THE PATH OF AVIATION INDUSTRY TOWARDS ENVIRONMENTAL SUSTAINABILITY

COIAE

A report from the Colegio Oficial de Ingenieros Aeronáuticos de España.

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FOREWORD

During year 2020, the COIAE published its first report on the aeronautical sector's sustainability. Our entity, like the entire sector, are very committed to the environmental issues and therefore, we are betting for a sustainable growth of the sector. What's more, this sector has shown with data and facts that it grows in a sustainable way, something that has been shown by the reduction of CO_2 emissions in recent years, or the research on the future use of hydrogen, among many other examples.

Since then, and as we had already announced, initiatives of all kinds to get closer and closer to sustainable aviation have not stopped multiplying (manufacturers, operators, airport and navigation companies, engineering companies ...). Given the acceptance of the first report and with the aim of updating the scientific data, the proposals to be made and the technological developments, the COIAE has decided to issue this second edition.

From this second edition, the reports will be updated annually, in order to be a reference in the sector.

Receive my cordial greetings,

Estefanía Matesanz

Dean of Colegio Oficial de Ingenieros Aeronáuticos de España

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EXECUTIVE SUMMARY

- The main objective of this report is to provide reliable information and to review the firm commitment of the aeronautical sector with the environment, which translates into being one of the sectors with more initiatives in progress to minimize its environmental impact.
- Noise mitigation and the reduction of pollutant emissions, both locally at the airports and those inducing global warming, are the main challenges to achieve an environmentally sustainable aviation industry. Minimizing the emission of carbon dioxide (CO_2) is the main objective in this effort, although other elements must also be considered, including nitrogen oxides (NOx) or the formation of condensation trails (contrails) and aviation-induced cloudiness (AIC). In 2018, the commercial aviation industry was responsible for 2.4% of CO_2 emissions globally.
- The COVID19 pandemic, which has hit society hard on a global scale, has also had a major impact on the commercial aviation industry, with long-term consequences on air traffic and a temporary reduction in its emissions.
- Despite its lower global emissions compared to other transport sectors, commercial aviation led the way
- This effort has been reinforced in recent years with additional commitments as the complete decarbonisation by 2050 pledged by the aeronautical industry in Europe, an objective increasingly assumed by many other companies and entities in the sector.
- In other to meet these ambitious goals, the aviation sector is investing considerable resources in multiple actions, covering emissions offset, improving operations or research and development of new technologies to reduce noise and emissions. In the last four decades, the energy efficiency improvement of commercial aircraft has been above 60%. A state-of-the-art aircraft consumes an average of 3 litres of fuel per 100 passenger-km. This value, and therefore the associated CO_2 emissions, is similar to the performance of an efficient compact car.
- The European Emissions Trading System (EU ETS) certified the reduction of 193 million tons of carbon dioxide emissions related to air traffic between 2013 and 2020. At a global level, in January 2021 went into operation the first phase of CORSIA, a regulatory framework to compensate CO_2 emissions from international civil aviation. Also this year, the European Commission has proposed the coordination of these two CO_2 emission control schemes, as well as the reinforcement of the reductions within the EU ETS.
- The improvement of infrastructures and control systems, both in flight and at the airports, allows for a more efficient coordination and management of air traffic, and the corresponding reduction of emissions and noise. In Europe, it is worth mentioning examples such as the Single European Sky (SES), and its technological branch SESAR, set to develop and implement the future common air traffic management system.
- The continuous technological development applied to aircraft, with gradual improvements in the propulsion systems (for example, increasing the bypass ratio), new materials (e.g. advanced composites) and aerodynamic innovations (among others, aiming for laminar flow) allows to design more efficient and increasingly less polluting aircraft. In the longer term, disruptive designs including, for example, counter-rotating open rotor engines, truss-braced wings or blended wing bodies will lead to even more significant improvements.

- Sustainable aviation fuels (SAF), from biological or synthetic renewable sources, are already a reality and open a viable option, in the short to medium term, to effectively reduce the environmental impact of aviation. Although aimed mainly to tackle CO_2 emissions, they also have the potential to mitigate other negative effects such as contrails. Their great advantage is that they can improve the sustainability of existing aircraft (drop-in concept), including those that operate long-haul, high-capacity flights. To calculate its environmental efficiency, its entire life cycle must be taken into account, including the direct and indirect impacts due to its production. The recent legislative initiative of the European Commission, Fit for 55, includes a SAF refuelling mandate and could provide the momentum needed for its widespread use.
- Commercial aviation using electric propulsion, which is expected to enter into service for regional aircraft during this decade, is yet the only way to perform flights with zero environmental impact, assuming the use of renewable energy and equipment.
- Electric engines allow for diverse and flexible configurations, with multiple hybrid options to optimize the performance. The electric power can be delivered by batteries or fuel cells. The electric propulsion opens up new possibilities and advantages in aircraft design (e.g. lower induced drag, boundary layer intake or distributed engines). The main technological obstacles to overcome are the low specific energy of batteries and the design of high-power electric systems, areas in which progress is being made very quickly.
- The introduction of hydrogen in aviation as a sustainable energy vector is one of the most promising ways to drastically reduce CO_2 emissions. Its application is particularly interesting for the most polluting segment of commercial aviation: aircraft flying around 2,000 km with more than 100 passengers. The industrial development and introduction of hydrogen is strongly promoted by several governments from Japan to Europe, as it is a very versatile element in decarbonization strategies. In the field of aviation, hydrogen plays a key role in the production of synthetic sustainable fuels, it can power electric propulsion via fuel cells, and it can also be burned directly in turbojets. Currently there are several commercial projects underway for its application in all these variants.
- Hydrogen mitigates the range problem of electric propulsion, thanks to a specific energy three times higher than kerosene, thus reducing the weight of fuel required. On the other hand, its energy density is at least four times lower than conventional fossil fuel, which leads to many design challenges due to the bigger space needed to accommodate bulky H2 pressurized or cryogenic tanks. Theoretically, its combustion only produces water as by-product, but more research on its environmental impact is still required as the H2O is released at high altitude (contrails and AIC), as well as continuing technological development to minimize the associated NOx emissions.
- The path to an environmentally sustainable aviation, beyond technological advances, will also require an ambitious regulatory and financing framework to foster the development and implementation of these sustainable solutions, so that they are competitive against fossil fuels.
- Noise due to aircraft, both from air and ground operations, is being continually reduced, with new airplanes displaying a noise footprint 30-50% lower than the previous generation. Nowadays, state-of-the-art aircraft are 75% quieter than 50 years ago.
- Achieving an environmentally sustainable commercial aviation is an ambitious goal, but within our reach. It will require the involvement and effort of the entire aeronautical industry, as well as the support of governments, international organizations and the passengers themselves. There is a wide toolkit of actions, strategies and technologies to achieve this goal, and the most likely path is a combination of all of them according to their optimal capabilities and different timeframes. As an example, in a horizon of 10 to 20 years, it would be feasible to achieve regional and short-range commercial air transport mainly based on electric and hybrid propulsion, with hydrogen combustion engines powering mid-range and high-capacity routes, and long-haul flights relying on sustainable fuels.

3 INTRODUCTION AND OBJECTIVE

The global challenge of this century is to achieve worldwide development that balances social, economic and environmental considerations, as reflected in the UN Sustainable Development Goals (SDGs).

This report provides an overview of the commercial aviation sector related to its environmental sustainability, the actions and projects already in place to improve it, as well as the proposed initiatives and upcoming technologies that will contribute to reach a future fully sustainable aviation.

The aviation sector includes aircraft, engine and equipment manufacturers, airlines, air traffic control and navigation organizations, airports, certification bodies, research and technology centres, all together contributing in multiple aspects to economic growth, social development and, particularly, to forging links between people at a national and international level.

Civil aviation is a global powerhouse that contributes decisively to improving our lives thanks to the creation of jobs and the speed of transport and distribution, promoting competitiveness, territorial cohesion and the connectivity of our societies. Aeronautics also fosters technological developments of general application, as well as a significant scientific and cultural exchange; all this while maintaining the highest level of security of all modes of transport, and working to minimize its environmental impact.

Figure 1 shows the global airline industry data in terms of GDP and employment. In 2019, before the COVID19 pandemic, 4.5 billion passengers and 61 million tons of cargo were safely transported through its global network[1]. In Spain, in 2019, 275.2 million passengers were transported by air, as well as a total of 1.1 million tons of cargo. This activity generates around 204,000 jobs (just over 1% of the total in the country) through around 6,200 companies [2].

According to data from the European Regional Airlines Association (ERA), the aviation sector contributes $823 billion to Europe's economic activity, representing 3.3% of all employment in the continent (12.2 million jobs), and 4.1% of Europe's GDP [14].

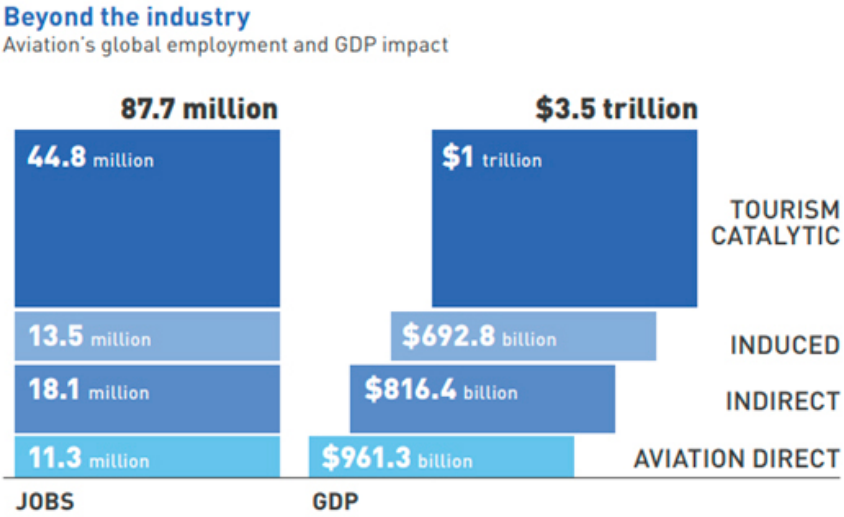


Figure 1. The aviation industry in numbers in 2018.

On the other hand, all these benefits from the air transport industry have an environmental cost that can be classified into local and global effects. The local impact, centred around the airports, includes noise, local air pollution and the impact on landscape. In the global effects, it is worth highlighting the consumption of non-renewable materials and, above all, greenhouse gases (GHG) and other emissions contributing to climate change.

Since it first appeared, airplanes have undergone major transformations, despite the fact that if you compare an aircraft from the 70s with a modern one,

Photo Archive

Figure 1. Source: ATAG/Oxford Economics analysis.

[1] ATAG: https://aviationbenefits.org/media/167517/aw-oct-final-atag_abbb-2020-publication-digital.pdf

its exterior appearance has barely changed. Actually, most of the changes have taken place in its interior, improving structural design, materials, and especially the electronics and the efficiency of the engines.

Since the signing of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, there has been growing attention on the influence of aeronautical activities on this global problem. In response, the development and evolution of the aviation sector in general has focused on improving people's lives and boosting the world economy in an increasingly sustainable way, with the application of new technologies and processes, new fuels and materials to reduce its environmental impact.

This report focuses on the path of the aviation industry towards mitigating first, and finally eliminating emissions and other negative effects on the environment. However, by no means this scope covers a sustainability review of the aeronautical industry, which should include, as well, social and economic analyses. As a matter of fact, the environmental sustainability study should also include life cycle analysis of all the elements necessary to fly, considering aspects such as the complete production processes of aircraft, infrastructures and fuels.

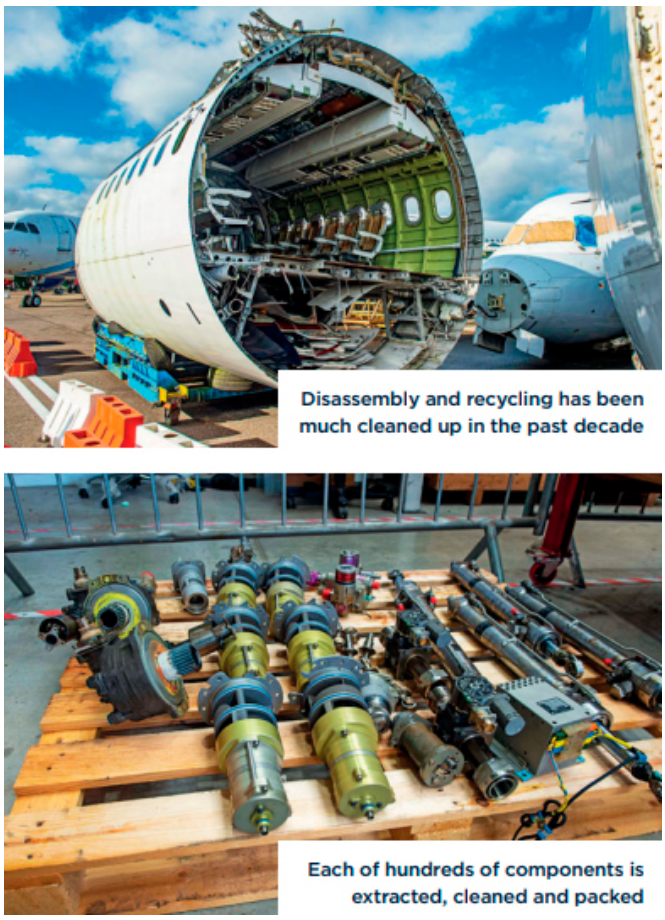


Figure 2. Recovery of components and material recycling from decommissioned aircraft.

