraft configuration, in particular the position and the number of engines on the architecture (twin-engine, four-engine, engines along the fuse-

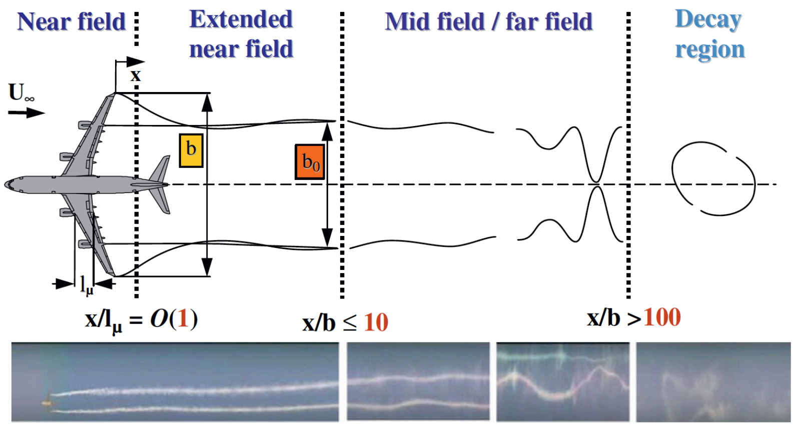

Figure 2.4: Diagram showing the various steps of progression of an aircraft's wake turbulence, according to Breitsamter[28]. The mean aerodynamic cord is written l_μ and the aircraft's span b.

lage, distributed propulsion...) and on deflection of the flight control surfaces (flaps, ailerons and tailplane)[28]. These vortices interact together (fusion and dislocations) and with the engine jets in the extended near field ($1 \leq x/b \leq 10$) leading to concentration of vorticity in a counter-rotating vortex pair. It is during this stage that engine effluents are trapped within the vortex cores[a]. These vortices persist over distances of about one hundred wing spans in a zone called the far field or vortex phase. Their mutual interaction leads to a self-induced downwards vertical motion[28] which eventually brings the vortex dipole to an altitude where water vapour may be subsaturated, thus leading to a decrease in ice crystal concentration by sublimation[25]. During their descent through the atmosphere, a secondary wake develops downstream of the vortices by viscous diffusion[29,30]. This phase of their evolution includes the development of natural cooperative instabilities which ultimately lead to their attenuation and dispersion via vortex reconnection, most often through the appearance of vortex rings[28]. Therefore, beyond the thermodynamic and microphysical processes governed by the composition of engine effluents and ambient meteorological conditions, the formation and persistence of contrails also depend on the evolution and dynamics of the trailing vortices during the vortex phase. Beyond that stage, the wake enters a decay region where the atmospheric conditions govern the evolution of the contrails and their potential transformation into induced cirrus clouds (thermodynamic and meteorological conditions, turbulence, diffusion and decay).

Other non-CO_2 effects

We now briefly present the other non-CO_2 effects, especially the effects due to NO_x, water vapour, aerosol-radiation interactions and to aerosol-cloud interactions. The effects due to NO_x reinforce radiative forcing, whereas those related

[a]Under certain atmospheric conditions, water vapour condensation is thus a marker enabling the visualisation of the vortices otherwise invisible.

to water vapour and to aerosol-radiation interactions are very weak. Currently, great uncertainty on the evaluation of the aerosol-cloud interaction impact and they are not taken into account in the evaluation of the aviation sector's climate impact for this reason. The description below of other non-CO_2 effects corresponds to sections taken almost literally from the article by Lee *et al.*[9].

NO_x. The high combustion temperature produces NO and NO_2 nitrogen oxides, of the generic name NO_x, which induce chemical reactions having both a positive and negative impact on the climate. In the short-term, NO_x react with the oxygen in the air to form ozone (O_3), which increases radiative forcing since ozone is a greenhouse gas, see figure 1.5. Concurrently, NO_x participate in the reduction of the effects of methane (CH_4) because they reduce their life time and local concentration, contributing to a decrease in radiative forcing. In the longer term, the reduction of methane leads to a decrease in stratospheric ozone and water vapour, inducing a negative radiative forcing. When all these reactions are taken into account, it appears that the NO_x contribution constitutes a positive forcing term, *i.e.* which positively contributes to the greenhouse effect and to the rise in atmospheric temperature, as it will be seen in figure 2.7 below.

Water vapour. Planes fly at an average altitude of 10 000 m, a region which corresponds to the troposphere at low latitudes and to the lower stratosphere at high latitudes. Indeed, the position of the tropopause decreases with latitude from around 17 km at the equator to 7 km near the poles. Therefore a large part of global aircraft fleet yearly emissions are produced in the lower stratosphere, mainly in the northern hemisphere. The accumulation of these water vapour emissions modifies the water content in the lower stratosphere and therefore the water vapour radiation balance[9].

Aerosol-radiation interactions. Aerosol-radiation interactions are caused by non-volatile particulate matter emitted during combustion, especially soot (defined as a mixture of black and organic carbon) and aerosols precursor of sulphate (SO_4^{2-}) and nitrate (NO_3^-). Soot aerosol is formed by the condensation of unburnt aromatic compounds in the combustion chamber and sulphate aerosol by oxidation of sulphur contained in the fuel. Sulphur is mainly emitted in the form of SO_2, whereas a small fraction ($\sim$3%) is emitted in the form of oxidised H_2SO_4. Most sulphate aerosols are produced after emission of compounds precursor of sulphur by oxidation in the ambient air. The two types of aerosol induce radiative forcing from aerosol-radiation interactions. The soot absorbs shortwave radiation which leads to net warming, and the sulphate aerosol diffuses incoming shortwave radiation, which leads to net cooling. As an example, global aviation emissions in 2000 increased the mass of soot and sulphate aerosols by a few percent and the number of aerosols from 10 to 30% near air traffic lanes in Northern extra-tropical regions.

Aerosol-cloud interactions. Aerosol-cloud interactions are processes by which aerosols influence cloud formation. For example, cloud droplets and ice crystals nucleate on aerosols. Soot and sulphate particles from aviation are the main primary and secondary aerosols from planes. Sulphate aerosol from aviation mainly affects liquid clouds in the background atmosphere. Sulphate aerosol is highly effective as cloud condensation nucleus for the formation of liquid clouds

	CO_2		ERF	
Period	$GtCO_2$	% emissions	$mW\,m^{-2}$	% anthropogenic ERF
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	—

Table 2.1: Climate impact of global aviation without taking non-combustion CO_2 emissions into account. The CO_2 column shows CO_2 emissions from the aviation sector over the periods considered and the percentage of the total anthropogenic emissions they represent. The ERF column reports the impact of air traffic on radiative forcing and the percentage it represents with respect to total anthropogenic ERF. Median values are used for the calculations, and the uncertainties, where known, are reported in the body of the text. The 2018 ERF share is not reported as annual shares are subject to significant fluctuations, see body of the text for further details. The calculation sources and methodology are described in detail in appendix B.

and also promotes the freezing of particles of solution at cold temperatures, leading to ice cloud nucleation[9].

2.2 Evaluation of the climate impact of aviation

2.2.1 Methodology and scope (global aviation)

Several approaches can be used to evaluate the climate impact of aviation. The easiest one consists in evaluating CO_2 effects. It is a robust method as CO_2 emissions are known with a low level of uncertainty, but are incomplete because non-CO_2 effects are not included. This section begins with the presentation of this method in section 2.2.2. A more comprehensive method, including non-CO_2 effects, consists in evaluating the impact on radiative forcing (given in effective radiative forcing, see chapter 1), is presented in section 2.2.3.

Furthermore, one can look at the recent impact, *i.e.* for a given year or period of time, or at the cumulative impact since the preindustrial era. This historical impact is relevant because, as explained in section 1.3.3, it is the cumulative emissions that matters when determining the Earth's equilibrium temperature. Nevertheless, from the standpoint of management of the fight against global warming, recent emissions count more. Thus, for human activity introduced recently and at a significant volume during the industrial era, such as digital technology or aviation, their share of past global total emissions is, notwithstanding an exceptional event, lower than the share of their current contribution. Vice versa, it would not be relevant to take activities into account if they have ceased at the time recommendations are made, even if they represent a significant contribution to emissions accumulated in the past. Hereinafter, we therefore present values representing the climate impact of aviation for the two methods. These figures are summarised in table 2.1 and are based on the IEA's data for CO_2 emissions and the data from Lee *et al.* for non-CO_2 effects.

In sections 2.2.2 and 2.2.3, only emissions caused by kerosene combustion are considered for global aviation, *i.e.* commercial aviation but also military and

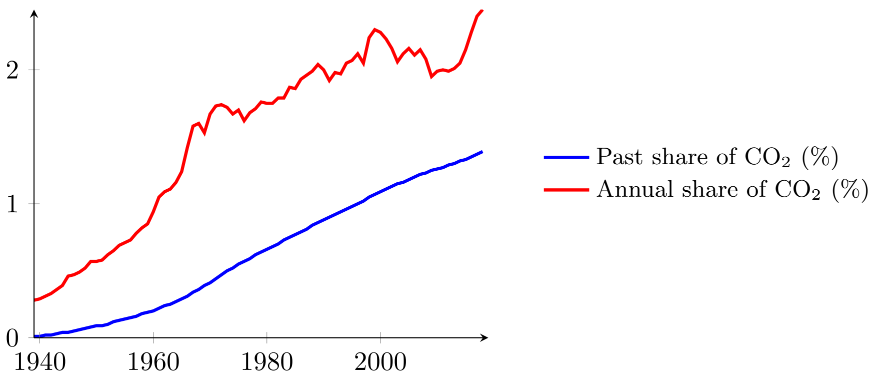

Figure 2.5: Change in past and recent shares (yearly) of aviation in global CO_2 emissions. The past share (in blue) corresponds to the value for total emissions from aviation since 1750 divided by the value of global total emissions. The annual share (in red) corresponds to the value for annual emissions from aviation divided by the value of global annual emissions. Calculations based on data from Our World In Data for CO_2 anthropogenic emissions, and data from the IEA for aviation CO_2 emissions.

private aviation (see section 2.2.5 for further details). Section 2.2.4 includes emissions due to kerosene production and section 2.2.5 narrows the scope to commercial aviation, which is more relevant to the rest of the report.

When uncertainties on a given figure are known, we indicate the 90% confidence interval limits after the value. For example, when we say that global aviation generated radiative forcing of 100.9 $\mathrm{mW\,m^{-2}}$ [55-145] between 1750 and 2018, 100.9 $\mathrm{mW\,m^{-2}}$ corresponds to the median value, and the probability of the actual value lies between 55 $\mathrm{mW\,m^{-2}}$ and 145 $\mathrm{mW\,m^{-2}}$ is 90%.

2.2.2 Evaluation of CO_2 emissions

We begin by presenting the figures concerning CO_2 effects. In 2018, global aviation emitted 1.0 $\mathrm{GtCO_2}$ through kerosene combustion[a], which represents 2.4% of total anthropogenic CO_2 emissions[b] the same year (for the details on these calculations and the following calculations, see appendix B). Now, if the focus is made on the cumulative historical impact from 1750, date commonly considered to be the start of the preindustrial era and taken as climate reference, we see that emissions from aviation represent 1.4% of total anthropogenic emissions between 1750 and 2018 (see table 2.1).

Both values have been increasing from 1940 as illustrated in figure 2.5. This means that aviation share in global CO_2 emissions is increasing. This is confirmed by looking at figure 2.6 which shows that, since 1990, emissions from the aviation sector are those that increased the most steeply, on an equal footing with electricity generation industries and slightly more rapidly than the transport sector (not including aviation). We also see in figure 2.5 that the share of aviation in past total CO_2 emissions is lower than its current share. This is

[a]This figure corresponds to global aviation, namely commercial aviation but also private and military aviation, the last two representing around 12% of the total emissions[1]. We will come back to this point in section 2.2.5.

[b]Including emissions related to land use.

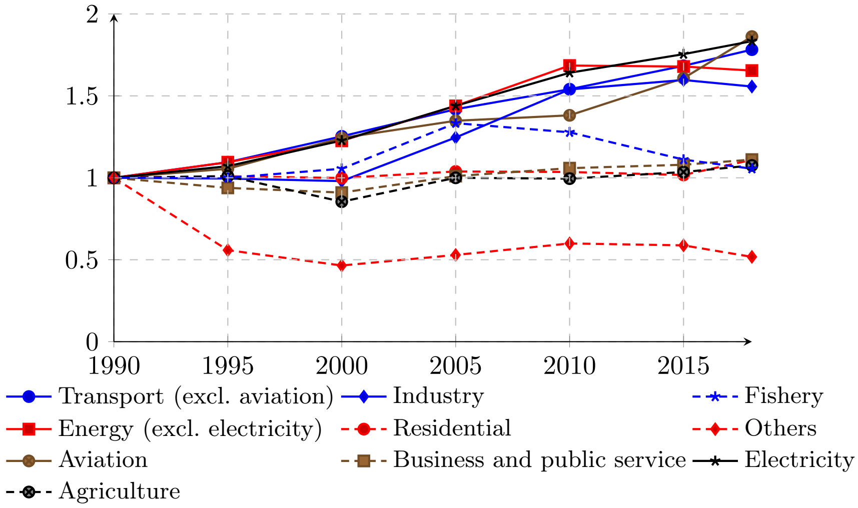

Figure 2.6: Change in CO_2 emissions compared to their 1990 level for different business sectors, according to the data from the IEA.

explained by the fact that aviation emissions increase more rapidly than those of other sectors, but also because emissions from the aviation sector only began in 1940, year commonly taken as reference for estimating the climate impacts of aviation, whereas the impact from radiative forcing has been evaluated from 1750. Over the period 1940–2018, emissions from the aviation sector represented 1.7% of total emissions, therefore effectively more than 1.4% over the period 1750–2018.

2.2.3 Evaluation of the impact of aviation on radiative forcing

To estimate the climate impact of aviation while including CO_2 and non-CO_2 effects, we use the results by Lee *et al.*[9] which evaluate this impact in terms of (effective) radiative forcing. Non-CO_2 effects are by nature varied and more difficult to evaluate than CO_2 effects. They are the main source of uncertainties for evaluating the climate impact of aviation, and certain effects, such as the interactions between aerosols and clouds, are not yet sufficiently well understood to be taken into account. These uncertainties are reported in figure 2.7 and are discussed in more detail below. As for CO_2 effects, their absolute or relative values can be evaluated as well as their past or recent impact. As we will see below, evaluation of the recent share of radiative forcing poses new methodological concerns compared to that of CO_2.

Impact on radiative forcing since the preindustrial era

Lee *et al.*[9] calculated that between 1750 and 2018, global aviation induced a radiative forcing of 100.9 $\mathrm{mW\,m^{-2}}$ [55-145]. Figure 2.7 details how this figure is distributed between CO_2 effects and the five non-CO_2 effects mentioned above. It appears that non-CO_2 effects are preponderant. They are responsible for 66% of radiative forcing, *i.e.* 66.6 $\mathrm{mW\,m^{-2}}$ [21-121] whereas CO_2 effects contribute

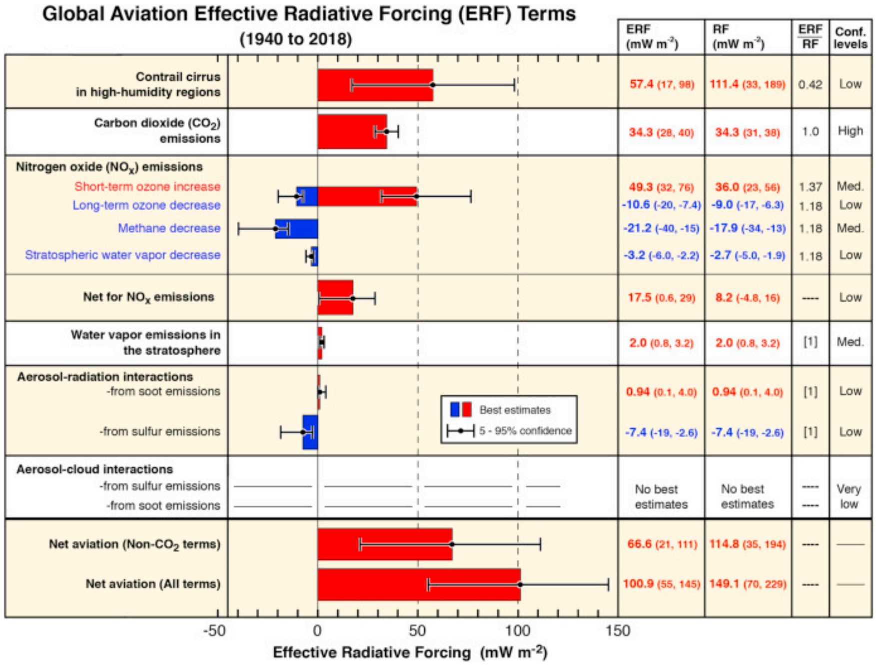

Figure 2.7: Breakdown of radiative forcing terms due to global aviation from 1940 to 2018. The bars and whiskers show the best estimations for radiative forcing and 90% confidence intervals respectively. The red bars show the warming terms and the blue bars the cooling terms. According to figure 3 (and its caption) by Lee *et al.*[9].

for 34.3 $\mathrm{mW\,m^{-2}}$ [28-40][a]. Contrails and NO_x are the predominant non-CO_2 effects since they respectively induced a radiative forcing of 57.4 $\mathrm{mW\,m^{-2}}$ [17-98] and 17.5 $\mathrm{mW\,m^{-2}}$ [0.6-29].

To understand what this radiative forcing of 100.9 $\mathrm{mW\,m^{-2}}$ represents, and in terms of managing the fight against global warming, it is important to determine the proportion of warming the 100.9 $\mathrm{mW\,m^{-2}}$ represent among human activity. Using the recent anthropogenic radiative forcing value, estimated at 2.66 $\mathrm{W\,m^{-2}}$ between 1750 and 2018[FSA+21], we see that aviation was responsible for 3.8% of global warming over the same period[b].

Furthermore, the data available[c] can be used to plot the variation in the aviation's share of the total anthropogenic radiative forcing. This evolution is given in figure 2.8 and exhibits very different behaviour from the corresponding figure for CO_2 emissions (blue curve on figure 2.5). Indeed, whereas for CO_2 effects, past impact increases almost linearly over time, thus reflecting the cumulative nature of CO_2, the past impact of radiative forcing has fluctuated since 2001. Indeed, the aviation share grew considerably from 2001 to 2007 before decreasing from 2007 to 2009, especially due to the decrease in ERF

[a] This figure does not take non-combustion emissions into account.

[b] When Lee *et al.* made their estimations, the anthropogenic radiative forcing value was only known up to 2011. Over the period 1750–2011, they thus estimated that aviation had been responsible for 3.5% [3.4-4.0] of global warming. The 3.8% value is therefore an update of this figure.

[c] We would like to thank Laurent Terray for providing the sources for figure 2.10 from the IPCC Working Group I Sixth Assessment Report[FSA+21].

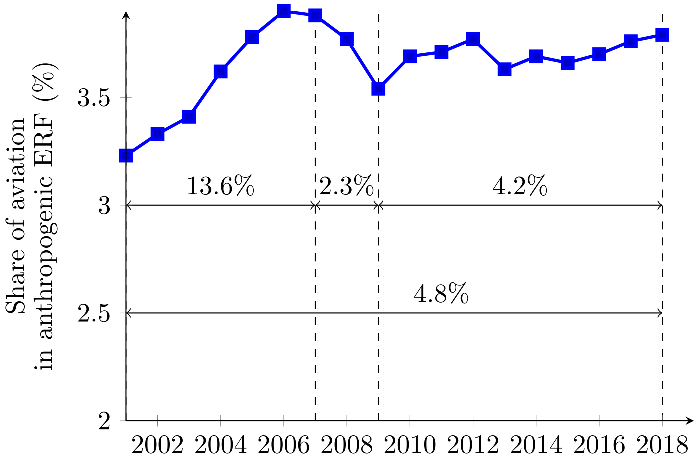

Figure 2.8: Change in the share of aviation in anthropogenic radiative forcing calculated since 1750. For instance, the value of the curve in 2010 corresponds to the ratio between the anthropogenic radiative forcing due to aviation between 1750 and 2010, divided by anthropogenic radiative forcing over the same period. The values above the arrows represent the most recent "share" of anthropogenic ERF due to aviation over the period considered. Calculations made based on data from Lee *et al.*[9] for radiative forcing values from aviation, and from the IPCC Working Group I Sixth Assessment Report for anthropogenic radiative forcing values[FSA+21].

from aviation as it can be seen in figure 2.9. However, unlike the share of CO_2 emissions which grew rapidly again after 2010 (see figure 2.5), the past share of ERF from aviation increased slightly from 2009. This slight variation is due to the decrease in global aerosol emissions, seen in figure 1.5, which leads to an increase in anthropogenic radiative forcing.

Recent impact on radiative forcing

Lee *et al.*[9] provide data on the impact of aviation on radiative forcing for each year between 2000 and 2018, which, combined with annual variations in anthropogenic radiative forcing, can be used to plot the counterpart of the red curve in figure 2.5, but for the impact on radiative forcing and not only the impact of CO_2 emissions. The red curve in figure 2.9. therefore represents the absolute value of the ratio, year after year, between the annual variation in radiative forcing due to aviation and the annual variation in total anthropogenic radiative forcing. For example, we see that in 2012, aviation was responsible for 11% of the increase in total anthropogenic radiative forcing. At first glance, it is tempting to interpret this ratio as the share of aviation in the annual variation in radiative forcing. Nevertheless, this interpretation must be taken cautiously because, unlike annual CO_2 emission values which are positive, the annual change in radiative forcing results from a difference between positive and negative terms. The ratio between the annual variation in radiative forcing from aviation and the annual variation in anthropogenic radiative forcing can therefore be negative if aviation increases radiative forcing in a year in which anthropogenic radiative forcing decreases (or vice versa). It can also be greater than 1 if aviation induces an increase in radiative forcing higher than the increase in anthropogenic radia-

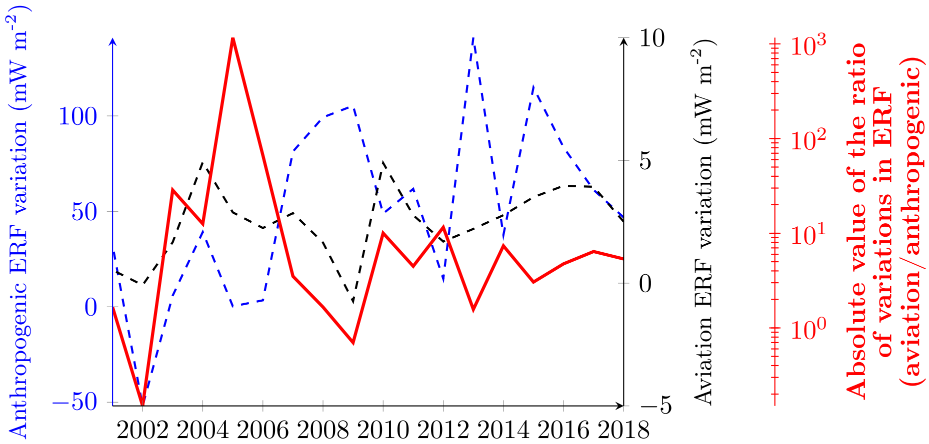

Figure 2.9: Dotted blue line: annual evolution in anthropogenic radiative forcing. Dotted black line: annual evolution in aviation-induced radiative forcing. Solid red line: absolute value of the ratio of the two curves. The last curve therefore represents, for each year, the absolute value of the "share" of the annual evolution in anthropogenic radiative forcing caused by aviation. The absolute value is considered in order to be able to take a logarithmic scale for the red curve. In 2002, the ratio is positive, but it results from a ratio of two negative values, since that year, anthropogenic radiative forcing and radiative forcing from aviation both decreased. Only the value for the 2009 ratio is negative, year in which anthropogenic radiative forcing increased, but that from aviation decreased.

tive forcing, which can happen if cooling effects are very significant. Therefore in 2009, anthropogenic radiative forcing increased whereas aviation led to a drop in radiative forcing, corresponding to a negative "share"; and in 2005, anthropogenic radiative forcing increased by $0.2\,\mathrm{mW\,m^{-2}}$ whereas aviation induced an increase of $2.9\,\mathrm{mW\,m^{-2}}$, leading to a "share" greater than 1000%, see figure 2.9.

Also, beyond the tricky interpretation of this figure, the "share" of annual variation in radiative forcing due to aviation is subject to significant fluctuations and, unlike what has been seen for CO_2 emissions (red curve on figure 2.5), no clear trend comes out over the period 2000–2018, as shown by the percentages per period in figure 2.8. One possible solution is to smooth these variations over several years. For example, over the period from 2000 to 2018, aviation represented 4.8% of the increase in radiative forcing, therefore a value higher than the 3.8% over the period 1750–2018. Since 2014, the annual variation is more stable and fluctuates between 3% and 7%, with an average of 5.4%. The most recent value available, in 2018, is 5.3%.

Uncertainties and on-going research

As mentioned in the beginning of this section, the various values presented above come exclusively from the recent assessment by Lee *et al.* [9]. These values are subject to uncertainties which are shown in figure 2.7 and which have been specified in the text. The greatest uncertainties are due to non-CO_2 effects, especially the effect on radiative forcing from cirrus caused by contrails but also NO_x. Furthermore, the uncertainties are so great concerning aerosol-cloud interactions that these effects are not included in the estimation by Lee *et al.*[9]. They could nevertheless fully change the evaluation of the climate impact of aviation. For aerosol-cloud interactions due to soot emissions, Lee *et al.* report values spanning a large range from $-500\,\mathrm{mW\,m^{-2}}$ to $300\,\mathrm{mW\,m^{-2}}$.

If we have chosen to rely on Lee *et al.* 's results in order to present a coherent, complete and up-to-date assessment, this should not obfuscate that a significant amount of research is currently devoted to reducing the above-mentioned uncertainties. There is also a lot of methodological argument on how to evaluate non-CO_2 effects, some of which leads to different assessments. Without aiming for exhaustiveness, let us mention some recent results related to the evaluation of the impact of contrails, of NO_x and of aerosol-cloud interactions that may complement Lee *et al.* 's assessment.

The evaluation of the climate impact of contrails is a very difficult task because it requires an understanding of a wide range of complex phenomena such as the creation contrail cirrus, their extent and life time, their optical properties and also other phenomena such as the interaction with natural clouds. Lee *et al.* 's assessment relies on numerical models to do this evaluation, as, until recently, limited data was available for direct measurements. However, the situation evolved significantly following the collapse of air traffic due to the COVID-19 pandemic. This event represented an unprecedented opportunity to check the validity of the models against observation by comparing situations with and (almost) without aviation. Several research teams have tried to assess the difference in cirrus coverage and optical thickness during the almost complete shutdown of air traffic in the couple of months after March 2022[31–35]. The results are contrasted: for instance, while Quaas *et al.* [35] detect a discernable impact of air traffic reduction on cirrus coverage[a], Digby *et al.* [32] conclude that "satellite observations of cirrus cloud do not exhibit a detectable global response to the dramatic aviation reductions of spring 2020." A direct comparison of these papers is difficult as they consider different scopes and use different methodologies with their strengths and weaknesses. Further research therefore seems necessary in order to reach a consensus. Concerning reassessment of contrail cirrus impact on radiative forcing with this new data, Gettelman *et al.* [36] find an ERF median estimate ($62\,\mathrm{mW\,m^{-2}}$ [3,121]) in line with Lee *et al.* 's estimate ($57.4\,\mathrm{mW\,m^{-2}}$ [17,98]), but with a larger confidence interval. The study by Quaas *et al.* [35] concludes with a best estimate of net radiative forcing of $62\,\mathrm{mW\,m^{-2}}$ [22,100]. If we use Lee *et al.* 's value of 0.42 for the ratio ERF/RF, this corresponds to an estimate of $25.6\,\mathrm{mW\,m^{-2}}$ [9.2,42] in terms of effective radiative forcing, to be compared to the estimate of $57.4\,\mathrm{mW\,m^{-2}}$ [17,98] of Lee *et al.* Finally, although this is not the heart of Digby *et al.* 's paper[32], they also provide a back-of-the-envelope[b] estimate of the ERF of induced cirrus, and come up with a best estimate of $8\,\mathrm{mW\,m^{-2}}$ [-3,22]. These results suggest that the climate impact of induced cirrus could be much weaker than the best estimate of Lee *et al.* 's, being 2 to 7 times smaller. In other words, they lean toward the lowest values of Lee *et al.* 's confidence interval. To conclude this discussion on the climate impact of contrails, it is interesting to mention Wil-

[a] To be more precise, they claim that for the period March–May 2020, "in the 20% of the Northern Hemisphere mid-latitudes with the largest air traffic reduction, cirrus fraction was reduced by $\sim 9 \pm 1.5\%$ on average".

[b] The authors explicitly mention that their "results should not be treated as purely quantitative."

helm *et al.* [37]'s paper: they show that weather variability has a strong impact on contrails instantaneous radiative forcing, and conclude that "there is a fundamental limit to the precision with which the RF and ERF of contrail cirrus can be determined".

Beyond induced cirrus, we can also mention on-going scientific debate that increases the level of scientific understanding concerning NO_x and aerosol-cloud interaction. Grewe *et al.* [38] recommend for example changing methodology for estimating the impact of NO_x in order to take into account the non-linear aspect of the chemical system within which these emissions occur. According to them, not taking the non-linearity into account underestimates the impact of NO_x. Concerning aerosol-cloud interaction, we mentioned earlier that no best estimate was given in Lee *et al.* 's assessment due to the wide range of values reported. However, Kärcher *et al.*[39] recently demonstrated that extreme values (positive and negative) of the impact on radiative forcing of the aerosol-cloud interactions were probably overestimated. Even if they do not give an estimate of radiative forcing, they conclude that the impact of aerosol-cloud interactions due to soot emissions is likely to be much lower than that due to cirrus caused by contrails, and may even be insignificant. A similar conclusion is reached by Zhu *et al.*[40] by comparing the radiative properties of cirrus clouds during the travel restrictions due to the COVID-19 pandemic to the ones before it. When soot emission is reduced, they observe a significant increase in ice crystal number concentrations, which leads to a rather small positive radiative effect. This discussion shows the need for further research to reduce the uncertainties that weigh on the evaluation of non-CO_2 effects.

2.2.4 Acknowledgement of CO_2 emissions on the kerosene full life cycle

In this report, we will need to include non-combustion CO_2 emissions related to the kerosene life cycle (extraction, transport, refining). Indeed, we are later going to examine to what extent changes in energy carrier can reduce the climate impact of aviation. Yet, if we only consider CO_2 emissions related to fuel combustion, then the impact of replacing kerosene with a biofuel, for example, is insignificant since combustion of fuel from fossil or vegetable origin emits almost as much CO_2. In fact, the potential usefulness of biofuels lies in the fact that the CO_2 emitted during their combustion is captured beforehand during biomass growth. It therefore comes from the air and not from geological reserves, and these emissions do not add to the CO_2 in the atmosphere since it was captured beforehand. This calculation therefore requires making comparisons over the entire life cycle. This reasoning is also essential to other technological solutions such as electric aircraft or hydrogen aircraft. Electricity and hydrogen are just energy carriers which, even if they do not emit any CO_2 to power a plane, they need to be produced upstream, and it is during this stage of production that CO_2 emissions potentially occur. Generally, life cycle assessment is the most objective method for having an exhaustive view of environmental impacts, and it prevents transferring these impacts upstream or downstream of the study scope.

CO_2 emissions over the kerosene full life cycle depend on several factors, such as for example the production site which influences emissions due to transport and extraction. These emissions represent around 20% of combustion-

	CO_2		ERF	
Period	$GtCO_2$	% emissions	$mW\,m^{-2}$	% anthropogenic ERF
2000–2018	18.0	2.6%	46.6	5.0%
2018	1.2	2.9%	2.7	—

Table 2.2: Climate impact from aviation including CO_2 emissions related to fuel production. The CO_2 column shows CO_2 emissions from the aviation sector over the periods considered and the percentage total anthropogenic emissions they represent. The ERF column reports the impact of air traffic on radiative forcing and the percentage it represents with respect to total anthropogenic ERF over the same period. The 2018 ERF share is not reported as these annual shares are subject to significant fluctuations. The calculation sources and methodology are described in detail in appendix B.

related emissions. Therefore, whereas combustion of a kilogram of kerosene emits 3.13 kg of CO_2, we took the standard value of 3.77 $kgCO_2/kg$[a] emissions when we include emissions over the entire kerosene life cycle (see appendix B.1 for a discussion on this value). It is important to realise that this value is a representative value, since, as explained previously, emissions excluding those related to the combustion of kerosene depend on the production location.

The results using this methodology are summarised in table 2.2. It can be seen that emissions from aviation, considering the kerosene full life cycle, amount to 1.2 $GtCO_2$ in 2018, therefore 2.9% of global CO_2 emissions the same year[b].

2.2.5 Focusing on commercial aviation

Even if considering global aviation is relevant to ensure an exhaustive assessment of impacts from aviation on the whole, it is preferable to focus on commercial aviation to evaluate prospective scenarios. Indeed, as it will be seen later, assumptions will be made for example on the evolution in traffic, technological improvements or aircraft load factor. These assumptions therefore concern commercial aviation alone and their application to military and private aviation is not relevant because their traffic and efficiency evolution obeys other logics.

The methodology for reducing the scope to commercial aviation is more complex and is described in appendix B.5. The results using this methodology are summarised in table 2.3. Considering the full life cycle, commercial aviation represented 2.6% of CO_2 emissions in 2018 and is responsible for 5.1% of recent effective radiative forcing (2000–2018).

[a]In fact, non-combustion emissions include a small quantity of emissions of greenhouse gases other than CO_2, and this value of 3.77 is measured in CO_2-eq. Nevertheless, for the reasons given in appendix B.1, we will consider that they are CO_2.

[b]As we do not have data on non-combustion emissions over the whole period considered, we will not attempt to estimate the share of aviation in total emissions by taking the full life cycle of jet fuel into account.

	CO_2		ERF	
Period	$GtCO_2$	% emissions	$mW\,m^{-2}$	% anthropogenic ERF
Direct emissions				
2000-2018	13.0	1.8%	45.1	4.9%
2018	0.9	2.1%	4.1	—
Global emissions				
2000–2018	16.0	2.3%	47.6	5.1%
2018	1.1	2.6%	4.2	—

Table 2.3: Climate impact of commercial aviation. The CO_2 column shows CO_2 emissions from commercial aviation over the periods considered and the percentage of total anthropogenic emissions they represent. The ERF column reports the impact on radiative forcing and the percentage it represents. The results are given for direct emissions (kerosene combustion) and global emissions (kerosene combustion, fuel production, other phases of the life cycle). The 2018 ERF share is not reported as these annual shares are subject to significant fluctuations.

2.3 Comparison of CO_2 and non-CO_2 effects

One fundamental difference between CO_2 effects and non-CO_2 effects stems from their different characteristic time scales. When part of the CO_2 emitted remains in the atmosphere for centuries[41], contrail cirrus persist for a few days at most[25,42] and aerosols remain in the atmosphere at most a year (and maximum one month if they are emitted in the troposphere)[5]. As a result, the impact of CO_2 effects is cumulative and over the long-term, whereas the impact of non-CO_2 effects is instantaneous and over the short-term. It follows that the impact from CO_2 effects depends on the absolute value of accumulated CO_2 emissions, whereas, all other things being equal, the impact of non-CO_2 effects depends primarily on the variation in annual emissions from aviation.

Let us consider a very straightforward example to qualitatively illustrate this point, and let's imagine, all other things being equal, that air traffic remains constant for a long period, which implies a constant rate of CO_2 emissions. Several climate effects compensate for each other and mean that these emissions at a constant rate induce a more or less linear increase in temperature. This is the principle of climate sensitivity, captured by a coefficient of proportionality between temperature and CO_2 emissions called TCRE, for *transient climate response to cumulative carbon emissions*. Although air traffic remains constant, CO_2 effects therefore have a linear impact on temperature, which shows their cumulative effect. The situation concerning non-CO_2 effects is very different. Let's consider contrails, which are responsible for most of these effects. If we make an assessment from one year to another, then as a first estimation, the effect of contrails one year is the same as the effect of contrails from the previous year, meaning that the impact of non-CO_2 effects is constant. Therefore, at constant traffic, the impact of CO_2 effects increases when that of non-CO_2 effects is stable. The same reasoning shows that:

- if traffic increases, then (all other things being equal) non-CO_2 effects induce an increase in radiative forcing;

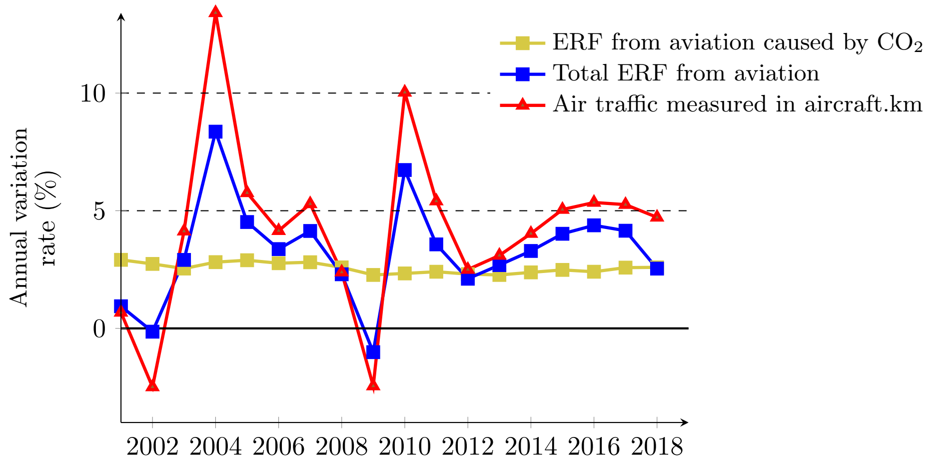

Figure 2.10: The blue curve shows the annual variation rate in radiative forcing from aviation, the yellow curve shows the annual variation rate in radiative forcing from aviation CO_2 effects, and the red curve shows the variation in traffic (measured in kilometres travelled by the aircraft) between 2001 and 2018. There exists a very strong correlation between the variation in the impact from aviation and the variation in traffic, due to the short-term impact of non-CO_2 effects. The cumulative effect of CO_2 effects is seen by a very stable annual variation rate in their impact. 2009 is a year during which traffic decreased and aviation (locally) contributed to the decrease in radiative forcing. Conversely, in 2004, traffic increased by 13% and the climate impact from aviation by 8%. The blue curve was generated using data by Lee *et al.*[9], and the red curve was generated from ICAO data available at airlines.org.

- and therefore symmetrically, if traffic decreases, then (all other things being equal) non-CO_2 effects induce a decrease in radiative forcing.

Therefore, the variation in the impact of non-CO_2 effects depends greatly on variation in traffic and their impact can therefore change over time, whereas, due to their cumulative and long-term nature, CO_2 effects are considerably less sensitive to short-term variations in traffic. This correlation between the change in impact of non-CO_2 effects with the evolution in traffic is clear in figure 2.10 which shows the evolution in annual variation rates in radiative forcing from aviation and traffic (measured in aircraft.km). This shows a strong correlation: the climate impact from aviation increases when traffic increases, and decreases when traffic decreases. Furthermore, the magnitude of the increases and decreases in climate impact is closely related to that of the change in traffic. Years 2002 and 2009 are two years from which we can learn significantly. Over the period 2000–2018, they are the only years in which traffic decreased (following global economic crises), and these decreases in traffic led to a negative climate impact (relative cooling effect from aviation). Other than the change in air traffic, specific strategies, described in detail in chapter 7, could also enable a possible decrease of the radiative forcing induced by these non-CO_2 effects.

In chapters 8 and 9 on the prospective scenarios for the transition of the aviation sector, the analysis will mainly be based on CO_2 emissions. Indeed, they have a long-term effect on the climate and their associated uncertainties are lower. In addition, the related methodologies are more robust, such as the notion of carbon budget. We will nevertheless propose potential approaches for integrating non-CO_2 effects, in particular base on the GWP$*$ metric described in detail in appendix A, which is more relevant for estimating the impact of non-CO_2 effects from aviation. We will then analyse some scenarios in order to put forward general trends on the strategies specific to non-CO_2 effects.

2.4 Environmental regulations

It is important to mention that the climate impact, but also in a broader extent the environmental impact of an aircraft is subject to regulations. Environmental requirements apply for aircraft certification. They include for example specifications CS-34 and CS-36 by the European Aviation Safety Agency (EASA), covering noise, NO_x unburnt hydrocarbons (HC) and carbon monoxide (CO), but also since 2017 CO_2 at overall aircraft level and non-volatile Particulate Matter (nvPM) at engine level. Today, in order to be certified, each aircraft and each engine must meet these environmental requirements. Certification authorities, such as the EASA, follow the guidelines by the ICAO presented in appendix 16 to the Chicago Convention[Pro17] which covers protection of the environment.

2.5 Impact of climate change on aviation

The various impacts of aviation on the climate have been presented in the previous sections. However, the link between aviation and climate is not one-sided and there is feedback between climate change and aviation. Air transport developed within a historically stable climate, in particular, local climate conditions largely determined airport location, runway layout and air traffic lanes. In the context of a changing climate, it is becoming necessary to identify the impacts stemming from changes in the physical properties of the atmosphere, and more broadly from climate change, in order to adapt infrastructures and aircraft to these new conditions as far as possible.

There are still too few studies to be able to establish a consensus on the extent of the impacts climate change will have on aviation. However, it is a subject of major concern as 74% of air transport stakeholders (especially States, airports and airline companies) consider that the aviation sector is already impacted or will be impacted by climate change in the near future[gro18]. The impacts of climate change on aviation can be of two types:

- direct impacts, related to the physical consequences of climate change (rise in air temperature, change of wind regime, rising ocean levels, etc.);
- indirect impacts induced by these changes at economic and social level, such as changes in tourist habits and social acceptability. In particular, the increase in temperatures (heat waves) could lead to certain tourist areas becoming less attractive[43]. Currently popular summer destinations such as Greece, could see tourist demand fall, and this from 2020–2030, with an even more marked reduction (40% drop in the number of tourists during the summer) after 2040[TD10].

Climate risk	Impact	Actors	Key:
Precipitation change	• disruption to operations e.g. airfield flooding, ground subsidence • reduction in airport throughput • drainage system capacity • inundation of underground infrastructure (e.g. electrical) • inundation of ground transport access (passengers and staff) • loss of local utilities provision (e.g. power).	✈ AO ANSP ✈ AO ANSP AO AO ✈ AO ANSP ☎ ✈AO ANSP ☎	Aircraft operators: ✈ Airport operators: AO ANSP: ANSP External: ☎
Temperature change	• Changes in aircraft performance • Changes in noise impact due to changes in performance • heat damage to airport surface (runway, taxiway) • increased heating and cooling requirements • Increased pressure on local utilities e.g. water and power (for cooling).	✈ ANSP ✈ AO ANSP AO AO ☎	
Sea-level rise	• loss of airport capacity • impacts on en-route capacity due to lack of ground capacity • loss of airport infrastructure • loss of ground transport access	✈ AO ANSP ✈ ANSP AO ✈ AO ANSP ☎	
Wind changes	• convective weather: disruption to operations • convective weather: route extensions • jet stream: increase in en-route turbulence • local wind patterns: disruption to operations and changes to distribution of noise impact	✈ AO ANSP ✈ ANSP ✈ AO ✈ AO	
Extreme events*	• disruption to operations, route extensions • disruption to ground transport access • disruption to utilities supply	✈ AO ANSP ✈ AO ☎ AO ☎	

Figure 2.11: Overview of potential impacts related to climate change on aviation according to Burbidge[44]. Note: ANSP (Air Navigation Service Provider) brings together air navigation support services (air traffic control, meteorology, etc.).

Indirect impacts are essentially economic and societal and do not fall within the scope of this report. Below we describe the most noteworthy direct impacts. The table in figure 2.11 presents a list of direct impacts from climate change on aviation, along with the actors involved (airports, airline companies, air traffic control).

2.5.1 Airport vulnerability

The main threats airports will have to face are due to the rising ocean levels (submersion) and changes in precipitation regimes (floods). Consequences for airports can be occasional (certain runways unavailable due to flooding) or permanent (airport becoming inaccessible due to high sea level). In any case, consequences are also likely on airways which may be interrupted, especially due to the lack of availability of ground infrastructures.

To identify the airports most vulnerable to rising sea levels, the method consists in determining those located within an area where coastal elevation is low, defined as the continuous area along coasts where the land is less than 10 metres above sea level. In this way, 1238 airports of different sizes have been identified, most of them being located in the United States, Southern and South-Eastern Asia, Australia and in island regions (Indonesia, French Polynesia, Bahamas, etc.). The 20 most highly frequented airports in areas of low coastal elevation represent 18% of all passengers transported in 2018 and 25% of global air freight (1.85% of the global GDP). Around one hundred of these airports are very likely to finding themselves beneath the sea level by 2100[45]. Adaptation of these airports to protect them from submersions (construction of dams, raising ground level artificially or off-shore infrastructures) would cost 57 billion dollars[45].

2.5.2 Modification of wind regimes

Climate change is also set to induce physical changes in the atmosphere, in particular for atmospheric currents such as the *Jet Stream*. These atmospheric currents originate at the interface between the troposphere (area in which the temperature decreases with altitude) and the stratosphere (area in which the temperature increases with altitude). This interface, called the tropopause, is located at an average altitude of 11 km therefore in air traffic lanes, and exhibits variations in altitude ranging from 7 km to 17 km depending on latitude and season. The majority of these currents flow from West to East, span thousands of kilometres and are a few kilometres wide. In each hemisphere, there is a low intensity subtropical Jet Stream, located between 10 km and 16 km above sea level, and a high intensity polar front Jet Stream, located between 7 km and 12 km above sea level. At the centre of these currents, the average wind speed is around $25\,\mathrm{m\,s^{-1}}$ and can occasionally reach up to $100\,\mathrm{m\,s^{-1}}$.

These currents have a significant impact on aircraft flight time. For example, a trip from New-York to Paris takes one hour less than the reverse journey. The position and intensity of the Jet Stream are subject to high daily and seasonal variations. The consequences of climate change on Jet Stream trajectory are twofold[46]:

1. it will be more winding, which will increase the likelihood of extreme weather events at mid-latitude;
2. it will shift North by around 1 degree latitude, while reinforcing the mean intensity of the Jet Stream.

Impact on travel time above the North Atlantic Ocean should be low, of around a few minutes maximum by 2100[47]. However, reinforcement of the Jet Stream will have a significant impact on the production of turbulent zones as it will be described in the next section.

2.5.3 Impact on turbulence

By increasing the likelihood of the occurrence of extreme events, climate change will also have an impact on meteorological phenomena, responsible for 12% of air traffic accidents[a], 65% of which are related to clear air turbulence[48]. The main mechanism by which clear air turbulence is created is by wind shear, caused by the Jet Stream for example. These turbulent events can be moderate (rapid drop in flight altitude of a few metres - drinks spill on the floor) to severe (sudden drop in flight altitude about tens of metres - persons not wearing a seatbelt can be ejected from their seat). By reinforcing the intensity of the Jet Stream, climate change will increase the probability of occurrence of moderate to severe turbulent events, as shown in table 2.4.

This impact on clear air turbulence largely depends on the geographical area and the time of year considered[49]. The highest impact occurs from April to May for which the probability of occurrence of moderate to severe turbulence increases by around 50%. This effect is reinforced in the North Atlantic region with a probability which is increased by around 150%.

[a] Accidents mainly involve physical damages to people or to the aircraft, death from turbulence remains rare. The annual cost of these accidents is estimated to be within a range of 150 to 500 million dollars.

Intensity CAT	Case 1		Case 2		Case 3		Case 4	
	10 km	12 km	10 km	12 km	10 km	12km	10 km	12 km
Moderate	+30.8	+19.6	+46.5	+30.0	+143.3	+74.4	+34.3	+26.0
Severe	+34.7	+20.5	+51.6	+34.2	+181.4	+88.0	+51.1	+40.2

Table 2.4: Increase in clear air turbulence between the preindustrial era and the period 2050–2080 (as a %), for two cruising altitudes. Case 1: global average (world) over the period December to February; Case 2: global average (world) over the period March to May; Case 3: yearly average (North Atlantic); Case 4: yearly average (Africa). The data are taken from Storer *et al.*[49].

2.5.4 Impact on icing conditions

The icing risk is a problem which affects ground operations or in-flight operations, requiring anti-icing systems (prevention) or de-icing systems (curative), both on-board the aircraft and on the ground. Ice forms in specific temperature and humidity conditions. In the lower layers of the atmosphere, it is due to the presence of supercooled droplets in an environment at negative temperature (between around 0 °C and −20 °C), which form preferentially in regions of the atmosphere with high water vapour content (more than 50% relative humidity). Global warming should see zones in which these conditions are found reach even higher altitudes. In the upper layers of the atmosphere, ice creation is related to the presence of a large quantity of very cold ice crystals ($< -50\,^\circ$C), often at the top of convection clouds. The formation of thicker cumulonimbus and elevation of the tropopause caused by the increase in temperature are believed to contribute to the increased probability of encountering icing conditions in the upper layers of the atmosphere.

2.5.5 Impact on aircraft performance

Other than the effects on infrastructures, there is a set of direct impacts from the increase in temperatures on aircraft performance. In particular, the hotter the air, the less dense it is, which decreases aircraft lift and engine thrust (these notions will be introduced and described in detail in chapter 4). These impacts can already be felt during extreme heat waves. For example, in 2019, following the heat waves at Phoenix airport, around twenty flights were cancelled and more than one hundred Boeing 737s were put under weight restrictions to be able to take off[50]. The impact on the maximum authorised take-off weight increases rapidly with temperature[51]. At Phoenix airport, a Boeing 737 is thus subject to a weight reduction of around 450 kg for a ground temperature of 38 °C and a weight reduction of 4500 kg at 47 °C (around 6% of its maximum take-off weight). Similar figures have been found for Airbus A320s at Madrid airport at ground temperatures of around the same order of magnitude[Pra20].

Given the effects of global warming, the average take-off distance in summer could increase by 1% to 6% depending on the location of the airport over the period 2021–2050, compared to the period 1976–2005, while reducing the maximum rate of climb[52]. In the case of a scenario leading to global warming of around +5 °C in 2100, and considering today's aircraft, the reduction in maximum take-off weight is estimated at 5% all year round, in particular in the Northern hemisphere at high latitudes. This corresponds to an approximate

10% to 20% reduction in payload[53]. On the other hand, in the case of a scenario in which global warming does not exceed +2 °C, the reduction in payload remains on average lower than 1%.

Chapter 3

Kaya identity

As discussed in section 1.3.2, the objective of the Paris Agreement to limit global warming to well below $+2\,^{\circ}\mathrm{C}$ requires a drastic reduction in greenhouse gas emissions, in particular CO_2 emissions. The Kaya identity presented in this chapter is used to identify the different action levers to reach this objective: **it is the key to understanding the rest of this report**. After having expressed it in a general context, a version adapted to the aviation sector is presented and discussed.

3.1 Historical formulation

The Kaya identity, introduced by the Japanese economist Yoichi Kaya in 1993[54], puts forward a breakdown of CO_2 emissions into four factors involving CO_2 emissions, energy used (E), gross domestic product (GDP) and the global population:

$$\underbrace{\mathrm{CO_2}}_{\substack{\mathrm{CO_2}\\ \text{emissions}\\ \mathrm{MtCO_2}}} = \underbrace{\frac{\mathrm{CO_2}}{\mathrm{E}}}_{\substack{\text{Carbon}\\ \text{intensity}\\ \mathrm{MtCO_2/EJ}}} \times \underbrace{\frac{\mathrm{E}}{\mathrm{GDP}}}_{\substack{\text{Energy}\\ \text{intensity}\\ \mathrm{EJ/€}}} \times \underbrace{\frac{\mathrm{PIB}}{\mathrm{Pop}}}_{\substack{\text{GDP}\\ \text{per capita}\\ \mathrm{€/hab}}} \times \underbrace{\mathrm{Pop}}_{\substack{\text{Population}\\ \\ \mathrm{hab}}} \tag{3.1}$$

where the four terms on which CO_2 emissions depend are:

- the **carbon intensity of the energy used** measured by the quantity of CO_2 released for each unit of energy used;
- the **energy intensity of the economy** giving the quantity of energy used to produce one Euro of wealth (goods and services);
- the **GDP per capita** pointing to the level of economic activity or wealth;
- the **global population**.

Each of the terms of this identity is a lever for reducing global CO_2 emissions, the first three corresponding respectively to the three levers mentioned in section 1.4: decarbonisation, efficiency and sobriety. This identity is a useful tool for analysing the change in CO_2 emissions and it is used by the IPCC[IPC00] and by the IEA[IEA20a] both to analyse past trends and to consider a forward-looking approach.

3.2 Application to the aviation sector

The principle of decomposing CO_2 emissions into different factors at the basis of the Kaya identity can be adapted to the aviation sector to analyse the change in its emissions. This can result in a decomposition of emissions into three terms which correspond to the different levers we can use to reduce the sector's carbon footprint. We can write for example

$$\underbrace{CO_2}_{\substack{\text{CO}_2\\\text{emissions}\\ \\ \text{MtCO}_2}} = \underbrace{\frac{CO_2}{E}}_{\substack{\text{Carbon}\\\text{intensity}\\ \\ \text{MtCO}_2/\text{EJ}}} \times \underbrace{\frac{E}{\text{Traffic}}}_{\substack{\text{Energy}\\\text{intensity}\\ \\ \text{EJ/pass.km}}} \times \underbrace{\text{Trafic}}_{\substack{\text{Traffic}\\ \\ \\ \text{pass.km}}} \tag{3.2}$$

where the following three terms are identified:

- **carbon intensity** is the quantity of CO_2 released for each unit of energy used[a];
- **energy intensity** is the quantity of energy used for a passenger to travel one kilometre;
- **traffic** is the distance travelled by all passengers and it is measured in passenger-kilometres[b] (*Revenue Passenger Kilometre* - RPK).

These three terms correspond to the three levers introduced in section 1.4, and total emissions are simply given by their product. Energy intensity is the efficiency lever, carbon intensity the decarbonisation lever, and traffic the sobriety lever.

Before considering the Kaya decomposition in a forward looking approach, it is useful to study the historical change in CO_2 emissions from the aviation sector with regard to the identity (3.2). Figure 3.1 illustrates the change in these three terms and in total CO_2 emissions between 1973 and 2018 starting from a baseline 1 in 1973. One can see that carbon intensity has not changed, which reflects the fact that the energy carrier is the same since 1973[c]. Energy

[a]In the Kaya decomposition in this chapter, we only consider CO_2 emitted during combustion of kerosene and not over its entire life cycle, due to missing historical data on upstream emissions.

[b]This unit of measurement, written pass.km, is used to measure air traffic and corresponds to the total distances travelled by all passengers. Therefore, when a plane travels 1000 km with 50 passengers on-board, the corresponding traffic is $1000 \times 50 = 5000$ pass.km which effectively corresponds to the total distance travelled by all of the passengers. This metric, which takes account of the plane's load factor, can be compared to the seat.km which is the number of seats theoretically available multiplied by the number of kilometres travelled, see decomposition (3.3). For a load factor of 100% the two metrics are equivalent.

[c]In figure 3.1, the carbon intensity values do not result from a calculation but are taken as constants. This is also the method used by Lee *et al.* [9], which considers that kerosene carbon intensity has remained constant since 1990. Certain data from the IEA suggest a marginal drop in carbon intensity since 1973, of around 1%, see the data for emission and for consumption for international aviation.

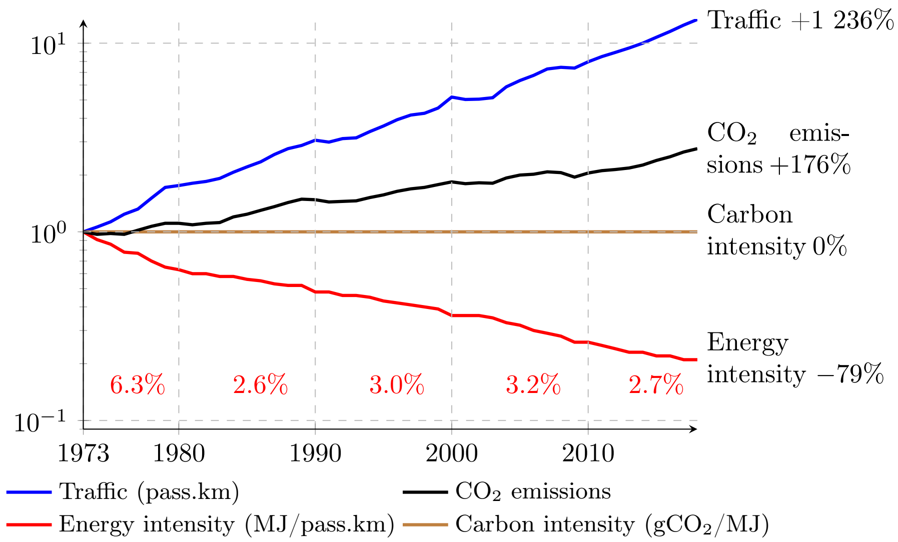

Figure 3.1: Change in the terms of the Kaya decomposition (3.2) for aviation emissions between 1973 and 2018, starting with a baseline 1 in 1973. A logarithmic scale is used for the ordinates. The energy intensity annual variation compound rate is shown for each decade. Therefore, between 1980 and 1990, the intensity decreased at a compound rate of 2.6% per year. Calculations based on data from the IEA and the ICAO.

intensity has decreased by 79% in 45 years, which corresponds to an improvement in average energy efficiency of 3.5% per year. As shown in figure 3.1, this decrease is not constant, annual gains ranging from 2.6% to 6.3% depending on the decade. These drops in consumption per pass.km were made possible through technical improvements in terms of aerodynamics, propulsion, aircraft weight, aircraft systems (see chapter 4) and operations (including the load factor). This improvement in energy efficiency in the aviation sector is more than twice as high as the global average calculated for all business sectors. Indeed, energy intensity in the world over all sectors decreased by 36% over the period 1990–2018[IEA20b], representing an average annual improvement of 1.5%. This comparison shows that the aeronautical industry has been a highly innovative sector for several decades now. Furthermore, technological improvements, especially in terms of safety, aeroacoustics and electromagnetic stealth, have often benefited a number of other sectors such as the transport and energy sectors. This long-standing ability to innovate indicates that the aeronautical sector will be capable of providing technological solutions for significantly reducing aircraft emissions.

Nevertheless, in the same lapse of time, the traffic increased a lot more rapidly, at an annual pace of 5.9%, increasing therefore from 618 billion passenger-kilometres in 1973 to 8257 in 2018. This eventually led to an increase in CO_2 emissions of 176% between 1973 and 2018. This phenomenon is partly explained by the rebound effect, highlighted from 1865 by the economist William Stanley Jevons in his book "*The Coal Question*". This paradox stipulates that efficiency gains can lead to an overall increase in resources consumed, and not a decrease as one might expect. This is due to an increase in existing uses and the devel-

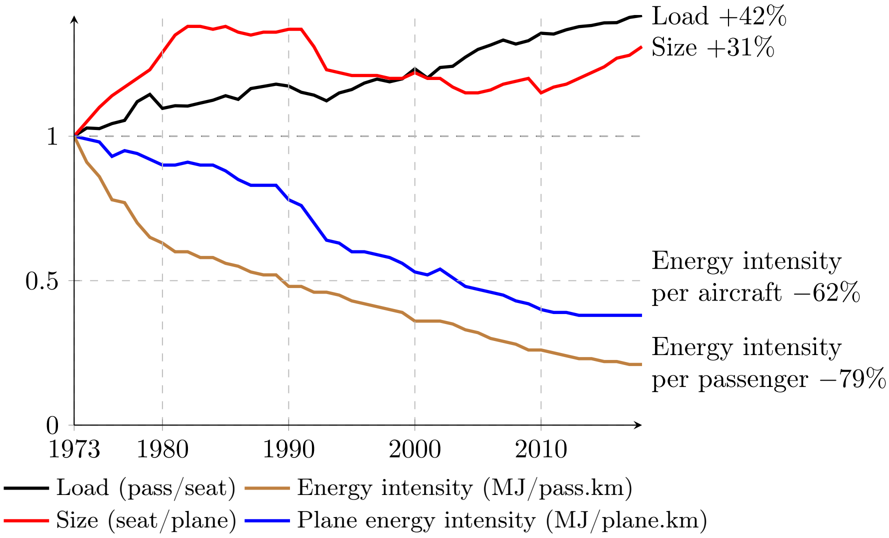

Figure 3.2: Change in the terms of the Kaya decomposition (3.3) for energy intensity per passenger between 1973 and 2018. Calculations based on data from the IEA and the ICAO.

opment of new uses made possible by improving efficiency and reducing costs.

It is possible to refine the Kaya decomposition (3.2) by breaking down the energy intensity term as follows:

$$\underbrace{\frac{\mathrm{E}}{\mathrm{pass.km}}}_{\substack{\text{Energy}\\ \text{intensity}\\ \text{per passenger}}} = \underbrace{\frac{\mathrm{E}}{\mathrm{aircraft.km}}}_{\substack{\text{Energy}\\ \text{intensity}\\ \text{per aircraft}}} \times \underbrace{\frac{1}{\mathrm{seat/aircraft}}}_{\substack{\text{Inverse}\\ \text{capacity}\\ \text{per aircraft}}} \times \underbrace{\frac{1}{\mathrm{pass/seat}}}_{\substack{\text{Inverse}\\ \text{load factor}}} \tag{3.3}$$

so as to reveal three new levers to be activated: load factor, aircraft capacity and energy intensity measured in energy required for a plane (and no longer a passenger) to travel one kilometre. The change in these different terms since 1973 is shown in figure 3.2, which denotes that the improvement in energy efficiency per passenger is a combination of the three terms: larger, more efficiently filled and more efficient aircraft.

Beyond this historical analysis, the Kaya identity, transposed to the aviation sector in equation (3.2) is a useful tool for analysing and evaluating prospective scenarios for the development of commercial aviation. **It is the key to understanding the rest of this report.** Section III focuses on each of the technological levers and considers their potential evolution by 2050. Chapter 5 describes the perspectives for the technological improvement of aircraft corresponding to the energy intensity term, whereas chapter 6 discusses the possibilities for the decarbonisation of the aircraft energy carrier corresponding to the carbon intensity term. This part also includes a last chapter 7 on the potential technological solutions for reducing non-CO_2 effects, even if these aspects cannot be analysed using the Kaya identity, due to its very construction. However, the last lever of the Kaya identity, namely traffic, will not be discussed in this part because it depends on economic, political and societal choices which fall outside the scientific scope of this report. This third lever is considered here as a variable in the scenarios for the evolution of the aviation sector, based on different assumptions about the two technological levers. This variable is either seen as an adjustment variable to make these trajectories compatible with the objective of the Paris Agreement, or as an input to these scenarios which then participates in determining its climate impact. This approach is detailed in chapter 8 that describes the context and assumptions for the prospective analysis that is carried out in chapter 9.

Part III

Technological levers

Limiting the impact of aviation on the climate requires reducing CO_2 and non-CO_2 effects. In this part we present the main technological and operational levers foreseen to date. Unless specifically stated, this part focuses on commercial aviation, meaning aircraft ranging from regional airliners to long-range airliners. After an introduction to how an aircraft works, we present an overview of measures to be implemented to improve aircraft efficiency, followed by decarbonisation measures, and finally we discuss levers for reducing non-CO_2 effects.

Chapter 4

Aircraft general principles

The objective of this educational chapter is to present the notions and concept of operations of an aircraft in order to understand the sources of its energy consumption in the next chapters. After having recalled how an aircraft flies, the chapter more specifically describes aircraft aerodynamics, propulsion and systems in detail. These elements will be useful in the remainder of this part for identifying the various technological levers for improving aircraft efficiency, hence, reducing fuel consumption.

4.1 How does a plane fly?

The first step is to effectively understand how an aircraft works. In cruise flight, the plane is at equilibrium and subject to four main forces shown in figure 4.1: its **weight**, the **lift**, the **drag** (*drag*) and engine **thrust**. Lift and drag are two components of a unique aerodynamic force resulting from the pressure and friction stresses exerted by the air on the aircraft. Lift is the component of the aerodynamic force perpendicular to the aircraft's forward speed direction, and compensates for its weight. Drag is the tangential component of this aerodynamic force and it acts in a direction that is opposite to the motion of the aircraft.

These two aerodynamic forces, lift $\vec{L}$ and drag $\vec{D}$, can be expressed via the equations (4.1) and (4.2)

$$\vec{L} = \frac{1}{2}\rho S V^2 C_L \vec{e}_z \tag{4.1}$$

$$\vec{D} = \frac{1}{2}\rho S V^2 C_D \vec{e}_x \tag{4.2}$$

where ρ is the air density at flight level, S the surface of the aircraft wing, V the aircraft true airspeed and C_L and C_D two dimensionless numbers which depend on the wing geometry, the angle of attack and the flight regime.

Using Newton's second laws of motion, the sum of these forces is zero in cruise regime (constant speed and altitude). Therefore, engine thrust enables to maintain a constant speed for the aircraft in order to both ensure lift generation to balance its weight and to compensate for the drag.

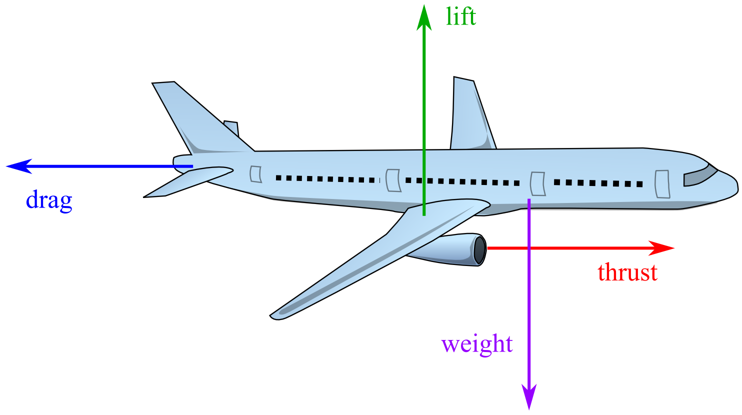

Figure 4.1: Illustration representing the four main forces acting on an aircraft.

4.2 Aircraft aerodynamics

Given the cruise flight equilibrium illustrated in figure 4.1, the main challenge in the aerodynamic design of an aircraft consists in maximising lift to be able to transport a larger payload while minimising drag to reduce fuel consumption. Aerodynamic efficiency can thus be measured easily by the lift-to-drag-ratio simply given the ratio between lift and drag coefficients:

$$f = \frac{C_L}{C_D} \,. \tag{4.3}$$

Therefore, at a given lift coefficient, an increase in lift-to-drag-ratio necessarily results in a drag reduction. Although from a physics standpoint drag only has two origins (pressure and friction), aircraft manufacturers are used to decompose the aircraft drag into five terms, two of which are predominant. First, the **skin friction drag** D_f, which amounts between 45 to 50 % of the total drag[55], is mainly caused by friction of the air on the wet surfaces of the aircraft[a], but it also contains some pressure drag and is also called form drag or minimum incompressible drag. Second, the **induced drag** D_i, which represents between 40 to 45 % of the total drag[55], corresponds to the drag induced by the lift generation on a finite span wing. Finally, the other types, which represent about 10 % of the total drag[55], include compressibility drag (or wave drag), the balancing drag and parasite drag.

As mentioned in section 4.1, the aerodynamic coefficients depend on the angle of attack, the aircraft's geometry and the flight regime. Therefore, drag coefficient can be written:

$$C_D = f\left(\alpha, \lambda, Re, M\right) \tag{4.4}$$

where α denotes the angle of attack, $\lambda = b^2/S$ the aspect ratio of the wing with b its span and S its surface, Re and M the Reynolds and Mach numbers.

[a]The "wet surface" of an aircraft corresponds to the surface which is in contact with the air flow. It therefore excludes surfaces on which there is flow separation.

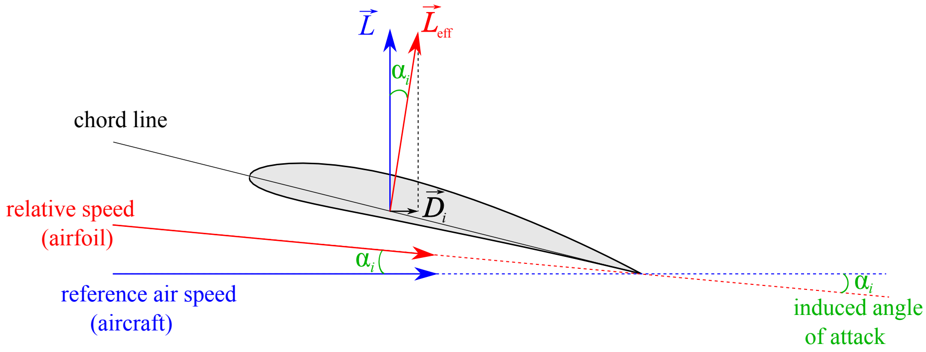

Figure 4.2: Induced drag is related to the downwards vertical movement (*downwash*) induced by the air bypassing the wing tip. The local lift force $\vec{L}_{\text{eff}}$ is not perpendicular to the reference air speed direction and its projection along this direction contributes to the so-called induced drag $\vec{D}_i$.

The Reynolds number, defined by $Re = (V\,L)/\nu$ where V is the aircraft's true airspeed, L wing characteristic length[a] and ν the air kinematic viscosity, measures the relative importance of inertia forces (which promote movement) and viscosity forces (which resist movement). At a low Reynolds number, the flow is said to be laminar whereas it becomes turbulent at a high Reynolds number ($Re \gtrsim 10^3 - 10^4$). The intensity of the wall friction significantly increases when the flow transitions from a laminar regime to a turbulent regime. The dependency of the skin friction drag coefficient on the Reynolds number (and therefore flight speed) goes from $C_{D_f} \sim Re^{-\frac{1}{2}}$ in laminar flow to $C_{D_f} \sim Re^{-\frac{1}{5}}$ in turbulent flow. Given that the Reynolds numbers on an aircraft are of the order of one million ($Re \sim 10^6 - 10^8$), the flow is generally turbulent and friction contributes for around half of the total drag.

The Mach number, defined as the ratio $M = V/a$ between the aircraft's true airspeed V and the speed of sound in air a, governs the flow regime. The subsonic regime corresponds to Mach numbers below unity ($M < 1$) whereas the supersonic regime is reached for Mach numbers higher than one ($M > 1$). In supersonic regime, specific irreversible phenomena (supersonic areas, shock waves) are at the origin of an additional component called compressibility drag (or wave drag). Modern airliners fly in subsonic regime and the shape of their wings has been designed to minimise this drag component via the introduction of supercritical airfoils and a sweep angle. It only accounts for 1 % to 2 % of the total drag.

Induced drag is the other main drag component accounting for almost half of the aircraft's total drag. It results from the generation of lift on a finite wing, where the air bypassing the wing tip due to the difference in pressure between the pressure side and suction side induces the generation of two counter-rotating trailing vortices (or wing tip vortices). These vortices induce a downwards vertical motion on the wing which reduces the local angle of attack seen by the wing airfoils and the projection of local lift along the reference air speed direction is not zero and contributes to drag, see figure 4.2. This drag component

[a]The characteristic length of the wing is generally taken as the mean aerodynamic chord (MAC), but different characteristic length can be used according to the part of the aircraft considered (for example the span b for the aircraft or the diameter of the engine nacelle).

decreases with the wing aspect ratio as in $C_{D_i} \sim \lambda^{-1}$.

4.3 Aircraft propulsion

Aircraft engine is an essential element of the aircraft because it is used to produce the thrust required to generate lift while compensating for drag. Most engines with which current commercial aircraft are equipped (more than 10 seats) rely on a gas turbine. It is a rotating thermodynamic machine comprising a multi-stage compressor, a combustion chamber and a multi-stage turbine. The compressor absorbs the mechanical power produced by the turbine, power initially produced via the combustion of kerosene with air in the combustion chamber. The remaining energy available contained in the gas turbine outflow can then be used to generate the propulsive force. Two engines families exist according to the way this available energy is converted and their operating principles are illustrated in figure4.3:

- **turbofans** or **turbojets**: the hot fluid exiting the turbine is accelerated in a nozzle to generate the thrust. When all the air flow passes through the combustion chamber, the engine is called a turbojet. In engines of modern commercial aircraft, called turbofans, a secondary flux adds to the primary flux passing through the gas turbine. This secondary flux bypasses the combustion chamber and goes directly from the fan[a] towards a jet nozzle and generates an additional thrust to that produced by the primary flow. The secondary flux thrust is higher than that of the primary flux, and its contribution to the total thrust increases with the bypass ratio, which corresponds to the mass flow ratio between the secondary and the primary fluxes. This type of architecture enables to improve substantially the engine efficiency compared to the turbojet. The most powerful civil engines deliver maximum power of around 80 MW (GE90 of the Boeing 777).

- **turboprop engines**: most of the available energy is converted into mechanical energy by a free turbine and, via a reduction gear, allows the rotation of a propeller which generates most of the thrust[b]. Typically, this type of engine can deliver maximum power of around 10 MW (TP400 of the Airbus A400M). This type of engine does not allow to reach flight speeds as high as those permitted by the use of a turbofan, as the flow velocity at the end of the propeller blades must not go far beyond the sonic limit (around $M \sim 1.4$) without affecting the propeller's aerodynamics and therefore engine efficiency. It is therefore necessary to limit the propeller's rotation speed (therefore flight speed) and/or propeller size (therefore engine power and the aircraft capacity).

The performance of these two families of aircraft engines is measured by the thermopropulsive efficiency. This overall engine performance is the product of two terms: **thermal efficiency** and **propulsive efficiency**. Thermal efficiency

[a]The fan, which is the first stage of compression shared by the two fluxes, exhibits a low compression ratio and a large dimension. It is driven by the low pressure turbine of the gas turbine.

[b]The residual thrust generated by the jet exiting the gas turbine only contributes up to 10 % of the propulsive force.

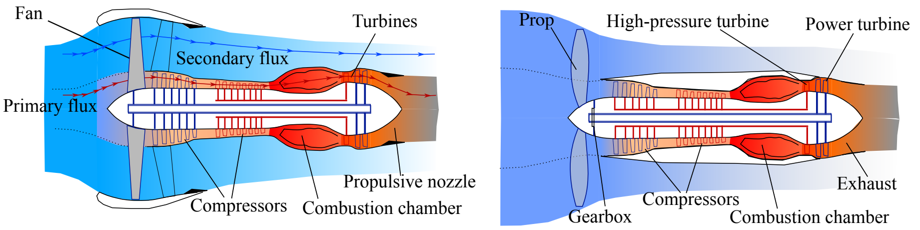

Figure 4.3: (left) Sketch of a turbofan in a meridian plane illustrating its operating principle. At the engine exit, the primary flux is shown by the red arrow whereas the secondary flux is shown by the blue arrow. (right) Sketch of a turboprop engine in a meridian plane illustrating its operating principle.

is defined as the ratio between the increase in the kinetic energy of the air passing through the engine and the energy produced by kerosene combustion. But, the energy of combustion is not fully converted in flow acceleration because part of it contributes to the increase in the fluid's internal energy[a], therefore to the heating of the exhaust gases. Therefore, thermal efficiency measures the losses associated with exhaust gas residual thermal energy. Propulsive efficiency corresponds to the ratio between the mechanical work of the propulsive force and the increase of the kinetic energy of the air flowing through the engine. Generation of thrust requires the acceleration of the flow through the propulsion system so that the velocity of the exhaust gases is higher than the flight speed. Paradoxically, this residual kinetic energy lost in the atmosphere is the second source of energy loss and is measured by propulsive efficiency. Therefore the thermopropulsive efficiency measures the energy losses which correspond to the residual total energy[b] of the exhaust gases. For example, the overall efficiency of the turbofans that power most of today's civil aircraft is currently around 25 % (around 60 % propulsive efficiency and around 40 % thermal efficiency). As for turboprop engines, their propulsive efficiency is better than that of turbofans, but their flight speed and altitude are limited. Another indicator commonly used to measure aircraft engine performance is the **specific fuel consumption** C_s. It is the ratio between the fuel mass flow rate and the thrust force. It measures the quantity of fuel required to produce a unit of thrust. At constant flight speed, it is simply the inverse of the thermopropulsive efficiency.

These two engine families currently rely on a gas turbine whose combustion chamber operates at constant pressure (Brayton cycle) and is called an isobaric chamber. However, propellers are based on the piston engine where the combustion chamber, called an isochoric chamber, operates at constant volume (Humphrey cycle). The choice of the engine type depends mainly on the power required, as shown in figure 4.4: low power with piston engines (low speed at low altitude), high power with turbofans (high speed at high altitude). Historically, aircraft used piston engines until the early 60s, when generalised use of turbofan and turboprop architectures was mainly dictated by a need to increase power in order to carry more passengers per plane. However, the transition

[a]The internal energy (or thermal energy) of a fluid corresponds to the energy of the molecular agitation, measured by the fluid temperature.

[b]The total energy of a fluid is the sum of its kinetic energy and its internal energy.

[a]The specific thrust is the thrust force produced per unit of air mass flow rate passing through the engine.

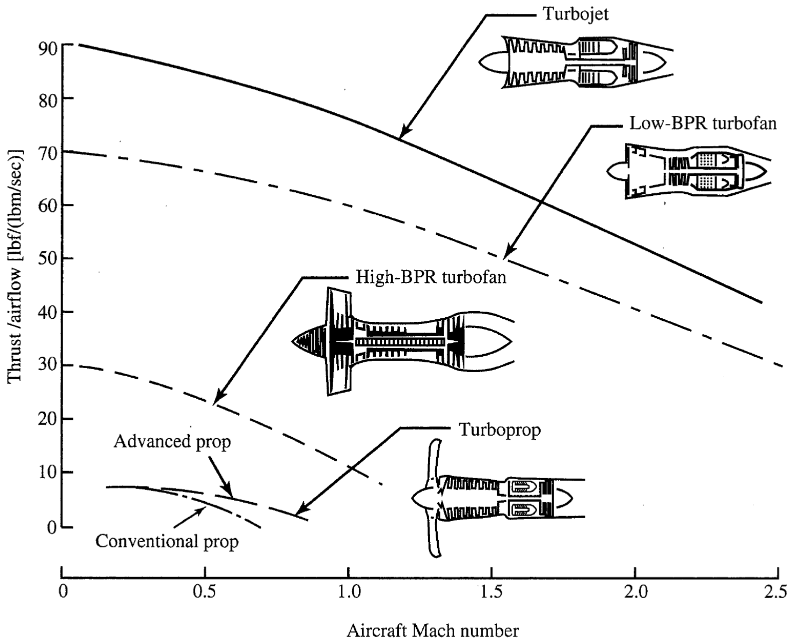

Figure 4.4: Distribution of the various possible engine types for powering an aircraft according to their specific thrust[a] and their flight Mach number, after figure 1-17a of Mattingly[56].

from isochoric to isobaric engines led to a decrease in efficiency, as illustrated in figure 4.5. Indeed, the thermodynamic cycle of isochoric combustion engines is more efficient because the combustion phase is isolated from the rest of the gas turbine cycle. In an isobaric combustion engine, a large part of the heating value of kerosene is lost in the form of heat transferred to the air passing through the engine. Nevertheless, thanks to continuous improvements, isobaric combustion engine efficiency has reached the same efficiency as that of isochoric combustion engines in the early 2000[57]. It is also important to mention that engines are not optimised for a single operating point as they have to run during different flight phases (taxiing, take-off, climbing, cruise and descent) characterised by different air intake pressures/temperatures and speeds along with different levels of thrust. Therefore, it is necessary to cruise for around two hours for consumption in the cruise phase to balance that of the other flight phases.

4.4 Aircraft systems

4.4.1 Aircraft system presentation

In addition to the propulsive functions and according to the different flight phases, an aircraft also needs to ensure additional functions, such as safety, navigation and communication. These functions are managed by different systems which require power and energy provided by the aircraft's engines. They can represent between 5 to 10 % of the aircraft's total fuel consumption. For example, for a short-haul aircraft, the systems used to manage ground opera-

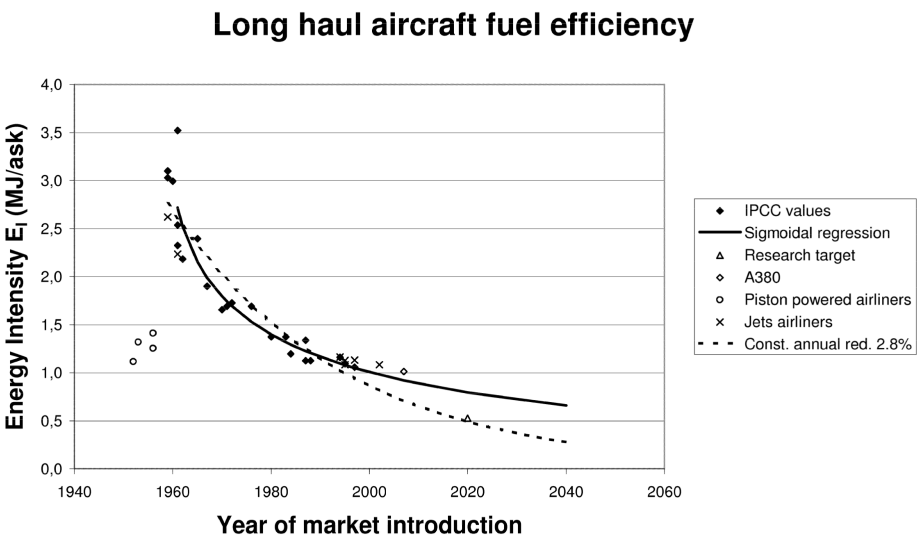

Figure 4.5: Evolution in energy efficiency (measured in MJ/seat.km) since 1950 according to Peeters and Middel[57].

tions represent around 6 % of flight fuel consumption[58]. They also represent an additional weight on-board and can create parasite drag which degrades the aircraft performances. The main aircraft systems are described hereinafter.