As an example, it is worth highlighting the existing recycling projects in the aeronautical sector, both at the manufacturing level and for aircraft reaching the end of their operational life (Sentry[2] project developed within the European Union research program Clean Sky), supported by companies dedicated to these fundamental tasks for the sustainability of aviation[3].

In the present context, it is inevitable to mention the crisis of COVID19, which has hit society hard on a global scale, both at the health and economic level, slowing down many fundamental activities, including air transport. Its impact on the aviation industry, beyond airline operations, also affected aircraft manufacturers and research activities. The cancellation of R&D programs, as an emergency response at the beginning of the crisis, has also affected some projects focused on sustainable aviation, as was the case of the E-Fan X[4].

On the other hand, the enormous challenge of the pandemic also presents an opportunity to move towards an even more sustainable and environmentally friendly aviation. This is recognized by the European Union by conditioning extraordinary aid for economic recovery with projects compatible with the European Green Deal [25], and its objective of reaching a decarbonized continent by 2050. The recent proposal from the European Commission Fit for 55 [19], seeks to implement concrete measures that revolutionize the transport sector and, with intermediate objectives in 2030, pave the way to fulfil the commitments of the Paris Agreement on climate change.

Several countries have also linked their extraordinary financial aid to sustainable criteria, such as France and its commitment to develop a carbon-neutral aircraft by 2035[5]. The aeronautical industry, always in a continuous process of technological improvement, is in a position to face this challenge successfully. An example of this trend is the evolution of the number of active electrical aviation projects (Figure 3), above 200 by the end of 2019[6].

2 https://cordis.europa.eu/project/id/632487/reporting/es
3 AELS, TARMAC Aerosave, Air Salvage International, etc.
4 https://www.airbus.com/newsroom/stories/our-decarbonisation-journey-continues.html
5 https://www.euractiv.com/section/aerospace/news/france-unveils-e15bn-in-aerospace-aid-sets-green-goals/
6 Roland Berger: https://www.rolandberger.com/en/Point-of-View/Electric-propulsion-is-finally-on-the-map.html

Photo Archive

Figure 2. Source: Billipix for Flight International, March 2021.

This path towards sustainable aviation is sustained in the short term on operational improvements, mitigation and compensation of emissions, and gradual developments of consolidated technologies. In the long term it will also include disruptive innovations, revolutionary changes and new technologies. The aviation industry successfully undertook changes of this magnitude in the past, and with the support of governments, private companies, passengers and society in general, it is ready to do it again.

Given the importance and visibility of the environmental impact in the field of sustainability, and particularly by its connection to climate change, this report will place special emphasis on the negative effects of aircraft operations: emissions of gases and particles, but also noise. In a first step, the aviation impact will be described and evaluated in context, comparing to other transport systems. Further on, it will be shown the efforts, progress and results that the aeronautical sector is achieving to control and minimize its environmental impact.

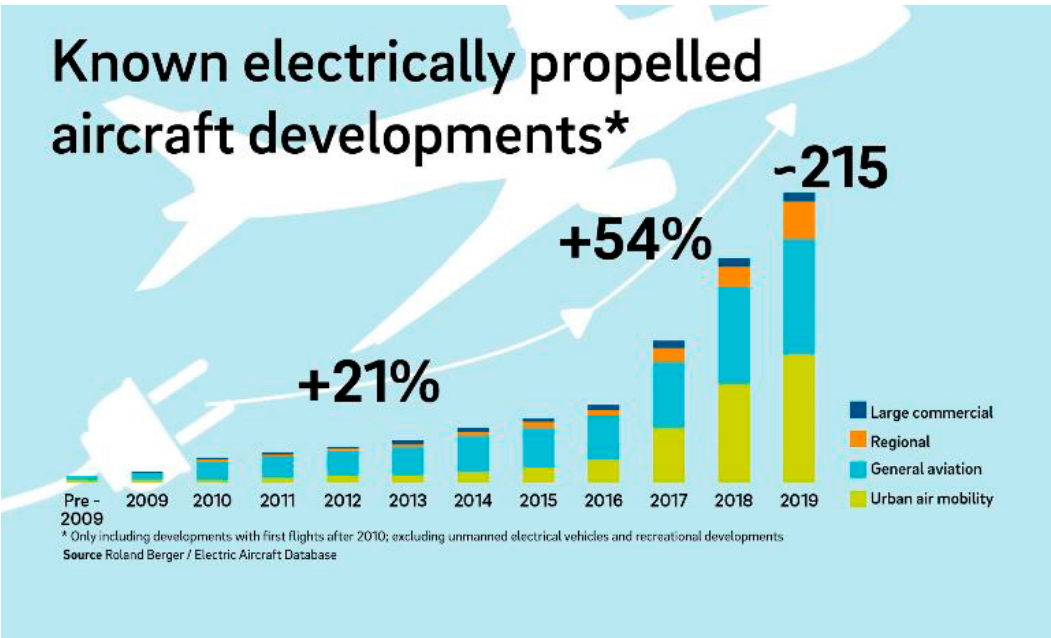


Figure 3. Number of active aviation projects with electric propulsion per year.

Photo Archive

Figure 3. Source: Roland Berger

4 ENVIRONMENTAL IMPACT OF AVIATION IN CONTEXT

The environmental impact of aviation, both in terms of emissions and noise generation, has been a subject of study and improvement by the aeronautical industry for decades. However, it was from the UN working group on climate change (IPCC[1]), particularly in its 1999 report [49], that it achieved great public relevance, connecting with the growing environmental awareness.

Greenhouse gas emissions due to human activities has been identified as the main cause of global warming [50]. In order to compare the intensity and impact of the different types of emissions and effects, it was introduced the concept of Radiative Forcing (RF). It measures the influence of any factor in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, compared to the preindustrial conditions defined at 1750, and is expressed in Watts per square meter (W/m2). As an example, the release of gases such as CO2 into the atmosphere helps to capture the outgoing thermal radiation, increasing the greenhouse effect, which is reflected by a positive RF. On the other hand, the albedo effect on clouds during daylight shows a negative RF, as the reflection of sunlight cools the planet. This metric has been recently refined by the introduction of the Effective Radiative Forcing (ERF), targeting longer term effects on surface temperatures by accounting for rapid adjustments in the atmosphere.

Thus, the global impact of an activity on climate change can be evaluated adding up the radiative forcing of all its effects, both positive and negative. For aviation, a comprehensive data update has recently confirmed a net contribution corresponding to 3.5% of human action on global warming [55]. This assessment includes all aircraft emissions, as well as the different interactions and secondary impacts:

- Greenhouse gas emissions (GHG): mainly CO2, but also NOx, SOX, soot, hydrocarbons, water and others.
- Condensation trails (contrails) and their potential transformation into cirrus clouds (AIC[2]).

1 Intergovernmental Panel on Climate Change
2 Aviation-Induced Cloudiness

The interactions of these emissions in the upper layers of the atmosphere are very complex, and still are the subject of continuous research and subsequent updates on their impact. Soot particles, for example, serve as seeds for the formation of the microcrystals that make up contrails in cold and saturated atmospheric conditions (ISSR[3]). Modifying the number and type of these particles, as we will see later, could potentially mitigate the global warming impact of contrails. Although still with a significant level of uncertainity, it is estimated that contrails and AIC could be responsible for around half of the total ERF from aviation [6].

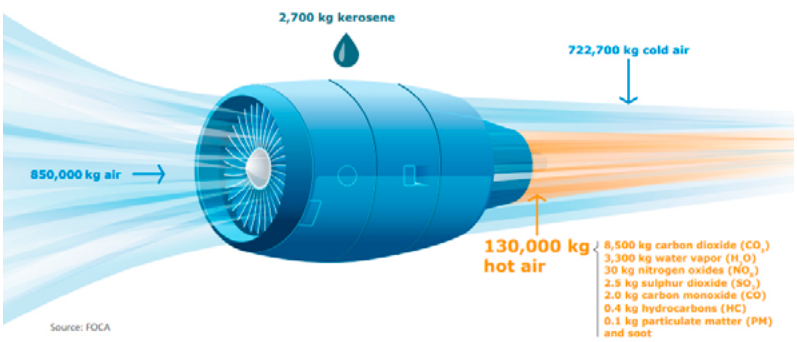


Figure 4. Typical fuel consumption and emissions associated per flight hour of an aircraft with two turbofans carrying 150 pax.

Moreover, sulfur oxides represent an example of the uncertainties still pending to be cleared. It is currently accepted that they contribute to cooling the atmosphere, but at the same time there are still relevant effects to be understood, such as their interaction during cloud formation, as is also the case with soot aerosols [55].

3 Ice supersaturated region

Photo Archive

Figure 4. Source FOCA

Nitrogen oxides (NOx) provides an even clearer case of the complexity of these interactions. It was well-established that it release in the upper atmosphere leads to two differente processes regarding greenhouse effect: on the one hand, clearly negative by acting as an ozone precursor (O3), but on the other, a positive one by removing methane (CH4), an even more powerful greenhouse gas [54]. However, two additional effects from NOx emissions have recently been identified: a long-term decrease in ozone, and the reduction of H2O, also a GHG. These two new interactions, which cool the atmosphere, were in turn counteracted by the change to the ERF metric, which strenghtens the role of NOx. After all these modifications, the overall effect of nitrogen oxide emissions is still considered to promote global warming [55], although this has not closed the debate yet, far from it. Two new studies have generated some controversy by reviewing the current model to defend one that the impact of NOx is much worse than estimated so far [34], while the other argues exactly the opposite, defending it plays a minor role and that cutting these emissions should not be a priority. Furthermore, according to their estimates and in some scenarios, in the future the impact of NOx could turn positive in terms of global warming [71].

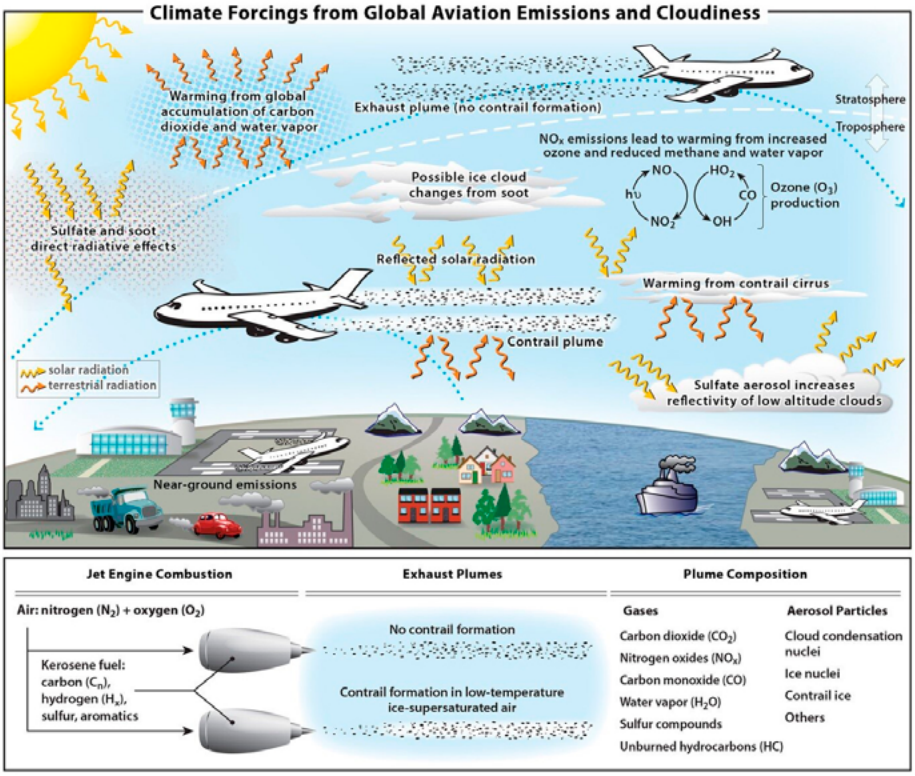


Figure 6. Aviation environmental impact on climate change [55]

Therefore, it is clear that a consolidated understanding of the mechanisms by which aircraft emissions drives climate change, beyond the effects of CO2, is essential to move towards a fully sustainable aviation. In fact, this is the focus of many research efforts such as the ACACIA project [13]. A solid understanging on the phenomena involved is critical, in order to align the efforts of the industry and effectively mitigating its environmental impact. Additionaly, it is also important to point out that the ERF index is explicitly dismissed as a direct indicator to set the priority of the different reduction strategies, since it covers short-lived GHG and long-term mechanisms in the atmosphere without the corresponding weighting [55].