Flight controls

The aircraft's altitude needs to be controlled, and this is ensured by the flight control system. The flight control system itself consists of a cockpit control system (control sticks, levers, rudder bars), an avionics system (computers, bus), actuating systems and primary and secondary control surfaces. The primary flight control system consists of the control surfaces (also called flight control surfaces): the ailerons to control roll, the elevator for pitch, the rudder and related actuators for directional balance. The secondary flight control system comprises slat and flap control surfaces (high-lift devices) which enable to increase lift at low speed when deployed (take-off, descent and landing). It also includes the trim tab which ensures good balance of the aircraft throughout the flight. Airbrakes are used in symmetrical deflection to reduce lift during the descent phase, for a more rapid descent. They are fully deployed on landing, again to reduce lift in order to push the aircraft to the ground and to increase braking efficiency (by increasing drag) and thus reduce landing distance. When asymmetrically deflected, the airbrakes can also be used to produce roll in addition to controlling lift, which means that depending on the manufacturer and model, they are considered to be primary and not secondary flight controls. It is also possible to consider the propulsion system and its thrust reverser (and corresponding actuating system) as part of the flight control system as a variation in thrust induces a change of attitude for the aircraft. Flight control systems mainly use electric power for the cockpit and the avionics (relatively low) and hydraulic power for the actuators that have to counteract aerodynamic forces on the control surfaces. An overview of actuator requirements of a commercial

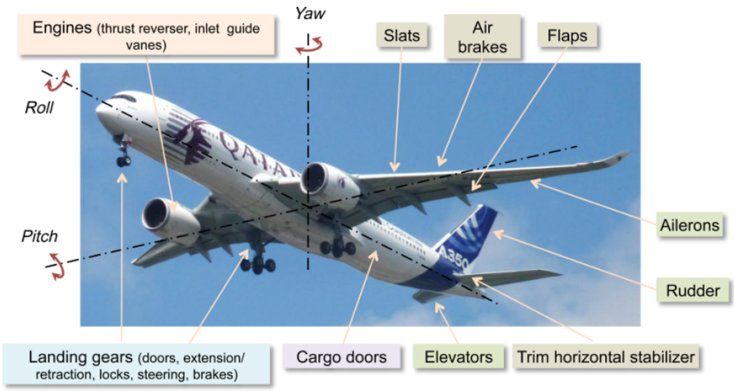

Figure 4.6: Actuation system needs of a commercial aircraft according to Maré[59].

aircraft is given in figure 4.6.

Air conditioning and ice protection

The air conditioning system (ECS for *Environmental Control System*) is another major system used to maintain a viable and comfortable environment, in terms of temperature and pressure in the cockpit and cabin, for the pilots, stewards and passengers, but also to renew the air (oxygen) efficiently. To operate, this system requires valves, compressors usually powered by pneumatic power but also fans, usually powered by electric power. On most of today's aircraft, the main part of the power required for the ECS is taken from the engines.

The de-icing system or anti-icing system is an additional system which ensures the presence of a limited quantity or even the absence of ice on different parts of the plane. For example, the airfoil leading edge is protected so as not to degrade its aerodynamic performance. In the same way, the system can be found on the inlet lip of the engine nacelle to prevent ice damaging the fan blades or degrading the aerodynamic performances of the air intake. The most commonly used technology for this system is hot air taken from a compressor stage (then partially cooled by a heat exchanger and the air taken from the secondary flow) which heats the leading edge. Another technology using pneumatic power are inflatable tubes which fracture the ice by mechanical deformation.

Power distribution and management

Next, an important function managed by other systems is power distribution and management. On most aircraft, for safety reasons, there are several hydraulic power, pneumatic power and electric power distribution systems. Hydraulic power and electric power can be provided by the engines via a power off-take equipment which convert the mechanical power on the compressor shaft of the turbofan via gear systems connected to a pump and a generator. Pneumatic power is produced by taking compressed air from an engine's compression stage. On the ground (and in the event of an engine failure), pneumatic and electric power are supplied by the auxiliary power unit (APU) generally located in the plane's tail or by connection to ground carts or to the airport's External Power. The various distribution systems contain components which distribute

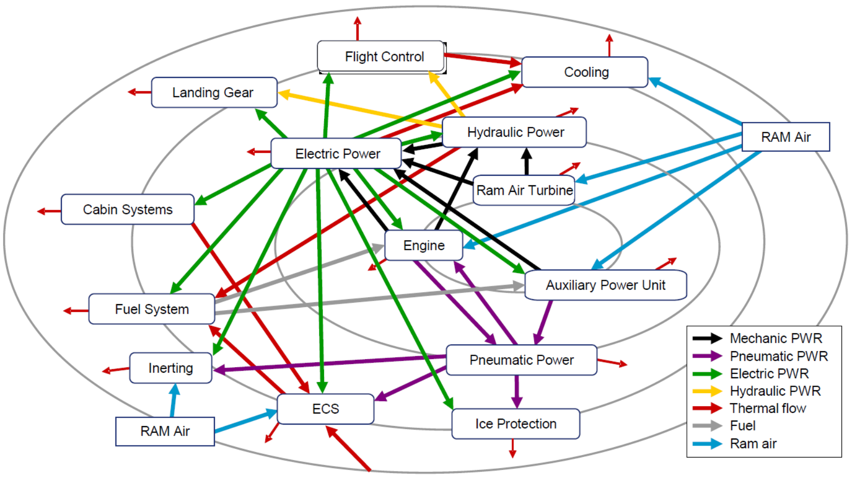

Figure 4.7: Aircraft systems and power flows for a commercial aircraft of the Airbus A320 type[59, 60].

power (hydraulic tubes, pneumatic tubes, leads and connectors) to the various systems and equipment described previously. Components to manage power and to store power (accumulators and batteries) are also necessary for ensuring stable and rapidly available power locally. Active (powered) components used to metre or regulate (hydraulic valves, pneumatic valves, electric power converters) are also necessary for adjusting power levels to the different loads (systems and equipment). These distribution systems and their components represent additional weight and their active components additional power to be supplied.

Other systems

Finally, other systems can be mentioned such as fuel systems supplying the turbojet with fuel stored in the tanks. They use components and equipment such as valves and pumps which require power and energy to operate. The landing gear system, supplied until now by hydraulic power, is used to deploy/retract the gear and to direct the front landing gear. Emergency systems can also be found on-board and represent a dead weight, such as the RAT (*Ram Air Turbine*). It is deployed to generate emergency power should power generation fail completely (turbojet and auxiliary power unit) in order to supply systems essential to an emergency landing, and to the flight control system. Finally, we can also cite commercial loads (oven, lighting, entertainment, connectivity) which represent a significant source of electric power consumption. Aircraft systems and related power flows are illustrated in figure 4.7.

4.4.2 Impact of systems on consumption

This section focuses on the non-propulsion systems. To measure the impact of systems on the consumption of aircraft it is necessary to measure their impact on the aircraft's drag, power consumption and empty weight. The main contributor to drag is the air conditioning system which requires air intakes as cold source for air/air heat exchangers. With respect to weight, the systems account for around 14 % of the empty weight of a single-aisle aircraft, therefore around 5800 kg. Concerning power consumption, total system power is around 1.2 MW for a single-aisle type aircraft, to be compared to the 20 MW power required for propulsion, therefore 5.7 % of total power. Table 4.1 summarises the weights and power of the main aircraft systems.

System	Power [kW]	Weight [kg]
Air conditioning	520	950
Airfoil ice protection	240	160
Pod ice protection	180	/
Generation and distribution (hydr.)	30	760
Generation and distribution (elec.)	50	1320
Flight controls	85	/
Commercial loads	60	/
Landing gear systems	56	/
Fuel systems	15	/
Avionics	10	/

Table 4.1: Impact of systems on power consumption (max.) and on empty weight for a single-aisle aircraft. The weights are not given for all the systems considered.

The order of magnitude of the power consumption of the systems represents the maximum values likely to be generated during aircraft operations. In reality, these values depend on the loads applied on these systems, such as for example displacement efforts and speeds for actuation systems or even temperature and pressure conditions and thermal pressure and flow for the environmental control system. These loads therefore depend on the aircraft's environmental conditions (turbulence and gusts, hot/cold day, day/night flight, etc.) as they dictate the physics responsible for loads (mechanical friction, heat exchange, etc.). These loads also depend on the aircraft's operational conditions (number of passengers, rate of climb/descent, quantity of fuel on take-off, etc.), on the flight phases as illustrated in figure 4.8 and safety requirements.

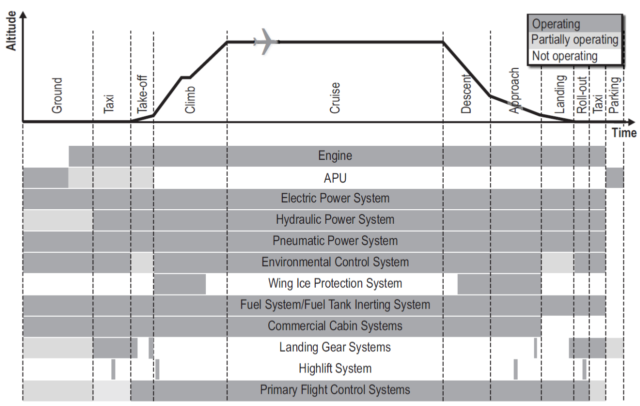

Figure 4.8: Operation of aircraft systems according to flight phases over a standard flight profile[60].

Therefore, drag and power consumption for each of these systems change significantly and their translation into fuel consumption is highly complex and directly related to operations. However, their extreme operating points can be used as design points to estimate their weight.

4.5 What is the impact of the aircraft speed on consumption?

Before introducing in more detail the ways to improve the energy consumption of an aircraft, it is interesting to evaluate the influence of flight speed V on the consumption of an aircraft. Two cases are studied here: an existing aircraft and an aircraft to be designed. Additional information on the impact of flight altitude will also be given.

4.5.1 Existing aircraft

Let us consider a given aircraft whose flight speed is reduced. Qualitatively, to balance its weight by flying at lower speed, the aircraft has to maintain its lift by playing on the terms of the equation (4.1):

- either by increasing its lift coefficient C_L, for example by increasing its angle of attack or by using high-lift devices such as flaps, which would induce an increase in drag coefficient;
- or by flying at a lower altitude where the air density is higher, which means the term ρV^2 is conserved in the equation (4.1) and which means drag remains also constant.

As a result, a decrease in flight speed cannot induce a decrease in drag D and therefore in the thrust required for the flight. Thus, a decrease in flight speed does not lead to a decrease in fuel consumption, all other things being equal[a].

An alternative analysis consists in considering the change in the two main drag components with flight speed, as illustrated in figure 4.9. On the one hand, skin friction drag increases with speed according to a dependency of $D_f \sim V^{1,8}$. On the other hand, induced drag decreases with the speed squared at leading order $D_i \sim V^{-2}$. There exists an optimal speed for which the aircraft has been designed from an aerodynamic standpoint. Therefore, flying an existing aircraft at any other speed than its optimal speed leads to an increase in its fuel consumption.

4.5.2 Future aircraft to be designed

Nevertheless the case of a future aircraft to be designed is different. Indeed, it is possible to reduce fuel consumption by flying at a lower speed if engines are changed, *i.e.* the turbofan is replaced by a turboprop. By flying at Mach numbers of around 0.6 (instead of 0.8), efficiency gains of around 20 % are possible, thanks to the better propulsive efficiency of the turboprop. As an example, a Bombardier CRJ700 (68 to 70 seats, turbofan) consumes around 5 l of kerosene per 100 pass.km, whereas an ATR 72 (68 to 78 seats, turboprop)

[a] A change in flight altitude will have an impact on engine performance.

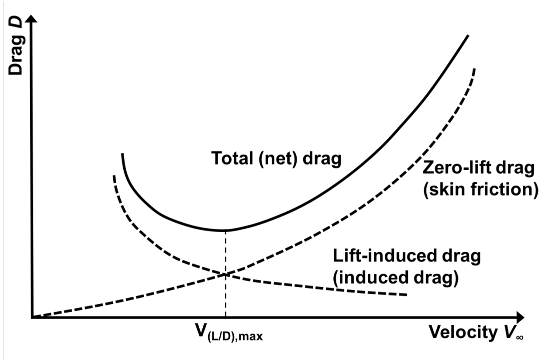

Figure 4.9: Change in total aircraft drag according to flight speed. The two main contributions to total drag are shown *skin friction drag* and *induced drag*. The figure is reproduced courtesy of Kirk[Kir11].

consumes around 3 l per 100 pass.km. For an existing aircraft, this consumption gain is cut by the increase in drag resulting from an non-optimal flight speed. However, if this change of engine type is made during the design of a new aircraft, the preliminary aerodynamic design of the aircraft will enable to combine this gain with those resulting from aerodynamics specifically designed for this flight point. Nevertheless, such a change of engine type comes with a decrease in power which restricts the maximum payload and is therefore only applicable for small or medium capacity aircraft (typically around 100 to 150 seats maximum).

4.5.3 Additional comments on flight altitude

Additionally, it is useful to spend some time discussing the flight level of an aircraft. At a given flight speed, there exists an optimal flight altitude for minimising the fuel consumption. This altitude increases as the aircraft becomes lighter by burning fuel during the flight. Flight altitude also has an impact on engine performance and on the contrail formation which occurs preferentially at an altitude between 7 km and 12 km.

4.6 How to improve aircraft efficiency?

To clarify the message, in this document, the notion of efficiency is related to fuel consumption per passenger-kilometre introduced in chapter 3. In order to identify the levers for action to be used to reduce fuel consumption, it is necessary to specify the phenomena at the origin of fuel consumption, which can be of two types. Those which are necessary to the aircraft's mission (e.g., for it to remain airborne) and those to which the aircraft is subjected to and that need to be reduced as far as possible (e.g. drag).

When cruising, the performance of an conventional aircraft can be easily estimated using the equation (4.5) of Bréguet–Leduc:

$$R = \frac{V}{g}\frac{f}{C_\mathrm{s}}\ln\left(\frac{M_\mathrm{i}}{M_\mathrm{f}}\right) \tag{4.5}$$

where R is the range, V the flight speed, g the Earth gravitational acceleration, C_s the engine specific consumption, f the lift-to-drag-ratio, M_i the total mass at the start of cruise and M_f total mass at the end of cruise. The final mass therefore corresponds to the initial mass minus the mass of the fuel M_fuel consumed during the cruise phase, *i.e.* $M_\mathrm{i} = M_\mathrm{f} + M_\mathrm{fuel}$. This formula only applies to aircraft consuming fuel and therefore does not include electrically powered or hybrid-electric aircraft, the performance of which must be evaluated otherwise[a]. The equation (4.5) can be rewritten as follows, by introducing the mass of the fuel consumed for the mission M_fuel:

$$M_\mathrm{fuel} = M_\mathrm{f}\left(e^{\frac{gRC_\mathrm{s}}{fV}} - 1\right) \tag{4.6}$$

In this form (4.6), it allows to identify three possible levers for improving aircraft efficiency, *i.e.* for reducing its fuel consumption for a given mission (for a given range R):

- improve engine performance by decreasing specific consumption C_s;
- improve the aerodynamic performance of the aircraft by increasing the lift-to-drag ratio f and to a lesser extent flight speed V[b];
- make the aircraft lighter by decreasing its empty weight (without payload and fuel) via the coefficient M_f.

In addition to these three levers, the improvement in aircraft systems weighing on engine consumption is the last area in which aircraft consumption can be significantly reduced. Indeed, these aircraft systems have an impact on consumption due to their weight, the energy they consume via the engines and the parasite drag they potentially generate.

In the past, these three levers have been addressed separately. Specific consumption of engines was an engine manufacturer's concern, lift-to-drag ratio the aircraft manufacturer concern, and the aircraft's weight the shared responsibility of all stakeholders (aircraft manufacturers and equipment manufacturers). Aircraft fuel consumption can be optimised according to two separate objectives, as per equation (4.6). Either one seek to decrease the mass of fuel consumed M_fuel for a fixed range R, or the aircraft's flight radius is increased for the same quantity of spent kerosene. In both cases, engine manufacturers will seek to reduce specific consumption C_s while ensuring the necessary thrust, whereas the aircraft designer will especially intend to minimise the value of the parameter $\frac{1}{V.f}$.

However, the different terms of equation (4.5) are not independent from one another. For example, the choice of the flight speed V imposes the choice of engine type (e.g. turboprop or turbofan) and therefore specific consumption C_s whereas integration of equipment (including the propulsion system) interacts with the aircraft aerodynamics, modifying its lift-to-drag ratio f.

[a] For an all electric aircraft which does not lose mass, another equation can be used to determine the range, see for example Gnadt *et al.*[61].

[b] Optimal flight speed defined in section 4.5 depends little on incremental improvements in aerodynamics. It is likely to be more sensitive to disruptive technology based on a change of architecture, and this point is discussed in section 5.6.

Chapter 5

Improving aircraft efficiency

As mentioned in the introduction of the report, commercial aviation is responsible for most aviation emissions. The objective of this chapter is to present leads for improving the energy efficiency of a commercial aircraft in order to reduce its fuel consumption. The chapter starts with the main "historic" areas considered to keep on improving aircraft efficiency. Here "historic" refers to incremental improvements based on small-scale changes to the current aircraft architecture which do not require any disruptive technology (engines, aerodynamics, structure, systems etc.). A last section discussing some disruptive technologies ends this chapter.

5.1 Improving engines

Improving engine efficiency, which can be measured by the decrease in specific consumption C_s, relies on gains in both thermal efficiency and propulsive efficiency, the product of which defines the thermopropulsive efficiency, see section 4.3. A gain in thermal efficiency depends on the efficiency improvement of the thermodynamic cycle via the components of the turbomachinery (compressor, combustion chamber and turbine). A gain in propulsive efficiency consists in decreasing the residual kinetic energy in the exhaust jet. The highest propulsive efficiency is reached when the difference between gas jet speed and flight speed is as small as possible. We therefore seek to generate a high air flow rate with the minimum speed difference with respect to the aircraft speed, and this is the role the fan plays in turbofan engines. The efficiency of current engines, without significant disruptive technology, can still be improved, especially by increasing the bypass ratio and the temperature at the combustion chamber outlet.

However, technological limits are being reached. For example, the materials used to make turbine blades are already highly complex (titanium alloys) but do not alone ensure blade resistance to extreme temperatures at the combustion chamber outlet (of around 1800 K to 2.000 K), which exceed the metal alloy melting temperature[62]. It is therefore necessary to cool the first stages of the turbine at the combustion chamber outlet with "cold" air from the compressor, a bleeding which reduces the efficiency of the engine[62]. It is therefore not possible to significantly increase the temperature at the combustion chamber outlet yet,

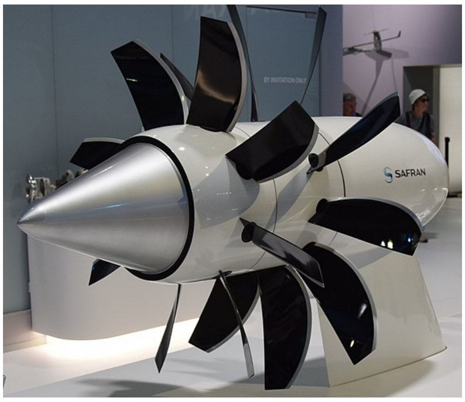

Figure 5.1: Open rotor presented at the 2017 International Paris Air Show by Safran, after wikimedia commons.

without affecting the performances of the thermodynamic cycle. In the same way, the increase in the bypass ratio faces problems such as increasing the size and weight of the engine with respect to its integration on the aircraft.

Very high bypass ratio (VHBR) and ultra high bypass ratio (UHBR) engine designs are based on the increase in bypass ratio up to around 20 (to compare to a current bypass ratio of around 10 for the latest generation LEAP or Trent engines). An increase in bypass ratio not only increases propulsive efficiency but also reduces the noise emitted by the engine, by decreasing gas jet speed. The expected gains are potentially around 5 to 10% on fuel consumption per pass.km, while reducing the noise emitted by around 7 dB, compared to the current generation[63].

It is the increase in the bypass ratio which enables turboprop engines to be particularly efficient. The (ducted) fan is replaced by an (open) propeller, which increases blade span, and thus ensures a very high bypass ratio. Therefore these engines can be used to reduce fuel consumption per pass.km by around 40%. However the propeller rotation speed, combined with the aircraft's forward speed, may induce the appearance of intense compressible effects (especially shock waves related to the presence of local regions of supersonic flow), which significantly deteriorate performances as soon as the flight speed or the size of the aircraft are increased. These engines are therefore limited to flight Mach numbers of around 0.65, lower than the flight Mach numbers reached with a turbofan (of around 0.85) but also mainly used to power 100-seats short-haul aircraft. A solution to offset this disadvantage is to ensure thrust using two contra-rotating propellers, which enables to reduce their rotation speed for a given level of thrust. These open rotor engine architectures are generally called *Contra-Rotating Open Rotors* (CROR)[64], see figure 5.1. This type of engines have a higher flight Mach number limit of around 0.75 and enables fuel savings per pass.km of around 10% to 20% compared to the best modern turbofans[65].

Although a lot more exploratory, it remains possible to improve the turbofan thermodynamic cycle, especially by using isochoric combustion, mentioned in section 4.3. These engines, called pulsating detonation engines (PDE) or rotating detonation engines (RDE) exhibit better performances than those of isobar engines, whether in terms of thermopropulsive efficiency or specific power. How-

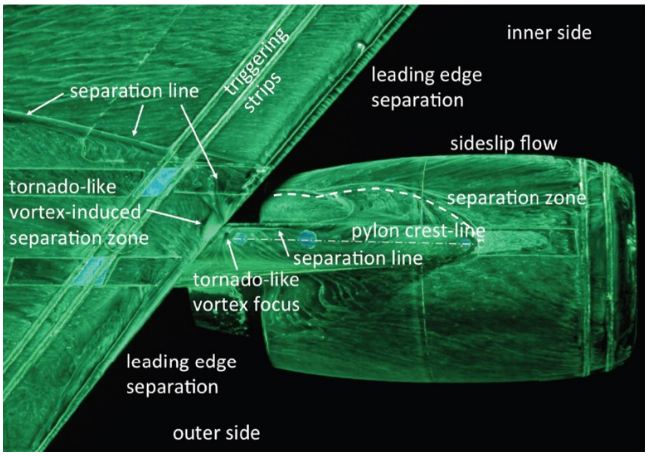

Figure 5.2: View of separation lines showing the complexity of flow in the wing area in interaction with the engine according to Bury *et al.*[68].

ever, their operation in unsteady regime requires more research efforts, in order to adapt the components downstream of the combustion chamber (the turbine in particular)[66]. Despite degraded functioning of a current turbine downstream of this type of combustion chamber, recent publications show thermal efficiency gains over the entire cycle of around 5%[67].

To conclude, future engine improvements mainly rely on larger dimensions (CROR, UHBR), which will further increase the coupling between the aircraft's aerodynamics, its weight and the engine. It is therefore necessary, now more than ever, to more effectively integrate the propulsion system within the aircraft airframe. Moreover, engine integration represents a potential source of fuel savings. Figure 5.2 shows the complexity of the flow in the case of a configuration where the engine is integrated under the wing, especially the presence of localised separations responsible for drag increase. Optimised aerodynamic design of the entire wing/engine integrated system is therefore a crucial aspect for reducing fuel consumption. Integration of propulsion systems directly on the aircraft airframe and no longer under the wing is one of the disruptive technologies considered in the next ten years (see section 5.6).

5.2 Improving aerodynamics

During cruise flight, in order to maintain airspeed (and therefore lift), engine thrust is used to compensate the drag component of the aerodynamic force exerted on the aircraft. The reduction in drag therefore has a direct influence on fuel consumption through the increase in lift-to-drag-ratio f in the equation by Bréguet–Leduc (4.6). However, gains in drag today remain difficult because air flow around a plane remains complex and difficult to predict.

For current civil transport aircraft flying at compressible subsonic speed (around Mach 0.8), there are three drag components for which significant improvements remain possible: skin friction drag, induced drag and parasite drag. Many gains have already been made in the past on aircraft aerodynamics (resulting in an improvement of the lift-to-drag-ratio f): optimisation of the shape,

Figure 5.3: Example of wing tip modification to reduce induced drag: spiroid winglet on a Falcon 50 after wikimedia commons.

lengthening of wings, better control surface design, etc. Given the different drag components of an aircraft, there are increasingly fewer avenues likely to lead to a significant improvement in aerodynamic performance, and they are mainly based on:

- design of wings operating in laminar state (reduction in skin friction drag),
- increase in wing span and modification of wing tip shape (reduction in induced drag),
- optimisation of the integration of the various aircraft components and control surfaces to reduce parasite drag related to their functioning and interactions.

Designing a wing operating with laminar flow, without changing the aircraft's speed, is a major scientific and technological challenge[69]. The advantage of a laminar regime is to reduce the dependency of wall friction on speed, by switching from a scaling of $F \sim V^{\frac{9}{5}}$ to $F \sim V^{\frac{1}{2}}$, which gives an increasing reduction in fuel consumption the higher the flight speed[70]. An order of magnitude calculation shows that, for a speed of around $250\,\mathrm{m\,s^{-1}}$, skin friction drag can be reduced by around 80% in laminar regime compared to turbulent regime. Around 20% of the aircraft total drag is attributable to the skin friction drag of the wing, the advent of laminar-flow wings[a] would therefore enable to reduce drag during cruise by around 15% maximum. A demonstrator has already been used to demonstrate the technical feasibility of extending the laminar region up to 50% of the chord: the BLADE (*Breakthrough laminar aircraft demonstration in Europe*) project especially, demonstrated an overall reduction in drag of 8%, corresponding to a gain in fuel consumption of around 5%, by implementing this technology on an Airbus A340-300[71]. However, this result could only be achieved for flight Mach number of 0.75, therefore slightly lower than the usual

[a] An laminar-flow wing is a wing for which the transition from laminar to turbulent flow is pushed towards the trailing edge. The natural transition occurs within the first few percents of the chord, close to the leading edge.

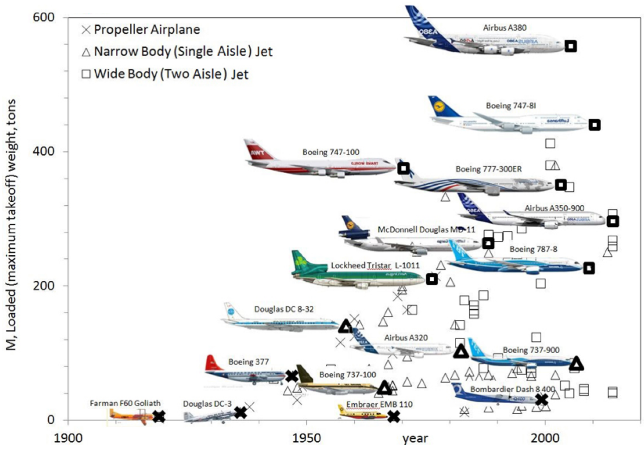

Figure 5.4: Change in maximum take-off weight of aircraft according to their year of commissioning according to Bejan *et al.*[75].

cruise flight Mach number of 0.82. A challenge inherent to the transition to laminar flow at a high Reynolds number also consists in being able to maintain this flow regime in all circumstances, including in the event of an impact and the deformation of the leading edge (even of only a few tens of millimetres) caused by insects swatted on the wing.

The induced drag, which is the other important component of the aircraft total drag, can be reduced by modifying the wing tip shape (spiroid winglet for example[72], as illustrated in figure 5.3), in order to achieve fuel consumption reductions of around 5% compared to configurations without winglet. An increase in wing span produces gains of the same order of magnitude[73], but requires to take better account of fluid/structure interactions, especially due to wing increased flexibility[74]. Whereas wing tip shape can be modified on an existing aircraft (and therefore rapidly spread out on a large scale), a change in wing span requires designing a new plane (and therefore delay substantially the time horizon for consumption gains).

5.3 Lighter aircraft

Many technological developments aim to reduce aircraft weight (optimisation of structures, composite alloys, etc.), which enable to increase the range for a given quantity of fuel, as shown in the equation by Bréguet–Leduc (4.5). However, without going in detail into the various technologies used, it appears that aircraft size and weight increase over the years as illustrated in figure 5.4, which generally contributes to improving pass.km efficiency. Indeed, despite the increasing change in total aircraft weight, when normalised by the number of seats, one can observe that it tends to decrease in a manner correlated with fuel consumption, as shown in figure 5.5.

A major contribution to a lighter structure, enabling the design of larger planes (and therefore to increase the number of seats) involves replacing metal structures by composite materials. Aeronautical structures are built by assembling a large number of parts (typically several million parts for a long-haul

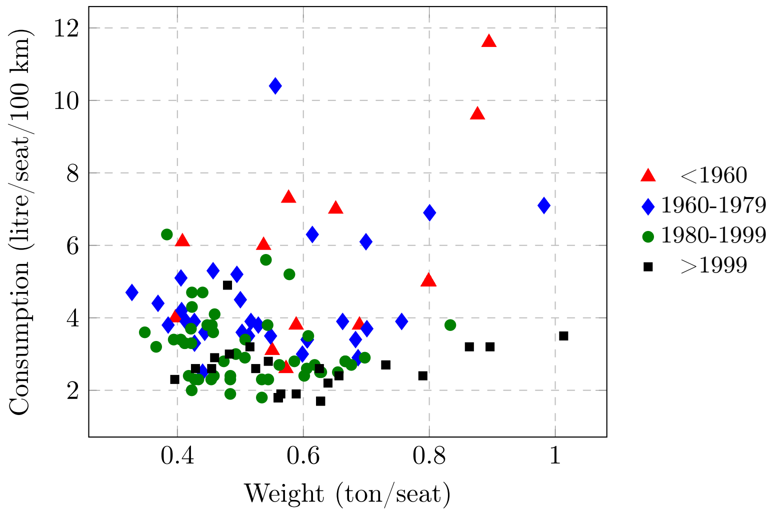

Figure 5.5: Change in fuel consumption per seat for 100 km according to aircraft weight per seat for different aircraft generations. Graph compiled from data by Bejan *et al.*[75].

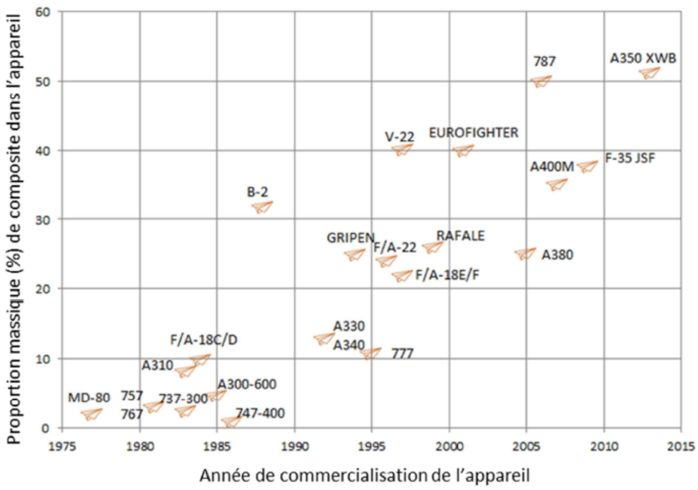

Figure 5.6: Change in the use of composite materials in aviation: weight percentage according to year of commissioning of the aircraft according to Montagne[76]. This figure contains both information on commercial and military aircraft.

airliner) connected together using mechanical fastening technologies (rivets, bolts, ...) and/or bonding technologies. To ensure reliability and durability, the preferred method is often the bolted or riveted assembly[76]. Composite materials exhibit a different behaviour from metals (breaking modes, fatigue, tolerance to damage for example). Significant research into understanding and modelling the behaviour of these materials is being undertaken to enable their more widespread deployment on aircraft. Figure 5.6 shows that most recent long-haul airliners (e.g. A350) already have more than 50% of their mass composed of composite material compared to less than 30% for airliners commissioned in the early 2000s. Weight gains can further be made through new additive manufacturing processes mainly (3D-printing), which also means fewer metal materials need to be used (nickel, titanium and aluminium). Pushed to its maximum potential, additive manufacturing can reduce fuel consumption by around 6% per pass.km[77].

5.4 Systems improvement

5.4.1 Aircraft system electrification

The improvement in non-propulsion systems mainly involves their electrification[78]. It relies on two strategies illustrated in figure 5.7. The first consists in replacing air power systems (bleed-less) by electrical systems enabling all at once, an increase in overall gas turbine efficiency, easier physical integration and streamlined maintenance. The second covers hydraulic-less aircraft design aiming to replace fluid power systems with electrical systems.

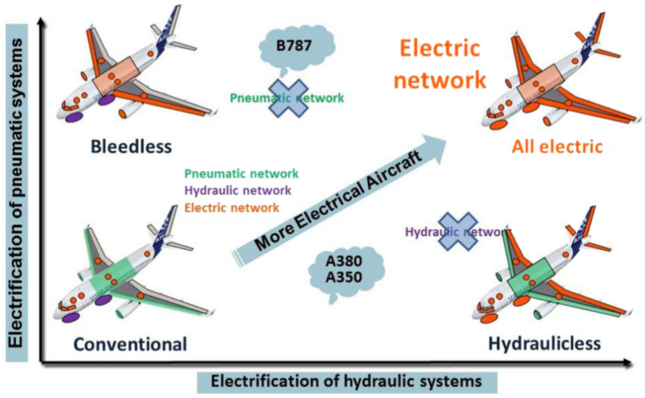

Figure 5.7: The two strategies of the more electric aircraft according to Giraud *et al.*[79].

To date, systems have only been partially electrified on the latest generation commercial aircraft but the direction taken by stakeholders is towards complete electrification with the concept of *More Electric Aircraft* (MEA). For large aircraft in particular, the primary objective is to reduce total weight while making them easier to integrate and maintain. As an example, replacing one of the fluid distribution networks by an electrical network on the Airbus A380 enabled a weight gain estimated at 500 kg[80]. This electrical network is used as a power source for certain flight control actuators and the thrust reverser actuator system. In addition, electrical systems are considered to be more environmentally-friendly than fluid systems due to removal of the Skydrol fluid[a]. The complete withdrawal of fluid equipment remains a challenge due to their performance and their ease of use for implementing certain essential functions. For example, damping must take place in the landing gear extension/retraction actuating system when a power failure occurs on its extension, in order to brake and dampen

[a]Skydrol is a hydraulic fluid belonging to the phosphate ester group. It is fire-resistant but it is known to be highly irritating to human tissue.

the impact at the end of travel (free-fall)[59]. This is done relatively easily in hydraulics by connecting a hydraulic resistance to both chambers of the cylinder. However, on electromechanical technology, this involves creating passive viscous friction in the electric motor, which is more complex and is not yet implemented on aircraft in operation.

To date, electrical system applications cover the entire range of Technology Readiness Levels (TRL), a TRL of 1 corresponding to the lowest level of readiness and a TRL of 9 to the highest). To improve gas turbine efficiency, the bleed air system (*bleed*) has been replaced by two electrically driven compressors on the Boeing 787 aircraft which has become the first commercial *bleed-less* aircraft. This same plane also includes electrification of other systems such as engine-start and ice protection system. The latter comprises electrical resistance elements which generate heat under the surface of the wing's leading edge, which promises less energy consumption than that of other ice protection technologies which use hot air from the engine. These architectural choices lead to a significant increase in the aircraft's electric power on-board the aircraft (1 MW on the Boeing 787) and therefore a significant increase in ATA 24 system weights (electric power). Nevertheless, Boeing estimates a gain of around 3% over the aircraft's overall consumption[81]. More general studies on system electrification, with an all electric aircraft for example, of which the propulsion only is managed by combustion engines, estimates a weight reduction of around 10% and a reduction in consumption per pass.km of around 9%[82].

5.4.2 Advantages of and barriers to electrification

Two serious advantages to electrification are the increase in the efficiency of the power transmission components and perhaps above all, a more efficient usage of the power. Consequently, an electrical system can almost provide just the right amount of power and energy required for the application. Indeed, the various electrical components are usually easier to equip and manage. Furthermore, new electrical distribution system architectures are currently being studied such as modular cores in order to more effectively manage power fluctuations and distribution in the various systems during a flight. These directions towards a more electric aircraft have been studied in the European research programmes MOET (*More Open Electrical Technologies*) and POA (*Power Optimized Aircraft*) but also French research programmes such as CORAC-GENOME (GEstioN OptiMisée de l'Énergie). The natural conclusion is that electrification is useful as it uses less engine power, on the condition that the associated potential increase in weight does not cancel out this gain.

Research work[83,Con09] began in the 2000s to remove the various barriers related to complete system electrification. The first research theme concerns the development of new system and equipment architectures and technologies to enable it to operate with an electrical power source. For example, the development of reliable and lightweight electro-hydrostatic actuators (EHA) and electromechanical actuators (EMA) with very long service life are being investigated for different applications such as landing gear or flight controls[84]. Electrification of the ice protection system also provides consumption gains, like for example with the Boeing 787 anti-icing system, but gains could be increased further with electromechanical de-icing systems[85]. The second concerns electric power distribution. It is present since the early days of commercial aviation, but more

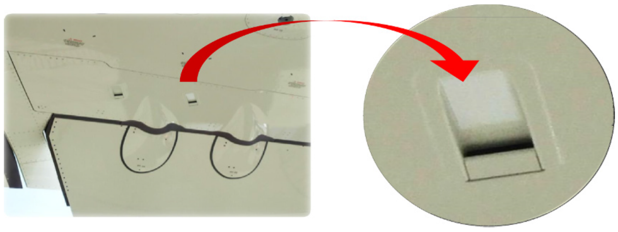

Figure 5.8: Air intake under the wing to cool the aileron actuators on an Airbus A350 according to Maré[86].

electric aircraft means there is a need for more systems using electric power and therefore an increase in the level of power the distribution system is required to generate and distribute. This increase in power requires the development of reliable high power components. For example, the wiring becomes a complex system, called the Electrical Wiring Interconnection System (EWIS), which is made up of wires, connectors, and contactors among others, and which requires a multiphysical and integrated approached to be designed.

In order to maintain a reasonable current level, and therefore a reasonable component weight, it is suggested increasing network voltage between 500 V and 1000 V. Nevertheless, this promotes electric arc and partial discharge phenomena, especially with the decrease in air pressure. The increase in the number of electrical and electronic components and power levels amplifies electromagnetic compatibility (EMC) issues. Finally, another general theme is the development of low loss and therefore high performance components, especially in terms of power electronics with wide gap components. The final goal is to reduce the power supplied by the turbofan engine and therefore consumption. This will also make thermal management of these losses easier. In effect, thermal management is a critical point in the electrification of aircraft as, unlike hydraulics or pneumatics, the losses are not transported and must be managed locally. For example, we can cite the use of air intakes to cool the relatively low power electrohydrostatic actuators on the A380 and A350 as shown in figure 5.8. It is also important to mention that the fuel system plays a crucial role in the thermal management of the propulsion system today as it provides a large quantity of fuel as cold fluid source. Switching to all electric aircraft, and therefore removing fuel and significantly increasing electric power, is a major challenge in terms of thermal management.

5.4.3 Electrification as opportunity for low-carbon ground operations

Another electrification area concerns ground operations and airport infrastructures. Ground operations also represent a source of high energy expenditure, especially for regional and medium range aircraft. A short-term solution is to perform the taxiing phases (currently engine driven) using on-board electrical systems (EGTS for *Electric Green Taxiing System*). These electric motors inside landing gear mean the engines do not have to be used (and they are inefficient at a very low speed), enabling fuel savings of 3% over a 1000 nm[a] (medium range)[87]. However, on missions during which the taxiing phase uses an insignificant quantity of energy with respect to the full flight, this system is considered to be an additional weight that is too heavy, around 400 kg[b], and too complex when weighed against the potential gains. Furthermore, as it is positioned on the landing gear, this additional weight could have a significant impact on the balance of an existing plane. Electric taxiing without increasing the aircraft's empty weight is nevertheless possible with the *taxibot* concept, a potentially autonomous electric-driven vehicle tasked with towing the aircraft between the boarding gate and the runway[88]. Other ideas in relation to system electrification could be promising, such as using the airport's electrical energy to supply not only commercial loads, before or even after starting the jet engines, but also other systems such as air conditioning. In effect, the latter is usually supplied (in air) by the APU which burns fuel to function in order to regulate the cabin temperature and ensure air renewal. This principle would be all the more promising the longer the boarding/disembarkation phases. Likewise but not related to electrification, it would be possible to generate air conditioning in the airport directly and to distribute it to the plane. The gain would be the same, except gains could also be made on the air conditioning system weight as generating cold air on a hot day on the ground is one of the sizing cases for this system.

5.5 Summary of potential improvements

We therefore have four potential ways of improving aircraft efficiency:

- engine performance (which has produced the best results in terms of efficiency to date),
- aircraft aerodynamics,
- mass reduction (via optimisation of structures and the use of lightweight materials combined with optimised manufacturing processes),
- systems improvement.

Some examples in figures can be found in table 5.1 page 85 with their TRL. They state that, disruptive technology aside, new aircraft produced by 2035 could consume between 20 and 30% less fuel per pass.km compared to the best aircraft currently (of the type A320neo). However, beyond this time horizon, it is little likely that significant gains can still be made without a major technological breakthrough.

Although not discussed in detail in this report, one should also bear in mind that improving performance does not come without constraints, for example, having to reduce the noise emitted by the aircraft[89] and to ensure its structural integrity. Complying with these constraints is often at the expense of

[a]mission. The symbol nm refers to nautical mile, a unit of length used in the aviation sector, which corresponds to 1852 m.

[b]Safran suspends electric jet taxiing project after Airbus ends talks, Reuters, 3[rd] of December 2019.

Category	Design	Year of commissioning	TRL	Fuel consumption gain
New engine architectures	Advanced turbofan	2020	8	20% (Trent 700)
	Ultrafan	2025	7	25% (Trent 700)
	GE9X	2020	8	10% (GE90-115B)
	UHBR	2025	5	5 à 10% (LEAP)
	Open Rotor	after 2025	3	15 to 20% (LEAP)
Advanced engine designs	Zero Hub Fan	2020	8	2 to 4%
Engine cycle	Adaptive and active flow control	after 2020	2	10 to 20%
	High composite content (2nd gen.)	after 2020	3	10 to 15%
Aerodynamics	Natural laminar flow	after 2020	8	5 to 10%
	Hybrid laminar flow	after 2020	7	10 to 15%
	Variable camber with new control surfaces	after 2020	5	5 to 10%
	Spiroid winglet	after 2020	7	2 to 6%
Systems	Electric taxiing systems	2021	8	3%
	Fuel cell	2020	7	1 à 5%

Table 5.1: Overview of potential technologies and anticipated gains in terms of reduced fuel consumption. For the engines, the comparative references in the last column are shown in brackets. Adapted from IATA[IAT20].

Figure 5.9: View of the *blended-wing body* design by Airbus in its programme ZEROe
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improvement in aerodynamic performance. It is one of the difficulties aircraft manufacturers have to face, namely that the actual gain in consumption from a technology is not always as significant as expected, which is for example due to reinforcement of the structure (extra weight) or thermal management (extra drag).

Last, to introduce a set of new technological improvements, a new aircraft programme needs to be launched. It usually takes 20 years between commissioning two generations of aircraft, like with commercialisation of the Airbus A320 in 1988 and its replacement the Airbus A320neo in 2016. This long time frame can be explained in several ways. It is necessary for instance to pay the considerable development costs off and to wait for a technology readiness level which will enable a performance gain of at least 15%. Development cycles in the aeronautical industry are also relatively long, typically between 5 and 7 years.

5.6 Disruptive technology: new architectures

The improvements described previously enable to reduce the aircraft consumption however the gains appear to be limited due to the extensive technological readiness of current aircraft. Disruptive innovations and technologies remain however possible to further improve aircraft efficiency substantially.

5.6.1 Modifying aircraft shape

It is therefore conceivable to radically change aircraft shape (for a generation commissioned by 2035 at the earliest), by replacing for example the standard *tube-and-wing* configuration, consisting of a fuselage, a wing and tails, with a flying wing (more precisely, architectures called *blended-wing body* for a hybrid flying wing). Unlike the *tube-and-wing* configuration, in which the fuselage makes almost no contribution to lift while making a significant contribution to the total drag, this type of configuration enable the lift generation via a

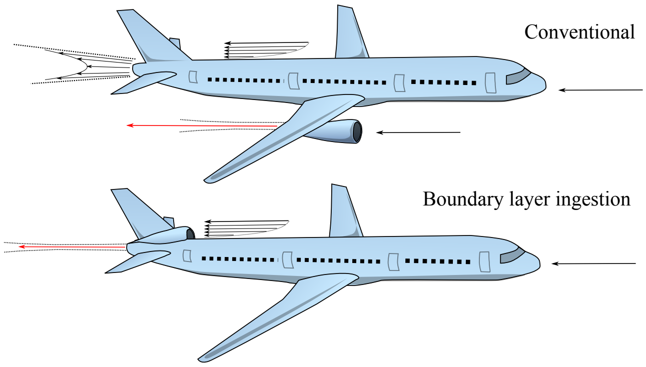


Figure 5.10: Principle of engine integration with boundary layer ingestion compared to conventional integration under the wing according to figure 4.1 by Binder[92]. The propulsion system re accelerates the fluid from the boundary layer, ideally up to the aircraft's flight speed, enabling a substantial gain both in propulsive efficiency and on drag.

single wing element, while substantially reducing the overall drag of the aircraft airframe. Beyond gains in terms of the aircraft's aerodynamic performance, this type of architecture also offers more efficient engine integration possibilities. Engines could be partially integrated in the central part of the flying wing, as shown on figure 5.9. This integration allows both to reduce overall drag (removal of mast parasite drag and reduction in engine nacelle and aircraft wake drag) but also to improve the engine propulsive efficiency. Indeed, the engine inlet flow will have been slowed upstream due to the development of the boundary layer along the aircraft. This principle, called boundary layer ingestion (*BLI*), consists in producing thrust by accelerating fluid flow from a speed lower than the flight speed. The engine exhaust flow velocity will therefore have a lower residual kinetic energy than in the case of a conventional engine architecture placed under the wing, which significantly improves the propulsive efficiency and reduces aircraft drag, as illustrated on figure 5.10. Boundary layer ingestion induces however strong distortion at the engine inlet which affects the performance of the thermodynamic cycle but which does not hamper the potential gain in fuel consumption reduction estimated between 3% and 4%[90]. This type of engine integration is not determined by a flying wing architecture and can very well be implemented on a standard *tube-and-wing* configuration. Finally, the flying wing architecture allows, for a given number of passengers, to reduce the aircraft's take-off weigh by around 15% and to increase its lift-to-drag-ratio by 20%[91]. Although it is a concept whose efficiency is still being studied, an improvement in overall energy efficiency of around 25% compared to an aircraft from the current B777 type generation seems possible[55]. Moreover, with the need to increase the dimensions of the fuel reservoir, as would be the case with liquid hydrogen fuel instead of kerosene, it should be emphasised that the aircraft's shape offers greater flexibility for distributing fuel mass than conventional architecture.

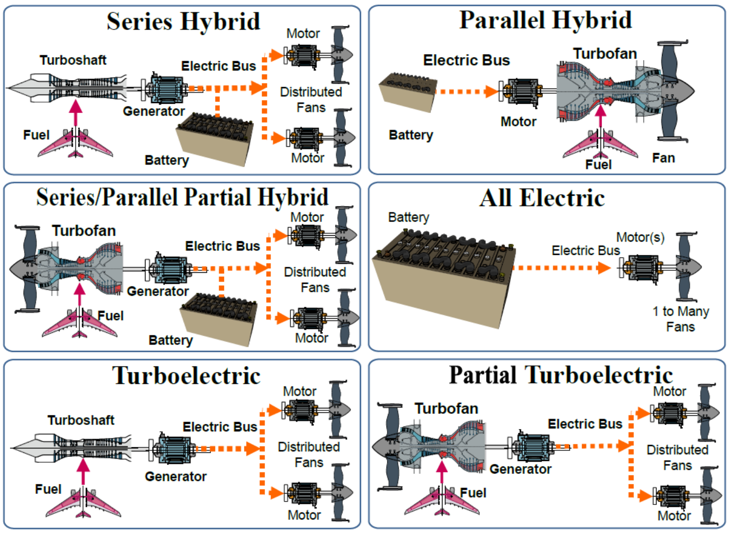


Figure 5.11: Hybrid-electric propulsion architectures.[94, Fel15].

5.6.2 Modifying aircraft propulsion

Hybrid-electric propulsion is another disruptive technology. The two main advantages sought are better overall propulsion chain efficiency and improved energy management. This makes it possible to imagine a large number of architectures, a few examples of which are given on figure 5.11. In any case, the power densities of the elements of the electrical system (engine, converters, cabling, . . .) are crucial for the viability of each of the solutions over the target range as they are likely to significantly increase the aircraft's weight. In the same way, low energy densities per unit of weight are barriers to the feasibility of solutions. For example, for an all electric (batteries), 150-seat, single-aisle aircraft, according to Epstein[93], with power densities of $12\,\mathrm{kW\,kg^{-1}}$ for the electrical system components (*e.g.* $5\,\mathrm{kW\,kg^{-1}}$ for an electric engine in 2020), it is necessary to combine energy densities for the $1500\,\mathrm{W\,h\,kg^{-1}}$ batteries (to be compared with the $200\,\mathrm{W\,h\,kg^{-1}}$ to $250\,\mathrm{W\,h\,kg^{-1}}$ for a lithium-ion battery cell in 2020) in order to achieve a range of 1000 km. Hybrid-electric architectures, using fuel, would therefore be more relevant for this category of aircraft, leaving the all electric architecture to smaller aircraft.

Switching to electric thrusters allows disruptive propulsion integrations such as boundary layer ingestion and distributed propulsion to be envisaged. Distributed propulsion can, like boundary layer ingestion, improve aero-propulsive efficiency by blowing or suction effect according to the thruster's position. This concept is also used to implement control functions such as differential thrust (*e.g.* yaw control) and thus to reduce the size of the control surfaces (*e.g.* rudder) and therefore aircraft drag.

Another potential use of electrical energy source and electric-powered thruster lies in the potential to recover energy during the descent and braking phase. Even if brake energy remains marginal compared to the energy used during the flight, the energy likely to be recovered during the descent could represent

4% to 15% of the potential recoverable gravity energy for a short-haul aircraft according to descent time and how much the propeller is used as generator[94]. However, this energy recovered by using the propeller as generator during the descent phase is believed to be less useful overall compared to a propeller operating solely to compensate for its own drag. Indeed, the increase in the cruising range due to this operating mode renders the solution less attractive[94].

Nevertheless, it is important to note that difficulties (*e.g.* thermal management) related to the increase in electric power on-board described in section 5.4 would be even greater due to the fact that propulsion system power is almost 20 times greater than that of non-propulsive systems. This is why cryogenic propulsion systems and superconductive components[95] are also envisaged in the longer term.

5.6.3 Disruptive technology assessment

At this stage, significant technological barriers remain to be removed for replacing conventional architectures with new disruptive ones. It is especially necessary to rethink aircraft design, which includes the certification process. Beyond the technological challenges, the advent of these new architectures, based on potential synergies between the various subsystems (airframe, engines and aircraft systems) also comes up against the current structure of the aeronautical industry where the clear segregation of skills (engine manufacturers, aircraft manufacturers, system manufacturers) is not compatible with a tightly coupled upstream design. These potential synergies underline the importance of developing multidisciplinary and integrated design methods and tools.

Chapter 6

Decarbonising fuel

Three ways of decarbonising aviation fuel are currently considered. They involve replacing the original fossil fuel with less CO_2-emitting alternative energy vectors: electricity, hydrogen and alternative jet fuels. It is important to underline that these are energy vectors and not energy sources. It is therefore necessary to first produce them, which can lead to efficiency losses and therefore increased primary energy needs, and also lead to additional CO_2 emissions if the production methods are not sufficiently decarbonised. These vectors are discussed in sections 6.1, 6.2 and 6.3 and their potentials and limits are discussed briefly in section 6.4. These sections are sorted by **type of energy vector on-board the aircraft**, and not by engine type. Therefore a distinction is made between electricity (section 6.1) and hydrogen (section 6.2) even if hydrogen can be used in a fuel cell to power an electric engine. Electric propulsion systems (and hybridisation solutions) were already discussed in section 5.6 and the focus here is made on energy vectors.

6.1 Electricity

We look at an all-electric aircraft which would load all of its energy in electric form, stored in batteries[a]. It is therefore an electrically powered aircraft such as those studied in section 5.6 where the advantages and limits of the propulsion system were discussed. The difference lies in the electric batteries whose specific features are discussed here.

The usefulness of an all-electric aircraft in terms of climate lies in the absence of any emissions during the flight of the aircraft because whatsoever fuel is burned, CO_2, NO_x, water vapour and non-volatile particulate matter emissions are fully suppressed, causing no climate impact during the flight. Potential emissions therefore occur during the electricity production phase and depend

[a] Another possibility is to add solar panels generating electricity on-board during a flight like the Solar Impulse aircraft by Bertrand Piccard. Even if this solar plane drew significant media coverage on its world tour, this solution is not conceivable on a commercial scale and does not fall within the scope of this report. Indeed, if the technology of the HB-SIB aircraft which flew around the world was used, more than 14 000 m^2 solar panels would be needed to power a small regional plane, which represents a surface area almost the size of two football pitches.

on the aircraft's energy efficiency (which dictates the quantity of electricity to be produced) and on the emission factor of the electricity mix. This factor strongly depends on the location of production. For example, the current carbon intensity of electricity is evaluated to 132 gCO_2-eq/MJ globally while it is 9.9 gCO_2-eq/MJ in France where electricity is mainly produced from low-carbon nuclear energy (see section 1.4).

Specific energy

The impact of batteries on energy efficiency mainly stems from the increase in the aircraft's weight induced by the specific energy of the batteries, which is lower than that of kerosene. Currently, the energy density of the best batteries is lower than 1 MJ kg^{-1}[96, 97] whereas that of kerosene is 43 MJ kg^{-1}, which implies that storing the same quantity of energy requires a weight 43 times greater. The overall impact on energy mass on-board in the form of batteries depends on other factors such as power system efficiency or aircraft weight (see below for further details). The energy density of batteries is therefore currently the limit which determines the size (number of seats) and the range of an aircraft. All-electric aircraft are today envisaged for light aircraft. With a density of 0.92 MJ/kg, Eviation plans to put an all-electric aircraft into service by 2022, Alice, which will transport 9 passengers out of 1000 km[a]. Assuming an energy density of 2.9 MJ/kg, a recent study by Gnadt *et al.*[61] estimates that an all-electric aircraft able to travel a distance of 900 km with 180 passengers would be possible. Nevertheless, current forecasts represent densities of around 1.5 MJ/kg to 2.2 MJ/kg and they may be achievable in around ten years[93, 98]. These density values would allow to produce a short-haul aircraft able to travel distances of around 500 km[93]. NASA engineers conclude that an all-electric "large transonic" aircraft will not be in service before 2045[99].

Climate impact

Even with very high specific energy density of 2.6 MJ kg^{-1}, the all-electric short-haul aircraft (800 km, 180 passengers) considered by Gnadt *et al.*[61] would be significantly heavier than its conventional counterpart, with a maximum take-off weight of 109.5 t instead of 42 t. Despite the gain in electrical system efficiency, the higher weight leads to a higher energy need: this electric aircraft needs 103 GJ of energy on-board whereas its conventional counterpart only requires 65 GJ[b].

In addition, the global carbon intensity of electricity is currently 132 gCO_2-eq/MJ whereas kerosene combustion emits 88 gCO_2-eq/MJ (including production-related emissions). For the all-electric aircraft considered by Gnadt *et al.* to become promising from a climate standpoint, one must have to wait at least until 2045 in the most voluntarist scenarios for carbon intensity of the global electricity mix to be low enough[61]. Electric aviation therefore only makes sense if low-carbon

[a] Alice specification, consulted on the 8^{th} of March 2021.

[b] The example of the Cessna Caravan illustrates this decrease in energy efficiency. In 2020, an all-electric Cessna Caravan made a thirty minute flight. This aircraft is estimated to travel 160 km with 4 to 5 passengers on-board, when the original thermal engine aircraft can travel up to 1980 km carrying 10 to 14 passengers. Sources: First Flight of MagniX eCaravan Showcases Maturity of Electric Aviation, Aviation Today, 29^{th} of May 2020 and Cessna Caravan, Cessna, consulted on the 10^{th} of March 2021.

Parameter	Unit	Value
Specific energy	$MJ\,kg^{-1}$	min 42.8
Density	$g\,l^{-1}$	775–840
Energy density	$MJ\,l^{-1}$	min 33.2

Table 6.1: Kerosene summary values, specifications for jet fuel A-1 by standard ASTM-D1655. Density is given at 15 °C: the value in $g\,l^{-1}$ is specified by the standard ASTM-D1655, the value in $MJ\,l^{-1}$ is obtained by a calculation based on previous values.

Parameter	Unit	Value
Specific energy	$MJ\,kg^{-1}$	119.96
Energy density (1 bar)	$MJ\,l^{-1}$	0.01
Energy density (350 bar)	$MJ\,l^{-1}$	2.9
Energy density (700 bar)	$MJ\,l^{-1}$	4.8
Energy density (liquid, −253 °C)	$MJ\,l^{-1}$	8.5

Table 6.2: Hydrogen summary values. Energy density is obtained by considering the specific energy indicated.

electricity is developed at the same time. Furthermore, if we only consider the short-haul sector (800 km) which only represents 5% of CO_2 emissions from commercial aviation[GZR19], we can therefore think that all-electric aircraft will only have a marginal impact on the decrease in emissions from commercial aviation.

In conclusion, a point of caution concerns the lifespan of batteries. Indeed, their intensive use, to be compared to that of a car for example, could mean they need to be frequently replaced, which may have a significant impact on the life cycle assessment of an aircraft, especially due to the mining activity generated by the extraction of lithium and the metals needed to manufacture current batteries.

6.2 Hydrogen

General information

The hydrogen plane is the solution highlighted by Airbus via its ZEROe plan[a] and supported in 2020 by the French government's recovery plan[b]. From a historical standpoint, it is a technical solution which was conceived in the 1950s as part of an American military project (Suntan project). NASA explored the concept in-depth in the 1970s, whereas a first hydrogen-powered aircraft prototype made its first flight in Russia in 1988 (the Tupolev 155).

Hydrogen (generic term which in fact refers to dihydrogen H_2) is a promising energy vector as it has a specific energy three times higher than that of kerosene (see tables 6.1 and 6.2). Therefore, 1 kg of hydrogen contains as much energy as 3.3 kg of kerosene, which means that a fuel weight three times lower would be required on-board to provide the same amount of energy. In light of previous

[a] ZEROe – Towards the world's first zero-emission commercial aircraft, Airbus, consulted on the 3rd of March 2021.

[b] Présentation du plan de soutien à l'aéronautique, Ministère de l'Économie, des Finances et de la Relance, 12th of June 2020.

Source	Type	Short haul	Medium haul	Long haul
Clean Sky[McK20]	F/T/H	-4%	+22%	+42%
Verstraete[100]	T	+18%	+5%	-12%
Renewables in transport 2050[SZWR16]	F	-10%	-10%	-10%
CRYOPLANE[Gmb03]	T	+14% to +18%	+10%	+9% to +14%

Table 6.3: Different estimations of the energy efficiency of a hydrogen plane compared to a conventional aircraft. Reading: according to the Clean Sky study, a long-haul hydrogen aircraft is estimated to consume 42% more energy than a conventional long-haul airliner. The second column shows the type of hydrogen plane considered in the study: gas turbine (T), fuel cell (F) or hybrid (H).

discussions about all-electric aircraft and the major weight problem of batteries, this is an essential advantage.

Nevertheless, liquid hydrogen energy density is four times lower than that of kerosene. For a given quantity of energy, a volume four times greater is required to store it in the form of liquid hydrogen than in the form of kerosene, which means that the aircraft architecture needs to be revised to be able to load larger tanks. Either the effective payload volume will be lower, or the architecture will be less effective from an aerodynamic standpoint but in both cases, it decreases the efficiency. Hydrogen can also be used in gaseous form but volume concerns are emphasised. Even at 700 bar, a huge pressure which requires extremely heavy tanks to resist it, hydrogen energy density is almost two times lower than that of hydrogen in liquid form. Hydrogen must therefore be stored on-board in liquid form, which means maintaining it at $-253\,^{\circ}\mathrm{C}$ in cryogenic tanks which are much heavier than kerosene reservoirs.

Fuel cell or gaz turbine

On-board liquid hydrogen can be used in two separate ways. First, via a fuel cell which performs the reverse reaction of water electrolysis and produces electricity from the combination of the stored hydrogen with the oxygen in the air. In this case, efficiency is decreased due to the electrolysis reverse reaction, but this loss is offset by using a high performance electric engine (see section 6.1). This solution is limited by the power-to-mass ratio of fuel cells.

The second way of using hydrogen is to burn it in a gas turbine. This solution means modifying current engines, for example, adding a heat exchanger to heat the liquid hydrogen or a flow regulator to reduce the fuel mass flow rate for the same engine thrust (to offset the higher specific energy of hydrogen)[Gmb03]. Finally, the two solutions can be combined in hybrid propulsion. For example, hydrogen could be used for take-off in gaz turbines able to provide the necessary power, then in a fuel cell for the remainder of the flight.

Impact on energy efficiency

The use of hydrogen therefore implies a decrease in on-board fuel mass and an increase in efficiency in the case of fuel cells. However these advantages may be potentially counter-balanced by an increase in tank weight (and possibly the propulsion system in the case of a fuel cell), a lower effective payload volume (or if not, then a reduced aerodynamic efficiency) and thermal management problems. Final energy consumption also depends on the way in which hydrogen is used, whether in a fuel cell, a gas turbine or a hybrid set-up. These different factors imply that forecasts of the impact on energy efficiency of future hydrogen planes diverge significantly from one source to another, as one can see in table 6.3. The 2020 Clean Sky study[McK20] shows that efficiency, compared to a conventional aircraft, deteriorates with range, which can attributed to the decrease in aerodynamic efficiency, whereas the article by Verstraete from 2015[100] concludes on the contrary that efficiency improves with range, especially due to the weight gain. There may be several reasons for these differences, such as the chosen architecture (tank location for example) or even the missions considered. Research remains necessary to confirm and refine these results.

Climate impact

Beyond these energy aspects, a decarbonised hydrogen production sector remains to be developed. Indeed, more than 95% of the hydrogen produced globally is currently produced from fossil energy, mainly through steam methane reforming. This is a very carbon intensive production emitting more than 12 kg of CO_2 per kilogram of hydrogen produced[101]: this is a very high emission index as illustrated by the calculations in section 6.4. Nevertheless, we can also produce hydrogen by water electrolysis. This requires electricity which, if it is produced in a decarbonised manner, may be used to produce low-carbon hydrogen. As for electric aviation discussed in section 6.1, hydrogen-based aviation only makes sense if decarbonised electricity production is developed at the same time.

Hydrogen production aside, a hydrogen-powered aircraft can generate climate impacts during flight. In the case of a fuel cell, which also has to be made, it only generates water and its climate impact depends on the atmospheric conditions in which it is discharged. The case of hydrogen used in a gas turbine is different. Hydrogen combustion continues to generate NO_x and water but other emissions (CO_2, SO_x, soot) are removed. There are more water emissions which promote the formation of contrails, but potentially induced cirrus have different microphysical and optical properties which are thought to decrease radiative forcing compared to cirrus induced by combustion engine contrails. Taking these two effects into account, Ponater *et al.*[102] conclude on a decrease in radiative forcing of around 20%, *i.e.* the climate impact of hydrogen-powered aircraft contrails is around 20% lower than that of a conventional aircraft. They also study scenarios for transition to a fleet of hydrogen-powered planes with gradual commissioning of such planes from 2015–2020, and come to the conclusion of a reduction in climate impact of between 15 and 50% by 2050, in a context of a rise in traffic. With regard to this hypothesis as to the date of commissioning, it is interesting to note that Airbus in its plan ZEROe, and Clean Sky in its last report, foresee them coming into service between 2030 and 2040.

Other aspects

Finally, although we do not address this question, safety is a significant challenge where hydrogen is concerned, especially due to the risk of leaks, flammability and detonation. Establishing safety regulations and standards, a process which was already set in motion at the European Organisation for Civil Aviation Equipment (EUROCAE), is a necessarily long and complex one. In the same way, there are also concerns with respect to hydrogen refuelling, storage (potentially cryogenic) and distribution on the ground (requiring infrastructures).

6.3 Alternative jet fuel

6.3.1 General information

The kerosene currently used in aircraft is produced by refining crude oil directly extracted from geological reserves: it is therefore of fossil origin. The fossil kerosene the most commonly used in aviation, jet fuel A-1, is a mixture of several chemical compounds called hydrocarbons. A hydrocarbon is an organic compound consisting exclusively of carbon and hydrogen atoms which form a chain (possibly with cyclic structures and/or double bonds) and takes the generic chemical formula C_nH_m where n is the number of carbons. More than 70% of the mass of jet fuel A-1 is made up of hydrocarbons with only single bonds[a] with a number n of carbons between 9 and 16[RFL+17]. Moreover, at most 25% of the mass of jet fuel A-1 is made up of aromatics.

Several conversion processes can be used to produce alternative kerosene from sources of carbon and hydrogen, the main ones being presented in figure 6.1. In this report, we will call **alternative jet fuel** (AJF) a kerosene obtained by such a process and without fossil carbon **as input**[b]. As it will be seen, this does not mean that they are not associated with emissions of fossil carbon, as such emissions associated to their production can occur. Nonetheless, if these emissions are sufficiently small, they can reduce the aviation CO_2 effects. Figure 6.2 is a bibliographic compilation on the emission factors for various AJF which will be introduced next. Furthermore, biofuels (AJF using biomass as input, see below) emit fewer non-volatile particles[103], which, according to recent preliminary results, seems to reduce the formation of contrails and therefore non-CO_2 effects. AJF are therefore also considered to reduce non-CO_2 effects, see section 7.1.2 for further details.

Because the chemical composition of AJF is very similar to that of fossil kerosene, they can be used, possibly mixed with fossil kerosene, in today's aircraft. For this reason, these fuels are referred to as *drop-in* fuels. It is a considerable advantage compared to the other decarbonisation solutions presented previously (electricity and hydrogen) which require significant technological developments which delay their use. Nevertheless, to date, legislation still requires

[a]They are therefore either alkanes, with chemical formula C_nH_{2n} and which do not have a cyclic structure, or cycloalkanes, with the chemical formula C_nH_{2n+2} and which have one cyclic structure.

[b]Many denominations can be found in the literature, such as renewable jet fuel or sustainable aviation fuel. However, they lack a clear definition. For instance, ICAO lists nine conversion processes that have been approved for SAF production, two of which use fossil carbon (petroleum) as input, see the ICAO's Conversion processes webpage, consulted on the 20th of April 2022.

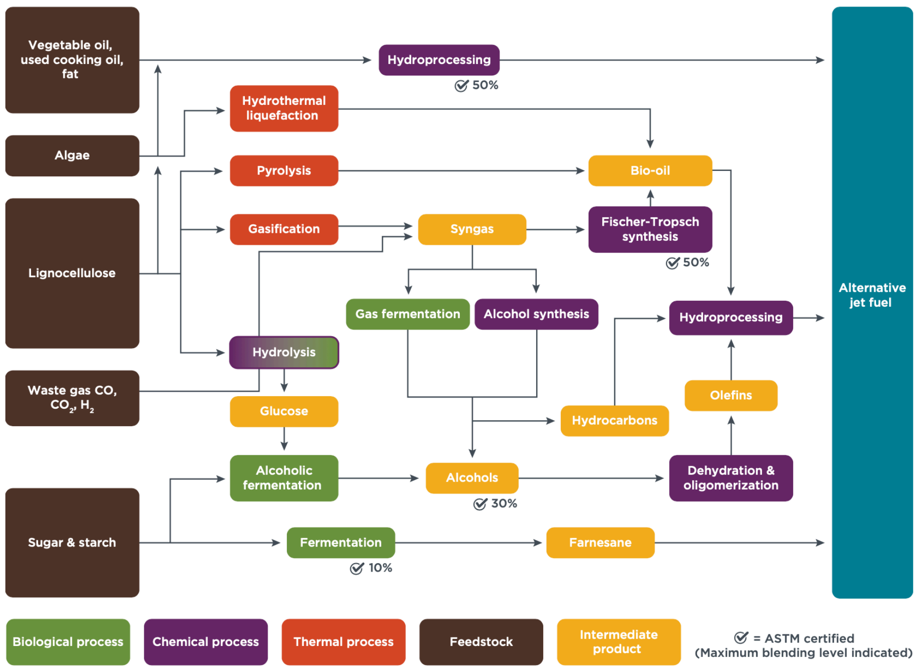


Figure 6.1: Main AJF production processes according to raw material. First generation biofuels are produced from oils, sugar and starch; second generation biofuels from lignocellulose; third generation biofuels from algae and electrofuels from CO_2 and hydrogen. According to figure 2 by El Takriti *et al.* [OPS21].

that these AJF be mixed with fossil kerosene, the incorporation rate representing the share of AJF in the final fuel. Seven conversion processes without fossil input are today certified by the ASTM International[a] D7566 standard[b]: five conversion processes for producing fuel with a maximum incorporation rate of 50% and two processes with a maximum incorporation rate of 10%. This legislation is subject to change, Boeing having recently conducted tests with 100% drop-in fuel[c], which could require to modify certain systems on today's planes.

In this report, we will classify AJF into two types, depending on the carbon source used (and which ultimately dictates the energy source required for its production, namely biomass or electricity):

- if the carbon source is biomass, it is called **biofuel**[d]. This is the set of conversion processes illustrated in figure 6.1 except for those which use gas as raw material (*Waste gas CO, CO_2, H_2*);
- if the carbon source is CO_2, it is known as **electrofuel** or **efuels**[e] as this CO_2 is combined with the hydrogen produced by water electrolysis. These

[a]ASTM International is the standardisation body which certifies aviation fuels.
[b]Conversion processes, ICAO, consulted on the 21st of January 2021.
[c]Ugo Viens, Boeing opts for 100% renewable fuel, IE portal, 26th of January 2021.
[d]These fuels are sometimes called *Biomass-to-Liquid*, BtL.
[e]The terminology electrofuels and efuels is sometimes used in a broader sense to cover all fuels produced from electricity, liquid or gas, and in particular hydrogen produced from electrolysis. The electrofuels in this report therefore correspond to fuels commonly referred to as *Power-to-Liquid* or PtL.

Figure 6.2: Greenhouse gas emissions of different AJF (including electrofuels, under the name PtL). The solid circles include LUC (*Land Use Change*) emissions, the empty circles do not include them. After figure 3 by El Takriti *et al.*[OPS21].

Raw material	Possible conversion processes
Vegetable oils	HEFA, CH
Sugar/starch	ATJ, APR, DSHC
Lignocellulose, waste	FT, LTJ, HDCJ (HTL)

Table 6.4: The vegetable oil conversion processes (excluding used cooking oils) and sugar and starch conversion processes are those which use plant storage organs and produce first generation biofuels. Second generation biofuels use lignocellulose, waste and used cooking oils. HEFA: Hydrogenated esters and fatty acids; CH: Catalytic hydrothermolysis; HDCJ: Hydroprocessed depolymerized cellulosic jet; HTL: Hydrothermal Liquefaction; FT: Fischer–Tropsch; LTJ: Lignin to jet; DSHC: Direct sugar to hydrocarbons; APR: Aqueous phase reforming; ATJ: Alcohol to jet. According to Wei *et al.*[104].

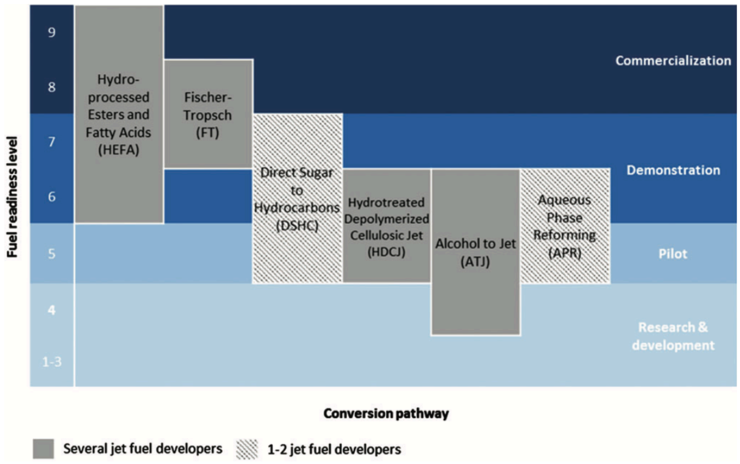


Figure 6.3: FRLs for different conversion processes. According to figure 2 by Mawhood *et al.*[105]

AJF are produced from CO_2, water and electricity. In figure 6.1, this is the conversion process which uses gases as raw material.

6.3.2 Aviation biofuels

Production processes

Biomass refers to all organic matter that can be converted into an energy vector which can be used for human activities. There is the vegetation biomass (food residues, wood, leaves) and the animal biomass (e.g. animal fats). This organic matter is made up of water and high-carbon material and therefore contains the elements necessary for producing fuel (carbon and at least part of the hydrogen), also called biofuel. Several conversion processes, shown in table 6.4, are possible depending on the raw material. They have different readiness levels as shown in figure 6.3 which presents their FRL (*Fuel Readiness Level*).

Plants store the energy in their storage organs: cereal or oil seeds, beet roots, oil palm fruits for instance. First generation biofuels are those which exploit these storage organs to convert the energy they contain in the form of liquid fuel.

There are two different conversion processes according to the way in which the plant stores energy. Either the plant stores energy in the form of carbohydrates (sugar or starch, which is the case for corn), or in the form of lipids (this is the case of canola, sunflower, palm oil and to a lesser extent soybean). In the first case, the conversion process aims to convert the sugars into kerosene (*Sugar & starch* processes in figure 6.1), and in the second case, to extract oil and then convert it into kerosene (*Vegetable oil* processes in figure 6.1).

Second generation biofuels use the plant's lignocellulose material, *i.e.* the material composing its structure: corn stalks for example in the case of agricultural residues, or wood. In figure 6.1 these are *lignocellulose* production processes: agricultural and forestry residues, specific energy crops (especially miscanthus and switchgrass for herbaceous plants, and willow and poplar for woody plants) and solid municipal waste. This category also includes biofuels produced from used cooking oils and animal fat (*Used cooking oil, fat* in figure 6.1). They do not come directly from plant storage organs, which creates some grey areas in this classification between first and second generation. Except when the raw material is oil or fat, these second generation biofuels are called **synthetic fuels** because, as it will be seen below, their conversion process involves a gasification step which separates atoms of carbon and hydrogen which are recombined through the Fischer–Tropsch synthesis reaction[a].

Third generation biofuels mainly rely on the use of micro-organisms such as micro-algae (*Algae* production processes in figure 6.1).

Raw material production and availability

For the aviation sector, only first generation biofuels produced from canola, soybean or palm oil have today reached a significant level of industrial production. For the transport sector more generally, 154 billion litres of biofuel were produced in 2018, a significant portion of which is ethanol produced from sugar and cereal crops. These 154 billion litres represented 3.4% of consumption in the transport sector[IEA19b], and 0.01% of this production (therefore 15 million litres) were aviation biofuels. These 15 million litres represented 0.004% of global aviation consumption in 2018[b].

Biofuels for aviation produced to date are mainly of the HEFA type (see appendix C) and produced from vegetable oils (from dedicated palm oil or canola crops, or used cooking oils) and animal fat[Ern17]. Neste, the largest producer of aviation biofuel, claims it can reduce greenhouse gas emissions by 80%. Nevertheless, at this time, production is based partly on palm oil and poses a number of socio-environmental problems condemned by environmental associations[KH20].

As it will be seen further, HEFA type fuels can be useful from a climate standpoint if they are produced from certain raw materials such as used cooking oils. Nevertheless, the source of these materials is limited[106, 107] (e.g. around 1 EJ for cooking oils[106], whereas aviation used around 14 EJ in 2018) which justifies

[a]Because electrofuels also involve a synthesis step to combine atoms of carbon and hydrogen, electrofuels also fall into the category of synthetic fuels, see section 6.3.3.

[b]According to the IEA, 15 million litres of aviation biofuels were produced in 2018[IEA19b] and commercial aviation consumed 337 Mtep of energy, which corresponds to a volume of almost 400 billion litres and therefore a ratio of 0.015/400≈0.004%. The ICAO estimates the production to 6.8 million litres of biofuel in 2018[ICA19c], which would thus represent less than 0.002% of consumption.

the development of other production processes, especially through the Fischer–Tropsch process, which can use raw materials with potentially larger source such as bioenergetic lignocellulose crops or agricultural and forestry residues[106,107]. This process has a lower yield than HEFA (around 40% for Fischer–Tropsch compared to 75% for HEFA[104,108–110]) and further accentuates the pressure on biomass resources[108]. Here, yield is defined as the ratio between the lower heating value (LHV) of the output fuel to the LHV of the input biomass. This definition does not take into account the additional energy required by the system to produce the biofuel. It is useful for evaluating the quantity of biomass required to produce a given quantity of biofuels. Note also that this yield is computed by considering the total output fuel: yet, the end product in the Fischer–Tropsch and HEFA pathways consists of a mixture of hydrocarbons of different lengths, only a single part of it being useful for aviation (the kerosene part). Selectivity is thus defined as the percentage of end product that can be used for aviation, which varies between 25 and 70%[111,112] (see appendix C). The choice of selectivity depends on the type of target fuel, mainly diesel or kerosene. As there are more prospects for diesel today, the selectivity (of kerosene) is in practice fairly low.

The Fischer–Tropsch process is well mastered, but only from fossil raw material (coal and natural gas). This production process was developed by Germany during the Second World War. From lignocellulose however, it is at the industrial demonstrator stage with an FRL of 7/8[105,113,114]: the BioTfueL project aims for example to have demonstrated the technology in 2021[a]. Third generation biofuels are currently at lower FRL.

Life cycle assessment and greenhouse gas emissions

Evaluating greenhouse gas emissions related to biofuels is tricky (see especially the significant variations in figure 6.2) and is a subject which is actively discussed within the scientific community. It requires a detailed life cycle assessment while considering the following three emission sources and sinks:

A/ biofuel combustion;

B/ biofuel production;

C/ land use change.

A/ Biofuel combustion. Combustion of a biofuel is usually considered as neutral in terms of CO_2 emissions. The reasoning is that the carbon released into the atmosphere by combustion is of vegetal and not of fossil origin: therefore the CO_2 released into the atmosphere by combustion of a biofuel has previously been absorbed by the plant material from the atmosphere by photosynthesis, where it is therefore released after having been converted into kerosene and then burned.

It is important to realise that this reasoning is based on a carbon accounting convention and not on a physical reality. Indeed, from a pure climate point of view, only carbon fluxes to and from the atmosphere matter. Combustion of a biofuel emits approximately as much CO_2 as a fossil fuel, and absorption

[a] BioTFuel: towards development of 2nd generation biofuels, Total, consulted on the 21st of February 2021.

of the CO_2 by the biomass is independent of the use which will be made of it. Furthermore, the carbon captured by the biomass is not physically the one emitted during the combustion.

This convention has advantages, but also involves carbon accounting error risks which were widely discussed in the scientific literature[115–118], by the scientific councils of European[Com11] and American environment agencies[Boa12] and by the IPCC[SBA+14]. Creutzig *et al.* [119] explain that "the neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories [...]. Carbon neutrality is valid if the countries account for LUC in their inventories for self-produced bioenergy"[a].

In fact, the "neutrality" of combustion can only be justified by comparing the net carbon flux in two cases: one case with combustion of the biofuel and one case without combustion of the biofuel. This alternative scenario is called a *counterfactual* scenario[b]. Neutrality is therefore justified if the net CO_2 emissions balance is the same in both cases. Therefore, as biofuel combustion emits CO_2 into the atmosphere which would not otherwise have been emitted in the absence of the said biofuel, this emission has to be offset by **additional** absorption, *i.e.* which would not have been present without the biofuel (this is called **additionality**). This is the meaning of the word "uptake" in the following citation from the IPCC, which concerns bioenergy in the general sense but also applies to the specific case of biofuels [SBA+14, p 877]: "if bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils". For example, if we take a situation without biofuel in which the biomass is produced at a given location (counterfactual scenario), and then, all other things being equal, we use this biomass to produce biofuel, then the neutrality hypothesis is not justified since we only added an emission flux without creating additional absorption[115].

The previous citation by the IPCC clearly shows that considering combustion neutral does rely on an offset principle. An emission at a given time and place is offset by an equivalent absorption, possibly in another place and at another time. However, since additionality is based by definition on a scenario which will not take place (the counterfactual scenario), it is impossible to guarantee it and only its likelihood can be estimated. This problem tends to be underestimated as it was highlighted in a study on offset projects from the *Clean Development Mechanism* by the UN, which showed that 85% of the planned projects had a low probability of being additional[CHF+16].

For combustion to be considered as neutral, it is therefore necessary for the biofuel life cycle to be analysed according to a rigorous and exhaustive method. As illustrated by the example of additionality discussed above, the most delicate point is understanding the influence of biofuel production on emissions related to land change use, which will be discussed further.

[a] The full original citation follows: "The neutrality perception is linked to a misunderstanding of the guidelines for GHG inventories, e.g., IPCC – Land Use, Land-Use Change and Forestry (2000) states "Biomass fuels are included in the national energy and carbon dioxide emissions accounts for informational purposes only. Within the energy module biomass consumption is assumed to equal its regrowth. Any departures from this hypothesis are counted within the Land Use Change and Forestry Model." Carbon neutrality is valid if the countries account for LUC in their inventories for self-produced bioenergy".

[b] There is in fact a subjective choice to be made about it, for example, a trend-based counterfactual scenario or a counterfactual scenario considering other possible futures.