Accordingly, and while keeping in mind the relevance of the other mechanisms already described, we will now focus on the study of carbon dioxide (CO2) emissions, due both to its key role in climate change and to the high degree of scientific certainty in its global cycle. This long-lived greenhouse gas remains, justifiably, the priority target of actions to achieve a more sustainable aviation [71] and, in fact, it is also used as a yardstick to compare the environmental impacts from different mechanisms and sources.

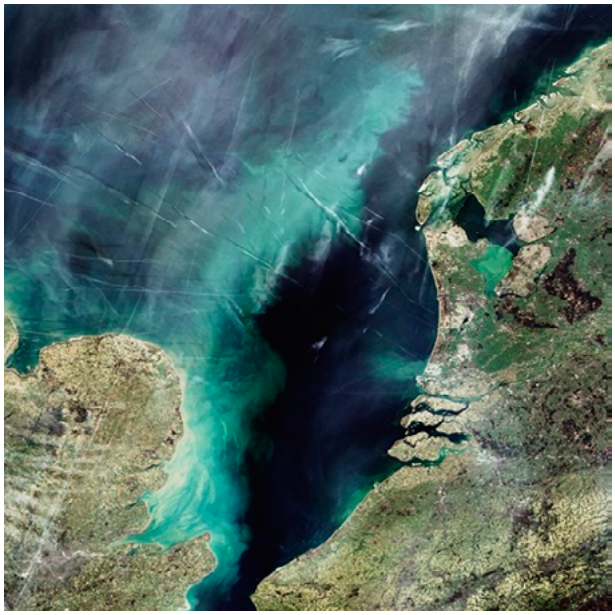


Figure 5. Contrails and aviation-induced cloudiness (AIC) over the North Sea.

Photo Archive

Figure 5. Source: ESA

In 2018, commercial aviation as a whole was responsible for 2.4% of CO2 emissions globally [33]. Despite the constant increase in air traffic, prior to the COVID19 pandemic, this figure remained stable during the last decades (2.5% in 2005 [54]). This can be explained due to both the increase in global emissions and, as we will see below, the continuous improvement in aircraft efficiency. Counting CO2 emissions by country, according to flight departures, the United States (24%) and China (13%) stand out as the two largest contributors [33].

To put these figures into context, it is revealing to compare them with the environmental impact of road transport, responsible for 17% of global CO2 emissions, as shown in Figure 7, or sea transport with 3%. According to the IPCC, the contribution of the entire transport sector worldwide accounts for approximately a quarter of the total CO2 emitted by human activities in 2010, and its contribution has grown rapidly, twice the global percentage that in 1970. This worrying increase comes, to the extent of 80%, from road transport [50].

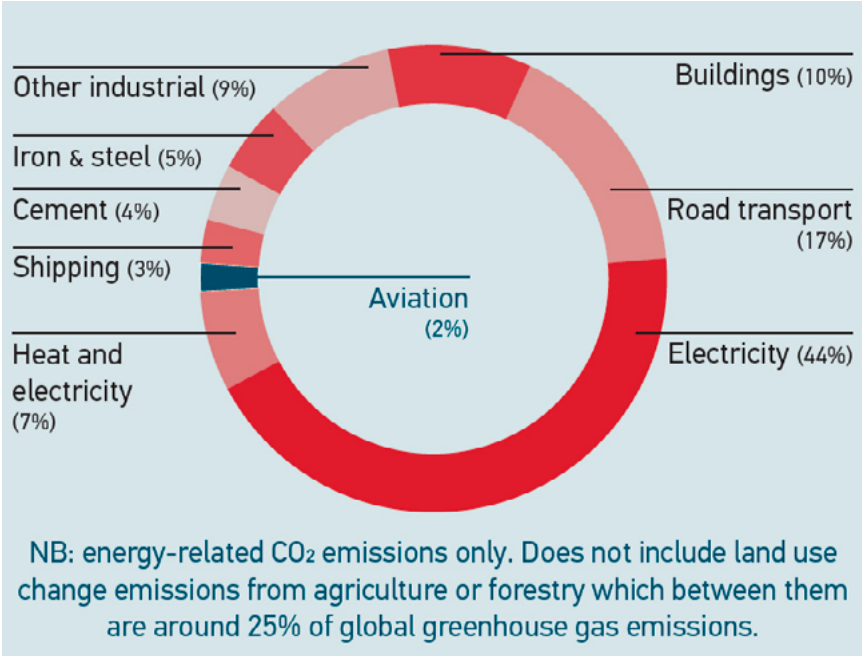


Figure 7. CO2 emissions due to aviation compared to the rest of global emitters in 2014

Figure 8 shows data from the European Environment Agency (EEA), where a similar distribution of CO2 emissions from the transport sector is confirmed at European level.

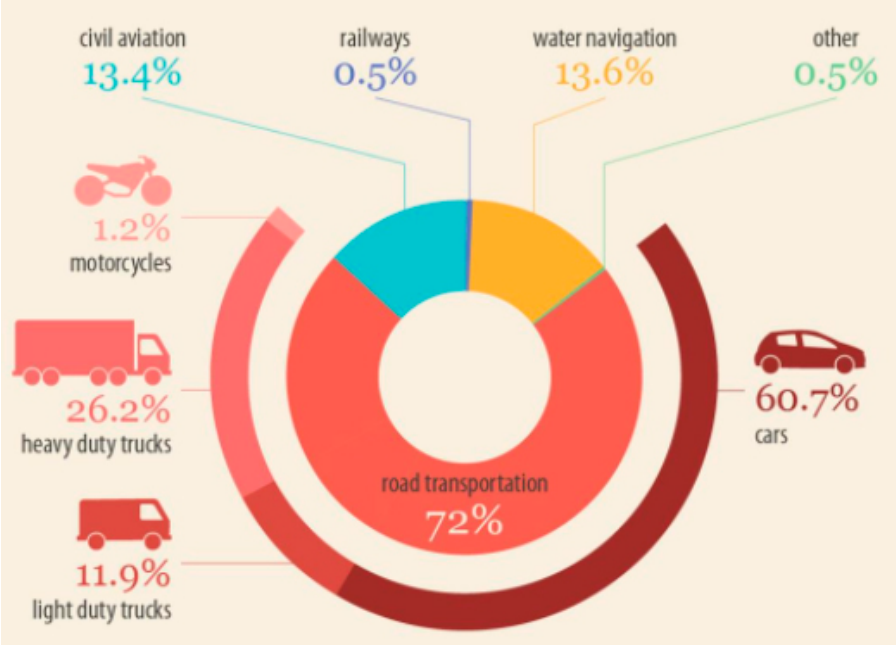


Figure 8. Distribution of CO2 emissions from the transport sector in the EU (2016).

On the other hand, Figure 9 shows the relevance of the different aviation segments in terms of CO2 emissions. The main emitters are flights boarding between 100 and 200 passengers with a range up to 2,000 km.

Passenger aircraft have constantly evolved over decades towards greater efficiency in their energy consumption per kilometre and passenger transported. Over a 40-year period, this improvement has been estimated above 60% [54]. Despite this fact, net emissions associated with commercial aviation have grown steadily in recent years, mainly due to the sharp increase in air traffic. This increase in emissions, estimated at 5.7% per year between 2013 and 2018 [33], has occurred despite the considerable mitigation due to technological advances in the airline industry, as can be seen in Figure 10. The

Photo Archive

Figure 7. https://aviationbenefits.org/environmental-efficiency/aviations-impact-on-the-environment/
Figure 8. Agencia Europea del Medio Ambiente. https://www.europarl.europa.eu/news/es/headlines/society/20190313STO31218/emisiones-de-CO2-de-los-coches-hechos-y-cifras-infografia

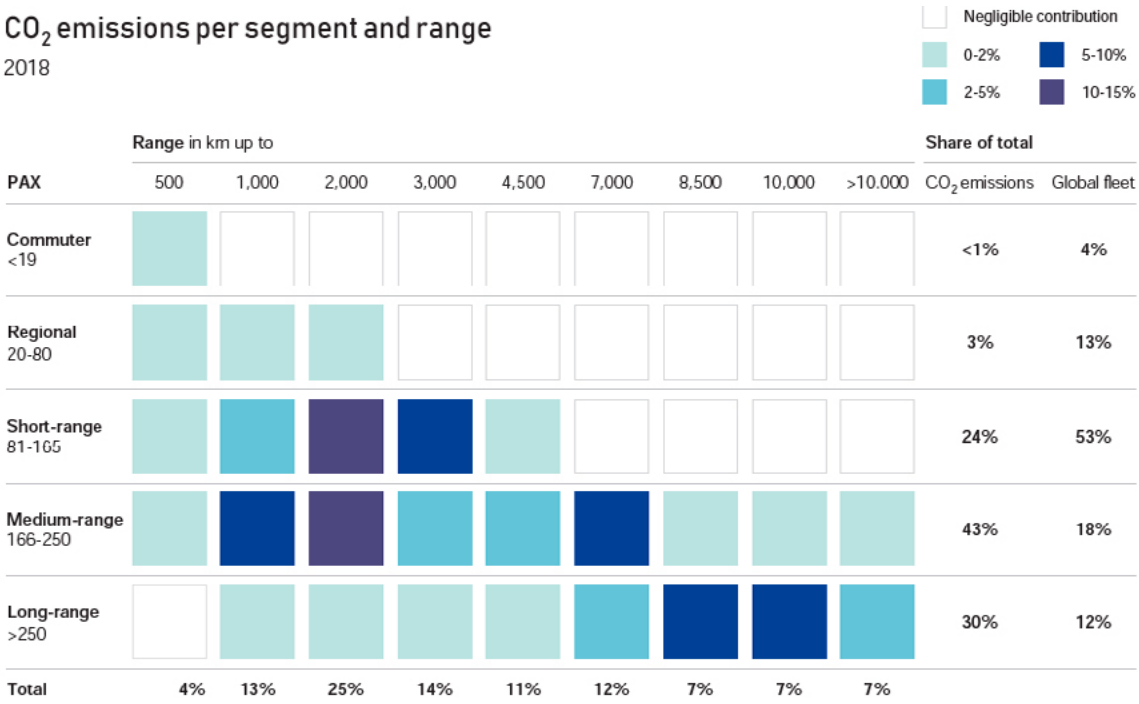


Figure 9. CO2 emissions from commercial aviation by flight range and passengers on board [28]

amount of fuel required per basic transport unit (fuel intensity) has declined steadily over the past decades. As an example, a state-of-the-art aircraft, such as the A350 or 737Max, consumes an average of 3 litres of fuel per 100 passengers•km. Despite the huge difference in speed and range, this value is similar to the consumption of a modern compact car[4].

Moving directly into comparing emissions, the key metric is the carbon emission intensity, which collects the CO2 emitted per passenger and kilometre. According to data from 2018 [33], the average passenger flight stands at 88 gCO2/pax•km, a figure that includes the oldest aircraft still in service. By way of comparison, new cars registered in Europe in 2019 emit an average of 130.3 gCO2 / km[5]. Furthermore, this value for modern cars is on the rise since 2017 despite the introduction of hybrid and electric vehicles. Using the usual occupancy rates in cars (1.5 pax), the average CO2 emission intensity for the most modern private road transport is 87 gCO2 / pax•km. Energy efficiency improvements for commercial aircraft, in a scenario without disruptive changes in technology or configuration, are estimated to be around 1–2% per year [50].

The current uncertainty makes it difficult to estimate the future growth of air traffic, which is still suffering after the sudden halt in 2020 due to the COVID19 pandemic, although the consequences are expected to expand even to the very long term (16% lower in 2050 [4]). It has been estimated that, in the period between April and July 2020, the slowdown in flights across Europe lead to a 78% drop in aviation emissions [15]. However, in all likelihood, in a few years the increase in air traffic will cause emissions to once again exceed the pace of improvements in fuel consumption. This implies that, to reverse the trend and reduce net emissions, new strategies must be adopted. Next, we will review the response of the civil aviation sector to this formidable challenge.