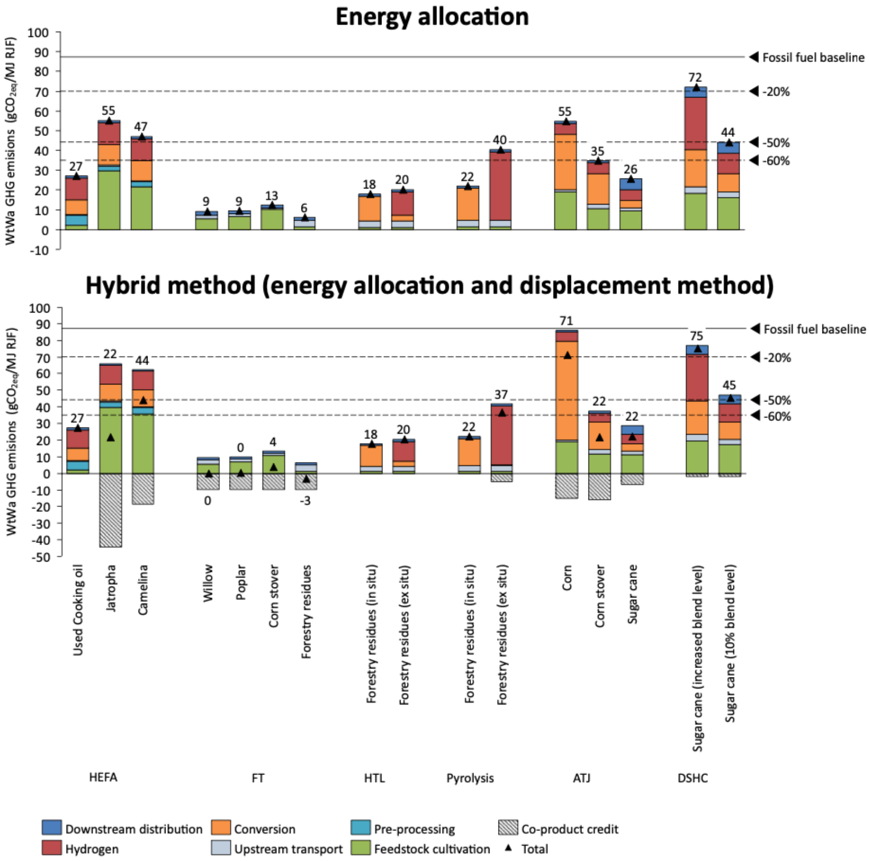
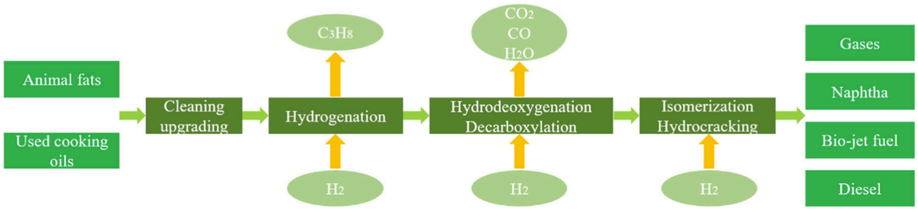
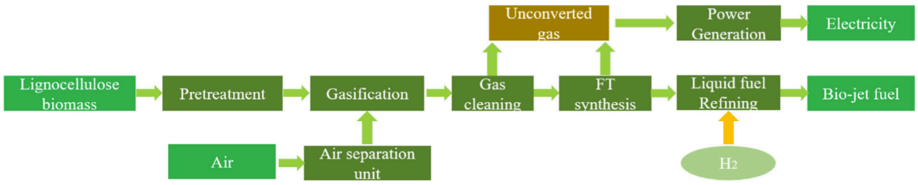


Figure 6.4: Greenhouse gas emissions from biofuel production. According to figure 3 by de Jong *et al.*[120].

B/ Production. The second area of biofuel emission is their production. This includes culture and transport of the biomass as well as production, transport and distribution of the biofuel. Emission factors for different production processes and different raw materials are illustrated in figure 6.4. One can see three main areas of emission: cultivation (especially for biofuels from corn or sugar cane), conversion of the biomass into biofuel, and finally hydrogen production. Indeed, most production processes (with the noticeable exception of Fischer–Tropsch) need hydrogen to convert the biomass into fuel, for example where a hydrogenation phase is required to break the double bonds between carbon atoms. This figure also illustrates that the emissions allocated to a biofuel depend on the methodology used for the life cycle assessment, which determines the way in which coproducts are treated. It can be seen in figure 6.5 that products other than kerosene are created during its production, which are fuels with other levels of refining, or even electricity in the case of Fischer–Tropsch. Figure 6.4 shows that second generation biofuels produced by the FT process from short rotation crops or from forestry residues have the lowest greenhouse gas emissions, of around 6 gCO_2-eq/MJ to 10 gCO_2-eq/MJ.



(a) HEFA process.



(b) FT process.

Figure 6.5: Details on the HEFA and FT processes. According to figures 1 and 4 by Wei *et al.*[104].

C/ Emissions induced by land use change. Two types of emissions related to land use change are conventionally distinguished:

Direct land use change (DLUC) is conversion of any land (forest, food crop, etc.) to grow raw materials for bioenergy, leading to a variation in the carbon store in this land;

Indirect land use change (ILUC) occurs when land is converted somewhere in response to an increase in bioenergy cultures somewhere else. Although ILUC cannot be measured or observed directly, it can be assessed using models.

To take a practical example, if a wheat field is replaced by a field of miscanthus, in response to which a forest is cut down to grow wheat, replacement of the wheat field is counted in DLUC emissions and replacement of the forest in ILUC emissions.

LUC emissions (DLUC + ILUC) take into account[121,EE15]:

- natural vegetation: carbon in above and below ground living biomass for forest, pasture, cropland pasture (including dead wood, litter, understory, litter, and harvested wood products for forests);
- agricultural biomass: carbon changes in agricultural biomass including above-ground and below-ground (root and rhizome) biomass;
- soil organic carbon: carbon changes in soil;
- oxidation of peatland: soil emissions from peatland drainage in Indonesia and Malaysia[a];

[a]These emissions can be included in soil organic carbon, but can be separated given their potential importance.

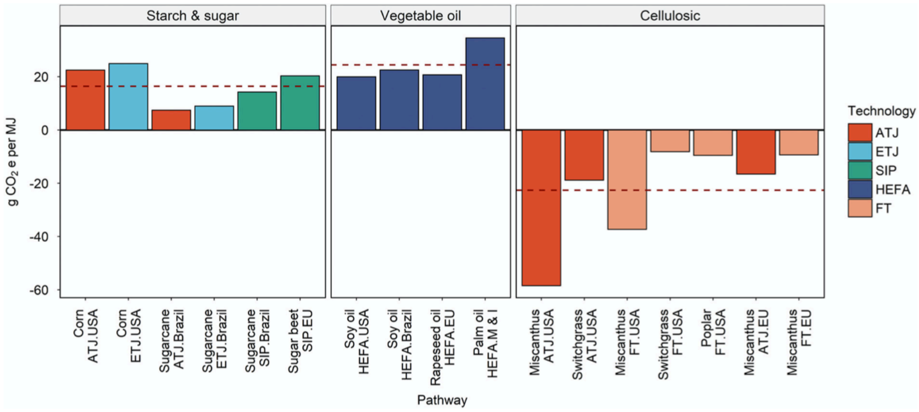


Figure 6.6: Biofuel LUC emissions with a 25-year amortisation period, after figure 2 by Zhao *et al.*[121].

- unused cropland: unused cropland may have carbon stock in the natural vegetation grown on the land, and it may have higher carbon sequestrated in soil compared with the cropland under cultivation. Thus, there could be land use change emissions from bringing unused cropland back to production;

- foregone sequestration: foregone sequestration from converting forest. It assumes that forest if not converted can still sequestrate carbon at a certain rate.

When all these terms are accounted for, biofuel combustion can be considered neutral, as previously discussed.

Also, estimating LUC emissions means fixing a time scale. Indeed, several of the emissions described above only occur once, for example like carbon released from peatland converted into an energy crop. This instantaneous emission therefore has to be spread over a time scale which must be set subjectively. The resulting estimation therefore necessarily reflects value judgements[SBA+14]. Finally, this subject will not be discussed in detail, but the temporality of emissions and absorptions is just as important. For example, emitting CO_2 which will only be offset in 20 to 30 years exacerbates the global warming problem which is also a short-term problem. In the case of biofuels, this problem can for example arise for lignocellulose crops which, even for short rotation crops, take many years to grow. The *dynamic* life cycle assessment was notably developed to take this problem into account[122].

The value of LUC emissions induced by the production of biofuels is a subject actively considered in the scientific literature[123–125,EE15,SWH10]. In this report, values reported in the recent article by Zhao *et al.*[121] are presented. They are summarised in figure 6.6 which completes, for biofuels, figure 6.2 by including miscanthus. It can be seen that first generation biofuels have positive LUC emissions, between 10 gCO_2-eq/MJ and 35 gCO_2-eq/MJ, whereas second generation biofuels have negative LUC emissions, up to almost -60 gCO_2-eq/MJ in the case of the ATJ production process from American miscanthus. These negative emissions indicate that these crops store carbon in the soil as they grow. Nevertheless, this effect is brought to cease once the land is saturated

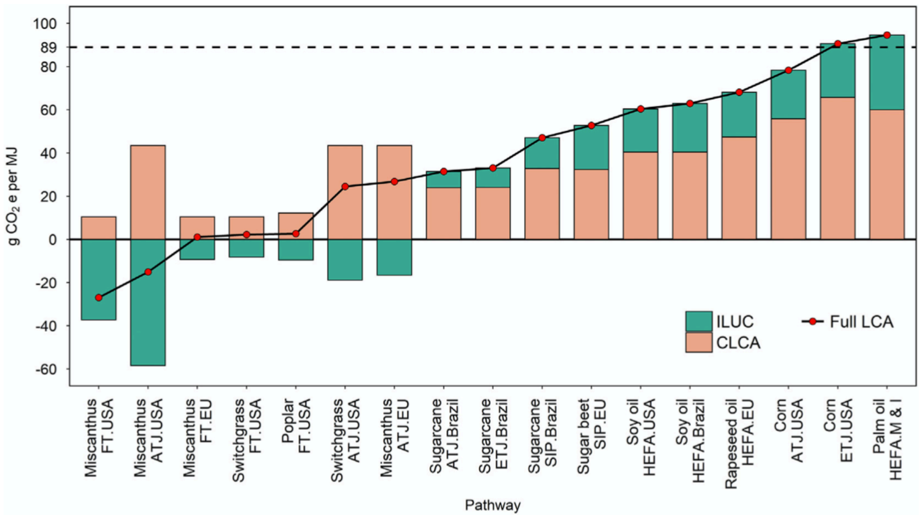


Figure 6.7: Total biofuel emissions including LUC emissions in figure 6.6. For these calculations, a 25-year amortisation period is considered for LUC emissions. According to figure 6 by Zhao *et al.*[121].

with carbon, which can take around twenty years, depending on the initial state of the soil[126].

Figure 6.7 shows the total emissions related to biofuels, when emissions related to production and LUC emissions are taken into account. The best production process is the FT process using miscanthus, which has negative global emissions. Out of the 17 conceivable production methods, the 7 best methods are the FT or ATJ process, from miscanthus, switchgrass or poplar, with emission factors ranging between $-28\,\mathrm{gCO_2\text{-}eq/MJ}$ to $30\,\mathrm{gCO_2\text{-}eq/MJ}$.

It can also be noted that certain first generation biofuels can be beneficial from a climate standpoint, the ATJ production process using Brazilian sugarcane emitting $30\,\mathrm{gCO_2\text{-}eq/MJ}$. These crops sparked off a debate on competition with food resources which led the European Union to limit their share in final energy consumption to 7% in the transport sector in 2018[a]. They continue nevertheless to be actively developed in countries where space is in theory a less limited resource, such as Brazil[b] or the United States. Second generation biofuels reduce these problems since they can be grown on land unfit for first generation crops. Nevertheless, they do not fully remove the pressure on the best croplands since their yields depend on soil quality[128].

Uncertainties

We end this section by mentioning the strong uncertainties weighing on the estimation of related greenhouse gas emissions. On the one hand, these emissions depend on many factors such as the location in which the biomass is grown, as

[a]Press release, Energy: new target of 32% from renewables by 2030 agreed by MEPs and ministers, European Parliament, 14th of June 2018.

[b]Despite that, the pressure on land is one of the main reasons for deforestation of the Amazon rainforest. One can cite for example the article by West *et al.*[127] which underlines the failings of offset programmes aiming to protect the Amazon rainforest.

can it be seen in figure 6.7 which specifies the origin of the raw materials. On the other hand, estimating ILUC emissions uses models based on observations of past economic responses to predict which land will be affected by land use change, which induces great uncertainties due to the large number of hypotheses considered, the potential differences between the scopes covered, and questions of local governance. According to Plevin *et al.*[129], these uncertainties are epistemic and cannot be reduced in the future. It is therefore always necessary to report value ranges.

6.3.3 Electrofuels

Electrofuels are AJF whose carbon derives from carbon dioxide. This carbon dioxide reacts with the hydrogen produced by water electrolysis to form kerosene which we thus call electrofuel, the prefix electro- referring to the fact that electricity is the only energy source required to produce these fuels. As it will be seen, this electricity is necessary for water electrolysis and possibly for capturing atmospheric CO_2.

Origin of CO_2

Carbon dioxide can come from two sources: from the atmosphere (which is known as DAC for *direct air capture*) or from one-off industrial sources emitting CO_2 such as coal plants, cement works or steelworks. CO_2 can indeed be produced by several industrial processes such as calcination, fermentation and especially by fossil energy combustion. Industrial sources offer gases with higher CO_2 content than the atmosphere. Their concentration can reach 35% for steelworks and even 100% (pure CO_2) for certain thermochemical processes such as the production of ammonia whereas, as seen in chapter 1, atmospheric CO_2 concentration is around 0.04%. This difference in concentration significantly affects the total efficiency of the electrofuel production process which can increase from 38 to 48%[130]. In the short-term, industrial sources seem to be more realistic because technologies used to capture atmospheric CO_2 only currently exist at a demonstrator stage, and represent significant financial and energy costs[131,Mal17]. In addition, even the most optimistic decarbonisation scenarios foresee these industries continuing to emit CO_2 in the near future. Nevertheless, this choice can cause considerable problems in the longer term, by inciting high CO_2 emitting industries to not reduce their emissions. This brings us back to the issue of regulation and accounting of emissions. When an aircraft burns electrofuel from which the CO_2 will have been captured beforehand from a cement works, should the emissions be allocated to the aircraft or to the plant? Even if this question may seem trivial, and easily resolvable by a simple fifty-fifty allocation, the complexity of the regulatory certification processes makes the situation more intricate. Christensen and Petrenko cite for example a "worst-case" scenario in which the same reduction in CO_2 emissions would be counted all at once in the European Directive RED II, in the emissions trading system EU-ETS, and in the CO_2 standards for vehicles[CP17], see also the report by the consultancy Cerulogy which mentions this problem[Mal17].

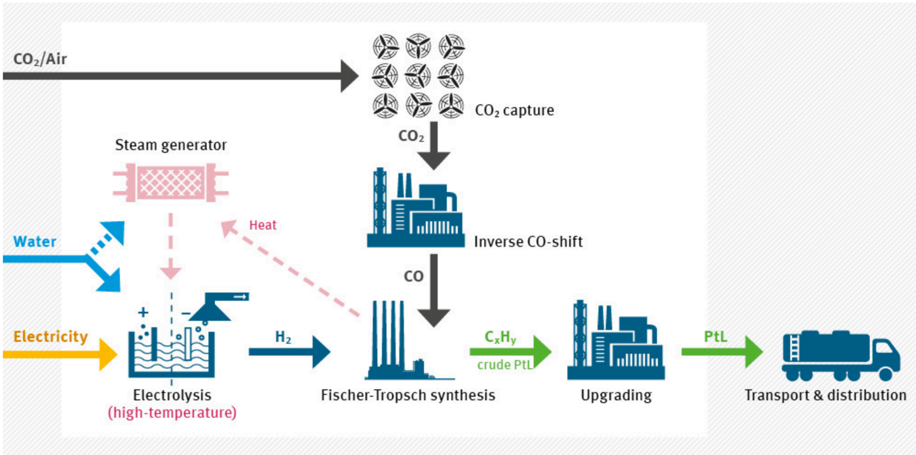


Figure 6.8: Electrofuel production via the Fischer–Tropsch process. The dotted pink arrow points to the potential use of heat given off during Fischer–Tropsch synthesis to produce hydrogen by high temperature electrolysis, with higher yield. This technology is being developed. According to figure 3 by Schmidt *et al.*[SWR+16].

Production processes

Two main processes are considered for the production of electrofuels: the Fischer–Tropsch process (shown in figure 6.8) and the so-called methanol process. These two production processes require the production of hydrogen by water electrolysis. In the methanol process, this hydrogen reacts directly with CO_2 to produce methanol which is then converted into hydrocarbons. In the Fischer–Tropsch process, the CO_2 is first separated into carbon monoxide (CO) by the RWGS (*reverse water-gas-shift*) reaction which then reacts with the hydrogen to produce synthetic gas, from which hydrocarbons are produced via the Fischer–Tropsch synthesis (see section 6.3.2 on biofuels). Because of the synthesis step, electrofuels also fall in the category of synthetic fuels, like second generation biofuels using the Fischer–Tropsch pathway. The methanol and FT pathways have an almost identical energy efficiency, ranging between 38 and 48% according to the CO_2 source used, and which could potentially be improved up to 60% with high-temperature water electrolysis techniques which are still in the development stage[130, 132, 133]. As for biofuels, these efficiencies do not take the selectivity into account, *i.e.* the part of end product in the form of kerosene for aviation.

Potential advantages and drawbacks

Emissions from electrofuels depend on the emission factor of the electricity mix supplying the electrolyser and the CO_2 capture system. As it will be seen in section 6.4, replacing kerosene by electrofuels produced from the current global electricity mix is likely to increase CO_2 emissions as the global mix is highly carbonised with an emission factor of around 132 gCO_2-eq/MJ[a]. However, by

[a]See footnote a on page 27.

using low-carbon electricity with an emission factor of around 5.5 gCO_2-eq/MJ[a], the gains in terms of emissions can be substantial.

Another accounting convention is to consider that the input electricity used to produce electrofuels is a renewable electricity produced in "excess". This accounting convention leads to emission factors as low as 1 gCO_2-eq/MJ of electrofuel produced*et al.*[134,SWR+16]. It is an extremely low index since the lowest emission index for renewable energies is around 3 gCO_2-eq/MJ for wind power[SBF+14].

Beyond the climate aspects, electrofuels potentially have many other advantages, especially compared to biofuels, for example in terms of water use[130].

6.3.4 SAF

The aeronautical sector, and more specifically the ICAO, use the term SAF, which stands for *Sustainable Aviation Fuel*, to describe AJF for aviation which are also "sustainable". Currently, there is no international consensus regarding a definition for SAFs. For instance, the ICAO's list of SAF conversion processes includes two processes including petroleum as input[b]. At its 38th meeting in 2013, the ICAO defined sustainability according to three criteria[c]:

1. achieve net GHG emissions reduction on a life cycle basis;
2. respect the areas of high importance for biodiversity, conservation and benefits for people from ecosystems, in accordance with international and national regulations;
3. contribute to local social and economic development, and competition with food and water should be avoided.

Later, in its 2019 environmental report, the ICAO provided a regulatory definition, which seems specific to biofuels[ICA19a]:

1. achieve a 10% minimum GHG reduction over the entire fuel life cycle (including DLUC and ILUC emissions) compared to kerosene of fossil origin;
2. not use biomass from high carbon stock land (virgin forests, peatland, wetlands).

The ICAO also developed a methodology within CORSIA for evaluating these criteria, thus making it possible to define fuels eligible for CORSIA (CEF stands for *CORSIA eligible fuels*)[ICA19a, ICA19b]. In principle, electrofuels enter into the category of SAF[ICA18], nevertheless, in practice, only biofuels have been considered by the ICAO for the moment[ICA19b].

[a] In this report, we consider electricity produced from solar, wind, hydraulic or nuclear power to be low-carbon. The figure of 5.5 gCO_2-eq/MJ is obtained by averaging the emission factors for these low-carbon electricity sources with a weighting representative of their respective share in current global electricity production. According to the IEA[IEA20c], these electricity sources represented respectively 49%, 14%, 6% and 30% of global low carbon electricity production in 2018, and their emission factors, according to the IPCC, amount to 6, 3, 12 and 3 gCO_2-eq/MJ respectively (median values found in table A.III.1 of appendix III of the IPPC Fifth Assessment Report[SBF+14]).

[b] Conversion processes webpage, consulted on the 21st of April 2022.

[c] Resolution A38-18, section 32 j, ICAO, Assembly Resolutions in Force, 4th of October 2013.

6.4 Comparison of decarbonisation potential with energy resources in 2018

This chapter ends with calculations providing trends regarding the link between CO_2 emissions and total energy used for the new energy vectors presented. These orders of magnitude aim to illustrate two main points concerning the different decarbonisation solutions:

1. their climate impact depends on the emission factor and on the efficiency of the various production processes;

2. the question of the quantity of primary energy required is important, as physical availability constraints could arise.

Addressing these questions over a future horizon (for example, 2050) is a delicate task, which involves making a number of assumptions, for example on the evolution of the electricity mix, on the available biomass or even on the scale and rate at which these new energy vectors will be used. Elements for reflecting on this subject can be found in chapter 9. To obtain significant orders of magnitude without having to make these assumptions, we present the results of calculations **as the situation currently stands**. In other words, calculations are conducted with values corresponding to those of 2018, for example the level of air traffic, electricity emission factor or even primary energy availability. For each of the four energy vectors considered (electricity, hydrogen, electrofuel and biofuel), the variation of CO_2 emissions and primary energy requirement are presented assuming that all kerosene of fossil origin used by aviation in 2018 is replaced, in 2018 conditions, by this energy vector.

These calculations have obvious limitations. Firstly, as we explained in the rest of the chapter, these new energy vectors are only available in the more or less long-term. Therefore even if some biofuels are already available, an all-electric long-haul airliner seems beyond reach in the coming decades. Furthermore, energy consumption by potential future all-electric and hydrogen planes is subject to strong uncertainties (see table 6.3 for hydrogen). Finally, even though these solutions are available, it would be more relevant to consider a mix of these solutions, for example electricity for regional aircraft, hydrogen for short and medium-haul aircraft and AJF for long-haul aircraft, with for the latter a mix between electrofuels and biofuels, and for biofuels a variety of raw materials and production processes.

Although the calculations made in 2018 conditions would need to be refined to overcome the limitations mentioned earlier, they can nevertheless be used to highlight the link between CO_2 emissions and energy. The results of these calculations are provided in table 6.5, from which it can be seen that:

1. to decarbonise aviation, it is not sufficient to change energy vector, the vector also needs to be low-carbon. Otherwise, these new energy vectors could **increase** CO_2 emissions. For electricity-based solutions, this would be for example the case if they were used in 2018 conditions;

2. in 2018, the quantity of low-carbon energy available (low-carbon electricity and bioenergy) was of the same order of magnitude as aviation's energy

requirements, and these low-carbon energies have been used in other sectors than aviation. Decarbonising aviation therefore involves significantly increasing their production (see section 9.4.3 where possible limits are discussed).

Calculation #1. Energy vector: electricity

In this first calculation the global fleet is assumed to be fully replaced by all-electric aircraft. The energy demand is assumed to increase by 58%, which is the evolution for all-electric short-haul aircraft studied by Gnadt *et al.*[61]. Thus, aviation energy demand amounts to 23.2 EJ. Based on the current global mix, whose emission factor is 132 gCO_2-eq/MJ, this would bring about 3.0 $GtCO_2$-eq of emissions, therefore an increase of 139% compared to 2018 emissions, and would represent 23% of global electricity production in 2018. Based on the current low-carbon mix whose emission factor is 5.5 gCO_2-eq/MJ[a], this would bring about 0.1 $GtCO_2$-eq of emissions, therefore a decrease of 90% compared to 2018 emissions. However, this would require using 70% of the low-carbon electricity produced in 2018.

This calculation is used to highlight the tension between available energy and decarbonisation potential. This example illustrates that either aviation must use abundant but relatively high carbon energy (global electricity), or less abundant but lower-carbon energy (low-carbon electricity).

Calculation #2. Energy vector: electrofuel

All of the kerosene supplied to global aircraft fleet is now assumed to be electrofuel produced by the Fischer–Tropsch process from industrial CO_2 and hydrogen produced by water electrolysis. This production requires 42.9 EJ of electricity, considering a 40% yield for the overall process and high selectivity of 70%. Either this electricity is taken from the global mix, which represents 45% of the available resource, and CO_2 emissions are multiplied by 4.5, or the electricity is low-carbon, which would require 1.3 times the total quantity of low-carbon electricity produced in 2018 but which would enable to reduce CO_2 emissions by more than 80%[b].

Calculation #3. Energy vector: hydrogen

It is now assumed that all aircraft use the hydrogen burned in a combustion turbine and that they need the same quantity of energy[c], therefore 14.1 EJ. With current production techniques and considering that the liquefaction phase

[a] See footnote a on page 109.

[b] Three remarks on methodology concerning this calculation. Firstly, for sake of simplicity we have not taken co-products into account, which overestimates emissions. Secondly, we did not consider combustion-related emissions, thus considering they must be allocated to the industrial source. For these two points, a specific study using life cycle assessment methodologies would be more rigorous. Lastly, we made the calculation by considering the electricity emission index (renewable or not) in 2018, see section 6.3.3. As part of the calculations made here, if we considered that electricity was produced during "off-peak" hours, it would be necessary to compare requirements to this energy source, see for example the report by the ICCT in which such a source is evaluated[CP17].

[c] This assumption is justified especially by the uncertainties currently weighing on the energy consumption of future hydrogen planes, see table 6.3. It is also the assumption made

Scenario	CO_2 emissions		Energy required	
	Gross value ($GtCO_2$-eq)	Variation	Gross value (EJ)	% of the resource
Situation in 2018	1.2	–	14.1	–
Calculation #1: electricity (primary energy = electricity)				
Global mix	3.0	+139%	22.3	23%
Low-GHG mix	0.1	-90%	22.3	70%
Calculation #2: electrofuel (primary energy = electricity)				
Global mix	5.7	+359%	42.9	45%
Low-GHG mix	0.2	-81%	42.9	134%
Calculation #3: hydrogen (primary energy = electricity)				
Current production methods	2.2	+76%	–	–
Electrolysis, global mix	3.3	+164%	24.6	26%
Electrolysis, low-GHG mix	0.1	-89%	24.6	77%
Calculation #4: biofuel (primary energy = biomass)				
HEFA/Palm oil	0,5 to 1,5	-61 to +18%	23.7	43%
FT/forestry residues	0,1 to 0,4	-89 to -71%	50.4	91%

Table 6.5: Summary table of CO_2 emissions and energy requirements for different illustrative calculations, if the 14.1 EJ of energy used by aviation in 2018 in the form of kerosene was used in the form of electricity, biofuel, electrofuel or hydrogen. As for today, the most effective decarbonisation methods (electrofuel, hydrogen or biofuels) would enable a drastic reduction in emissions (between -70 and -90%) but would require a significant increase in energy resources: double the low-carbon electricity for electrofuels and hydrogen, and between 40% and 90% of the available biomass for biofuels.

requires 45 MJ/kgH_2, this would increase CO_2 emissions by 76%. If liquid hydrogen was produced by water electrolysis, the result would depend on the electricity used. Based on the global mix, this would require 26% of global electricity and would multiply aviation emissions by 2.6; based on the low-carbon mix, this would require three quarters of the low-carbon electricity from 2018, and would have a significant impact as it would see emissions drop by 89%.

Calculation #4. Energy vector: biofuel

To conclude, the HEFA and FT production processes are now considered. For the HEFA process, an energy efficiency of 85% and emission factors between 34 gCO_2-eq/MJ and 103 gCO_2-eq/MJ are considered while for the FT process, an energy efficiency of 40% and emission factors between 10 gCO_2-eq/MJ and 25 gCO_2-eq/MJ are considered. In both cases, a 70% selectivity is assumed. This value influences the quantity of bioenergy required but is not taken into account in greenhouse gas emissions. Concerning the HEFA process, one can see the importance of the raw material. We only considered palm oil here, which can increase or decrease emissions depending on land use change. This process would need to use more than 40% of the bioenergy available in 2018. The FT process reduces emissions but exacerbates the pressure on energy resources. It allows a 71 to 89% reduction in emissions, but requires twice as much bioenergy as the HEFA process, therefore more than 90% of the total bioenergy available in 2018.

by Ponater *et al.*[102] in their study on prospective scenarios for the deployment of a fleet of hydrogen planes.

Chapter 7

Reducing non-CO_2 effects

As explained in section 2.1.2, non-CO_2 effects are due to emissions other than CO_2, to the physicochemical properties of the environment in which these emissions take place, and to the structure and dynamics of the aircraft's wake. Reducing emissions other than CO_2 could decrease non-CO_2 effects. Indeed, only the interaction between aerosols and solar radiation has a cooling effect ($-6.5\,\mathrm{mW\,m^{-2}}$), but this effect is much lower than that caused by the formation of contrail-induced cirrus clouds ($+57.4\,\mathrm{mW\,m^{-2}}$) which is facilitated by the same aerosols. From this point of view, all the measures used to reduce aircraft consumption, without increasing other emission factors such as NO_x, help decrease non-CO_2 effects. As noted previously, the non-CO_2 effects from current aircraft are not yet fully understood and are subject to ongoing research. To date, little scientific literature quantifying precisely the strategies for attenuating non-CO_2 effects is available.

7.1 Changing emissions

To reduce particulate emissions during a flight, it is possible to act on two factors which are the engine and the fuel.

7.1.1 Engine

A first lever that concerns the engine consists in reducing NO_x emissions. Nevertheless, the quantity of these emissions depends on the flight phase due to the engine rotation speed[135]. Technological aspects relating to fuel combustion need also to be taken into account. Indeed, as mentioned in section 5.1, aircraft engine efficiency can be improved by increasing the temperature at the outlet of the combustion chamber but a higher temperature leads to the formation of more NO_x per unit of kerosene[136]. Therefore the objective of reducing NO_x emissions goes against improving energy efficiency and optimisations are therefore necessary in order to come to a compromise. Recently, Skowron *et al.* [137] studied this compromise and concluded that an improvement in efficiency was preferable to a decrease in NO_x emissions.

In the longer term, new types of engines are also considered to prevent the formation of contrails. Engines emitting less soot generally seem to be taking this direction. The new combustion chambers called *dual annular combustors* which have two rows of injectors distributed over the circumference are more efficient thanks to a more homogeneous distribution of the fuel flow rate and produce larger ice particles but 76% less particles than those produced by a conventional combustion chamber (*single annular combustor*)[138].

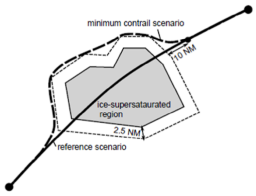
Finally, electric engines do not produce any particles and, since there is no combustion, do not modify the chemical and thermodynamic properties of the air. In theory these engines remove all non-CO_2 effects but this is true only if one considers such component in the strict sense of the term. However, if the electric engine power is generated via a fuel cell supplied by liquid hydrogen rather than batteries, the aircraft will still produce water during the flight and will be likely to produce contrails.

7.1.2 Fuel

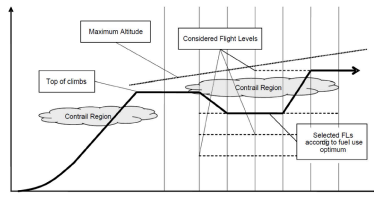
Additives have been proposed to change the properties of kerosene, however, Gierens *et al.*[139] conclude that they do not prevent the formation of contrails and that their impact on the composition of engine effluents (and ultimately their climate impact) remains uncertain.

Recently, several experimental and theoretical works have covered the impact of AJF, biofuels in particular, on soot emissions and on the number and microphysical properties of ice crystals. As explained in section 2.1.2, soot emission and contrail formation are related because soot particles act like condensation nuclei which promote the creation of contrails and induced cirrus clouds. AJF differ from kerosene as they have a smaller quantity of aromatics. Because these are the main precursors of soot, it follows that AJF should emit less soot than conventional fuels. Experimental works from two studies confirmed it and suggested that a 50/50 mix between conventional kerosene and a AJF decreases soot emissions by 50 to 70%[39,103] (the first study[103] focuses on biofuels, whereas the second study[39] also considers a AJF produced by the Fischer–Tropsch process from coal). Theoretical works[140,141] predict that a 50% decrease in soot emissions (as observed experimentally in the study[39]) should lead to a decrease in the number of ice crystals of around 35 to 50%. Experimentally, it has been observed that this decrease is rather around 45 to 75%[39]. This reduction in the number of ice crystals also comes with an increase in their size[39,141]. Both effects (fewer but larger ice crystals) should reduce the radiative impact of contrails and induced cirrus clouds, which has been confirmed theoretically. Indeed, Burkhadt *et al.*[142] showed that a 50% to 80% decrease in the number of ice crystals reduces radiative forcing of contrail-induced cirrus clouds by 21 to 50%. Considering that these cirrus clouds are responsible for around 60% of the climate impact of aviation, these results therefore suggest that using biofuels at an incorporation rate of 50% could reduce the climate impact of aviation by around 10 to 25%.

Finally, a hydrogen engine could reduce NO_x emissions by redesigning the combustor in order to low lean blowout limit of hydrogen[Gmb03], and it would remove soot and sulphur emissions; however, there would be higher water vapour emissions[102]. This would result in a higher probability of occurrence of contrails but with different microphysical properties, especially lower optical thickness. In conclusion, the climate impact would be positive with a reduction of around 10% in the impact related to contrails (in terms of radiative forcing), in addition



(a) Example of horizontal flight diversion strategy in order to avoid the formation of contrails, according to figure 1 of Rosenow *et al.* [145].



(b) Example of vertical flight diversion strategy in order to avoid the formation of contrails, according figure 44.3 by Matthes *et al.* [146].

Figure 7.1: Illustration of horizontal (left) and vertical (right) flight diversion strategies in order to avoid the formation of contrails.

to the decrease in impact from NO_x[102]. It is interesting to note that in the absence of soot emissions, ambient air particles play an important role in the formation of contrails, a remark which also potentially applies to the use of biofuels exclusively[141].

7.2 Changing trajectories

As explained in section 2.1.2, the cirrus induced by condensation trails can only form in regions supersaturated with ice. A study conducted within the Japanese airspace[138] showed that 17.8% of flights generate condensation trails and that only 2.2% of all flights are responsible for 80% of the contrail energy forcing[a]. This study, which needs to be confirmed by other similar studies, suggests that a minority of flights have a significant climate impact, and that significant gains are conceivable if these aircraft adapt their trajectory to avoid these zones, by changing flight times and period. Indeed, the impact of contrails depends on their location and time of occurrence (day, night, season) and most of these impacts are due to winter night flights[24,34,36,139,143].

Contrail avoidance strategies have been considered since the early 2000's[144]. The main strategy considered is to divert the aircraft trajectory and especially the altitude of flights[139]. This modification can lead to increased fuel consumption, but the excess consumption remains in theory low (see below). Noppel and Singh[24] distinguish three strategies for changing altitude: 1) change cruise altitude on a global scale; 2) restrict cruise altitudes based upon atmospheric conditions for certain regions over a certain time period; 3) change aircraft cruise altitude during flight depending on ambient conditions.

Detailed studies can be used to quantify the application of different strategies for preventing contrails, see for instance the review paper by Simorgh *et al.*[147]. For example, Matthes *et al.*[148] considers a flight within an area of high potential for contrail formation and estimates a potential reduction in overall climate effects of 40% (*i.e.* CO_2 effects and non-CO_2 effects), at the cost of 0.5% overconsumption. Other scenarios are considered by Teoh *et al.*[138]. A first scenario, including only small changes of trajectories not leading to fuel overconsumption, results in a 20% reduction in contrails energy forcing. A second scenario,

[a]Energy forcing is the radiative forcing of the cloud integrated over its area and its life time: as the name suggests, it is therefore an energy that can typically be expressed in joule.

considering the generalisation of diversion strategies, shows a possible 59.4% reduction in contrails energy forcing at the cost of a kerosene overconsumption of 0.014% for the entire fleet. A third scenario then focuses on the introduction of new combustion chambers without change of trajectories, leading to a reduction in contrails energy forcing by 68.8%. Finally, a last scenario combining these new combustion chambers with generalised diversions shows a 91.8% reduction in contrail energy forcing at the cost of overall excess consumption of 0.027%. In a follow-up paper, Teoh *et al.* [149] investigated further strategies that were also taking into account fuel consumption. For other examples of horizontal diversion strategies, see for instance Rosenow *et al.* [145]. Examples of horizontal and vertical diversion strategies are illustrated in figure 7.1.

Implementing such diversion strategies requires the ability to predict whether a given flight will create a persistent cirrus contrail with a warming effect. Gierens *et al.* [150] conclude that contrails can be predicted with some success, but there are problems to predict contrail persistence, which is necessary as there are mostly the cirrus induced by contrails that have a significant climate impact. Moreover, as most strategies come with a fuel penalty, albeit small, there is a trade-off to be made between CO_2 and non-CO_2 effects. The significant uncertainties, discussed in Section 2.2.3, that weigh on the assessment of the impact of induced cirrus may therefore represent a barrier to the rapid implementation of avoidance strategies, but Wilhelm *et al.* [37] argue that these uncertainties will persist for the coming decades, if not forever, and so they should be no argument to postpone actions to mitigate contrail's warming impact. All in all, the debate on whether the time is ripe or not to implement mitigation strategies is vigorous[a], as can be seen in the recent series of commentaries in the online media Green Air following a conference entitled "Mitigating the climate impact of non-CO_2 – Aviation's low-hanging fruit" organised by the Royal Aeronautical Society in March 2021[b]. K. Shine and D. Lee argued that "navigational avoidance of contrails to mitigate aviation's climate impact may seem a good idea – but not yet"[c], to which J. Green answered that "now is the time for action"[d]

7.3 Reducing trailing vortices lifetime

As mentioned in section 2.1.2, the counter-rotating vortices which develop downstream of the aircraft are driving the vortex phase of the development of condensation trails as they traps in their core a large part of the water vapour discharged by the engines[27]. They represents an essential precursor to the appearance of induced cirrus clouds in the dissipation phase. A lever for attenuating non-CO_2 effects associated with condensation trails is therefore based on reducing lifetime of these trailing vortices to accelerate the dispersion of engine effluents. This strategy can be achieved by an early triggering the natural

[a] If the scientific debate is not settled, industrial solutions are already offered to prevent contrail formation, for instance by companies such as SATAVIA.

[b] Easy does it for greener skies, Royal Aeronautical Society, consulted on the 16th of March 2022.

[c] Navigational avoidance of contrails to mitigate aviation's climate impact may seem a good idea – but not yet, K. Shine and D. Lee, Green Air, 22 July 2021.

[d] Navigational avoidance of contrails to mitigate aviation's climate impact – now is the time for action, J. Green, Green Air, 27 August 2021.

instabilities of the trailing vortices[151].

The most powerful instability commonly observed is the Crow instability[28, 152]. It consists of a long wavelength sinusoidal deformation of the two vortices which can be seen directly on the contrails as illustrated in figure 2.4. Crouch *et al.*[153] suggested and tested experimentally a control solution based on the symmetrical deflection of the ailerons at a frequency corresponding to that of the Crow instability in order to produce its early triggering. Nevertheless, this control system was only found to be effective with the flaps out, which makes this proposal little attractive for the cruise phase. More recently, Brion *et al.*[154] theoretically determined that a disturbance placed in the region of maximum receptivity for Crow instability would halve the vortex lifetime. This zone corresponds to the location of the vertical tail which leaves the possibility of positioning a control system on it. However, no technical solutions have been studied or put forward since then. All of these studies for reducing the trailing vortices lifetime and therefore for reducing the effect of condensation trails should notably be taken into account for the design of flying wing aircraft[139].

Finally, the integration of the propulsion system on the aircraft's architecture is also an important issue which influences the formation of condensation trails, due to the relative position of the engine outlets with respect to the wing tips where the trailing vortices are generated[27].

Part IV

Scenarios

Even if the impact of aviation on the climate (chapter 2) and the possible technical and operational levers (chapters 5, 6 and 7) can be relatively objectified, drawing conclusions from them to devise prospective scenarios is far more delicate in practice. It suffices, to convince oneself, to compare the Waypoint 2050 report by ATAG[ATA20] to that of the consulting firm BL Evolution[LBMB20]: by 2050, the first assumes that traffic will **increase** by 3 % per year while the second concludes that it needs to **decrease** by 5.5 %. This great disparity in the visions of the future of aviation is all the more spectacular in that both claim they are in line with climate goals such as the Paris Agreement. In this section we provide some elements to reflect on the subject. Chapter 8 presents the methodology for evaluating scenarios for aviation that we have selected, in particular the notion of carbon budget for aviation is introduced. After a literature review of academic papers addressing prospective scenarios for aviation, chapter 9 presents a discussion on a few scenarios leading up to 2050 using CAST, a tool for simulating aviation climate pathways.

Chapter 8

General context

The objective of this chapter is to introduce the tools and methodologies which will be used in chapter 9 to analyse transition scenarios for the aviation sector. Detailed explanations are provided especially on the notion of carbon budget and on its use in aviation.

8.1 Paris Agreement and IPCC scenarios

The generally accepted framework for climate targets, in which the scenarios and paths discussed in the next chapter will be contextualised, is the Paris Agreement. This agreement, signed by 195 delegations at the COP21 in 2015, aims to contain global warming "well below 2 °C with respect to pre-industrial levels and [to] pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels". Further to this agreement, the UN asked the IPCC to produce a report to describe the paths compatible with the objective of limiting global warming to +1.5 °C.

This report, entitled Special Report 1.5, was published in 2018[IPC18]. Based on numerous prospective works from the scientific literature, the IPCC defines in this report four groups of scenarios, called P1, P2, P3 and P4, within which global warming is in principle limited to +1.5 °C in 2100. These scenarios differ in the underlying technical, social and economic hypotheses, especially technological progress, change in lifestyles and economic growth. Scenario P3 is therefore a trend scenario according to which societal and technological development follows historic curves, but it assumes the development and the deployment of carbon capture and storage technologies. Nevertheless, these technologies pose a number of problems, clearly identified in the scientific literature, and which are summarised in the following citation, taken from the Special Report 1.5 by the IPCC [RSJ+18, page 96][a]:

> "Carbon Dioxide Removal deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5 °C."