4 ATAG. https://aviationbenefits.org/environmental-efficiency/climate-action/efficient-technology
5 http://CO2cars.apps.eea.europa.eu/

5 TOWARDS A SUSTAINABLE AVIATION

The aeronautical industry as a whole, including manufacturers, airports and airlines, is fully aware of this environmental challenge, and has been working on the solutions for years. Thus, the ATAG organization[1], representing the main players in the sector, signed in 2008 a commitment to act against climate change[2], setting two ambitious objectives:

1. An average improvement in air transport efficiency of 1.5% per year, measured in CO_2 emitted per tonne•km flown (RTK[3]), between 2009 and 2020.
2. Setting a cap for net CO_2 emissions by 2020, committing to carbon-neutral growth from that year onwards.

There is a wide range of actions and strategies necessary to achieve these objectives, but they can be classified into four categories:

- Carbon offset and economic measures.
- Infrastructures update and efficiency gains in aeronautical operations.
- Continuous development of aircraft environmental efficiency, including the widespread use of sustainable aviation fuels (SAF).
- Introduction of new propulsion technologies, mainly electric aviation and solutions based on green hydrogen.

The aim is to contain first and then reduce, as quickly as possible, the net contribution of commercial aviation to greenhouse gas emissions. In September 2020 ATAG published WayPoint2050 [4], a report on the progress already made, and potential paths to reach the third long-term goal. In fact, the improvement in aircraft efficiency has exceeded 2% per year since 2009 [4], meeting the first objective. Additionally, regarding the second commitment, in January 2021 came into operation the CORSIA carbon offset scheme.

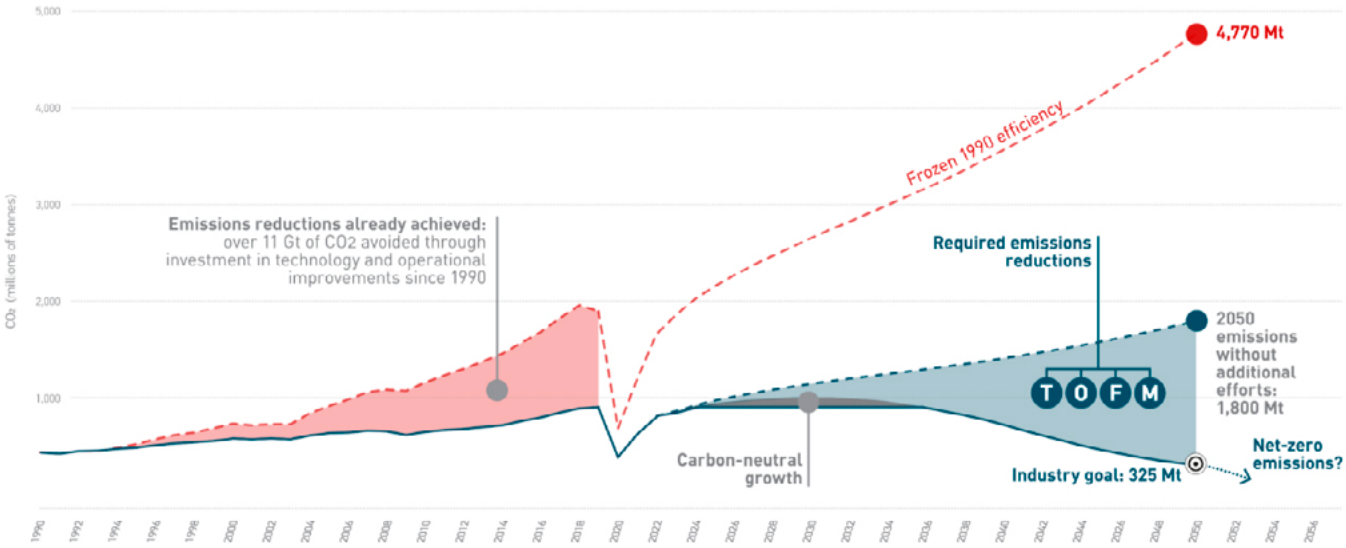


Figure 10. Air transport CO2 emissions evolution and projections. Carbon emissions already avoided (pink) and projected reductions (blue)

4 https://aviationbenefits.org/environmental-efficiency/climate-action/

Photo Archive

Figure 10. Source: www.IATA.org / Waypoint2050

1 Air Transport Action Group
2 ATAG. 3rd Aviation & Environment Summit. 22nd April 2008.
3 Revenue tonne kilometres

ICAO, the UN agency for the management of international civil aviation, agreed in 2016 to launch this project to limit net CO_2 emissions from airlines. This is a cornerstone in the strategy to mitigate emissions in the short term and has been accepted by all players in the sector, including IATA. The details and implementation of CORSIA will be reviewed in detail later.

Another fundamental responsibility for ICAO is the implementation of a series of mandatory regulations for the certification of airplanes and engines in relation to noise, local air quality (NOx, hydrocarbon residues, CO, particles) and climate change (CO_2). The effort on this subject has led to a mandatory global environmental certification for civil aviation.

In Europe, the aviation industry took one step further in early 2021, with the ambitious goal presented in the Destination 2050 document: net carbon neutrality by 2050 [60]. To this end, the potentials of the different decarbonization strategies were evaluated. The findings showed a viable path, as shown Figure 11, fundamentally based on increases in efficiency (aircraft and operations), and the widespread adoption of sustainable fuels (SAF and hydrogen).

This commitment to achieve net zero carbon emissions in aviation by 2050 has also been recently assumed by IATA, which represents airlines at global level, at its meeting in October 2021 (Fly Net Zero[5]).

The European Union, for its part, is undoubtedly a key player in the drive towards sustainable air transport. In 2011 it released a vision for the commercial aviation of the future: FlightPath 2050 [20], with similar targets to the ATAG commitment, although expanding them to include NOx emissions, noise and aircraft recycling. To achieve such ambitious goals, the Clean Sky 2 program was launched, an extension of a very productive public-private collaboration to fund innovative projects in the field of sustainability. The continuity of this effort is ensured through initiatives such as Clean Aviation and the Horizon Europe funds.

Moreover, in July 2021 the European Commission presented its legislative proposal Fit for 55, with the purpose of aligning different economic sectors with the European Green Pact to achieve an ambitious 55% reduction in CO_2 emissions in 2030[6]. Air transport is one of the economic areas involved, and the proposal includes a mandate to refuel with SAF, the integration of the EU ETS cap-and-trade system with CORSIA and changes in the aviation fuel tax system. These initiatives will be reviewed in the corresponding sections of this report.

In the United States, similarly to the programs in EU, the CLEEN I and II schemes promoted research in sustainable aviation. They were launched by the Federal Aviation Administration (FAA), and will continue with a third phase. For its part, the federal agency NASA has a long record of research in this field. It recently announced an intensive program[7] to foster the development and testing of technologies for a new generation of more sustainable aircraft (Figure 12).

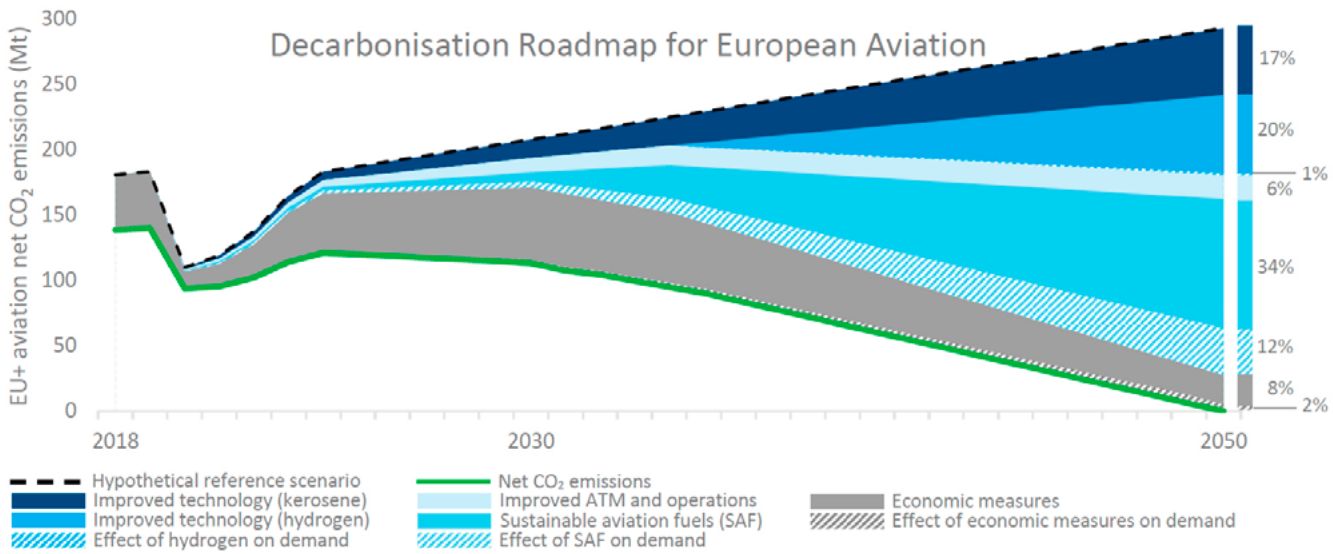


Figure 11. Destination 2050. Mix of strategies suggested for the decarbonisation of European aviation.

5 https://www.iata.org/en/pressroom/2021-releases/2021-10-04-03/

6 Reduction compared to the carbon emissions in 1990.

7 https://www.nasa.gov/aeroresearch/nasa-aims-for-climate-friendly-aviation

In addition, in September 2021 the US government announced an ambitious program with different initiatives to move towards a decarbonized aviation in 2050. Besides promoting research in different areas to lower aircraft emissions, including the development of high-capacity batteries, it seeks to support the introduction of sustainable aviation fuel[8]. Likewise, other countries have also launched R&D frameworks to reduce aviation emissions, such as the United Kingdom with Jet Zero and the Sustainable Aviation Group.

With regard to other emissions and impacts of aviation, beyond CO_2, scientific knowledge has also advanced in recent years although, as already indicated, it is still subject to a high level of uncertainty. In September 2020 EASA[9] published a comprehensive report describing these mechanisms, the metrics to compare their impact and the potential of mitigation strategies like SAF, kerosene hydrotreatment or changing the altitude of flight paths [13].

Circular economy and Ecodesign are natural extensions of sustainability initiatives within the aviation industry. The original three R (Reduce, Reuse, Recycle), are now expanded with new concepts as Redesign or Repair. As an example of application, the TARMAC AEROSAVE company has recycled more than 135 aircraft since 2007, recovering materials accounting for up to 92% of the total weight of an aircraft [43]. Airports have also joined this effort, such as Gatwick and its eradication of non-recyclable waste. Furthermore, in 2021 their global association (ACI[10]) also made the commitment of reaching net zero emissions by 2050[11]. Later in this report these concepts will be reviewed in more detail with additional examples.

Figure 12. Proposals from NASA's research program for a more sustainable new generation of aircraft.

Today, at all levels, there is an unequivocally move towards a sustainable and environmentally friendly society. The initiatives, programs and tangible realities described in this section showed that civil aviation is not lagging behind in this endeavour. On the contrary, the aviation industry is committed to going further with very ambitious goals towards environmental sustainability. Next, we will review in more the detail the available strategies and technologies to get it there.

10 Airports Council International
11 https://www.greenairnews.com/?p=1219

Figure 13. Flight tests to evaluate the potential of SAF for contrail reduction (NASA-DLR)

8 https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/
9 European Union Aviation Safety Agency

Photo Archive

Figure 12. Source: NASA
Figure 13. https://www.nature.com/articles/s43247-021-00174-y/figures/1

6 ACTIONS, INNOVATION AND TECHNOLOGY

6.1. CARBON OFFSET AND ECONOMIC MEASURES

The aviation industry has always stood out for its capacity for technological development. The environmental challenge it faces today will require indeed a new effort in innovation that, as we will see later, is already underway in multiple directions and, most importantly, is starting to yield results.

However, the timeframe required for the design, manufacture and entry into service of a new aircraft, leaving aside the basic research, is quite long. In addition, most of the huge current commercial fleet will continue to fly for years to come, even if its renewal began immediately. Therefore, it was essential to find a short-term solution to mitigate the environmental impact from commercial flights right away. Emissions offset programs are the temporary tool to gain time for aviation on its path to sustainability.

Already for some time polluting emissions from commercial flights, normally focusing on CO2, have been offset by investing in projects that reduce or remove an equivalent amount of emissions. In fact, today most airlines offer this kind of schemes at individual level for passengers, or directly offset part or even all their carbon dioxide emissions[1]. The main challenge of this approach is the verification of the compensation projects, ensuring their additionality and permanence, and avoiding problems such as carbon leakage or double accounting [6]. Additionally, if the benefits are to be global, the different schemes and certifications need to work in close coordination. In this sense, the airline industry itself has launched a joint system to offset emissions through the IATA's Aviation Carbon Exchange[2].