[a] One can also cite Andersonet al.[155]: "Negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble.", Smith et al.[156] who qualifies as "extremely risky" the fact of significantly counting on these technologies, or even the EASAC[EAS18] which concluded that "these technologies only offer limited realistic potential to remove carbon from the atmosphere, and not to the scale set out in certain climate scenarios."

Indicator	P1	P2	P3	P4
Carbon budget and total quantity of CO_2 captured by BECCS over the period 2020-2100 ($GtCO_2$)				
Carbon budget	390			
BECCS	0	151	414	1191
Gross carbon budget	390	541	804	1581
Energy available in 2050 (EJ/year)				
Primary energy from crude oil	23	84	33	116
Primary energy from biomass	45	67	119	310
Electricity production from nuclear	24	21	57	58
Electricity production from renewable energies	142	191	138	154
Total electricity production	185	248	225	251

Table 8.1: Characteristics of the P1 to P4 scenario from the IPCC Special Report 1.5 °C. The energy values correspond to those in 2050 whereas the values for the CO_2 correspond to the 2100 time horizon and therefore to cumulative values for BECCS. The carbon budget is the median value for +1.5 °C: it is the net quantity of CO_2 we can emit into the atmosphere (see section 1.3.3). The gross carbon budget corresponds to the sum of this carbon budget and the anthropogenic carbon sinks (here only in the form of BECCS): it is therefore the gross quantity of CO_2 we can emit. Additional explanations on these two notions are provided in the body of the text. The value for the carbon budget was taken from Grubler *et al.* [157], values for BECCS from the IPCC Special Report 1.5 Summary for Policymarkers[IPC19] and energy values were taken from the IAMC 1.5 °C Scenario Explorer[HKK+18] hosted by IIASA[a].

The fact that the IPCC qualifies carbon capture technologies as a "major risk" is the reason for which scenario P1, the only scenario not relying on such technologies, will be used as preliminary reference for the following analyses. In this scenario, gross CO_2 emissions decrease from 43 $GtCO_2$ in 2019 to 4.3 $GtCO_2$ in 2050, therefore a 90% decrease. This represents a drop in emissions at a rate of 7% per year for 30 years[b]. For comparison to help realise the extent of the changes required, over the last ten years (period 2010–2019) CO_2 emissions increased by 0.9% on average per year, and the Covid-19 health crisis reduced emissions by 7%[158] in 2020.

Even if scenario P1 will most of the time be taken as a reference, we will also consider the other scenarios, especially when performing sensitivity analysis. This analysis shall especially be based on distinct values for both the BECCS and the biomass availability. The different values of these four families of scenarios that will be used in the following are summarised in table 8.1 as well as other informative values useful to better understand the different scenarios.

Table 8.1 provides in particular values for carbon budgets and for the BECCS. As a reminder, the carbon budget is the net quantity of carbon humanity can emit into the atmosphere (see section 1.3.3). Therefore, the median carbon budget at +1.5 °C can be respected by emitting 380 $GtCO_2$ and without removing anything from the atmosphere, or by emitting (for example) 1380 $GtCO_2$ while developing negative emission technologies which remove 1000 $GtCO_2$ from the

[a]The International Institute for Applied Systems Analysis (IIASA) is an independent international research institute located in Austria.

[b]This value is obtained by considering that the AFOLU sector will follow a more ambitious emission reduction path and will become a carbon storage sector.

atmosphere. We thus define the **gross carbon budget** as the sum of the carbon budget and the quantity of CO_2 removed from the atmosphere. In this report, and for illustration purpose, only BECCS will be considered as anthropogenic sinks[a]. This is useful to directly compare gross emissions with this gross carbon budget.

8.2 International aviation governance

Even if the IPCC's paths set general scenarios, especially in terms of global CO_2 emissions, these scenarios are not detailed per business sector or by country. The idea behind the Paris Agreement is that each country signing it provides nationally determined contributions (NDC) that it considers compatible with the agreement's global target. The European Union therefore submitted a list of NDCs for all of its members, including France, declaring a target of a 40% reduction in its domestic greenhouse gas emissions in 2030 compared to 1990, target which was then increased to 55%[b].

As part of the Paris Agreement, emissions from domestic aviation, which represents flights leaving from and arriving in the same country, are counted in the national inventory of the corresponding country. International aviation, which represents flights with a different departure and arrival country, is not covered by the Paris Agreement. Indeed, emissions from international aviation (like emissions from international maritime transport) are not taken into account in the national inventories due to lack of agreement on the country or countries to which the emissions should be allocated: should it be to the country of origin, the country of destination, the country in which the plane or the airline company is registered, or the country in which the kerosene was purchased? As international aviation represents around 60% of total emissions from commercial aviation[GZR19], its regulation is therefore an important issue. To address it, the UN delegated the responsibility for controlling emissions from international aviation to the ICAO at the first conference of the parties in 1995[c]. In 2010, the ICAO set itself the "aspirational goal" of stabilising emissions from international aviation from 2020 and thus speaks of neutral carbon growth from that date[d]. In 2016, the ICAO adopted an offset system, CORSIA (*Carbon Offsetting and Reduction Scheme for International Aviation*), for emissions above the 2019 level[e][ICA19b]. This target differs significantly from the IPCC's global targets which recommend a drastic decrease in CO_2 emissions and not a stabilisation. The aeronautical industry set a more ambitious objective in 2009 to decrease emissions by 50% by 2050 with respect to their 2005 level[IAT19, ATA20]. In 2021, ATAG has raised this objective to carbon neutrality in 2050[ATA21].

The European Union devised a more voluntarist policy and has thus included intra-European flights in its EU-ETS (*European Union – Emissions Trading*

[a] It would be possible for example to take the AFOLU sector into account or direct carbon capture into account (DACCS for *Direct Air Capture with Carbon Storage*).

[b] Intended Nationally Determined Contribution of the EU and its Member States, UNFCCC, 6th of March 2015, and 2030 climate & energy framework, European Union, consulted on the 21st of January 2021.

[c] Emissions from fuels used for international aviation and maritime transport, UNFCC, site consulted on the 18th of May 2021.

[d] Consolidated statement of continuing ICAO policies and practices related to environmental protection — Climate change, ICAO, 4th of October 2013.

[e] The year of reference was initially 2020 but was put back to 2019 due to the health crisis.

System) since 2013. Flights outside Europe were excluded so the ICAO could set up CORSIA[a]. Since 2013, a free quota of 38 $MtCO_2$ per year has been allocated to intra-European aviation. Since then, the emissions in question increased from 53.5 $MtCO_2$ in 2013 to 67 $MtCO_2$ in 2018, forcing airline companies to purchase around 100 million carbon credits[b]. From 2021, the free quota allocated to aviation will be reduced by 2.2% per year until 2030, thus participating in the 90% greenhouse gas emission reduction target in the transport sector. Finally, it is important to note that, as much for CORSIA as for EU-ETS, only the CO_2 effects from aviation are taken into account. The European Union published a report on non-CO_2 effects in 2020 which examines how to take them into account in the EU-ETS[ALO+20].

8.3 Determination of carbon budgets for aviation

In this section, we will describe in detail the methodology that will be used to define what we consider to be sustainable paths for aviation. To do that, the notion of carbon budget is used, both for +1.5 °C and for +2 °C. The scenarios will mainly be analysed from the point of view of CO_2 emissions. Two specific sub-sections complete this part: in section 8.3.3 the methodologies currently developed and used to integrate non-CO_2 effects are presented, and in section 8.3.4 carbon offsetting is briefly discussed.

8.3.1 Calculation of reference global carbon budgets

As explained in section 1.3.3, the IPCC calculated the total carbon budgets corresponding to the targets set out in the Paris Agreement, for different temperatures and uncertainties. In the next part, global carbon budgets for +1.5 °C and +2 °C are considered with a likelihood of success of 50% (these budgets will therefore be qualified as *median budgets*). Even if the 2100 time horizon is appropriate in the case of the climate, for industrial sectors like aviation such a long time scale is less relevant. Therefore only paths up to 2050 will be considered. The approach for defining reference global carbon budgets is illustrated for the temperature target of +1.5 °C.

The median global carbon budget for +1.5 °C was 580 $GtCO_2$[RSJ+18] at the end of 2017. As the amount of CO_2 emissions for the years 2018 and 2019 is known, respectively 42 $GtCO_2$ and 43 $GtCO_2$[3], the carbon budget from 2020 is therefore 495 $GtCO_2$[c]. Furthermore, the IPCC states that, over the time scale considered (up to 2100), a "flat" rate of 100 $GtCO_2$ must be removed to take account of feedback effects[d]. We thus reach a global budget of 395 $GtCO_2$

[a] Reducing emissions from aviation and Emissions cap and allowances, European Commission, consulted on the 21st of January 2021.

[b] Allocation to aviation, European Commission, consulted on the 29th of March 2021. The lobby Airlines for Europe considers that between 2013 and 2018, purchasing these credits cost airline companies 1.3 billion euros.

[c] This value, calculated based on the carbon budgets featured in Special Report 1.5 °C, is similar to that given in the IPPC Sixth Assessment Report.

[d] This "flat rate" is justified by the following sentence from the executive summary from chapter 2 of the IPCC Fifth Assessment Report[RSJ+18]: "Remaining budgets applicable to 2100 would be approximately 100 $GtCO_2$ lower than this to account for permafrost thawing and potential methane release from wetlands in the future, and more thereafter." In the recent IPCC Sixth Assessment Report, there is a slight difference in this flat rate and it is not always

between 2020 and 2100[a], and we can therefore say that the Paris Agreement (for $+1.5\,^\circ C$) aims for cumulative CO_2 emissions to remain below this threshold. To establish the paths for global CO_2 emissions, we assume a decrease in emissions at a constant rate from their 2019 level (therefore $43\,GtCO_2$) so that cumulative emissions up to 2100 stand at $395\,GtCO_2$. This imposes a rate of decrease of around 10% per year[b]. Therefore, the carbon budget available through to 2050 amounts to around $380\,GtCO_2$.

In the same way, the global carbon budget for $+2\,^\circ C$ indicated by the IPCC is $1500\,GtCO_2$, from which it is necessary to remove $190\,GtCO_2$ as explained above (past emissions, feedback loops). A decrease in emissions of around 3% per year is necessary for this budget (and not more) to be used by 2100, and it corresponds to a budget in 2050 of $860\,GtCO_2$.

To take the use of BECCS into account, where applicable, gross carbon budgets are calculated and the same approach is used.

8.3.2 Calculation of carbon budgets for aviation

Once the global carbon budget for 2050 has been calculated, it is necessary to allocate part of it to aviation. Indeed, the global carbon budget does not predict the way in which it is allocated between the various business sectors (not to mention geographical distribution), especially with respect to the aviation sector. **The choice of this allocated share is political (economic, societal, ...) and it is not the place of this report to determine it.** As a result, in the rest of this work, the global carbon budget share allocated to commercial aviation will be considered as a parameter that can be varied in order to conduct a sensitivity analysis and to study its influence, especially on the annual rate of air traffic growth it enables.

Even if the share that must be allocated to the aviation sector is not fixed, an interesting reference value corresponds to the recent share of aviation in global CO_2 emissions. Recall that commercial aviation accounted for 2.6% global CO_2 emissions in 2018 (see section 2.2.5). This figure includes combustion-related emissions and emissions from kerosene production and from other aircraft life cycle phases. This value is the share to be allocated to the aviation sector in an undifferentiated approach by which all business sectors would reduce their emissions at the same rate from 2018. In scenario P1 for example, we saw that emissions would have to decrease by 90% between 2019 and 2050 to reduce them from $43\,GtCO_2$ to $4.3\,GtCO_2$. If all business sectors (including aviation) decreased their emissions by 90%, then the share of the global carbon budget allocated to each sector would be exactly equal to its share of emissions in 2018. Therefore, as part of this undifferentiated approach, aviation would be allocated 2.6% of the global carbon budget.

Allocations below or above this value can also be considered. Allocation of a larger share to aviation basically requires other business sectors reducing their emissions at a rate faster than average. Without fixing the share that must be

included. For example, in the case of permafrost, the feedback loop would induce between $11\,GtCO_2$-eq and $150\,GtCO_2$-eq per additional degree.

[a] This figure is comparable to the $390\,GtCO_2$ from scenarios P1 to P4, see table 8.1.

[b] This value is higher than the 7% announced in section 8.1 as here the AFOLU sector follows a similar emissions reduction path to other business sectors, and is not assumed to store carbon.

Temperature	Share allocated to the aviation sector	Aviation sector carbon budget ($GtCO_2$)
+1.5 °C	2.1%	8.0
	2.6%	10.0
	3.1%	11.7
+2 °C	2.1%	18.2
	2.6%	22.8
	3.1%	26.8

Table 8.2: Examples of carbon budgets for aviation by 2050 according to the temperatures mentioned in the Paris Agreement (considering the associated median carbon budgets without BECCS) and to the share allocated to the aviation sector.

allocated to it, it is nevertheless useful to report the arguments which come up regularly in the public debate to discuss the aviation sector's share:

- **it is necessary to allocate more to the aviation sector** because 1) it is a vital sector for the economy, 2) it is one of the most difficult sectors to decarbonise (*hard-to-abate*), 3) some sectors will offer additional room for manoeuvre to other sectors, due to their capacity to decarbonise at a lower cost or faster, or even become carbon storage sectors such as agriculture and forestry potentially.

- **it is necessary to allocate less to the aviation sector** as 1) it is a non-essential sector with respect to primary needs, 2) this approach rewards the biggest polluters and 3) the differentiated approach of the Kyoto protocol requires more reduction from sectors with higher emissions intensity[1].

Close to the academic field, research is currently looking at conceivable allocation methods[159], like a report to the European Parliament which debates the different options possible[CGSC15] or approaches aiming to optimise the use of available economic resources under the constraint of a total carbon budget.

Once the reference global carbon budget and the share allocated to the aviation sector are set, it is possible to calculate the carbon budget for the aviation sector in 2050. Different values are reported in table 8.2, where three values of share allocated to the aviation sector are considered: the reference value of 2.6%, and two values corresponding to variations (arbitrarily chosen) of ±0.5%, leading to values of 2.1% and 3.1%. In this table, we consider the two extreme temperature values (+1.5 °C and +2 °C) mentioned in the Paris Agreement. Therefore, considering the median global carbon budget for +1.5 °C and an allocation of 2.6% for the aviation sector, the carbon budget for +1.5 °C for aviation is 10 $GtCO_2$. At the rate of the 2019 emissions from aviation, this carbon budget would be fully consumed in around 9 years. With the same assumptions, but considering warming of +2 °C, the carbon budget for aviation is 23 $GtCO_2$ by 2050. Considering the 2019 emissions from aviation, this carbon budget would be fully consumed in around 20 years.

As a result, by restricting the study to air transport alone, a scenario for the transition of the aviation sector would be considered in line with the targets of the Paris Agreement if cumulative CO_2 emissions from aviation up to 2050 do not exceed the share of the considered carbon budget allocated to the aviation sector.

To conclude this discussion, one has to mention a limitation to this method, namely that the principle of the NDCs from the Paris Agreement stipulate that each country traces its own roadmap for decreasing its emissions. We could therefore imagine that each country decides to allocate a different carbon budget to aviation. For example, in France, aviation (domestic and international) represented 5.5% of national CO_2 emissions in 2018, which could therefore justify a different share allocated to the aviation sector[a].

8.3.3 Extension of the approach to non-CO_2 effects

The notion of carbon budget is usually only applicable to CO_2 emissions. However, non-CO_2 effects currently represent around two thirds of the climate impact from aviation. It is therefore interesting to extend the approach to adopt methodologies for taking these effects into account in transition scenarios. Two approaches are presented below.

A first methodology consists in looking at the response to transition scenarios in terms of temperature. This has the advantage of enabling us to compare values directly with temperature targets, but requires the use of climate models for making these estimations. This methodology differs from the carbon budget approach which has the advantage of focusing on emission accounting, but it is closer to the Paris Agreement, the targets of which are given in terms of temperature. This type of approach, using more or less complex climate models, is for example used in recent works by the German Aerospace Centre (DLR)[160] or Oxford University[161].

A second methodology consists in comparing equivalent emissions with carbon budgets extended to non-CO_2 effects. These extended carbon budgets can be used to integrate other climate effects, such as methane emissions, which are excluded from conventional carbon budgets. Conventional carbon budget calculation methods, which are used to produce extended carbon budgets, are not discussed here[b]. This approach has the advantage of using the same carbon budget logic and does not use climate models. Nevertheless, this less precise approach means climate metrics need to be used, such as the GWP$*$ metric described in appendix A, to estimate equivalent emissions. The impact in terms of temperature can also be assessed based on these estimations, according to the metrics used. This approach is for example developed in the recent work by Planès *et al.*[164] and will be used in chapter 9 to illustrate scenarios including non-CO_2 effects.

8.3.4 Remarks on offsetting

In previous sections of this chapter, the hypothesis of a centralised political decision on a carbon budget for aviation has been implicitly put forward. A different approach would be to adopt an economic vision and to rely on market mechanisms, typically carbon offsetting systems, which enables airline companies to increase their carbon budget by purchasing emission quotas within a

[a] CITEPA, April 2020 – Format Secten.

[b] See for example the work by Damon Matthews *et al.*[162] or Rogelj *et al.*[163] for details on the calculations.

trading system. This is why we do not explicitly address offsetting in this report: it ultimately relates to a political and accounting choice concerning the way in which CO_2 emissions are allocated. In other words, in this report, we see offsetting as a mechanism which can be used to adjust the carbon budget for the aviation sector, and which can therefore be taken into account via a different choice of carbon budget.

In theory, the principle of offsetting may seem attractive (we recall the CORSIA agreement setting up this mechanism on a global scale, to come into effect in 2021). The underlying economic theory shows indeed that offsetting should make it possible to optimise the distribution of the efforts by the various economic stakeholders to reduce emissions, and therefore maximise the reduction in emissions for a given global effort. However, the efficiency of the offsetting mechanisms strongly depends on their practical implementations, in particular regarding economic and legal aspects. The first mechanisms implemented to date have received strong criticisms from civil society[a], from the scientific community[165–167][b] and also from the aviation sector, the CEO of United Airlines having recently declared that traditional carbon offsetting measures have done almost nothing to prevent the increase in emissions[c].

[a] See for example the call from 100 organisations to prohibit offsetting.

[b] See also the survey by the Guardian on this topic, Carbon offsets used by major airlines based on flawed system, warn experts, Patrick Greenfield, 4th of May 2021.

[c] United Airlines commits to reaching net-zero emissions by 2050 through carbon capture technology investment, GreenAir, 10th of December 2020.

Chapter 9

Analysis of scenarios for commercial aviation

After a review of the literature on the subject in section 9.1, in this last chapter, we present the analysis of several prospective scenarios for commercial aviation, mainly focused on CO_2 emissions. These studies were carried out using CAST, a tool recently developed at ISAE-SUPAERO to address aviation/climate issues. Three main families of sustainable scenarios are considered in section 9.2 followed by an industrial scenario in section 9.3. In section 9.4 the chapter ends with a broadening of the scope by discussing about non-CO_2 effects and energy resource availability.

9.1 Literature review

The climate impacts of aviation and the foreseeable action levers being known, numerous works focused on the evaluation of prospective scenarios at least since 1998[168]. Most of these studies discuss limiting global warming below +2 °C and only take CO_2 effects into account. Therefore, it is difficult to directly relate these results with the efforts to be made to comply with the Paris Agreement which is formulated in terms of temperature and not CO_2 emissions, and where the +2 °C is only mentioned as an upper bound.

The meta-analysis by Gudmundsson and Anger[169] based on 30 different scenarios (including those by the ICAO), with annual air traffic growth rates between 1.2% and 4.6%, shows that incremental technological improvements do not make it possible to lower emissions from the aviation sector by 2050 below their year 2000 level. The only scenario with traffic growth meeting this reduction target implies major disruptive innovation with the advent of hydrogen as energy carrier.

In his study, Åkerman[170] also concludes on the need to stabilise the number of flights per inhabitant to levels slightly higher than those of the 2000s, to limit atmospheric CO_2 concentration to 450 ppm. To reach this conclusion, he considers that the aviation sector is allocated its reference share, *i.e.* he assumes that the emissions allocated to the aviation sector up to 2050 are in proportion with the global carbon budget, equal to the aviation sector's contribution in

2000, therefore 2.7%. The scenarios considered do not include disruptive innovation such as a flying wing or hydrogen engine, but rather assumes a reduction in flight speed combined with a massive conversion of the fleet to turboprop. Åkerman justifies this choice by the level of risk: such a scenario has very high feasibility unlike scenarios based on disruptive innovation.

More recently, the work by Terrenoire *et al.*[171] evaluated different scenarios by 2100 and shows that, according to the ICAO's scenario based on a 4.6% increase in air traffic per year and an improvement in energy efficiency of 2% per year, the cumulated contribution of aviation to anthropogenic warming over the period 1940–2100 would be 5.2%. However, the contribution of aviation over the period 1750–2011 was evaluated by Lee *et al.*[9] at 3.5% of global warming, which includes non-CO_2 effects which are not included in the study by Terrenoire *et al.* Therefore, the contribution of aviation to global warming is likely to increase significantly by 2100 with the ICAO's scenario. Among all the scenarios studied by Terrenoire *et al.* , the most ambitious presumes a linear reduction in emissions from 2020, to reach half of the 2005 emissions by 2050. However, the mechanisms leading to such a decrease are not specified. According to this scenario, the cumulated contribution of aviation to total anthropogenic warming by 2100 would only be 1.9%, which would constitute a net reduction compared to the past 1750–2011 period.

Grewe *et al.*[160] evaluated the climate impact of different scenarios for aviation in light of the Paris Agreement targets, including all climate effects of aviation. Using climate models and considering an allocation to aviation of 5% of the temperature targets from the Paris Agreement, they are able to evaluate the sustainability of scenarios for aviation. They especially conclude that it is little likely that industrial objectives reach the Paris Agreement targets. This result is similar to that from the recent report by Lee[Lee18] which concluded that the ICAO's carbon neutral growth target is incompatible with the Paris Agreement. Grewe *et al.* also consider more ambitious objectives at European level proposed by the ACARE (*Advisory Council for Aviation Research and Innovation in Europe*) and show that they can be compatible with the Paris Agreement targets. Finally the authors analyse the technological hypotheses on which the ACARE's scenarios are based, and conclude that these objectives will probably not be reached, thus bringing the feasibility of these scenarios into question.

A recent publication by Klöwer *et al.*[161] studies the impact of air traffic on temperature, and more precisely on the 0.3 °C to 0.8 °C which separates us from the +1.5 °C and +2 °C limits of the Paris Agreement. The authors conclude that if air traffic resumes its pre-COVID path, then aviation will be responsible for between 6 and 17% of these +0.3 to +0.8 °C. They therefore highlight two scenarios for stabilising the impact from aviation in terms of temperature: massive introduction of low-carbon fuels so carbon intensity is decreased by 90%, or a drop in traffic of 2.5% per year. These two measures especially have the effect of decreasing the radiative forcing of non-CO_2 effects. Concerning the decrease in traffic, it could only be temporary to give the aviation sector time to develop sustainable technological solutions[161].

Planès *et al.*[164] also analysed the compatibility of a number of scenarios (including one scenario put forward by the ATAG) with the Paris Agreement targets, using CAST[a], for *Climate and Aviation – Sustainable Trajectories*, a

[a]CAST is available at the following address: https://cast.isae-supaero.fr/.

numerical tool which simulates trajectories for aviation and evaluates their climate impact. By allocating a carbon budget to aviation in a similar way to the approach proposed in section 8.3, it is therefore possible to estimate whether the scenarios studied exceed the allocated carbon budget or not. A similar approach including non-CO_2 effects is also described there in detail. The main conclusions of these works will be discussed in detail in this chapter.

Finally, specific research focused on the introduction of carbon offsetting systems such as CORSIA or EU-ETS mentioned in section 8.2. These systems may be necessary to make up for the difference between the set target and the reduction in emissions actually reached in 2050[172]. The study by Scheelhaase *et al.*[173] compares the two mechanisms and shows that the European system would be more effective than the ICAO offsetting system until 2035 if it was applied by all the countries signing CORSIA. Because this scenario is considered to be little likely, the authors conclude that the best compromise for the European Union would be to keep the EU-ETS for intra-community flights and to apply CORSIA for flights outside Europe. A recent report by the European Commission concluded that “a certain number of characteristics of CORSIA imply that its level of ambition for the international aviation sector is not aligned with the global level of ambition required to meet the temperature targets of the Paris Agreement, and that it is lower than those targets” and that “participating in CORSIA — and leaving all international aviation (as defined by the ICAO, including between EEA countries) outside the scope of application of the EU-ETS — runs the risk of compromising these targets and weakening the EU’s current climate policies”[IAN+20].

9.2 Examples of sustainable scenarios

In this section, various technological scenarios for the transition of the aviation sector are studied and sensitivity analyses are conducted on several variables. Here the study focuses on CO_2 emissions, non-CO_2 effects being discussed in the section 9.4.2. The analysis is based on the methodology presented in chapter 8 and on the use of CAST.

9.2.1 Characterisation of technological scenarios

The aim of this section is to illustrate various sustainable scenarios for aviation, which were discussed in further detail in Planès *et al.*[164]. These technological scenarios are described by the following four characteristics:

1. aircraft energy efficiency;
2. load factor;
3. flight and ground operations;
4. fleet decarbonisation rate.

We note in particular that the description of a technological scenario does not include rate of traffic growth. These rates are either calculated to fit in with the carbon budgets for aviation (at +1.5 and +2 °C) defined in section 8.3, considering different allocations for aviation; or they are fixed beforehand and then the corresponding share of global carbon budget is then computed. Concerning the impact of the Covid-19 epidemic, it is assumed that air traffic will regain its 2019 level in 2024.

The first three levers (aircraft efficiency, load factor and operations) relate to improving global energy efficiency in order to consume less fuel per passenger-kilometre. On the one hand, this can be achieved by the means discussed in chapter 5, namely incremental improvements or disruptive innovation on aircraft. The evolution in this efficiency per plane depends both on future aircraft architectures but also on the rapidity of global fleet renewal. On the other hand, global energy efficiency can be improved by improving aircraft load factor (fewer empty seats) but also operations in flight and on the ground. This last lever, not specifically addressed among the action levers in this report, can be used for example to reduce the impact of consumption in ground phases and to improve flight paths in order to minimise fuel consumption.

Different notions need to be defined when it comes to decarbonisation. We first introduce the notion of fuel decarbonisation rate as the reduction in CO_2 content in the energy used compared to conventional kerosene. Thus, a 50% decarbonisation rate for a fuel means it emits 50% less CO_2 compared to kerosene. Using emission factors from ADEME[a], it corresponds to a carbon intensity of 43.4 gCO_2-eq/MJ compared to the 86.7 gCO_2/MJ of kerosene[b].

We then define more globally the rate of fleet decarbonisation as the reduction in mean CO_2 content in the energy used by the entire fleet compared to conventional kerosene. As a result, a 50% fleet decarbonisation rate can mean several things. For example, that the entire fleet is using fuel of which the decarbonisation rate is 50% or that half the fleet is using fuel of which the decarbonisation rate is 100% when the other half is using kerosene.

To simplify future analyses, we consider that the only low-carbon fuel used by the aircraft fleet is a biofuel produced by the Fischer–Tropsch process, assuming a production efficiency of 40%. We consider that the fuel decarbonisation rate is 75%, therefore around 21.7 gCO_2-eq/MJ and also, we do not apply a limit to its incorporation rate. As a result, the share of the fleet using this biofuel by 2050 simply needs to be varied to obtain the fleet decarbonisation rate. For example, if half the fleet is using this biofuel (and the rest kerosene), the fleet decarbonisation rate is 37.5%. In particular, in all our results, the maximum decarbonisation rate of the fleet is 75%.

Beyond these four characteristics, additional parameters are available to adjust the timing of the different action levers, such as the year the lever begins to be activated and the rate at which the transition occurs. The rate at which the various levers are activated is discussed in section 9.4.1, and the default values from CAST will be used.

[a] A discussion on kerosene emission factors can be found in appendix B.5.

[b] In this chapter, aviation emissions are given in CO_2-eq in particular because they can be partly due to biofuels. Nevertheless, for sake of simplicity and in order to avoid going into detail concerning the proportions of these emissions caused by CO_2 compared to other greenhouse gases, in the rest of the chapter we will compare the emissions from aviation with different carbon budgets, even when emissions from aviation include a proportion of greenhouse gases other than CO_2. To obtain an order of magnitude, Stratton *et al.* [SWH10, table 40] evaluate that for a biofuel produced from switchgrass and coal, CO_2 emissions represent around 90% of CO_2-eq.

Scenario	A	B	C
Annual improvement in energy efficiency 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 decarbonisation rate in 2050	0%	37.5%	75%
Result: emission factor in 2050	89	52	17

Table 9.1: Main technological hypotheses for the three illustrative scenarios studied using CAST. The resulting emission factors in 2050 are expressed in gCO_2-eq/pass.km.

Scenario	A	B	C
Energy efficiency			
Annual improvement	1%	1%	1.5%
Cumulative improvement in 2035	14%	14%	20%
Cumulative improvement in 2050	26%	26%	36%
Operations			
Annual improvement	0%	0.28%	0.43%
Cumulative improvement in 2035	0%	6%	9%
Cumulative improvement in 2050	0%	8%	12%
Efficiency + Operations			
Annual improvement	1%	1.28%	1.92%
Cumulative improvement in 2035	14%	19%	27%
Cumulative improvement in 2050	26%	32%	44%

Table 9.2: Details for the scenarios A, B and C concerning improvement in efficiency and operations.

9.2.2 Description of technological scenarios

We consider three technological scenarios A, B and C, corresponding to the following hypotheses:

Scenario trend without decarbonisation (A): trend improvement (taking into account slowdown due to technological limits) for the load factor and energy efficiency, no improvement in operations and no low-carbon fuel use;

Scenario trend with partial decarbonisation (B): trend improvement (taking into account slowdown due to technological limits) for the load factor and energy efficiency, improvement in operations and use of low-carbon fuel for half the fleet;

Scenario disruptive innovation and total decarbonisation (C): improvement and disruptive innovation for energy efficiency, significant improvement in load factor and operations and use of low-carbon fuel for the entire fleet.

These hypotheses are described quantitatively in tables 9.1 and 9.2.

These hypotheses determine the fleet's global emission factor[a], given in grams of CO_2-eq per passenger-kilometre (gCO_2-eq/pass.km) in the last line of table 9.1. Scenario A is the least ambitious, with an emission factor of 89 gCO_2-eq/pass.km by 2050 and scenario C is the most ambitious, with an emission factor of 17 gCO_2-eq/pass.km. As a comparison, for the global fleet, the average emission factor in 2019 was 131 gCO_2-eq/pass.km when the latest generation aircraft are able to achieve emission factors lower than 100 gCO_2-eq/pass.km.

Concerning the values considered for the energy efficiency, they correspond to a decrease in consumption of 26%, 26% and 36% by 2050 for scenarios A, B and C, respectively (see table 9.2). In chapter 5, we saw the different levers for improving energy efficiency in order to conceive new aircraft by 2035, consuming around 20% to 30% less than the most efficient aircraft today. These hypotheses put forward are therefore consistent with these figures, taking into account the time required to renew the fleet. Furthermore, the hypotheses put forward concerning the improvement in operations are based on values similar to those from the ATAG Waypoint 2050 report, around 10%[ATA20]. The hypotheses on the load factor correspond to trend hypotheses, which are a little more optimistic for C, thus extending the trends from figure 3.2 (in 2018, the average load factor was 82%[b]). The hypotheses put forward on fleet decarbonisation rate are more difficult to interpret because they combine two elements. On the one hand, fuels with a decarbonisation rate of 75% are already available (higher rates are even possible) and flights have been made using 100% biofuels, making it possible to envisage aircraft with a decarbonisation rate of 75% in the short-term. Scaling up for an entire fleet depends however on other factors, especially the maximum authorised incorporation rate, industrial production capacity, availability of energy resources and evolution in traffic. These various elements are discussed in section 9.4.3 and suggest that a zero fleet decarbonisation rate for scenario A is extremely pessimistic and that conversely, the 75% hypothesis for C is extremely optimistic especially in the case of fast growing traffic.

To conclude, it is useful to establish several scenarios because future technological improvements are highly uncertain, as much in terms of gain as in time scale. These illustrative scenarios can therefore be used to produce conceivable ranges of variation.

9.2.3 Scenario analysis

Once the technological scenarios are defined, several analyses can be performed. Firstly, we consider the framework of the IPCC P1 scenario, without using BECCS. The median carbon budgets for +1.5 °C and +2 °C are considered and the methodology presented in chapter 8 is used. A sensitivity analysis is performed on the carbon budget share allocated to aviation. In each case, and for the three illustrative technological scenarios, the maximum air traffic annual growth rate is calculated in order to balance the cumulative emissions from aviation with the carbon budget allocated until 2050.

Figure 9.1 summarises the results. It can be seen that, logically, a more ambitious technological scenario (C compared to A for example) or a less re-

[a]We recall that, following our methodology, this emission factor concerns the CO_2 effects of commercial aviation, including emissions due to fuel production.

[b]Source: ICAO via the site airlines.org, consulted on the 25th of August 2021.

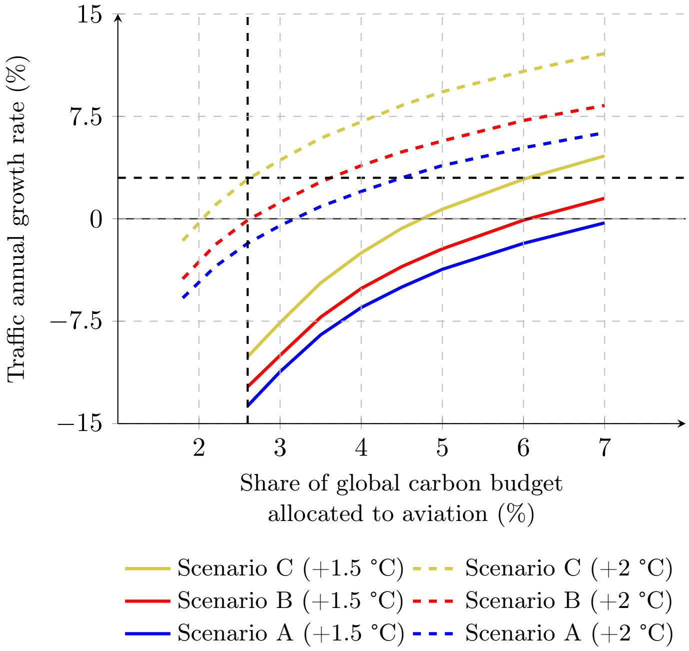


Figure 9.1: Air traffic annual growth rate according to global carbon budget share allocated to commercial aviation for the scenarios A, B and C. Results given for median carbon budgets for +1.5 °C (solid lines) and +2 °C (dashed lines), without considering the use of BECCS. The vertical dotted line shows the reference share of 2.6%, and the horizontal dotted line shows the 3% growth rate announced by the industrial sector. Results produced using CAST.

strictive climate target (+2 °C instead of +1.5 °C) can achieve higher growth rates. For a climate target of +1.5 °C, allocating to aviation a larger share than its current share of 2.6% is necessary for maintaining or increasing air traffic, regardless of the illustrative technological scenario considered. In the case of scenario C for instance, it would be necessary to allocate to aviation roughly the double of its reference share to allow for an annual traffic growth of around 3%. The exact value, along with other values for the carbon budget consumed by aviation to enable a 3% yearly growth in traffic, are provided in table 9.3. Considering the 2.6% reference share, strong decrease in air traffic is needed to meet the allocated carbon budget for +1.5 °C.

For a +2 °C target, the results are slightly different. A decrease in air traffic is required for the least ambitious technological scenario A. However, for the most ambitious technological scenario C, growth in air traffic similar to the trend growth is conceivable by allocating the 2.6% reference share to aviation (see table 9.3). This corresponds to a traffic doubling between 2018 and 2050. With scenario C, a stagnation or a slight increase in traffic would even be possible by allocating a smaller share than the reference share to aviation, thus leaving some room of manoeuvre to other sectors.

The results above are framed within the IPCC P1 scenario and therefore do not take the potential use of BECCS into account. BECCS would increase

Scenario	A	B	C
Median carbon budget at +1.5 °C	10.2%	8.2%	6.0%
Median carbon budget at +2 °C	4.5%	3.6%	2.6%

Table 9.3: Share of the global carbon budget consumed by aviation for allowing an annual air traffic growth of 3%. Median carbon budgets are used without considering the use of BECCS.

the gross carbon budget (see table 8.1), which justifies performing a sensitivity analysis for different gross carbon budgets. In addition to taking BECCS into account, it makes it possible to also consider multiple temperature targets along with the different possibilities for achieving them. Figure 9.2 summarises the results in the case of technological scenarios B and C. The results are presented in the form of a figure relating global gross carbon budgets, the share allocated to aviation and air traffic growth rates. These figures are used to find the results obtained for median carbon budgets without BECCS and to extend them to other gross carbon budgets with BECCS. They are also used to facilitate arbitration between several variables. It is interesting to note that, for a more ambitious technological scenario, the level lines are shifted towards the bottom left corner of the graph. This means for example that a more restrictive climate target can be met with given allocated share and air traffic growth rate.

Nevertheless, two limits remain on the analysis of these illustrative scenarios. First, these scenarios only consider CO_2 emissions. A concise and illustrative study including all non-CO_2 effects is provided in section 9.4.2. Second, scenarios B and C require the use of low-carbon fuels to supply the aircraft fleet. For each scenario, it is therefore necessary to evaluate the quantity of energy resources required for aviation and to compare this value with the expected global availability in 2050. These two specific aspects are studied in section 9.4.3.

9.3 Analysis of an industrial scenario

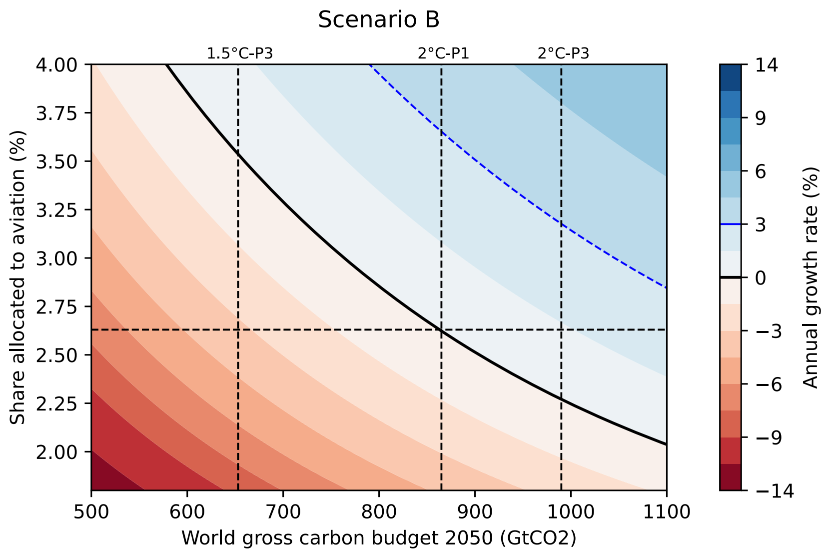
9.3.1 Scenario 1 - Waypoint 2050

In this section, a scenario put forward by the ATAG in its recent Waypoint 2050 report[ATA20], namely scenario 1 “pushing technology and operations”, is analysed. Industrial scenarios are important as they often coincide with those of the ICAO. In 2019, the ICAO took the target set by the IATA in 2009 for neutral carbon growth from 2020[a] and set up CORSIA with this objective in mind. This scenario, for which the emissions are represented in figure 9.3, is based on five hypotheses:

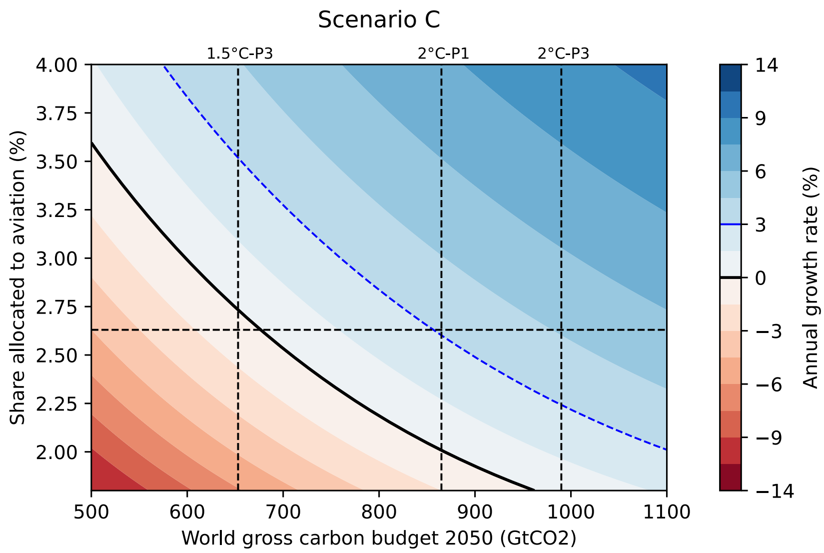
1. 3% growth in traffic per year[b];
2. improvement in operations (decarbonisation of taxiing, trajectory optimisation, ...);

[a]For the ICAO, see the *Working Paper* ICAO A40-WP/54, ICAO Global Environmental Trends – Present And Future Aircraft Noise And Emissions, 5th of July 2019. In 2009, IATA set itself the most ambitious objective of reducing emissions by 50% in 2050 compared to the 2005 level[IAT19].

[b]This growth forecast corresponds to an update of pre-Covid objectives which were around +4.5%.



(a) Sustainable annual rate of growth of air traffic according to the gross carbon budgets considered for scenario B.



(b) Sustainable annual rate of growth of air traffic according to the gross carbon budgets considered for scenario C.

Figure 9.2: Sensitivity analysis on global gross carbon budgets for the two technological scenarios B and C. For a given global gross carbon budget and a share allocated to aviation, the simulations conducted using CAST provide the corresponding annual air traffic growth rate. The dotted horizontal line shows the share of CO_2 emissions from air transport in 2018 which is around 2.6%. The vertical dotted lines show the various median gross carbon budgets calculated for 2050: that for +2 °C without BECCS used previously (written 2 °C-P1) and those for +1.5 °C and +2 °C with the BECCS values from the IPCC's scenario P3 (written 1.5 °C-P3 and 2 °C-P3). The dotted blue line shows the annual trend growth rate of 3% corresponding to industrial forecast.

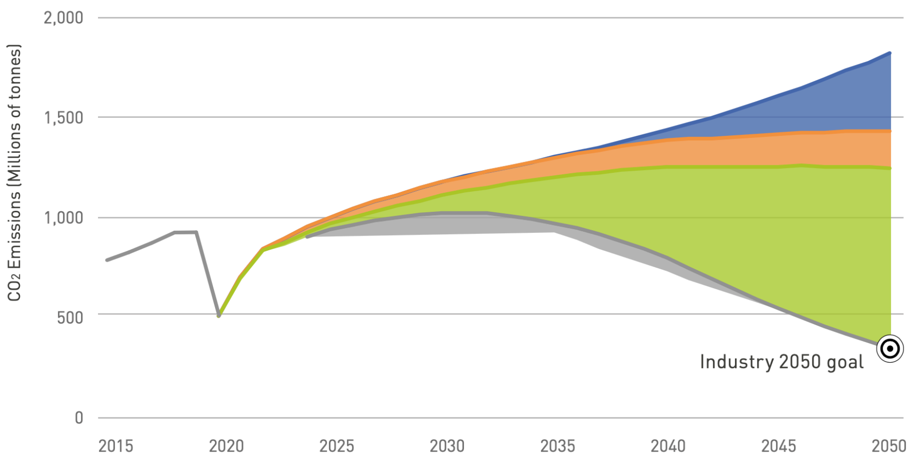


Figure 9.3: Scenario 1 "Pushing technology and operations" from the ATAG's Waypoint 2050 report, with annual growth in traffic at +3%. Technological improvements (blue), improvements in operations (orange), use of SAF (green) and carbon offsetting (grey) make it possible to decrease emissions. According to the ATAG[ATA20] (p. 24).

3. improvement in load factor;
4. priority development of electric and hybrid aircraft for the short-haul aircraft category with less than 100 seats, to be commissioned from 2035/2040;
5. retrospective approach[a] for the remaining effort (reduction in CO_2 of around 900 Mt) to attain the objective: a range of 290 Mt to 390 Mt (360 Gl to 490 Gl) SAF with a 74% to 100% emission reduction factor by 2050.

Furthermore, carbon offsetting measures (in grey in figure 9.3) are also planned but play a marginal role because, by definition of the backcasting approach, the decarbonisation rate is seen as an adjustment variable for meeting climate objectives. Qualitatively, this scenario is similar to scenario C presented previously.

9.3.2 Climate analysis of the industrial scenario

Based on figure 9.3, cumulative CO_2 emissions generated by aviation have been estimated for this industrial scenario. These emissions are compared in figure 9.4 with scenario A with the same growth in air traffic (3% per year), which serves as a benchmark to determine the impact of the planned technological improvements. It is interesting to note that the industrial scenario can be used to significantly reduce cumulative emissions from air transport up to 2050 compared to the trend scenario, but these differences between the two scenarios become significant only after 2030. Nevertheless, despite technological improvements, this scenario requires different carbon budget allocation for +1.5 °C and +2 °C. Indeed, in this scenario, it would be necessary to allocate a share to

[a]The retrospective, or *backcasting* approach, consists in estimating the quantity of SAF required to reach the set climate objective. It is therefore opposed to the prospective approach which consists, based on estimations of the quantity of SAF available, in deducting the climate consequences.

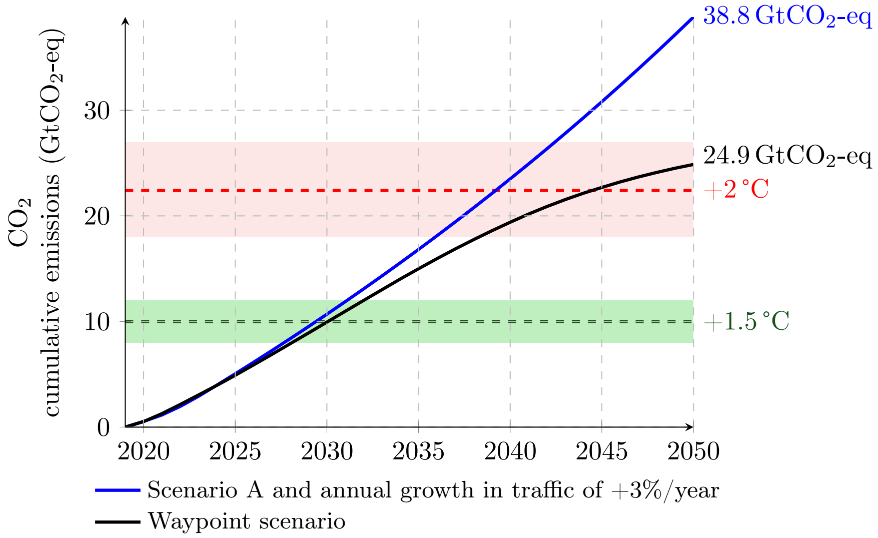


Figure 9.4: Evolution in cumulative CO_2 emissions for the industrial scenario presented (black curve). The trend technological scenario (A), presented in the previous section, with annual growth of 3%, is provided in comparison (blue curve). The coloured horizontal areas correspond to the intervals of the carbon budget allocated to aviation. These intervals are calculated by allocating between 2.1 and 3.1% of the global budget to aviation based on median carbon budgets at +1.5 °C (green area) and +2 °C (red area). The dotted lines represent the reference carbon budget corresponding to allocation of 2.6% of the global carbon budget to aviation.

aviation of 6.6% and 2.9% of the median carbon budgets for +1.5 °C and +2 °C respectively, therefore more than the reference share of 2.6%. With the reference allocation of 2.6%, the carbon budget for +1.5 °C would be fully consumed by 2030 for the industrial scenario.

9.3.3 Methodological assessment

This industrial scenario presents several methodological issues. First, the emissions reported are only those related to kerosene combustion[a]. However, as explained in section 2.2.2, the impact of biofuels is only relevant over the kerosene full life cycle, in which non-combustion CO_2 emissions are also included leading to an increase of about 20%. The emissions from this scenario are therefore under-evaluated.

Second, the ATAG compares the 2050 emissions to emissions set in two of the IEA's scenarios limiting warming to +2 °C to prove that the proposed trajectory is compatible with the Paris Agreement. However, +2 °C is only an upper limit mentioned in the Paris Agreement, and it is effectively cumulative emissions, and not those from a given year, which matter.

Furthermore, some data required to evaluate the Waypoint 2050 scenario are missing, such as for example the hypotheses put forward on the improvement

[a]Indeed, the ATAG considers emissions from commercial aviation (excluding military and private aviation) equal to 0.9 $GtCO_2$ in 2018, whereas over the entire life cycle they were around 1.1 $GtCO_2$ (see appendix B.5).

in efficiency before 2035 or even the change in load factor. These missing data are necessary to reproduce this scenario and therefore prevent an analysis as accurate as those conducted for scenarios A, B and C. It is not possible for example to perform a sensitivity analysis on the share of the carbon budget allocated to aviation and the growth in traffic as done in table 9.3.

To conclude, the backcasting approach does not enable an accurate and realistic trajectory as it overestimates the impact of decarbonisation. This point will be discussed in detail in the next section.

9.4 Additional studies

Further to the analysis of the various scenarios presented previously, several additional analyses are performed in this section. First, the impact of an earlier implementation of decarbonisation measures is studied. Second, a sensitivity study on fleet decarbonisation rate is carried out to address issues related to potential limited energy resource.

9.4.1 Impact of lever activation time

Because these are the cumulative CO_2 emissions which matter when it comes to climate issues rather than the single final value reached in 2050, the time at which decarbonisation measures are implemented is a key issue.

To illustrate this phenomenon, the technological scenario C is considered with a median carbon budget for $+2\,^{\circ}\mathrm{C}$ and the reference share of 2.6% of the global carbon budget allocated to aviation. In addition to the so-called "standard" reference scenario, another scenario, labelled "accelerated", with the same technological characteristics but with an implementation of fuel decarbonisation measures starting 3 years earlier, is studied. Figure 9.5 represents the progression of these two scenarios in terms of energy CO_2 content for the entire fleet. This parameter is used to evaluate the CO_2 emissions from fuel per unit of energy (MJ), including fuel production. It is a mean value for the entire fleet.

Figure 9.6 shows these two versions of scenario C. Figure 9.6a shows the trajectory of the annual CO_2 emissions of the "standard" scenario C with an annual traffic growth of 2.9% calculated to balance the cumulative emissions with the carbon budget allocated to aviation. Figure 9.6b shows the trajectory of the annual CO_2 emissions of the "accelerated" scenario C. The introduction of low-carbon fuels before 2035 can be seen clearly in the figure (in green), unlike the "standard" scenario C. In this case, an annual traffic growth of 4.2% enables to balance cumulative emissions with the carbon budget allocated to aviation. Indeed, using low-carbon fuels earlier in this second scenario allows for greater annual air traffic growth for the same carbon budget.

It is important to note that the "standard" scenario C matches the timeline planned by the various aviation stakeholders. Indeed, focusing on SAF only, the data from CAST show that the "standard" scenario C would require 4.7 Mt SAF in 2030 compared to 16.1 Mt for the "accelerated" scenario C. This range of 5 Mt to 16 Mt, and especially its lower value, is compatible with the various forecasts by aviation stakeholders described in detail in section 9.4.3.

This result can be generalised to any lever of action. The earlier a measure is implemented, the better its impact because these are the cumulative emissions

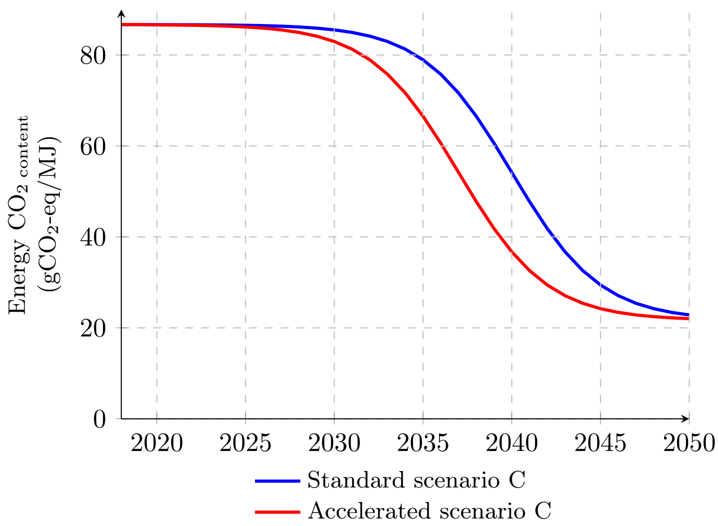


Figure 9.5: Evolution in energy CO_2 content for the two scenarios C.

which are important. Failure to rapidly implement disruptive innovation is one of the reasons to explain the difficulty underpinning decarbonising aviation. Beyond the example of low-carbon fuels, hydrogen is an excellent example to illustrate this aspect because it is only expected to be used for aviation by 2030 at the earliest.

9.4.2 Taking into account non-CO_2 effects

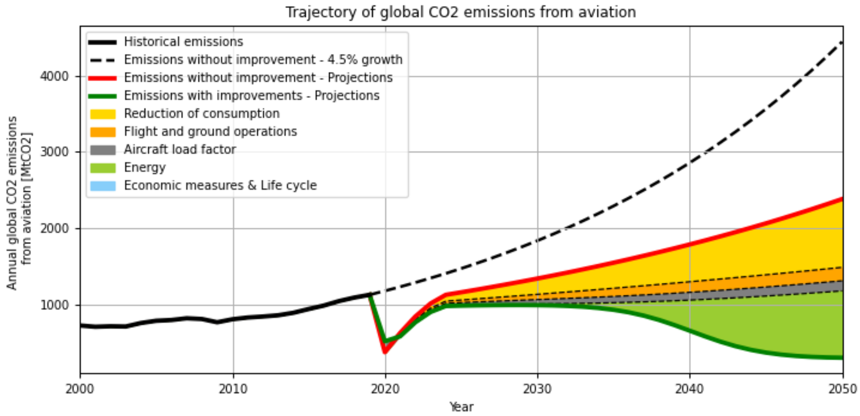
In the previous sections, the analysis focused only on CO_2 emissions from the aviation sector. The aim of this section is to provide elements of discussion on the integration of non-CO_2 effects in the climate transition scenarios.

The methodology used is more complex than using conventional carbon budgets[a]. The approach consists in comparing an extended carbon budget including non-CO_2 effects, introduced in section 8.3.3, with equivalent cumulative CO_2 emissions from aviation through to 2050. The latter are calculated based on the climate metric GWP∗, defined in appendix A, and given in $GtCO_2$-eq∗[b]. In the next part, this methodology is considered with median carbon budgets without BECCS. For example, the extended carbon budget (including non-CO_2 effects) is thus estimated to be 981 $GtCO_2$-eq∗ for +2 °C.

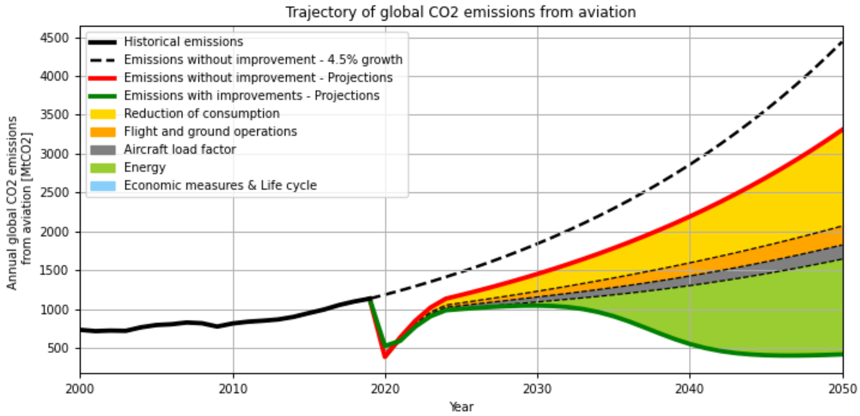
The technological scenario C is taken as an example of application. Two cases are studied here: the illustrative scenario presented previously and the same scenario including strategies for reducing non-CO_2 effects. Here, these strategies focus on contrails and consider one of the scenarios by Teoh*et al.*[138]: the path diversion strategies are generalised, which enable to reduce the climate impact of contrails by 59.4% at the cost of kerosene overconsumption for the entire fleet of 0.014%. In the two cases, the annual rate of growth is set to 2.9%, which ensures to respect a median carbon budget for +2 °C with a 2.6% share

[a] The methodology is described in detail in the works by Planès *et al.*[164]

[b] This unit, which is used to express equivalent emissions calculated using the metric GWP∗, is often written $GtCO_2$-we for *warming-equivalent*.



(a) Trajectory of CO_2 emissions in the standard scenario C for +2 °C.



(b) Trajectory of CO_2 emissions in the accelerated scenario C for +2 °C.

Figure 9.6: Influence of the time of introduction of low-carbon fuels in scenario C for +2 °C. Introducing low-carbon fuels earlier allows for greater air traffic growth for the same climate target. Curves obtained with CAST.

allocated to aviation. Figure 9.7 represents equivalent cumulative emissions for these two scenarios. Cumulative CO_2 emissions are almost equal, the very low overconsumption induced by the strategy for reducing the contrails occurrence being imperceptible. However, this strategy allows to significantly reduce the total equivalent cumulative emissions via non-CO_2 equivalent emissions, from 91.3 $GtCO_2$-eq$*$ to 27.0 $GtCO_2$-eq$*$. This second scenario would therefore consume 7.5% and 2.7% of the extended carbon budgets for +1.5 °C and +2 °C respectively. As a comparison, by including non-CO_2 effects, commercial aviation is responsible for 5.1% of recent global warming (2000–2018).

It is interesting to note that equivalent emissions for non-CO_2 effects can become negative, as illustrated in figure 9.7. In certain cases, it can even lead to negative total equivalent emissions, which corresponds to a decrease in the climate impact from aviation compared to 2018. For example, technological scenario A, with an annual growth rate of -1.8% (which complies with the median carbon budget for +2 °C with an allocated share of 2.6%) and the strategy for

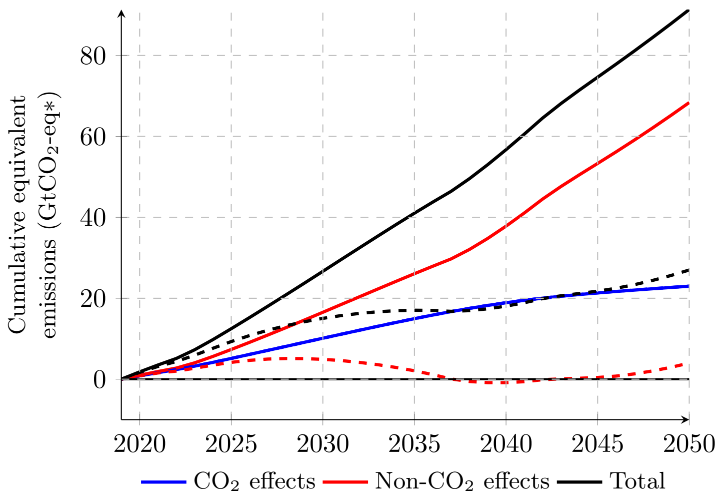


Figure 9.7: Cumulative emissions in GtCO$_2$-eq$*$ for scenario C (solid lines) and scenario C including strategies on contrails (dotted lines). The equivalent emissions from non-CO$_2$ effects can become negative using the metric GWP$*$, which can be assimilated to a removal of carbon from the atmosphere.

reducing contrails, leads to total equivalent emissions of -2.4GtCO$_2$-eq$*$.

This short study can therefore be used to highlight several conclusions. First, the strategies based on path diversions to avoid contrail formation can be implemented rapidly, within 5 to 8 years according to a report to the European Union[ALO+20]. (see however section 7.2 presenting the current scientific debate about whether they should be implemented rapidly or not). Due to the short life time of these non-CO$_2$ effects, it is possible to limit future global warming induced by aviation, or even to reduce the impact and therefore to generate relative cooling compared to 2018 (but still warming overall). **Strategies specific to non-CO$_2$ effects therefore represent a powerful lever in the short-term for meeting the targets of the Paris Agreement in terms of temperature**. Nevertheless, ambitious strategies must also be implemented simultaneously for the reduction of CO$_2$ emissions, so as not to replace warming caused by non-CO$_2$ effects by warming caused by CO$_2$ emissions, which has a stronger impact on temperature in the long-term[174].

Limits to these analyses must however be mentioned. The impact of alternative fuels on non-CO$_2$ effects is not estimated here, whereas some, like biofuels, could reduce the occurrence of contrails-induced cirrus clouds (see chapter 7). Ongoing research is conducted on efficient methods for estimating these impacts[160]. Also, the evaluation methodologies used need to be further refined and the analysis of scenarios need to be more exhaustive.

9.4.3 Influence of fleet decarbonisation rate

In the scenarios studied previously, fleet decarbonisation rate has a predominant influence on the level of sustainable air traffic. Here the influence of the decarbonisation rate is studied in two steps. First, the foreseeable rates are estimated based on the forecasts for available biofuels, then a sensitivity analysis is performed to study the influence of decarbonisation rate on both the maximum traffic growth rate and the energy resources.

Biofuel production forecasts

Column “Forecast” of table 9.4 gathers several estimates of biofuel production by 2030 and 2050, globally and at European level. These forecasts are taken from the scientific literature, institutional reports or provided by aviation stakeholders. To evaluate biofuel availability, the most frequently used scientific methodology consists in determining the portion to be converted into biofuel for aviation based on biomass availability, by applying several successive filters. Staples *et al.*[175] consider three filters with three hypotheses for each. The first

Source	Forecast (EJ/an)	Decarbonisation rate
Global (2030)		
ATAG (backcasting approach)[ATA20]	1.3 to 2.1	6 to 11%
ATAG (trend approach)[ATA20]	0.1 to 0.3	0 to 2%
ICAO[ICA19c]	0.0 to 0.2	0 to 1%
Global (2050)		
ATAG (backcasting approach)[ATA20]	11.3 to 16.9	42 to 63%
ATAG (trend approach)[ATA20]	0.8 to 2.9	3 to 11%
Staples (estimations F1)[175]	7.0 to 80.4	26 to 75%
Staples (estimations F2)[175]	0.6 to 15.4	2 to 58%
Staples (central estimation)[175]	5.9	22%
Searle et Malins[176]	$\sim$ 1 to 3	$\sim$ 1 to 2%
Europe (2030)		
EASA extrapolated[EAS19]	0.0 to 0.2	0 to 5%
de Jong[125]	0.1 to 0.3	3 to 9%
ICCT[OPS21]	0.1 to 0.2	2 to 4%

Table 9.4: Biofuel availability forecasts globally and in Europe, in 2030 and 2050, and corresponding fleet decarbonisation rate. Additional information is provided in the body of the text for the references by Staples and Searle and Malins, and for the decarbonisation rate calculation. Only the estimations in the F1 hypothesis by Staples provide for a biofuel offer higher than the demand from the aviation sector considered in Waypoint 2050. The ICCT’s figures contain a small fraction (3%) of electrofuels.

filter is the total available bioenergy, for which they consider the hypotheses S1 (510 EJ), S2 (178.7 EJ) and S3 (41.0 EJ). The last two estimations are compatible with the values ranging from 45 EJ to 310 EJ of the IPCC P1 to P4 scenarios detailed in table 8.1. The second filter is the price of bioenergy and the three hypotheses are A1 (4 \$/GJ), A2 (2 \$/GJ) and A3 (1 \$/GJ). The third filter is the share of bioenergy allocated to aviation. The three hypotheses are F1 (bioenergy is allocated in priority to the aviation sector, the other sectors requiring bioenergy share the remainder), F2 (the various sectors are served in proportion to their energy demand) and F3 (the other sectors have priority over aviation, which can only use the remaining bioenergy). The quantity of biofuel available according to the hypotheses is shown in figure 9.8. In 2014 and 2015,

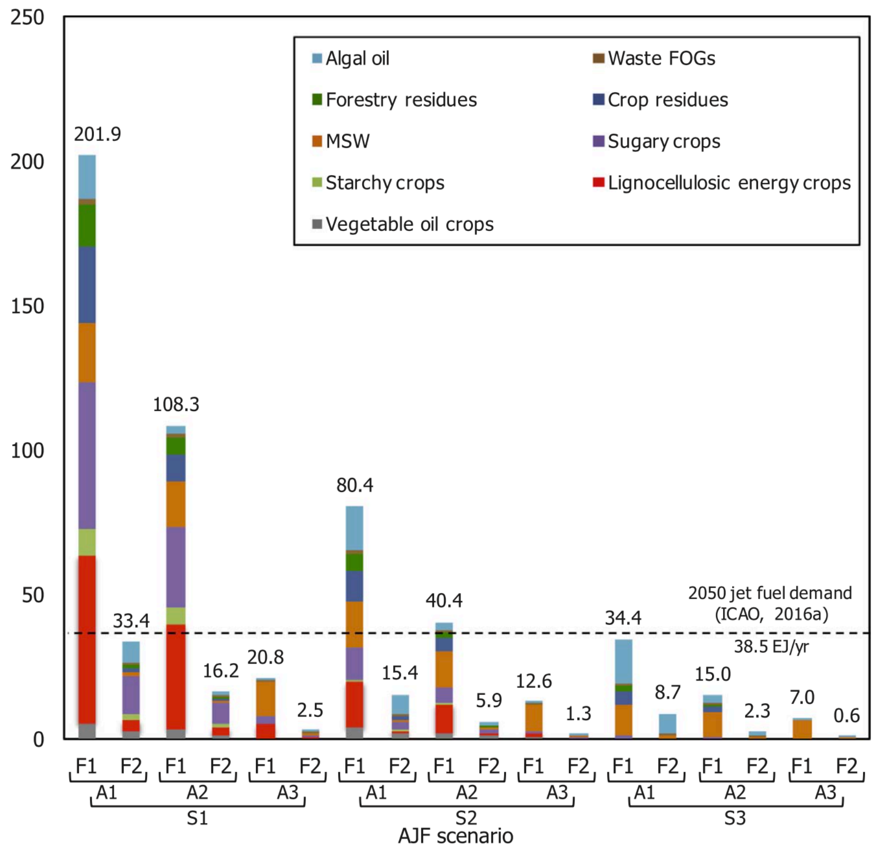


Figure 9.8: Quantity of biofuel (EJ) available for aviation in 2050 according to different scenarios after figure 5 by Staples *et al.*[175]. The fuel demand for 2050 forecast by the ICAO differs from that used in table 9.4 due to more recent forecasts from Waypoint 2050 (38 EJ for Staples *et al.* compared to 19.9 EJ for Waypoint 2050).

two literature studies concluded that it would be very doubtful to have more than 300 EJ of bioenergy available in 2050[119, 177], which rules out hypothesis S1. This maximum value of 300 EJ is consistent with the maximum value for bioenergy in scenarios P1 to P4 (310 EJ, see table 8.1). Concerning the rules of allocation for filter F, similar issues to those presented in chapter 8 for carbon budgets arise. In the case of hypothesis F3 giving priority to other sectors, aviation would have no biofuel (this is why hypothesis F3 does not feature in figure 9.8). As for hypothesis F1, it corresponds to an upper limit which is very unlikely to happen[a].

As a result, the focus is made on hypotheses S2 or S3, A1, A2 or A3 and F1 (as upper limit) or F2 (as median value)[b] which are the only ones for which the forecasts are reported in table 9.4. Among the twelve scenarios resulting from the combination of these hypotheses, six lead to an estimation compatible with the ATAG's backcasting estimations. Among the latter, one is not an upper limit and corresponds to hypothesis F2: 178 EJ of bioenergy is required and it is valued at 4 \$/GJ. Staples *et al.* note that this scenario involves building 110 new biorefineries per year, a figure they compare to the 60 biodiesel refineries commissioned each year between 2002 and 2011.

Searle and Malins[176] take a general look at the bioenergy that will be available in 2050, without focusing on just aviation. They apply a method similar to that of Staples *et al.* but use different filters, for example agricultural productivity or political stability. They consider several previous studies which they correct by applying any missing filters, and conclude that between 60 EJ to 120 EJ of bioenergy could be available. This figure is compatible with the upper limit of 300 EJ mentioned previously and covers the values from the IPCC's scenarios P1, P2 and P3 in table 8.1. They thus consider the competition in bioenergy uses and estimate that between 10 EJ to 20 EJ (*i.e.* 8% to 17% of total bioenergy) could be allocated to the transport sector. It is therefore the deposit which the aviation sector would compete for with the road transport, rail transport and maritime transport sectors. The aviation sector accounting for around 10% of energy consumption in the transport sector, this suggests a potential deposit of a few exajoules for aviation and at most about ten if aviation is given priority. In comparison, the ATAG's backcasting approach requires several tens of exajoules.

These considerations show that the energy demand from the aviation sector may face limitations in energy availability and may call into question the high estimates of biofuel production, especially those used in the ATAG's backcasting approach which does not take these limitations into account. Counting on a traffic growth scenario based on massive use of biofuels carries the risk of exacerbating the climate problem if biofuel production does not follow the expected evolution. This risk, related to the very nature of the prospective scientific scenarios, extends beyond the case of biofuels, and has been recently questioned

[a] To illustrate competition for biofuels, it is interesting to consider that in 2018, only 0.01% of biofuels were dedicated to the aviation sector[IEA19b] whereas aviation represented 12% of energy consumption in the transport sector according to the IEA.

[b] It would be useful to add an intermediate "hypothesis" between F1 and F2 to this discussion. For example, the fact that sectors such as the road transport sector have more decarbonisation options than the aviation sector, in particular using electricity, could be taken into account. This could justify the aviation sector to get a larger share of bioenergy than its current energy demand. In fact, arguments similar to those put forward in section 8.3.2 apply in both directions.

by a former IPCC chair[a].

Even if the focus has been made on biofuels in this section, this remark also applies to electricity-based energy carriers such as hydrogen and electrofuels. The recent report by the Clean Sky consortium (performed by the McKinsey consulting firm) on the hydrogen plane evaluated an electricity need between 75 EJ to 112 EJ to supply the 2050 aircraft fleet with a hydrogen and electrofuel mix[McK20]. This figure is significant since it represents between 40 and 60% of the 185 EJ electricity produced in P1, or between 30 and 45% of the 251 EJ electricity produced in P4.

Conceivable decarbonisation rates

Going from biofuel production to an estimated (fleet) decarbonisation rate requires hypotheses on the fuel decarbonisation rate and on the energy demand. For the fuel decarbonisation rate, we take a 75% hypothesis as in the rest of the chapter. For the global aviation energy demand, we used the industrial forecasts provided in Waypoint 2050, *i.e.* 15.3 EJ in 2030 and 19.9 EJ in 2050, and for the European demand in 2030 we used the ICCT's[OPS21] estimation of 2.7 EJ. The last column in table 9.4 shows the resulting decarbonisation rate. For example, the work by Staples *et al.* reaches a 2 to 58% decarbonisation rate, considering proportional distribution, and rates which can reach 75% considering bioenergy priority allocations. In light of the other estimations presented, the lower values cannot be ruled out.

These results are based on a given traffic growth hypothesis. If traffic grows more slowly than the industrial forecasts, then all other things being equal, it results in a increase of the fleet decarbonisation rate. In the next section we analyse the links between decarbonisation rate, traffic growth rate and energy demand.

Decarbonisation rate sensitivity analysis

Previous discussions show that the fleet decarbonisation rate foreseeable in 2050 is very uncertain. The objective of the previous section was to provide the main parameters and conceivable ranges. This decarbonisation rate will depend on the rate of growth of air traffic, on the energy resources allocated to aviation and on economic parameters such as the price of bioenergy.

A sensitivity analysis can however be performed on the decarbonisation rate. Here, we will study the impact of decarbonisation rate on the traffic growth rate and on the consumption of primary energy. Indeed, a high fleet decarbonisation rate allows a higher traffic while respecting a given carbon budget, but a higher traffic leads in turn to an increase in fuel and therefore primary energy consumption. To get relevant orders of magnitude, we consider, for illustrative purposes, the median carbon budgets without BECCS with the 2.6% reference allocation to air transport. Concerning the technological hypotheses, a scenario similar to scenario B is studied with a varying fleet decarbonisation rate. Therefore, energy efficiency is improved by 1% per year and in 2050, the load factor reaches 89% with operations reducing consumption by 8%. The fleet decarbonisation

[a]Source: Climate scientists: concept of net zero is a dangerous trap, James Dyke, Robert Watson and Wolfgang Knorr, The Conversation, April 2021.

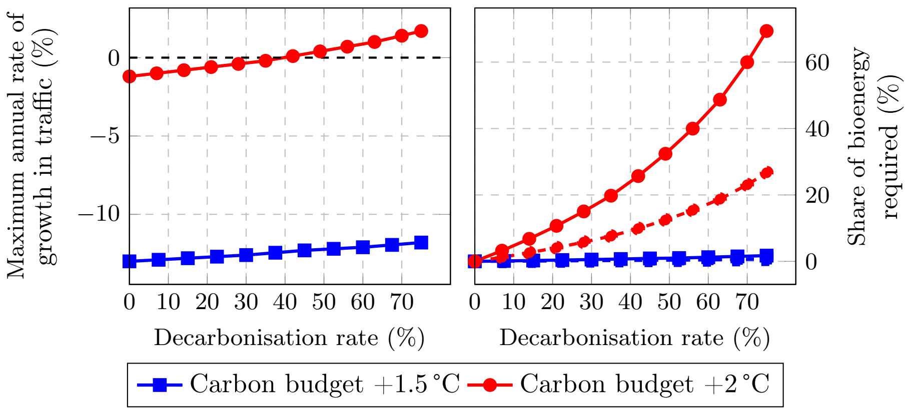


Figure 9.9: Results for scenario B with variable decarbonisation rate. Left-hand figure: maximum traffic growth according to decarbonisation rate (see table 9.5 for extreme values). Right-hand figure: share of bioenergy required compared to scenarios P1 (solid line) and P3 (dotted line) according to decarbonisation rate.

Fleet decarbonisation rate	0%	75%
Carbon budget +1.5 °C	-13%	-11.8%
Carbon budget +2 °C	-1.2%	1.7%

Table 9.5: Results for scenario B with variable decarbonisation rate. Maximum rate of air traffic growth according to carbon budget for extreme fleet decarbonisation rate values. Reading: if the decarbonisation rate reaches 75% (all the kerosene has been replaced by biofuels), then in scenario B, traffic could grow by 1.7% per year while respecting the carbon budget at +2 °C.

rate in 2050 is varied between 0% (no biofuel) and 75% (only biofuel). Scenario B corresponds to the case where the decarbonisation rate is 37.5%.

The results are shown in figure 9.9 and table 9.5. The curve on the left in figure 9.9 represents the annual growth rate of air traffic which can be used to balance cumulative emissions with the corresponding carbon budget, for different fleet decarbonisation rates. With the objective of limiting global warming to +1.5 °C, a decarbonisation rate of 75% (therefore the entire fleet is using biofuel), imposes an annual rate of decrease of -11.8%. The impact of decarbonisation is fairly low, since a growth rate of -13% (corresponding to a decrease) per year would be necessary without any decarbonisation measures. However, with the objective of limiting global warming to +2 °C, decarbonisation has a stronger impact: without decarbonisation, traffic would have to decrease by 1.2% per year, whereas a 75% decarbonisation rate allows for a 1.7% yearly growth in traffic.

The curve on the right in figure 9.9 shows the evolution with the rate of decarbonisation of the share of energy resources consumed with respect to the total quantity available. A very marked difference between the objectives at +1.5 °C and +2 °C is observed as well as a very rapid growth in resources with increasing decarbonisation rate. These two behaviours illustrate the same phenomenon, namely that a higher decarbonisation rate allows for a higher air traffic growth, and therefore exponentially increased pressure on energy resources. Conversely, if traffic declines steeply as it is the case for the $+1.5\,^{\circ}\mathrm{C}$ target, then pressure on resources decreases even further to become very low.

Limits of this analysis

The results in this section aim to provide significant orders of magnitude, and they deserve to be analysed in more detail. First, it would be interesting to refine the methods of allocating energy resources: what share of biomass (or more generally of energy resources) can be allocated to aviation? It is an intricate question whose answer depends on the energy needs and the deployment of alternative technologies for other business sectors but also on political and economic choices. Then, a more detailed sensitivity analysis on biomass availability limits could be used to produce results similar to those on carbon budgets. Only two studies were conducted here. One with the forecast bioenergy production from scenario P1 and the other with that from scenario P3, corresponding to a median value from the scientific literature of around 100 EJ. Finally, it would be necessary to include more low-carbon energy carriers in this study and to combine them: biofuels other than those produced by the Fischer–Tropsch process, hydrogen and electrofuels, which require different primary energy and which have different emission factors.

Part V

Conclusions and perspectives

Conclusion

Context

From 1965, a report to the US President Lyndon B. Johnson warned against the rise in temperatures induced by an increase in atmospheric CO_2 concentration[Mac65]. Since then, scientific observations year after year have become more accurate and alarmist, inciting for example more than 15 000 scientists to publish a warning to humanity in 2017[178]. According to the IPCC, limiting global warming to 1.5 °C requires "rapid and profound transitions in energy, land, urban and infrastructure systems (including transport and construction), and industrial systems [...]. These systemic transitions are unprecedented in terms of scale, but not necessarily in terms of rate, and involve significant reductions in emissions in all sectors, a large portfolio of means of attenuation and a significant increase in investment in these options [...]"[IPC18]. Observing the Paris Agreement and achieving zero emissions in the second half of the 21st thus requires decreasing global CO_2 emissions from now on, at a pace comparable to the decrease seen in emissions in 2020 further to the global health crisis.

Although the aviation sector is only responsible for less than 3% of global CO_2 emissions, it plays a specific role in the public and scientific debate. Out of the fourteen special reports by the IPCC, "Aviation and the Global Atmosphere" from 1999[PLG+99] is the only report focusing on a specific economic sector. From 1968, Lozano *et al.*[179] raised questions as to the pollution induced by aviation emissions, and Sawyer published an article in 1970 named "Reducing jet pollution before it becomes serious"[180]. Even if the aviation sector was therefore aware of these issues well before the IPCC report, it is only recently that they have become prominent in the public debate and because the consequences of climate change become increasingly pressing, the public debate becomes increasingly polarised. This document falls within this scope and aims to spread to a large audience the state-of-the art of scientific knowledge on this subject by highlighting both the opportunities and limits of the aviation sector to ensure its impact complies with the Paris Agreement.

Climate impact

The aviation sector contributes to the accentuation of global warming in two ways, described in the second part of the report. CO_2 effects correspond to the CO_2 emissions due to kerosene combustion but also its production, and non-CO_2 effects correspond to other emissions (especially NO_x and soot) and to condensation trails. Non-CO_2 effects are mainly caused by condensation trails, and they are around twice as strong as CO_2 effects. CO_2 and non-CO_2 effects are fundamentally different in nature. CO_2 effects are cumulative and long-term, and therefore depend on the cumulative value of emissions, whereas non-CO_2 effects are instantaneous and short-term, and therefore depend on the variation in the number of condensation trails.

The aviation sector has considerably improved the efficiency of aircraft and of numerous other operational factors. Thus, between the early 70s and 2018, energy intensity (measured in MJ/pass.km) was reduced by almost 80% and the load factor increased from less than 60% to more than 80%. Nevertheless, these improvements were not enough to compensate for the rise in traffic, which has been multiplied 12-fold in the same lapse of time, and which has contributed to the increase in CO_2 emissions in the sector, over this period.

Quantitatively, CO_2 emissions from global aviation, due to kerosene combustion, have risen from 0.37 $GtCO_2$ to 1.0 $GtCO_2$ between 1970 and 2018, which corresponds to 2.4% of global CO_2 emissions in 2018. By also integrating non-CO_2 effects, aviation is responsible for 3.8% of anthropogenic global warming since the start of the industrial era. Its recent contribution is greater and can for example be estimated at 4.8% over the period 2000—2018. By restricting the study to commercial aviation and including the emissions for the entire life cycle, air transport emitted 2.6% of global CO_2 emissions in 2018 and its recent contribution over anthropogenic warming as a whole is estimated at 5.1% over the period 2000–2018.

To alleviate the impact of aviation on the climate, levers are considered to reduce the CO_2 and non-CO_2 effects.

Non-CO_2 effects: promising strategies

Two main levers to fight non-CO_2 effects were discussed in chapter 7. On the one hand, non-CO_2 emissions from alternative fuels are different from those of fossil kerosene. Biofuels contain for example fewer aromatics, meaning their combustion releases less soot, hydrogen combustion emits less NO_x (but more water vapour) whereas an all-electric aircraft would not have any direct atmospheric discharge. Therefore alternative fuels could play a positive role in attenuating non-CO_2 effects. The impact of these solutions still needs to be evaluated with precision, in particular concerning condensation trails.

Moreover, one of the most promising leads for decreasing non-CO_2 effects concerns operational strategies. They rely for example on the modification of aircraft trajectories. Indeed, condensation trails only transform into cirrus clouds with a high climate impact under certain specific meteorological conditions. Yet, only a small number of flights is responsible for most condensation trails, which opens the way to effective contrail avoidance strategies by modifying a small number of flight paths at the expense of very low fuel overconsumption.

One major advantage of these strategies is that they could have a significant short-term effect on the climate. Indeed, due to the short lifetime of these non-CO_2 effects, widespread implementation of these strategies would rapidly lead to mitigation or even reduction in global warming caused by aviation compared to 2018.

Currently, these leads seem highly promising for significantly and rapidly reducing non-CO_2 effects. Work still needs to be done however to confirm these recent scientific results, and to develop implementation strategies. Also, these solutions cannot replace CO_2 emissions reduction measures, which are preponderant in the long-term on the change in temperature.

CO_2 effects: technological opportunities...

As for all other energy-related sectors, three levers are available to the aviation sector to reduce CO_2 emissions. They include improving efficiency (using less energy for the same journey), decarbonisation (using low-carbon energy carriers to replace fossil kerosene) and sobriety (limitation or even reduction in traffic). We described the first two levers in detail in the third part of the report, considering in the fourth part, the level of traffic as an adjustment variable used to meet a given climate objective.