The commitments made by numerous airlines, and many other companies, to reduce carbon emissions are also supported by alternative compensation options such as Book & Claim[3] schemes, based on promoting the use of sustainable fuels, or even initiatives to capture and store CO2 directly from the atmosphere (DACCS[4]).

In this way, the market for voluntary carbon offsets has been gaining complexity, popularity and volume in recent years, engaging actors from different industries. Currently there are numerous agencies monitoring and quantifying compensation projects based on their own standards (CORSIA has approved already seven of them as eligible). In this way, the aim is to ensure that the emission targets are met by the offset projects, either by avoiding emissions or directly by removing gases from the atmosphere. Additionally, in many cases, there are also other benefits aligned with the SDGs.

Moving to the mandatory emissions limitation and offset frameworks, the European Union's emissions trading system (EU ETS[5]) includes the aviation sector since 2012. It is a cap and trade scheme, with a progressively decreasing limit for the total emissions, assigning initial allowances to airlines every year, and forcing them to trade or buy external carbon credits if they exceed their emission rights. Although originally it was supposed to cover all domestic and international flights with origin or destination in countries of the European Economic Area (EEA), international pressure managed to put on hold its application to flights external to the EEA, giving time for ICAO to launch its scheme at global level (decision known as stop-the-clock). The low

1 https://www.easyjet.com/en/sustainability
2 https://www.iata.org/en/programs/environment/carbon-offset/
3 https://boardnow.org/book-and-claim-explained-what-is-book-and-claim/
4 Direct air carbon capture and storage. https://www.reuters.com/article/united-arlns-climate-occidental/united-airlines-invests-in-carbon-capture-project-to-be-100-green-by-2050-idINKBN28K1NE
5 https://ec.europa.eu/clima/policies/ets_es

prices of ETS carbon credits, which allowed airlines to continue increasing their emissions, led to a series of system modifications in 2017 that managed to reverse the situation. Currently, emission allowances cost around 50 € per ton of CO2. Between 2013 and 2020 this system certified the reduction of 193 million tons of CO2 emissions from aviation [26].

With the arrival of CORSIA in 2021, a global emissions control, trading and offsetting scheme, the necessary integration or coordination with the EU ETS framework represents a political, regulatory and operational challenge of the highest level. The European Commission proposal presented in July 2021, part of the Fit for 55 legislative package, keeps intra-European flights under the umbrella of ETS, leaving the compensation of external ones to the ICAO's system. In addition, ETS would be reinforced with an accelerated reduction in the total number of emission allowances (4.2% per year), and the elimination of free basic units for airlines from 2026 [23].

Figure 14. CORSIA carbon offset scheme for international flights.

In 2016, ICAO approved the launch of CORSIA[6], a system for offsetting CO2 emissions produced by international commercial aviation. This mechanism, which from the start covers practically all international flights, has been designed to compensate carbon emissions from airlines exceeding the 2019 level. For that purpose, airlines need to acquire the corresponding emission rights, originated in decarbonization projects in other sectors where the reduction of emissions is easier or more efficient. Recalling the ATAG commitment in 2008, this proposal materializes the third objective of that roadmap to mitigate the environmental impact of aviation.

Certainly, the key to the success of this compensation effort will be the robustness of its control system, thus ensuring these decarbonization actions are truly effective. For example, it must be checked that the carbon reductions would not have occurred had the compensation mechanism not been mediated.

6 https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

Along these lines, in 2019 ICAO issued a standard with criteria to define the eligibility of offset projects (EUC) [45], and set up a technical committee for their evaluation (TAB). CORSIA became operational on the first of January 2021 and, prior to the COVID19 pandemic, it was expected to mitigate around 2.5 billion tonnes of CO2 by 2035 [14].

The scheme will be deployed in three phases, and although participation in the first two is voluntary, the international response has been very positive, as can be seen in Figure 15. At least 77% of world air traffic will be covered by CORSIA from its start. Eventually, participation in this scheme will be mandatory for all ICAO member countries from 2027[7], with some marginal exceptions for small or underdeveloped countries. Each member state will be responsible for monitoring the emissions of outbound flights from its territory. The calculation of CO2 to be compensated will be made based on air traffic growth factors and the actual emissions of each airline. This is important as it will encourage fleet modernization to reduce the amount of carbon offset imposed on the airline.

Under CORSIA, airlines must settle their accounts every three years, purchasing allowances from the carbon offset market if their assigned emissions are exceeded. In addition, offset obligations can be discounted proportionally to the use of sustainable aviation fuels, with a much lower CO2 footprint.

Figure 16. Example of carbon offset project: users learn to use the biogas generated by a local anaerobic digestion facility

7 CORSIA has a regulatory status as part of Annex 16 of the Convention on International Civil Aviation (Chicago Convention).

Photo Archive

Figure 14. Source: ICAO
Figure 16. https://www.goldstandard.org/projects/sichuan-rural-poor-household-biogas-poa

In 2020 ICAO, in a controversial decision[8], raised the maximum level of emissions allowed, moving from the mean of the years 2019-2020 to considering only the data from 2019. This change was justified by the impact of the pandemic of COVID19 in air traffic in 2020, which would distort the calculation of emissions due to the anomalous decrease in flights[9]. As a result, the European Commission itself recognizes that the launch of CORSIA will not lead to any carbon compensation from airlines until at least 2024 [22].

The main criticisms of this compensation system are therefore that it falls short to decisively curb the gross increase in CO2 emissions from aviation, limiting its application to international flights, and for those offsetting only the emissions above the proposed limit. Additionally, it fails to address other emissions and negative environmental effects associated with aviation. However, the experience of the European EU ETS system, despite their significant differences, proves that direct reductions in emissions can be achieved with these schemes, although they require a precise design and constant updating to ensure their effectiveness. In this sense, the revision of CORSIA foreseen by ICAO for 2022 will be of paramount importance. This scheme, despite its shortcomings, is a necessary first step in the transition towards sustainable civil aviation.

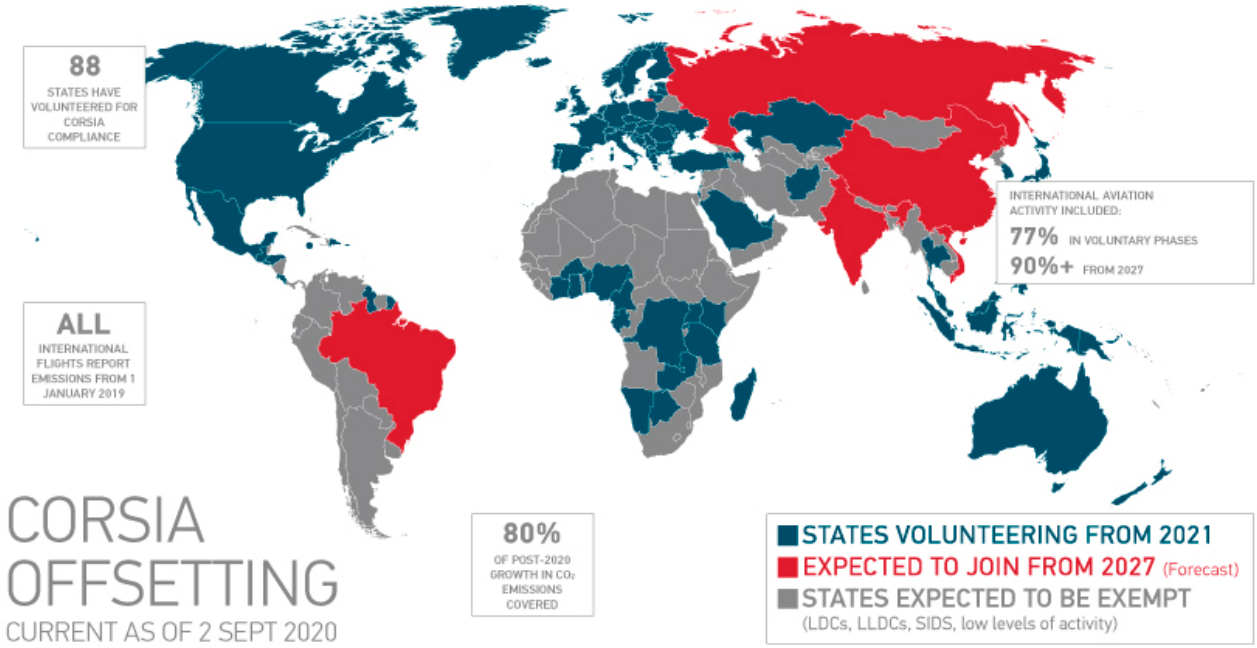


Figure 15. Countries joining CORSIA by stages (status by sept 2020)

In the field of economic measures, there has also been an intense debate on the effectiveness of fees or taxes, either directly on emissions or on aviation fuels, to reduce the impact of aviation on the environment [15]. In fact, the long-established tax exemption on aeronautical kerosene could come to an end in the European Union if the reform of the EU ETD (Energy Taxation Directive) is approved. This significant shift is also included in the recent legislative proposal from the European Commission Fit for 55. The tax would be proportional to the environmental impact of the fuel and would apply only to intra-European flights, with an exemption for freight flights and a transition period of 10 years. Several alternatives are on the table with an average rate of 0.33 €/L, a significant extra cost that would not apply to sustainable fuels, thus promoting their competitiveness [21]. It is expected that airlines would pass on this additional financial burden directly to the flight tickets.

Other political measures that have occupied the public debate recently are the restrictions on domestic flights with viable rail alternatives, of questionable environmental effectiveness [8], or mandates for SAF refuelling that will be reviewed later.

Photo Archive

Figure 15. https://aviationbenefits.org/environmental-efficiency/climate-action/offsetting-emissions-corsia/corsia/who-volunteers-for-corsia/

8 https://www.icsa-aviation.org/wp-content/uploads/2020/07/ICSA-Statement-on-Revision-of-CORSIA-Baseline.pdf

9 https://www.icao.int/Newsroom/Pages/ES/ICAO-Council-agrees-to-the-safeguard-adjustment-for-CORSIA-in-light-of-COVID19-pandemic.aspx

6.2. AIR TRAFFIC MANAGEMENT AND OPERATIONS

In the context of aviation sector, three types of operations are distinguished: Air operations, airport operations and air traffic management operations.

- Flight operations: scheduling process, the flight itself and the maintenance of the aircraft.
- Airport operations: activities in and the vicinity of the aerodrome, such as handling, use of ground-based systems, and ground movement management.
- Air traffic management (ATM) operations: activities that have a direct impact on the flight of the aircraft, the flow of traffic and the way airspace is used.

Operational improvements are a great opportunity to improve the environmental footprint of aviation. They include a wide variety of measures designed to make operations more efficient. but the full potential from operational initiatives is not always achieved due to conflicting air navigation requirements as safety, environment, economic and capacity.

Around the world, both airlines and airports, are working hard to reduce their emissions, making great strides such as investments in global market-based measures, replacement of diesel and gasoline land vehicles with electric alternatives, and even developing their own renewable fuel sources. Some airports have already reduced their fixed infrastructure CO_2 emissions by more than 50% since 1990 [26]. Advances in air traffic control and management are playing a key role in becoming flights cleaner and greener by having the potential to make flights much more direct, spending less time in the air.

SINGLE EUROPEAN SKY (SES)

This initiative, SES, was launched in 1999 to improve the performance of air traffic management (ATM) and air navigation services (ANS) through better design, planning, management and integration of European airspace (between Member States, civil and military use and technologies). As a result of the SES, flight times are reduced (due to shorter routes and fewer delays) and, consequently, flight costs and aircraft emissions are reduced. The benefits of the SES, upon completion around 2030-2035, could triple airspace capacity, reduce ATM costs by 50%, improve safety tenfold and reduce the environmental impact of aviation by 10% compared with 2004[1]

Regarding the proposal for a revision of the SES presented by the European Commission in 2013 known as European Sky 2+ package[2], on 22 September 2020, the Commission proposed an upgrade of the SES regulatory framework[3] in order to provide more sustainable and resilient air traffic management in line with the "European Green Deal", on which negotiations in the Council had been stalled since 2015. Since the Parliament's July 2021 plenary session, the co-legislators started negotiations, with the positions of the Parliament and the Council very different[4].

The SESAR (Single European Sky ATM Research) Joint Undertaking, (SJU) founded by CE and Eurocontrol set up in 2007, manages the technological and industrial dimension of the SES. It aims to improve ATM performance by modernising and harmonising systems through innovative technological and operational solutions. The total estimated cost of the development phase of the SESAR programme (for the 2008-2024 period) is EUR 3.7 billion, to be distributed equally between the EU, Eurocontrol and industry[26].

SESAR JU is taking further measures to meet its commitment to a sustainable future, addressing research projects and activities, categorised into three strands: Exploratory Research, industrial research projects and validation and very large-scale demonstrations. Examples of existing projects launched in 2021[5]:

PJ33-W3 FALCO - FLEXIBLE ATCO ENDORSEMENT AND LDACS COMPLEMENT, a SESAR industrial research project which is investigating solutions for making air traffic management more flexible, efficient and responsive to changing traffic demand

1 https://www.europarl.europa.eu/factsheets/en/sheet/133/air-transport-single-european-sky:
2 https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659421/EPRS_BRI(2020)659421_EN.pdf
3 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A579%3AFIN
4 https://www.europarl.europa.eu/thinktank/es/document.html?reference=EPRS_BRI%282020%29659421
5 https://www.sesarju.eu/activities-projects

and conditions. The project will also trial LDACS, a technology offering spectrum-efficient data link connectivity and digital voice communications

ALBATROSS[6], a 2-year very large-scale SESAR demonstration project (2020-12-01 > 2021-11-30) that will inventory the sources of fuel/CO_2 waste of the larger set of activities related to the normal Gate-to-Gate operation of a flight, including predeparture, departure, climb-cruise-descent, arrival, ground operations for taxing and parking, and proposing adequate mitigations. These mitigations will be selected from mature operational solutions with demonstrated fuel/CO_2 savings, from SESAR catalogue of solutions

There is an increasing implementation of the free route airspace (FRA), which is a specified volume of airspace in which users can freely plan a route between defined entry and exit points. Subject to airspace availability, routeing is possible via intermediate waypoints, without reference to the air traffic service (ATS) route network. Inside this airspace, flights remain subject to air traffic control. The FRA fosters the implementation of shorter routes and more efficient use of the European airspace. Eurocontrol estimates, once free route airspace is fully implemented at Europe-level, potential savings could reach 500,000 nautical miles/day, 3,000 tonnes fuel/day and 10,000 fewer CO_2 tonnes/day[7].

Thanks to these actions by the SES and the Free Route Airspace (FRA), more than 2.6 million tonnes of CO_2 have been saved since 2014 (approximately 0.5% of total CO_2 emissions from aviation) [26] and CO_2 emissions have remained stable in recent years despite increased air traffic, and despite the impossibility of taking optimal or unobstructed routes due to adverse weather, or avoiding dangerous areas and other operational limitations. So, according to an analysis carried out in 2017, the target of not flying more than 2.60% additional distance flown, which consequently entails a decrease in flight time, is on track to meet due to better flight planning and the reduction of unnecessary route restrictions such as military areas.

6 https://www.dlr.de/ft/en/desktopdefault.aspx/tabid-17585/
7 https://www.eurocontrol.int/concept/free-route-airspace

The proportion of flight time flown in Free Route Airspace during 2017 was 20% compared to 8.5% in 2014. By the end of 2019, 55 ACCs have either fully or partially implemented free route airspace operations. Full operations European wide are expected by 2023/2024 as shown on Figure 17 bellow.

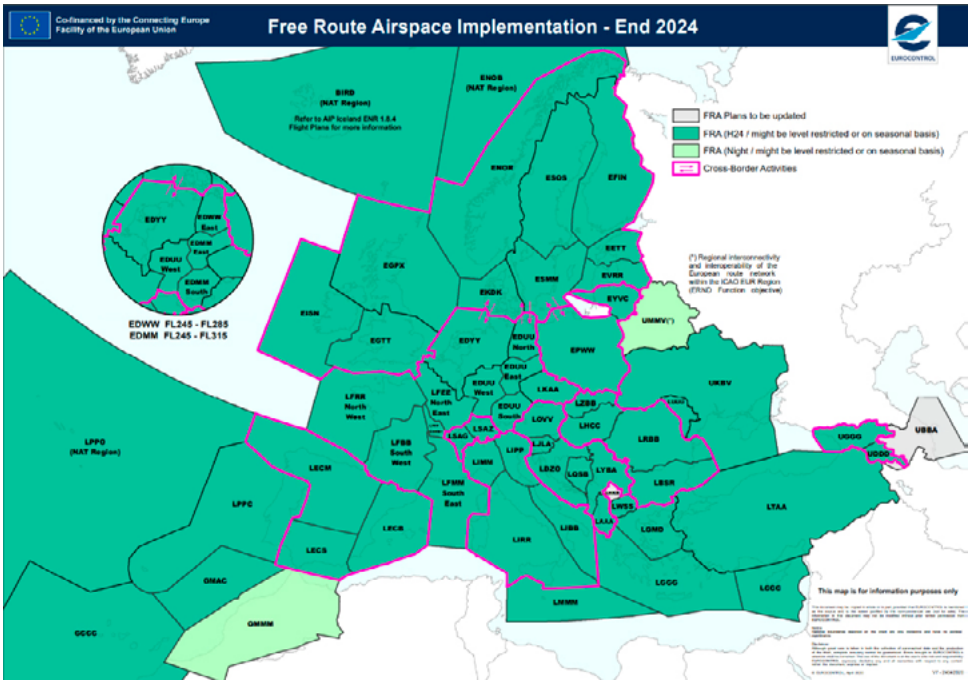


Figure 17. Projected FRA implementation in Europe at the end of 2024.

EASA and Eurocontrol, in their May 31, 2021, publication "Five Pillars for a Single European Green Sky" [8], mention the following:

- These five pillars are: **Re-focused green objective, green performance, green charging, green digitalisation and green oversight.**
- Adopting a holistic approach as part of the revision of the Single European Sky Package focused in these five pillars for a Green Single European Sky, if implemented together, would allow the ATM system to contribute its utmost to the European Union climate-neutrality ambition by enabling aircraft and airspace users to further reduce their carbon footprint
- The Environmental Key Performance Indicator ("Horizontal Flight Efficiency") improved only marginally by 0.44% and this limited improvement was due to three main stumbling blocks:

8 https://www.eurocontrol.int/publication/five-pillars-green-single-european-sky

Photo Archive

Figure 17. https://www.eurocontrol.int/sites/default/files/2021-05/eurocontrol-fra-implementation-end-2024-v8-04052021.pdf

- Slow technology uptake and still not fully exploit the advantages of digitalisation and automation.
- Fragmented governance and no uniform approach to manage the path towards sustainable aviation., being crucial to agree on the contribution necessary by each actor.
- Lack of adequate performance indicators. The limits of the current indicators have been made most transparent in 2020 when, despite no traffic delays, the environmental performance was not substantially improved over 2019. New indicators will be required to implement the revised regulatory framework to allow for tracking of the environment and climate performance targets.

According to EUROCONTROL[9], for EUROCONTROL airspace taken as a whole, horizontal en-route flight efficiency remained, with seasonal variations, relatively stable during 2016-2019, and only improved as traffic declined due to the COVID-19 pandemic. Nonetheless, there were notable changes at country level. The example of Italy shows in below Figure 19 a marked improvement in horizontal flight efficiency following the implementation of free route airspace in late 2016.

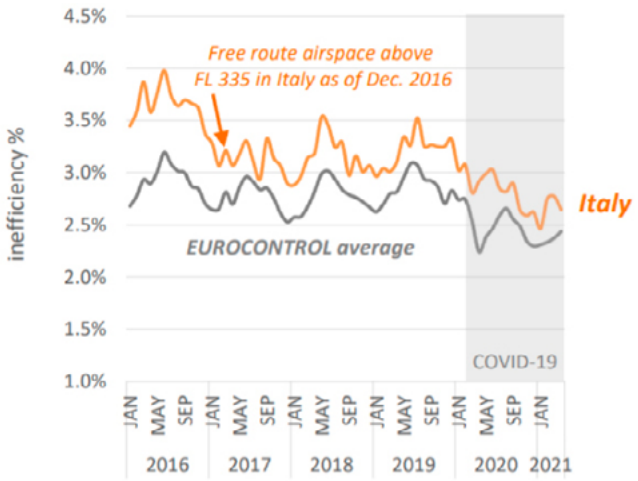


Figure 19. Evolution of the efficiency of horizontal en-route flight.

CLIMATE IMPACT OF NON CO_2 EMISSIONS

According to the report from the Commission to the European Parliament and the Council [13], there are operational options for limiting or reducing non-CO_2 impacts from aviation:

- The Single European Sky (SES) has various environmental performance indicators linked to the fuel efficiency / CO_2 emissions of the air traffic management system. This could be further developed to potentially consider the impact of non- CO_2 emissions and added to the route-charging concept.
- Improvements in air traffic management that result in a reduction of fuel burn / CO_2 emissions will generally reduce non- CO_2 emissions.
- Contrail avoidance by changing flight paths horizontally or vertically generally have fuel burn penalties as this involves flying longer distances or at sub-optimum altitudes.

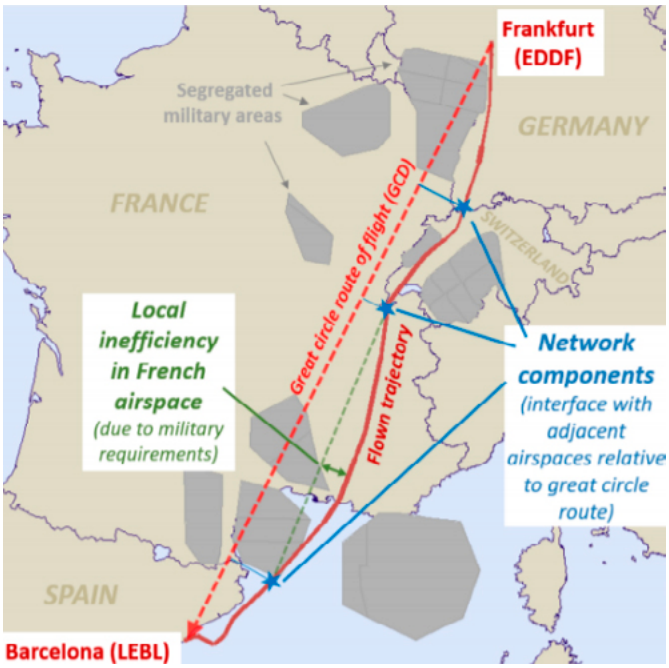


Figure 18. Example of inefficiency in flight paths.

From the "Mitigating the climate impact of non-CO_2", RAeS (Royal Aeronautical Society) conference, March 2021, hosted by the RAeS Greener by Design Specialist Group in collaboration with DLR (the Federal Republic of Germany's research centre for aeronautics and space): the climate impact of aviation from non-CO_2 effects can be mitigated through various measures, including new engine technologies to reduce emissions, use of sustainable aviation fuel and air traffic management (ATM) and contrail avoidance through diversion of flights and ATM measures could represent a fast way (hours or days) to reduce the impact of aviation on the earth radiation budget.

9 https://www.eurocontrol.int/sites/default/files/2021-07/eurocontrol-data-14-horizontal-flight-efficiency.pdf

Photo Archive

Figure 18. https://www.sesarju.eu/activities-projects
Figure 19. https://www.sesarju.eu/activities-projects

Dr Marc Stettler from Imperial College London has demonstrated that, by diversion of 1.7% of flights, contrail radiative forcing can be reduced by 59%. If flight diversion is used simultaneously with cleaner engines, the contrail radiative forcing can be reduced by 92% (which amounts to 57% of the total radiative forcing)[10]. And, on the other side, as commented, flight diversion increases fuel consumption and CO_2 emissions. Professor Ian Poll from Cranfield University quantified this fuel penalty for avoiding ISSRs (ice-supersaturated areas) and concluded the overall extra fuel burn was insignificant. If an aircraft is diverted 2000 ft above the ISSR, there is a 1.5% increase in fuel, and 1.4% when diverted 2000 ft below and this fuel penalty is only for the duration of the diversion, not the whole flight. Besides, a reduction in altitude results in a reduction in NOx emissions as an added Benefit.

The ANS (Air Navigation Service) related impact on the environment can be analysed on the Aviation Intelligence Portal[11], as this impact is closely linked to operational performance (fuel efficiency) which is largely driven by inefficiencies in the flight trajectory and associated fuel burn (and emissions). The portal is provided by the Performance Review Unit (PRU) which is part of EUROCONTROL's Aviation Intelligence Unit (AIU). The overview [12] shows a consolidated view of the main components. More detailed analysis can be found in the respective section of this mentioned website.

OPERATIONAL IMPROVEMENTS AT AIRPORTS

The operating efficiency of the airport influences the average additional time of arrival sequence and measurement (ASMA zone) or the average additional taxi time per departure.

10 https://www.greenairnews.com/?p=927
11 https://ansperformance.eu/
12 https://ansperformance.eu/efficiency/

To improve this efficiency, arrival and departure management systems (AMAN) have been implemented which, together with the Airport Collaborative Decision Making (A-CDM) integration system, aims to improve the sequence of arrivals and departures. In addition, in recent years, the AMAN system has been extended to en-route airspace 180-200 nautical miles from the arrival airport, which has assisted in better sequencing of traffic.