There are many technological levers for improving aircraft efficiency and the main levers are presented in chapter 5. They include improvement of engines, aircraft aerodynamics and aircraft systems along with reduction in aircraft weight. By 2035, they enable us to imagine new aircraft consuming 20 to 30% less than the most efficient planes today. Also, new architectures (e.g. blended-wing body), which would represent a breakthrough compared to the conventional *tube-and-wing* architecture in use since the advent of modern-day aviation in the 1960s, would allow for even greater gains in efficiency.

Concerning fuel decarbonisation, three potentially low-carbon energy carriers, discussed in chapter 6, are currently envisaged for decarbonising the aviation sector: electricity, hydrogen and synthetic kerosenes (biofuels and electrofuels). Developing all-electric aircraft and hydrogen aircraft represents major challenges in terms of engineering. For hydrogen aircraft for example, this requires to rethink the whole aircraft architecture to adapt for the larger volume imposed by the use of hydrogen and to find solutions to the many issues related to its storage and distribution in liquid form at $-253\,^{\circ}C$. Synthetic kerosene has the huge advantage of being *drop-in*, meaning it can be used directly in today's aircraft, unlike hydrogen which requires the design of new aircraft and new transport and airport infrastructures.

Under certain conditions, these alternative energy carriers may allow to decrease CO_2 emissions from aviation. For biofuels, this means choosing feedstocks which are effectively low-carbon, such as used cooking oils, agricultural and forest residues or certain specific bioenergy crops such as miscanthus or willow. These feedstocks can typically enable a decrease in CO_2 emissions of around 75% over the entire life cycle, or even act as a carbon sink. For electricity, hydrogen and electrofuels, the primary energy from which they are derived is electricity. In this case, the gains in terms of CO_2 emissions depend on the carbon intensity of the electric mix and can be substantial for electricity produced from low-carbon energy.

... limited by the rapidity and extent of their use

These different solutions have in view an aircraft emitting considerably less CO_2 than currently, for example a blended-wing body powered by low-carbon hydrogen. Nevertheless, the climate situation is urgent. The global carbon budget at +1.5 °C will be fully used up in less than 10 years at the rate of pre-covid emissions, which means that emissions have to start decreasing from now, and in a significant manner, at a rate comparable to that induced by the health crisis (∼7%). In addition, the later the decrease in emissions begins, the greater it will have to be: in 2011, Åkerman calculated that emissions would have to decrease by 3.7% per year if they begin to decrease from 2010, by 5.3% per year from 2015 and by 9% per year from 2020[181]. However, emissions have not decreased since these forecasts, and it is effectively an effort of that magnitude that needs to be made now for a trajectory limiting warming to +1.5 °C.

Furthermore, disruptive innovations (e.g. blended-wing body or hydrogen aircraft) are not expected before 2035, or even 2045 for an all-electric aircraft with a relevant size and range from the point of view of CO_2 emissions. Electricity-based solutions will only become interesting when the global electric mix will become low carbon. In the case of an electric aircraft for example, it would take around 20 years to reach sufficiently low emission factors. Improvements in energy efficiency allow for a few percentage gains per year (of around 1.5% per year for technological solutions and 0.5% per year for operations), and alone do not suffice to decrease emissions if traffic were to increase significantly. Finally, biofuels represent the most ready decarbonisation solution, but their production remains very limited. They represented 0.004% aviation fuel in 2018 and the studies available to date show that in the event of a high rise in traffic, it is little likely that they represent more than 20% of global aviation energy consumption in 2050. Voluntarist policies are currently under consideration to facilitate their development, like the ReFuelEU European initiative.

Consequently, the technological levers to reduce CO_2 emissions in the aviation sector are limited by the rapidity and extent of their use. It ensues that, based on the assumption of an underlying increase in traffic, these technological levers will not be sufficient to decarbonise the aviation sector at the average pace required to observe the Paris Agreement. Logically, it is therefore either necessary to slow the increase in traffic, or to authorise the aviation sector to decarbonise at a slower pace than the average pace. Besides the technological solutions summarised in this report, the decarbonisation rate in the aviation sector, quantified by the share of the global carbon budget allocated to it, and the level of traffic are the only two parameters determining the sustainability of a given path.

Aviation sector carbon budget and increase in traffic

The relationship between the rate of increase in air traffic and the global carbon budget share allocated to the aviation sector is discussed in chapter 9. Therefore, if we allocate 2.6% of median global carbon budgets to the aviation sector (which is its share of CO_2 emissions in 2018) and bearing in mind the illustrative technological scenarios presented in this report, a drastic decrease in air traffic (greater than 10% per year) would be necessary to limit global warming to 1.5 °C. To limit global warming to +2 °C, the results are less clear-cut. The most pessimistic scenario would require a yearly 1.8% decrease in air traffic, whilst the most optimistic scenario would allow a yearly increase of 2.9%. It is important to recall that even if the +2 °C target is often taken into account by most stakeholders, such as the ATAG[ATA20] for example, but also the European Union, it is an upper limit. The Paris Agreement explicitly sets the target well below +2 °C and encourages for a continuing effort to limit warming to +1.5 °C.

These figures are the result of an analysis based on the assumption that the aviation sector has 2.6% of the global carbon budget, which is akin to presuming that the aviation sector reduces its emissions at the average pace required to observe the Paris Agreement. However, the reasoning can be reversed, and we can for example estimate the share of the carbon budget required to enable the annual traffic growth of 3% forecast by the industry. In the context of the illustrative technological scenarios presented in this report, it would therefore be necessary to allocate between 6.0% and 10.2% of the global carbon budget to the aviation sector for +1.5 °C, and between 2.6% and 4.5% for +2 °C. In almost all cases, this share being higher than the current share of aviation in CO_2 emissions, it necessarily implies that other business sectors will have to reduce their emissions at a faster pace than the average one.

What share of the carbon budget should be allocated to the aviation sector? This question is mainly political and economic, it touches upon lifestyle and fairness concerns on a global scale. Even if the objective of this report is not to answer that question, it can be used to shed the necessary light on the debate which has to take place on this issue, by providing factual elements that can be used to make the link between the carbon budget and rate of (de)crease in air traffic.

Considering all levers

The urgency of the climate situation means it is necessary to consider all levers that can be used to reduce the climate impact of aviation to the proportions described by the IPCC.

Technological improvements are essential and must be developed. They especially raise research and engineering questions for the entire aeronautical sector. The technological solutions potentially implemented in 10 to 15 years, such as the hydrogen plane, blended-wing body or electrofuel, allow to envisage low-carbon aviation in the future. However they will come too late to achieve on their own the necessary immediate and massive reduction in emissions reported by the IPCC in order to contain the rise in temperatures "to well below +2 °C". However, certain mature levers can and must be mobilised from today, especially the reduction in contrails by marginal changes of flight path, incremental technological improvements, improved operations and the development of low-carbon biofuels.

Moreover, all these improvements must be made at the same time (and not in opposition) with political discussions on the two levers discussed in this report, the level of air traffic and the share of the carbon budget allocated to aviation. In particular, if the traffic increases at the rate envisaged by the aeronautical industry, it will consume a larger share of the carbon budget than its current share of emissions, meaning that other business sectors will have to reduce their emissions more rapidly than the average pace.

Perspectives: a systemic view of the aviation sector's transition

Systemic impacts of aviation

The fact that human activities such as aviation significantly alter the climate indicates a change of scale in humanity's influence on the world. The human being is even said to have become a major geological force in the same way as tectonic, erosive or climatic processes spanning millions of years. In 2000, Crutzen and Stoermer named a new geological epoch, the Anthropocene (literally "the human epoch"), which ends the Holocene geological epoch which began 11 700 years ago[182, 183]. Even if this proposition is still debated in the geology community[a], the concept of the Anthropocene has already made its way into the scientific community looking at global changes to the Earth system such as global warming[IPC19].

A very important lesson drawn from this concept is that, as the impacts of human activities become global, these activities are coming up against the physical limits of the Earth system. In this report on aviation, the carbon budget and the quantity of primary energy available are two examples of planetary boundaries we have discussed in detail. The carbon budget represents the anthropogenic CO_2 limit not to be exceeded to limit global warming to a certain temperature, whereas we have seen, especially in chapters 6 and 9, that the energy demand from aviation could face limitations in the global quantity of primary energy available (in the form of electricity or biomass).

Beyond these two limits, widespread development of low-carbon bioenergy and electricity potentially required by the decarbonisation of the aviation sector could be constrained by other planetary boundaries.

Example 1: Systemic impacts of biofuels

Biofuels may enable to decarbonise energy and thus represent a potential solution to the climate problem. Nevertheless, many broader socio-environmental

[a]The Anthropocene working group currently considers that there is sufficient scientific evidence to justify a new geological epoch, and that the artificial radionuclides disseminated during nuclear testing in the 1950s are believed to be the best stratigraphic indicator of this new epoch. Anthropocene Working Groupe, Subcommission on Quaternary Stratigraphy, consulted on the 18th of March 2021.

consequences are being studied in the scientific literature. As already mentioned, the use of first generation biofuels has been limited in Europe in order to prevent competition with agricultural production for human food. Second generation biofuels also cause a number of issues. First, they continue to compete with the human food production through indirect economic mechanisms, by potentially causing a rise in farming prices[184]. Also, intensive single-crop farming (maize or canola) and residue collection practices may contribute to land erosion and compaction and to the decline in biodiversity. They also require a large quantity of water and inputs which disturb the nitrogen and phosphorus cycles[185–187,EPA09]. The development of bioenergy therefore causes problems potentially as serious as global warming (decline in biodiversity, famines), which restrict the scale to which these solutions can be developed in a sustainable manner[184,188].

This point is discussed in detail in the IPCC Special Report on land[IPC19], which emphasises the importance of taking land use into account with respect to the development of bioenergy. Therefore, mass bioenergy development would be very good for attenuating global warming but would decrease capacities for adaptation to warming, increase desertification and land degradation and increase food safety risks. The development of BECCS for capturing several $GtCO_2$ per year would thus see a rise in the population at risk of hunger by up to 150 million people. Also, mass conversion of land can also have negative side effects on water supply and biodiversity[IPC19].

Example 2: Systemic impacts of low-carbon electricity

The production of low-carbon electricity, central to all potential scenarios for the reduction of global warming, poses the same kind of problems[18,189]. An analysis can be performed for example for the production of renewable electricity.

Indeed, the mass development of renewable energies increases site coverage, which is the first factor of decline in biodiversity[IPB19]. Then, the development of renewable energies also requires using electricity storage facilities. Moreover, one of the solutions considered, hydrogen production from electrolysis, requires water which can be a limited resource in places suitable for the production of renewable electricity, such as desert areas with a high insolation.

Furthermore, the construction of electricity production infrastructures from renewable energies can require large quantities of mining resources (concrete for the wind turbines but also rare metals and copper, etc.). Exploiting these resources potentially leads to socioeconomic issues in countries where they are used[190] and to mass pollution of ecosystems surrounding the mines[191–193]. Also, even if, to date, the boom in new technologies and efficiency gains have made it possible to answer to the exponential demand for mining resources despite the decrease in deposit concentration, potential supply shortages are foreseeable in the short-term for two reasons. On the one hand, at a constant rate of improvement in energy efficiency, the first physical constraints are due to appear in the years to come as we approach thermodynamic limits[194]. On the other hand, some raw materials have become "critical" due to their economic importance and risks related to their supply chain[Eur20]. For some raw materials, the near monopoly situation in a country leads to geopolitical challenges which depend on the political stability of exporting countries. In 2020, the European Union identified 30 critical raw materials, 18 of which related to renewable energies[Com20a].

These different elements lead us to conceive the ecological transition in a systemic manner, especially by relying on scientific research started back in the 70s.

A systemic view of the transition

From the report by Meadows...

Jean-Baptiste Say wrote in his 1832 economy lesson that "natural resources are inexhaustible"[b]: reaching the planetary boundaries brings into question this vision of a both stable and infinite world. From the 1970s, a team of scientists from MIT commissioned by the Club of Rome took a look at the sustainable nature of the exponential growth of different socioeconomic and environmental indicators since the end of the Second World War. These indicators include for example the world population, GDP, primary energy consumption or even international tourism[195].

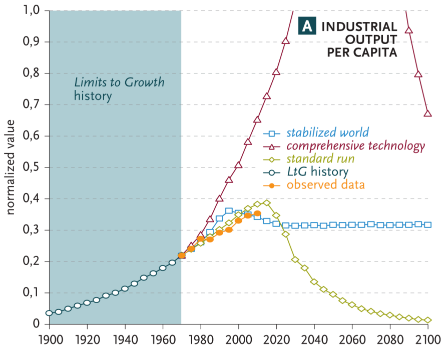
The first version of their report *The limits to growth*[196], more commonly known by the report to the Club of Rome or Meadows report, was published in 1972 and was met with great success. This work uses the theory of systems dynamics and computer modelling to analyse the causes and long-term consequences of demographic and economic growth, which are the only two possible sources of exponential growth. To do that, they consider the increase in the population and the use of resources, and the physical limits the population may find itself confronted with, notably natural resources and the Earth's ability to absorb industrial and agricultural pollution. An important conclusion to the first version of the report is that without regulation of demographic and economic growth coupled with changes in social behaviours and improvement in energy efficiency, the models systematically produce paths where world population eventually collapses, especially due to degradation in production capacity caused by pollution. In particular, the *trend* scenario which continues past trajectories, and the *all technology* scenario, which is only based on technology to resolve problems[c], both lead to rapid and sudden collapse of the population.

This report has been updated on a regular basis since its first version in 1972, especially by the original authors on the occasion of its thirtieth birthday in 2004[197]. For its fortieth birthday in 2012, the Australian physicist Graham Turner compared three scenarios studied in the Meadows report to the past change in eight indicators between 1972 and 2012[198]. These three scenarios are the trend and all technology scenarios mentioned above, along with the *stabilised world scenario* which prevents population collapse. Figure 9.10 illustrates this comparison on four of the eight indicators, and shows that the trend scenario exhibits the closest match with the data observed. On some other indicators,

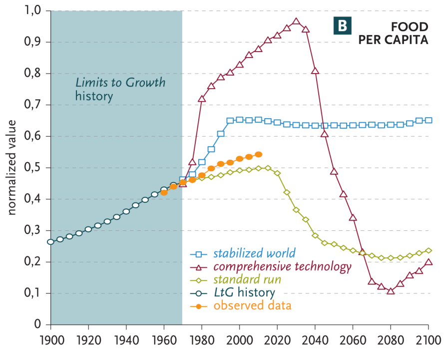
[a] The same report by the European Union thus identified 26 critical materials for aerospace and defence such as cobalt, lithium or titanium

[b] Jean-Baptiste Say, "Cours complet d'économie politique pratique", vol. 1, Brussels, Meline, 1832, p. 83, *in* "L'évènement Anthropocène", art. cit.

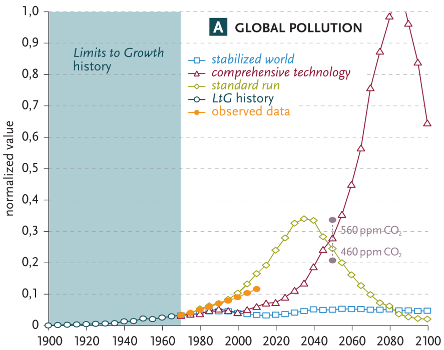
[c] Like Jean-Baptiste Say, this scenario makes the assumption of infinite natural resources but for a different reason, namely the economic concept of *substituability* according to which technological progress will always be able to make up for the lack of a given resource.



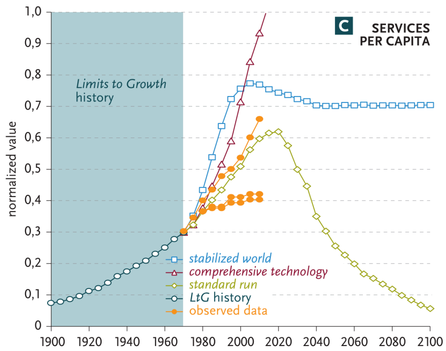
(a) Industrial production per person.



(b) Food production per person.



(c) Global pollution.



(d) Services.

Figure 9.10: Comparison of past changes in four indicators over the period 1972–2012 with the forecasts for three scenarios from the Meadows report of 1972. The trend scenario is the closest to the historical data. According to figures 2 and 3 by Turner[198].

especially demographic indicators, the data are closer to the all technology scenario but no data is compatible with the *stabilised world* scenario. In 2012, Turner concluded that the data available confirm that the trajectory followed since 1972 is that of the trend scenario which leads to population collapse in the first half of the 21st century. Furthermore, the successive updates of the original report emphasise the fact that even if sustainable scenarios remain possible, the window for their realisation is becoming increasingly narrow as we continue to follow the trend scenario. This conclusion generalises the comment made earlier concerning the decrease in CO_2 emissions, which must be all the stronger the later it starts.

... to the planetary boundaries

A multidisciplinary team of scientists (including Paul Crutzen) went into the idea of the physical limits highlighted in the Meadows report in depth in 2009. It identified nine planetary boundaries which defined a safe operating space for humanity[199] (see figure 9.11): global warming, erosion of biodiversity, disturbance of nitrogen and phosphorus cycles, land use changes, ocean acidification, freshwater use, stratospheric ozone layer depletion, increase in atmospheric aerosols loading and the release of novel entities into the environment. Transgressing one

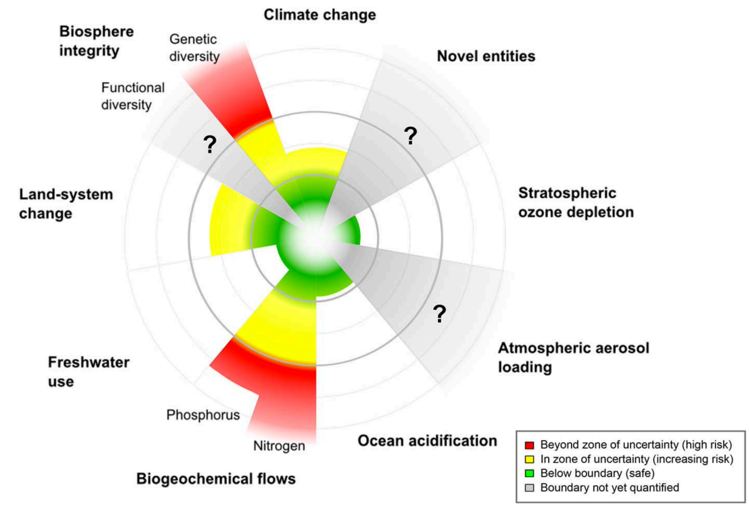


Figure 9.11: The current status of the control variables for seven of the nine planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. The control variables have been normalised for the zone of uncertainty (between the two heavy circles); the centre of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by grey wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity. After the figure 3 and its caption by Steffen *et al.*[200].

or more of these boundaries corresponds to the entry into a non-linear world where changes in physical mechanisms can trigger abrupt transformations and runaway effects, have a long-term impact on the earth's ecosystems and endanger the existence and development of our societies.

As an evidence of the impact of human activities, four of these boundaries had been transgressed or were being transgressed[200] in 2015, and a new one was transgressed in 2022[201]. They are the four boundaries shown in yellow or red on figure 9.11, namely global warming, erosion of biodiversity, disturbance of nitrogen and phosphorous cycles and land-system change.

A fundamental lesson to be learned from this work is that we are living in a finite world governed by complex interactions. This finding has far-reaching implications for resolving environmental issues such as global warming since any solution may exacerbate the pressure on the other planetary boundaries. This phenomenon is described in the literature as environmental displacement[189].

9.4.4 A systemic view of the aviation sector's transition

By seeking to decrease its climate footprint through the development of low-carbon energy carriers, the aviation sector could therefore accentuate other socio-environmental problems by increasing the production of bioenergy and renewable electricity. This concern is obviously not specific to the aviation sector, and it precisely highlights the need to plan the aviation sector's transition (and that of all business sectors) within a broader framework in order to avoid focusing on one problem while ignoring bigger problems[202]. A sensitive question is that of the available resources in a low-carbon world. For example, Graham Turner concludes his update to the Meadows report by warning against the fact that "the question of restricted resources is a greater problem than climate change"[198].

The transition to a low-carbon world must therefore be thought of as a whole. It raises intricate questions on allocation of resources, organisational, economic and sociotechnical choices, prioritisation of uses, with differentiated effects which are more or less likely to cause such displacements. Facing this global ecological challenge therefore requires more than temporary or sector-specific progress, and all solutions (technical or otherwise) must be placed within a bigger picture and wider frame of analysis such as that of planetary boundaries.

Part VI

Appendices

Appendix A

Equivalent metrics

A.1 GWP (Global Warming Potential) metric

A.1.1 Definition

The GWP of a gas G, over a time horizon H, is defined as the ratio of the total radiative impact of the gas in question to the radiative impact of the CO_2. Thus, it is given by

$$\mathrm{GWP} = \frac{\int_0^H \mathrm{RF}_{\mathrm{G}}(t)\mathrm{d}t}{\int_0^H \mathrm{RF}_{\mathrm{CO_2}}(t)\mathrm{d}t} \tag{A.1}$$

where $\mathrm{RF}_{\mathrm{G}}(\mathrm{t})$, expressed in $\mathrm{W\,m^{-2}\,kg^{-1}}$, is the impact on radiative forcing at instant t of one kilogram of gas G, released at instant 0. The integral $\int_0^H \mathrm{RF}_{\mathrm{G}}(t)\mathrm{d}t$ is called absolute GWP, and the GWP is therefore the absolute GWP of the gas in question relative to the absolute GWP of the CO_2. The GWP is used to convert emissions of a gas G into CO_2-eq using the formula

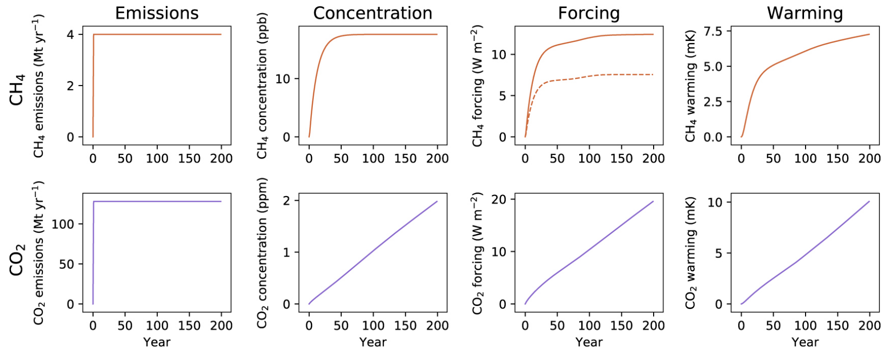
$$\mathrm{E}_{\mathrm{CO_2\text{-}eq}} = \mathrm{GWP} \times \mathrm{E}_{\mathrm{G}}.$$

As can be seen, this conversion requires to set a time horizon H, and this can have a very strong influence on the conversion. For instance, methane is a very powerful greenhouse gas, but with a short lifetime, around 12 years: therefore its GWP is 84 at 20 years and 28 at 100 years[MSB+13]. The time horizon is usually set at 100 years.

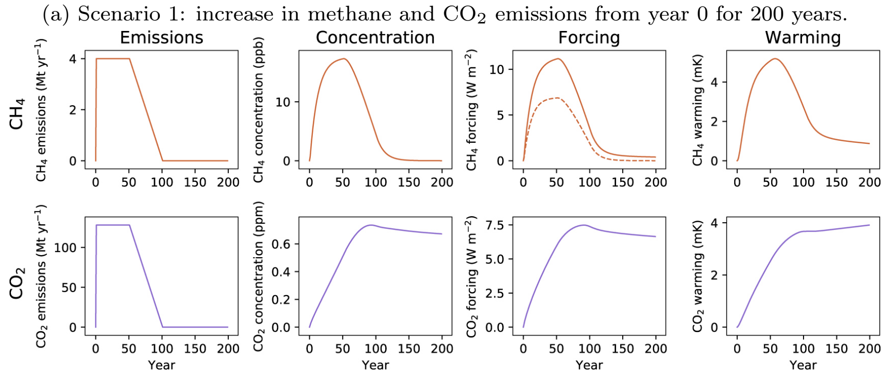
A.1.2 Limits

As explained in section 2.3, non-CO_2 effects take place over very different time scales than CO_2 effects. This difference in lifetime implies that using the GWP for all short-lived air pollutants such as condensation trails or methane is problematic. To explain this, we consider two scenarios of methane and CO_2 emission illustrated in figure A.1.

In the first scenario (figure A.1a), annual methane and CO_2 emission rates increase suddenly at the start of the scenario, then remain constant for 200 years. As CO_2 has a long lifetime, this rise in emission rate causes a linear increase in atmospheric CO_2 concentration, and ultimately a linear rise in radiative



(a) Scenario 1: increase in methane and CO_2 emissions from year 0 for 200 years.



(b) Scenario 2: increase in methane and CO_2 emissions from year 0 for 50 years, emissions then dropping to 0.

Figure A.1: Two scenarios in which methane and CO_2 emissions vary over time. The response in terms of temperature is very different for a long-lived cumulative gas such as CO_2 and for a short-lived gas like methane. In particular, in figure (b), we see that a reduction in emission rate is implies a stabilisation of temperatures for CO_2 and a decrease for methane. According to figures 1 and 2 by Lynch *et al.*[174].

forcing and temperature. In contrast, as methane has a short lifetime, the rise in its level of emission causes a rise in its atmospheric concentration, but the concentration eventually stabilises after around 50 years, once the methane disappears as quickly as it is released. The impact on radiative forcing and temperature is thus very different compared to CO_2. For methane, radiative forcing and temperature increase very steeply for around 40 years, and then the rate of increase decreases significantly. After around one hundred years, radiative forcing has almost even stabilised. It is interesting to note that, on the time scale of a century, the increase in temperature due to methane emissions is higher than that due to CO_2, despite much lower emissions, thus reflecting the fact that methane is a more powerful greenhouse gas than CO_2.

If we overturn the reasoning, it ensues, as in a stationary process, that a **drop** in methane emissions causes a decrease in temperatures. This phenomenon is illustrated in figure A.1b in which a second scenario is considered. As for the first scenario, the annual emission rate increases initially, but unlike the first scenario, the rise is only sustained for 50 years, after which time the emissions decrease in a linear manner to 0 in 50 years. For CO_2, the drop in emissions induces a stabilisation of concentration, radiative forcing and temperature. For methane on the other hand, we see that the concentration, radiative forcing and warming curves follow the same trends as the emission rate, *i.e.* increase then decrease.

We thus see that by converting methane into CO_2-eq using the GWP method, we convert it into something which, implicitly, remains in the atmosphere for centuries, which is not the case of methane. This method cannot therefore be used to reproduce something which may happen in reality, namely the decrease in radiative forcing (or temperatures) in the event of a drop in emissions. In other words, the GWP metric equivalent is not a good indicator of the impact of radiative forcing for a short-lived gas, and the GWP$*$ was introduced precisely to get round this problem.

A.2 GWP$*$ metric

A.2.1 Definition

The idea behind the GWP$*$ is to convert emissions of a short-lived gas based on the **variation in its emission rate**, and not on its absolute emissions as for the GWP. As we have seen, emissions in CO_2-eq using the GWP method are calculated by expressing an emission pulse of a ton of a given gas as the climate impact equivalent to that of a ton of CO_2: the GWP is then defined as the ratio between absolute GWP's (see equation (A.1)), and CO_2-eq emissions are calculated by $E_{CO_2\text{-eq}} = E \times GWP$ where E is the emission absolute value.

To calculate CO_2-eq$*$ emissions using the GWP$*$ method, we compare the climate impact of the **rise** in the rate of emission of a gas, and not a pulse, always with a **pulse** of CO_2. CO_2-eq$*$ emissions are then calculated using the following formula:

$$E_{CO_2\text{-eq}*} = \frac{\Delta E}{\Delta t} \times GWP_H \times H \tag{A.2}$$

where ΔE is the variation in the annual emission rate of the gas in question, Δt the time interval over which this variation is calculated, and GWP_H the GWP of the gas over the time horizon H[a].

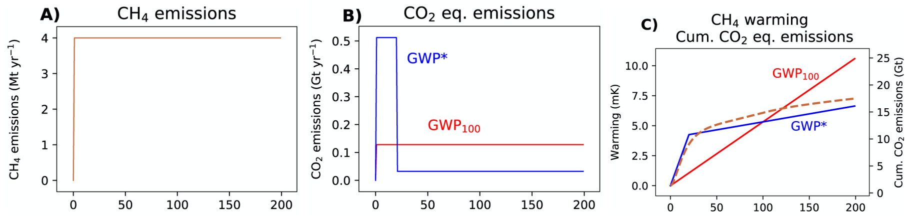
A.2.2 Difference between GWP and GWP$*$

Figure A.2 shows the results using the GWP and GWP$*$ metrics on the scenarios as in figure A.1. It illustrates that the GWP$*$ metric is much more suitable for methane, as its cumulative CO_2-eq$*$ emissions are closely correlated with the change in temperatures, unlike its CO_2-eq cumulative emissions.

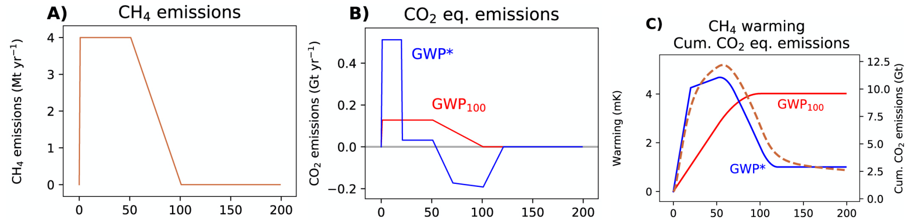
Two important observations are to be made further to this definition:

1. unlike CO_2-eq emissions, CO_2-eq$*$ **emissions may fall into the negative**;
2. the CO_2-eq$*$ value depends on the emission **trajectory**.

[a] An equivalent formula can be used based on radiative forcing, namely $E_{CO_2\text{-eq}*} = \frac{\Delta F}{\Delta t} \times \frac{H}{AGWP_{CO_2}}$ where ΔF is the variation in radiative forcing and $AGWP_{CO_2}$ the absolute GWP of CO_2.



(a) Scenario 1: increase in the annual methane emission rate. CO_2-eq$*$ emissions reach zero after 20 years, which is the time frame over which the variations in emission rates are calculated in the equation (A.2).



(b) Scenario 2: increase then decrease in the annual methane emission rate. CO_2-eq$*$ emissions fall into the negative after 50 years, at the time when emissions decrease.

Figure A.2: Illustration of the GWP$*$ metric for the two scenarios of figure A.1. Figure B shows the methane-CO_2 equivalence: in blue using the GWP$*$ metric and in red using the GWP metric. Figure C illustrates the impact on temperature (dotted curve), CO_2-eq emissions (red) and CO_2-eq$*$ (blue). We see that the cumulative emissions calculated using the GWP$*$ metric more effectively reflect the variation in temperature than the GWP metric. According to figure 4 by Lynch *et al.*[174].

Concerning the first observation, CO_2-eq$*$ emissions becoming negative corresponds to absolute emissions decreasing. This behaviour, surprising at first glance, corresponds to the fact that, from a climate standpoint, **lowering the emission rate of a short-lived pollutant is akin to a carbon sink**. Indeed, when the emissions of a short-lived pollutant decrease, its atmospheric concentration decreases, thus diminishing radiative forcing. If we determine the equivalence between these pollutants and CO_2, everything happens as if we were removing CO_2 from the atmosphere.

Concerning the second observation, Lee *et al.*[9] calculated using the GWP$*$ metric a ratio of around 2 between non-CO_2 and CO_2 effects, which means that nonCO_2 effects have a climate impact around two times greater than CO_2 effects. When we add the two effects together, Lee *et al.* concluded that "CO_2-warming-equivalent emissions based on global warming potentials (GWP$*$ method) indicate that aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone." This ratio of 2 corresponds to the fact that non-CO_2 effects are today around twice those of CO_2 effects. It is nevertheless important to bear in mind that, by design, this value depends on the variation in radiative forcing over the period in question (which is between 2000 and 2018) and that it could change significantly, especially if air traffic were to evolve. This explains in part the meaning of "currently" in the previous citation. For example, in the event of a drop in traffic as is currently the case following the health crisis (or as it was the case in 2009, see figure 2.10), the CO_2-eq$*$ emissions from non-CO_2 effects would become negative, thereby partially or totally offsetting the warming impact of CO_2 effects[161][a].

[a]In this sentence, the reference is the year in which traffic began to decrease since it is from that time that the decrease in traffic acts as a carbon sink for short-lived effects such as condensation trails. Nevertheless, this should not obfuscate that non-CO_2 effects have effectively made global warming worse before this, triggering feedback effects which persist as one can see in figure A.1b in the case of methane.

Appendix B

Details for calculating the impact of aviation on the climate

Here we provide details on the calculations made in section 2.2 to evaluate the climate impact of aviation, especially in section 2.2.2.

B.1 Emission factor

In this report, we took the kerosene emission factor value of 73.2 gCO_2/MJ, value found in Stratton *et al.*[203] Considering a standard mass energy density of 43.15 $MJ\,kg^{-1}$, this corresponds to a value 3.13 $kgCO_2/MJ$ which is consistent with the 3.16 $kgCO_2/MJ$ found by Lee *et al.* who note that this value is known with an uncertainty of around 1 %[9]. The value we selected is therefore a low value.

Concerning the emissions over the entire kerosene life cycle, we used the standard value from table S6 in Stratton *et al.*[203] which is 87.5 gCO_2/MJ. Strictly speaking, it is gCO_2-eq/MJ as non combustion emissions include a small part, typically less than 3 %, of methane and nitrous oxide. Nevertheless, as we need (especially in chapter 9) to compare CO_2 emissions from aviation to carbon budgets, we neglect greenhouse gas non combustion emissions other than CO_2. Using a value expressed in CO_2-eq in CO_2 artificially increases the CO_2 emissions, but this convention is consistent with the fact that the value found by Stratton *et al.* falls in fact within the low range of values usually selected for non combustion emissions. Indeed, this value is slightly lower than those used by the FVV[a] (88.7 gCO_2-eq/MJ)[SZWR16], by the ICAO (89 gCO_2-eq/MJ)[b] or by Europe via its RED II programme (94 gCO_2-eq/MJ)[c].

[a] This is the research association for combustion engines, *Forschungsvereinigugn Verbrennungskraftmaschinen E.v.* in German.

[b] Source: EASA, Sustainable Aviation Fuels, consulted on the 1st of February 2021.

[c] Cited by [CP17, p26].

B.2 Energy consumption

Once the emission factor set, we can evaluate CO_2 emissions based on energy consumption data. To do that, we took the data from the IEA[a] which provides energy consumption data for aviation since 1973. In 2018 for example, aviation used 337 Mtep[b] of energy (202 Mtep for international aviation and 135 Mtep for domestic aviation), which represents 14.1 EJ of energy and therefore 1.03 $GtCO_2$ emissions. For the period between 1940 and 1973, we used the data by Sausen and Schumann[204].

B.3 Anthropogenic emissions

The emission factor and the consumption data can be used to evaluate raw emissions in the aviation sector. To calculate the share they represent, we used the data from the Global Carbon Budget for CO_2 anthropogenic emissions. Emissions since 1750 (including emissions related to land use) are available in the Global Carbon Budget 2020 supplement[3c]. For 2018 emissions, we used the data from the Global Carbon Budget 2018[4], therefore 10 GtC for emissions caused by fossil fuel combustion and 1.5 GtC for emissions caused by land-use change, giving a total of 11.5 GtC or 42.2 $GtCO_2$.

B.4 Sources for calculations of the climate impact evaluation

CO_2 emissions are calculated using the same method described previously. For the radiative forcing calculations, we used the data from Lee *et al.*[9] provided in their supplementary material for the aviation sector between 2000 and 2018, which we corrected for recent periods by including CO_2 emissions related to the kerosene life cycle. To calculate the proportion that this impact represents relative to anthropogenic forcing, we used the sources from figure 2.10, chapter 2 of the IPPC Group I Sixth Assessment Report[GTA+21d]. Data on traffic are courtesy of the ICAO via airlines.org.

B.5 Results by limiting the scope to commercial aviation

Here we provide details of the calculations announced in part 2.2.5 to measure the impact of commercial aviation. These results are provided in table 2.3.

As explained above, the values provided in chapter 2 on combustion-related emissions were calculated based on the IEA's data. What the data covers contains some ambiguity. On the one hand, since 2006, the IEA has been demanding that kerosene for military aviation not be reported with kerosene for commercial

[a] IEA Sankey Diagram, consulted on the 1st of February 2021

[b] One ton of oil equivalent (1 tep) is a unit of energy which represents 41.868 GJ.

[c] Available on the web page of the Global Carbon Budget 2020.

[d] These data were kindly provided to us by Laurent Terray, to whom we extend our warmest thanks.

Source	Estimation ($MtCO_2$))
Gössling et Humpe[1]	921
ICCT[GZR19]	918
IATA	905
ATAG	895
Our method	891

Table B.1: Estimation of CO_2 emissions from commercial aviation (passenger and freight) in 2018 according to different sources.

aviation, but states in the same time that it is not sure that this instruction is followed[IEA19a]. In principle, the 1.0 $GtCO_2$ in table 2.1 (1033 $MtCO_2$ to be precise) do not therefore include military aviation. Nevertheless, this value is used by Lee *et al.* who study global aviation, and it is also comparable to the 1046 $MtCO_2$ for global aviation estimated by Gössling and Humpe[1]. This is why we consider the previous figures to effectively include global aviation.

Concerning commercial aviation, several concordant estimations are available for 2018. The first four lines of table B.1 thus summarise four different estimations with emissions between 895 $MtCO_2$ and 921 $MtCO_2$, therefore relatively similar results.

In order to generalise these estimations and to limit the study to commercial aviation, we have used the following methodology (which yielded the value reported in the last line of the table B.1). The article by Gössling and Humpe[1] evaluated the share of military and private aviation at respectively 8 % and 4 % of energy consumption within the aviation sector (see figure 1), out of a total of 14.1 EJ for global aviation according to the IEA: a corrective coefficient of 88 % is therefore considered. Using a combustion emission factor of 71.8 gCO_2/MJ considered by the ADEME[a], the use of this reference kerosene consumption enables an estimation of 891 $MtCO_2$ direct CO_2 emissions (combustion of kerosene) from commercial aviation in 2018, therefore 0.4 % difference with the value of 895 $MtCO_2$ announced by the ATAG. Finally, in addition to kerosene combustion and production, a 2 % increase in CO_2 emissions is considered to include the other phases of the aircraft life cycle[164].

[a]This coefficient is lower than those used by the IEA and by Stratton *et al.*[203] of around 73 gCO_2/MJ. In the same way, by including fuel production, the ADEME considers an emission factor of 86.7 gCO_2/MJ against 87.5 gCO_2/MJ for Stratton *et al.*[203].

Appendix C

HEFA/HVO and Fischer–Tropsch way

C.1 HEFA/HVO way

HEFA/HVO is the most commonly used production pathway today and probably also in the near future. Nevertheless, we see on figure 6.2 that for it to be truly promising from a climate viewpoint, it must only use specific feedstocks (oils, animal fats), which may constitute limited resources[106,107]. It involves two main steps[104]:

- a hydrogenation step in which hydrogen is used to break down the triglycerides of the starting raw material (vegetable oils, etc.) into elementary fatty acids, to extract oxygen from the fatty acids, and to saturate the double bonds between carbon atoms of some of the fatty acids. It produces saturated hydrocarbons (alkanes) with linear chain lengths from 15 to 18 carbon atoms (C_{15} to C_{18}). These reactions generate water, propane, CO and CO_2
- the classical refining step based on isomerization and hydrocracking which allows the previously obtained alkanes to be branched and the carbon chains to be broken in order to obtain molecules that can be used in the composition of jet fuel (around C_{12}.

These steps require a non-negligible amount of hydrogen: for the conversion of soybean oil, for example, it is typically necessary to provide 10 MJ in the form of hydrogen for 100 MJ in the form of soybean oil input[205].

C.2 Fischer–Tropsch way

Gasification of the biomass combined with the Fischer–Tropsch process seems the most promising opportunity for industrial scale production of second generation biofuels[109,120]. It consists in two main steps:

- Gasification is a thermochemical process which converts a solid fuel (coal, wood, straw, etc.) into a gaseous combustible and this via the injection in residual and controlled quantities of an oxidizing agent (O_2, air, CO_2, water vapour, ...)[a]. It produces synthetic gas or *syngas* which is a mixture of carbon monoxide CO and hydrogen H_2;

- the Fischer–Tropsch process is a set of chemical reactions which convert synthetic gas into liquid hydrocarbons, the general formula for the reaction is $CO + 2H_2 \rightarrow -CH_2- + H_2O$ where $-CH_2-$ is the elemental brick of hydrocarbon chains.

It should be noted that this production method is exothermic and produces heat that is typically converted into electricity[KLLW08, OPS21].

[a] Gazeification.info, consulted on the 21st of January 2021

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Can we analyse and assess the impact of aviation on the climate? Can we compare CO_2 and non-CO_2 effects? Which technological solutions are being considered to make aviation sustainable? Can we relate the growth rate of air traffic to the share of the global carbon budget allocated to aviation? Can we assess the availability of energy resources?

These questions motivated the writing of this report at ISAE-SUPAERO. Their answers largely depend on societal choices and on technological and economic developments which rely on future decisions. Rather than giving a definitive answer to these questions, this report aims to provide each individual, from our scientific standpoint, with the elements required to reach his own conclusions on these matters, as objectively as possible. Through this report and its impact, we furthermore aim to stimulate debate and participate in the emergence of a collective position on these issues.

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