There are various operational measures that can be used to reduce emissions around an airport. Table 1 below describes some of those that concern airport design and facilities.

On 14 July 2021 the European Commission adopted a package of proposals to make the EU's climate, energy, land use, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels[13].

Some of the proposal affect directly to the above measures related to aircraft facilities for reducing e greenhouse gas emissions, pollution and noise from stationary aircraft, as the proposal for the Alternative Fuel Infrastructure Regulation introduces the obligation to provide electricity supply to all stationary aircraft in the Trans-European Transport Networks, (TEN-T core and comprehensive network airports) instead of jet fuel. This obligation will apply to all gates, as of 2025, and to all outfield posts, as of 2030. In addition, by no later than 2030 Member States will need to ensure that all electricity supplied to stationary aircraft comes directly from the electricity grid or from on-site generated renewable energy[14].

13 European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541
14 Questions and Answers - Sustainable transport, infrastructure and fuels https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3525

Measure	Description	Comments
Airport Layout	• Provide an efficient runway, taxiway and layout. • Site selection (for new airports).	• Minimizes taxiing and congestion. Facilitates more efficient ground movements through and improved infrastructure (taxiway design, rapid exit taxiway location and design, aircraft passing/holding bays, etc.) • Allows for optimization of regional transit access, weather (low fog areas, etc.).
Airport Facilities	• Provide 400-Hz fixed electrical ground power (FEGP) and, where necessary, pre-conditioned air (PCA) at gates/ maintenance areas and encourage their use. • Improve low visibility take-off and landing capabilities, supported by surface movement guidance and control systems, where necessary. • Use LED airfield lighting, where appropriate.	• Reduces or eliminates APU, GPU and air conditioning unit usage. Typically requires substantial capital investment, but often realizes fuel/maintenance savings. • Reduces congestion and delay in bad weather and can reduce the need for diversions to other airfields. • Directly reduces primary energy use.

Table 1. Airport features that minimize fuel consumption and emissions [47]

It must be taken into account that several operational measures could be applied to reduce aircraft emissions at, or in the vicinity of, an airport, but on the other side, noise reduction measures implemented at the airports can result in increased fuel burn and emissions such as:

- Noise abatement procedures and noise-sharing regimes that increase distances flown.
- Preferential runways that require extra flying and taxi times.
- Noise fines that can result in changes to procedures or take-off mass, reducing efficiency.
- Time restrictions that can cause congestion in holdings, arrivals, departures and that cause more flight time, delays and restrictions, etc.

Efforts to reduce fuel burn and emissions should consider these interdependencies.

To achieve the objectives set for 2035 mentioned previously, several operational initiatives are being carried out which will be detailed below:

OPERATIONAL IMPROVEMENTS IN AIR TRAFFIC MANAGEMENT (ATM)

In 2015, harmonized definitions, metrics and parameters to measure continuous ascent operations (CCO) and descent operations (CDO) were agreed by a task force of European ATM stakeholders, including definition of " noise CCO / CDO" and "fuel CCO / CDO ". A European-wide study of current CCO/CDO implementation was performed in 2017 where flights were measured and their fuel burn, CO_2 and financial impact estimated. The results obtained indicate the following [26]:

- A greater potential to reduce noise and fuel use during descent (CDO) compared to climb-out (CCO), and overall, the room for improvement is less in the noise CCO/CDO compared to the fuel CCO/CDO.
- The ability to perform CCO/CDO profiles also appears to be linked to airspace complexity rather than airport capacity.
- A typical flight with level segments could benefit on average from CO_2 savings of up to 48 kg for a CCO and 145 kg for a CDO. The potential CO_2 benefits from optimising European wide CDOs were estimated to be ten times more than those of optimising CCOs.
- There is a much smaller potential to optimise the noise CCO/CDO compared to the fuel CCO/CDO. Acknowledging that the optimisation of environmental benefits depends upon local conditions.
- The CCO/ CDO implementation should, where possible, focus on the optimisation of the flight profile from top of descent.

Witch the CCO/CDO operations, the total potential savings in Europe is up to 350,000 tonnes of fuel, which is equivalent to 1.1 million tonnes of CO_2 emissions per year. However, it should be noted that the ability to fly 100% CCO or CDO may not be possible for several reasons such as safety (i.e., time or distance separation), weather or capacity [26].

Collaborative Decision Making at the Airport, A-CDM, is another ATM operational measure that aims to improve the management of both air traffic and capacity at airports, based on the sharing of accurate and timely information and the adoption of new procedures, mechanisms and tools.

The objectives of the A-CDM are:

- Increase resource efficiency.
- Improve punctuality or reduce delays.
- Improve the predictability of events.
- Improve the performance of the ATM network.

The benefits are:

- Airlines: improvement of program compliance, possibility of prioritization.
- Handling agents: improvement of the predictability of operations, better use and optimization in the use of resources.
- Airport: improved punctuality, more efficient use of immobile resources.
- Air Traffic Control: optimization of the use of the air side, reduction of congestion.
- CFMU: increased slot compliance, optimization of the use of airspace capacity.

Airport CDM is now globally recognised. A-CDM is fully implemented in 30 airports across Europe . On average, the implementation of A-CDM allows a reduced taxi time of. 0.25 and 3 minutes per departure. The 2016 A-CDM impact assessment report identified the potential savings generated from 13 of the 17 A-CDM airports, demonstrating tangible improvements in taxi time performance that translates into some 102,700 tonnes of CO_2 emissions considering 2.1 million departures[15].

Table 2 below describes procedures that reduce the environmental impact of an airport.

15 https://www.eurocontrol.int/sites/default/files/2019-04/a-cdm-impact-assessment-2016.pdf

Medida	Operación	Comentarios
Procedimiento de la aeronave.	• Operaciones de descenso continuo (CDO). • Operaciones de subida continua (CCO).	• Descender con motores a baja potencia reduce el consumo de combustible y el ruido bajo la trayectoria de vuelo, pero puede depender de la gestión del espacio aéreo y las limitaciones de capacidad. • La subida continua para evitar la necesidad de vuelos nivelados a bajas altitudes reduce el consumo de combustible y el ruido bajo la trayectoria de vuelo, pero puede depender de la gestión del espacio aéreo y de problemas de capacidad.
Acciones discrecionales del piloto.	• Minimización del uso de empuje inverso en el aterrizaje. • Rodadura sin motor.	• El piloto debe conservar plena autoridad sobre la operación segura de la aeronave. • El piloto debe conservar la autoridad total sobre la operación segura de la aeronave. Las reducciones de emisiones son específicas del lugar y de la aeronave.
Otros procedimientos.	• Reducir el tiempo del motor al ralentí. • Remolque de Aeronaves.	• Las emisiones de HC y CO son mayores durante el ralentí. Reducir esta fase también puede resultar una disminución de la operación del motor. • El remolque de aeronaves puede reducir significativamente el uso de motores de aeronaves. Pueden producirse problemas logísticos en los aeropuertos con zona de maniobras limitada.

Table 2. Operational opportunities to minimize fuel consumption and aircraft emissions at airports [47]

Additional operational initiatives further solutions which are expected to provide substantial environmental savings are shown in the following table [67]:

SESAR solutions	Environmental Benefits
Arrival Management extended to en -route Airspace (AMAN) E-AMAN allows for smoother traffic management by earlier sequencing of arrival traffic at a point further away from the airport.	Less fuel burn from reduced vectoring at lower levels, reduced holding and maintaining more fuel-efficient flight levels for longer.
Enhanced Terminal Airspace using RNP-Based Operations: This allows aircraft to follow precision flight paths to reduce distance flown and avoid noise sensitive areas.	Less fuel burn and lower noise.
Departure Management Synchronized with Pre-departure Sequencing: Pre-departure management delivers optimal traffic flow to the runway by factoring in accurate taxi time forecasts and route planning derived from static data.	Reduced waiting time at the runway holding point, which saves fuel and allows air navigation service efficiency.
Departure Management integrating Surface Management Constraints: The solution integrates surface planning and routing functions to build a very accurate departure sequence, taking the tactical changes into account.	Less fuel burn and emissions.
Time-Based Separation for Final Approach: Current distance separations replaced with time intervals in order to adapt to weather conditions and maintain runway approach capacity.	Less fuel burns due to reduction in holding times.
Automated Assistance to Controller for Surface Movement Planning and Routing: The route planning functionality allows controllers to graphically edit routes and automatically compute estimated taxi times, contributing to more predictable surface operations.	Improved taxi times resulting in less fuel burn.
Development of a new GPS receiver and data transmitter, known as ADS-B: Currently air traffic controllers use radar data to help planes land or take off, GPS helps create more efficient flight patterns.	Save fuel and improve arrival time, reduce unnecessary emissions when an aircraft is idle on the runway.

Table 3.Other operational initiatives [67]

MORE INITIATIVES AT AIRPORTS:

In February 2021, Paris Region, Choose Paris Region, Groupe ADP, Air France-KLM and Airbus launched an unprecedented worldwide call for expressions of interest for the hydrogen branch in airports. This open innovation initiative is a key step to initiate this technological breakthrough across the entire hydrogen value chain within the airport city. It is focused on three main themes.[16]:

- Storage, transport and distribution of hydrogen (gaseous and liquid) in an airport environment (storage systems, micro-liquefaction, aircraft fuelling, etc.).
- Diversification of hydrogen use cases in airports and in aeronautics (ground handling vehicles and equipment, rail transport at airports, energy supply for buildings or aircraft during ground operations, etc.).
- Circular economy around hydrogen (recovery of hydrogen dissipated during liquid hydrogen fuelling, recovery of a by-product from a reaction to produce decarbonated hydrogen, etc.).

It must be highlighted the NetZero2050 initiative with the commitment of ACI EUROPE (Airports Council International) and its members to reduce carbon emissions and achieve net neutrality by 2050. Currently 357 airports are already in the ACA program with 47 carbon-neutral airports (level 3+)[17].

In Spain, both ENAIRE and AENA have a strategy towards sustainability within their corporate social commitment; the first as the main provider of air navigation and aeronautical information services, and the second, as the first airport operator to manage Spanish public airports and heliports.

ENAIRE is being a pioneer in the integration and exchange of data in the "Network Manager" network, contributing to the improvement of the efficiency, capacity and safety of the airspace through the use of new technologies and continuous innovation through development of own tools that exchange information with EUROCONTROL and other providers: "Flow tools", a multidisciplinary set of applications for solving global problems at the local level, which allows the analysis of raw data from multiple sources; "Perseo-Emissions", which allows the calculation of the different emissions (CO_2, NOx, SOX , etc.) produced by air traffic in Spain; or the application to monitor the points of an airway where air traffic controllers offer pilots the possibility of making more direct routes, detecting which are the points where these direct routes are provided, and calculating the distance savings achieved compared to the planned route in the original flight. During 2018, this tool has allowed airlines to save 7 million nautical miles, thanks to the direct authorized in Spanish airspace, thus avoiding 243,000 tons of CO_2 emissions into the atmosphere and saving fuel for airlines[18].

In addition, ENAIRE has facilitated the implementation in Spanish airports of CD operations, has designed more precise procedures that minimize noise and has implemented an integrated management system that helps to ensure the protection and conservation of biodiversity, achieving in 2015 that all the energy consumed by ENAIRE come from renewable sources[19].

AENA, on the one hand, has implemented energy efficiency measures in its facilities so that they reduce electricity consumption, while increasing its need energy from renewable sources. And, on the other, it has established actions to reduce fuel emissions and collaborative work with third parties, carrying out the characterization, control, surveillance and correction of the atmospheric emissions generated, and monitoring noise caused by its activity. In addition, 8 airports have ACA certifications, which covers 70% of the network's passengers[20]. The Adolfo Suárez Madrid-Barajas and Josep Tarradellas Barcelona-El Prat Airports, which generate half of the network's emissions, have already risen from Level 2 to 3, which implies, in addition to having a management and emission reduction program, to involve third parties and evaluate their emissions. Likewise, the Cesar Manrique-Lanzarote, Malaga-Costa del Sol and Palma de Mallorca Airports have renewed the ACA certification; while Alicante-Elche, Menorca and Santiago-Rosalia de Castro have renewed Level 1.

Examples of these measures are the implementation of the A-CDM, the replacement of APUs by supplying electricity at 400 Hz on the jetway and ground support vehicles (GSE) by other alternative or eco-clean technology, the promoting the use of SAF

16 https://www.chooseparisregion.org/calls-for-applications/h2-hub-airport

17 The Airport Carbon Accreditation Program, ACA, is a certification granted by the Airports Council International (ACI EUROPE). It is an accreditation system based on four levels (Level 1 "Inventory", Level 2 "Reduction", Level 3 "Optimization" and Level 3+ "Neutralization"), which respond to progressive commitments to reduce CO2 emissions, having as a final goal to achieve zero net carbon emissions. https://www.airportcarbonaccreditation.org/index.php

18 https://www.enaire.es/es_ES/2020_03_25/ndp_premio_sostenibilidad

19 https://www.enaire.es/sobre_enaire/sostenibilidad-medioambiente_servidumbresl/nuestro_compromiso

20 https://portal.aena.es/es/corporativa/aeropuertos-aena-adscritos-programa-airport-carbon---accreditation-avanzan-certificacion-alcanzar-neutralidad-en---carbono-en-2026.html?p=1237548067436

and the installation of systems using solar energy, cogeneration plants and wind turbines in their facilities, etc. Currently, 100% of the jetway parking already have these systems and the implementation of new ones is planned, as well as the replacement of old equipment so that airports will have 470 of 400 Hz electricity supply points for aircraft by 2030, and the objective is to have 152 charging points for electric vehicles in the public areas of the AENA [1].

In addition, AENA carries out the environmental evaluation of its projects (EIA) in accordance with the environmental evaluation law 21/2013, of December 9th, considering the environmental variable in decision-making for the execution of projects, and carrying out Isolation Plans Acoustic (IPA)

All these actions meet the commitment acquired in 2019 to adhere to the NetZero2050 initiative of ACI Europe (International Airports Council), consisting of achieving zero net carbon emissions at airports by 2050, and without including emission compensation mechanisms. In this regard, Aena's Board of Directors approved in March the 2021-2030 Climate Action Plan: 'Zero Emissions Course', which will allow to achieve carbon neutrality in 2026 and obtain a 94% emissions reduction by 2030 per passenger associated with Aena operations, on the way to achieve Net Zero in 2040.

To reach these strategic objectives, in which the involvement of all Aena areas is necessary, the implementation of a set of actions and effective measures is included, establishing indicators that will measure their compliance. The Climate Action Plan, which represents an investment of close to 550 million euros in the period 2021 and 2030, is structured in 3 strategic programs: Carbon neutrality, Sustainable aviation and Community and sustainable value chain[21].

At the second ACI EUROPE Aviation Sustainability Summit 20 May 2021, the airport trade body made a series of announcements reaffirming the commitment of Europe's airports to climate action and significantly raising their ambitions to achieve Net Zero CO_2 emission:

- AACI EUROPE confirmed the commitment of the European airport industry to achieve Net Zero for CO_2 emissions under its control by 2050 at the latest.
- 235 airports run by 63 operators across 29 countries have now backed this industry commitment - thus individually committing to the same objective.
- In addition to all 211 airports that had done so before the COVID-19 crisis and that continue to stand by their pledge, a further 24 airports have joined the European airport industry commitment to Net Zero. These 235 airports accounted for 68% of European passenger traffic in 2019.
- 91 airports run by 16 operators are set to deliver on their Net Zero commitment already by 2030.

Based on Europe's airports 2019 traffic volumes and estimated carbon footprint, this Net Zero commitment will eliminate a total of 3,14 million tons of annual CO_2 emissions as of 2050[22].

21 https://portal.aena.es/es/corporativa/aena-invertira-alrededor-550-millones-euros-en-plan-accion-climatica-en-periodo-2021-2030.html?p=1237548067436

22 https://www.aci-europe.org/press-release/317-airport-industry-reconfirms-and-accelerates-net-zero-CO2-targets.html

6.3. GRADUAL IMPROVEMENTS IN DESIGN AND EFFICIENCY

6.3.1. Technology Development Programmes.

Looking for this technological progress towards sustainability and greater competitiveness, the aeronautical industry has carried out high investments in R & D& I (in Spain, around 8% of the turnover of this sector ; in 2018, they were a total of € 19 bn, with an investment 4 times greater in USA than in Europe), with both private and public initiatives, being mainly in the US, NASA, and in Europe, the aeronautical activities carried out within the Framework Programs of the European Union.

R&D PROGRAMS IN EUROPE RELATED TO THE ENVIRONMENTAL IMPACT OF AERONAUTICS

- CLEAN SKY programme.

In Europe, a public-private Joint Technology Initiative (JTI) of the EU and European industry was developed, Clean Sky, which is part of the EU 7th Framework Programme for Research, Technological Development and Demonstration (2007-2013), with €1.6 billion budget, 50% of which are contributed by European Aeronautics industry and 50% from the European Commission. As a priority objective, which is based on ACARE's Strategic Research Agenda, the introduction of new technologies has been set to achieve more environmentally friendly aircraft, taking all the necessary steps to significantly reduce the impact of the air transport in the environment. Clean Sky 1 program comprises 7 project areas with 6 integrated technology demonstrators, from which various developments will be obtained, which will be supervised in an integrated way by the Technological Evaluator, which will analyse the viability of every technology.

The technology demonstrators were: Green Regional Aircraft (GRA), Eco-Design (ECO), Sustainable and Green Engines (SAGE), Smart Fixed Wing Aircraft (SFWA), Systems for Green Operations (SGO) and Green Rotorcraft (GRC).

Examples of demonstrators[1]: replace aluminium fuselage parts with composite material, replace hydraulic or pneumatic power with electric power, test different vehicles with 2-shaft, 3-shaft, geared and open-rotor configurations, the integration of passive flow, active flow, and load control technologies into new Smart Wing concepts, etc.

Figure 20 includes the details of the environmental objectives set in the different Integrated Technology Demonstrators.

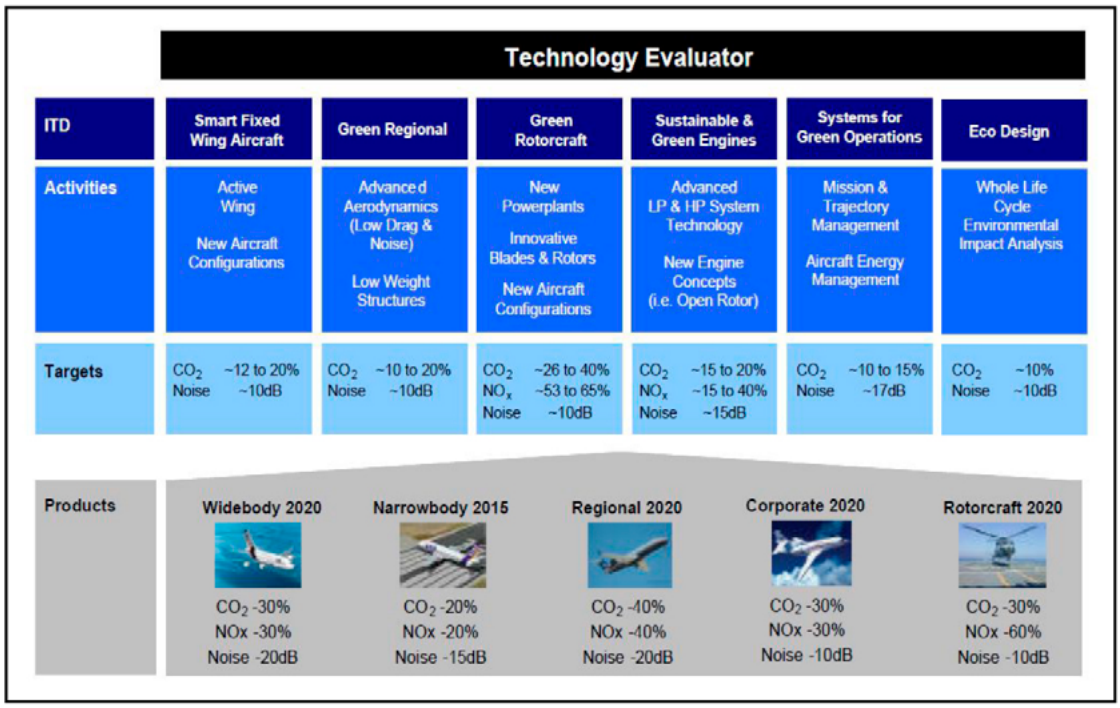


Figure 20. Activities and Objectives of the technology demonstrators in Clean Sky [9]

1 https://www.cleansky.eu/node/45; https://www.cleansky.eu/discover

In May 2014, the Council of the European Union agreed to extend the JTI Clean Sky (Clean Sky 2[2]) with a budget of € 4 billion, which would build on the achievements of Clean Sky 1, and its mission was to develop innovative technologies that significantly reduce the environmental impact of aircraft and, in general, air transport, resulting in less noisy and more fuel-efficient aircraft. The technological innovations of this program were grouped into large passenger aircraft, aircraft regional, IADP fast rotorcraft, airframe, engines, systems, small air transport and eco-design, as technology to integrate open rotor designs, boundary layer ingestion technologies, advanced aircraft rear design, demonstration of UltraFan flight test, active flow control for UHBR engine integration, natural and hybrid laminar flow control, etc.

Under Clean Sky framework program several projects are being worked on to address environmental challenges related to engines and aerodynamics, one of the integrated technology demonstrators was Sustainable And Green Engines (SAGE), whose activities were dedicated on the one hand to advanced systems technology, and on the other to new engine concepts such as SAGE2 Counter-Rotating Open Rotor (CROR), Ultrafan, and the aerodynamic demonstrator BLADE, among[3]. The progress of the program to date (last report of 2019) is found in reference [10].

Different Events and documents related to progress, contributions or analysis of the clean Sky program have taken place throughout this year 2021[4], highlighting the GLIMPSE2050 (Global Impact Assessment of Regulations and Polices for Sustainable Aviation by 2050) project, which carried out the environmental-impact assessment of the selected regulations and policies, individually and combined, and came to the conclusion of a 11% reduction in CO_2 and a 14% reduction in NOx could be achieved[5].

On 27th April 2021, the European Parliament voted with a majority for a Horizon Europe programme, successor to the Horizon 2020 program (8th framework program, with a budget of almost € 80 billion). Finally, in the 2021-2027 period, Horizon Europe will have a total budget allocation of EUR 95.517 billion in current 2021 price[6].

R&D PROGRAMS IN USA RELATED TO THE ENVIRONMENTAL IMPACT OF AERONAUTICS

In the period between the 90s and the first half of the 2000s, NASA developed in collaboration with other organizations the AST (Advanced Subsonic Technology)[7] and UEET (Ultra-Efficient Engine Technology Program) programs [64]. AST, with the objective of developing high leverage technologies that will assure the future competitiveness of U.S. civil transports, and finding new ways to enhance the safety, productivity and environmental acceptance of the national air transportation system. UEET was divided into 6 major projects dedicated to the development and transmission of revolutionary propulsion technologies that would enable future generation of vehicles at a wide range of flight speeds

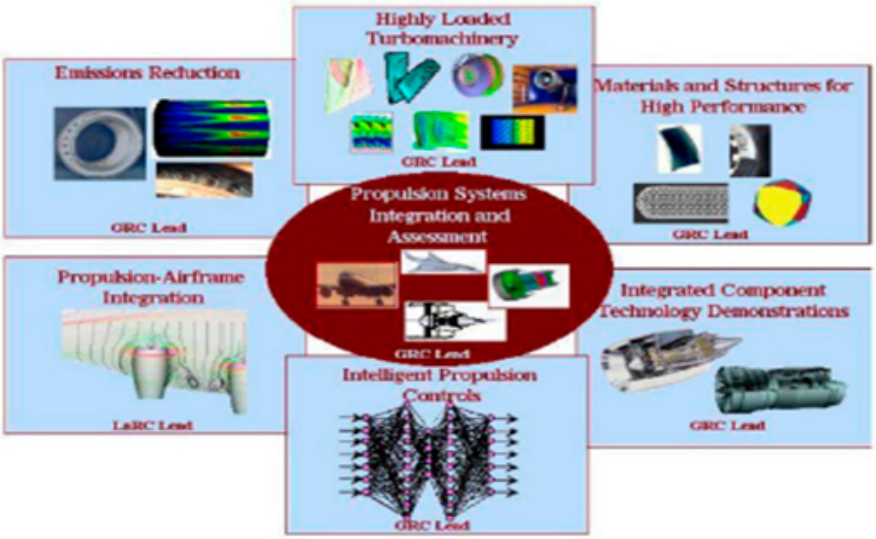


Figure 21. UEET program [17]

Advances at AST such as: a combustion chamber that reduced NOx by 50% in the PW4000 engine test followed by P&W certification and product implementation. Another chamber concept, the TAPS (Twin Annular Premixing Swirler), demonstrated a 62% reduction in NOx in the GE-Snecma CFM56 engine. Also, other Rolls-Royce combustion components demonstrated the potential to achieve a 50% reduction in NOx without adverse effects on CO and UHC (unburned hydrocarbon). UEET, aimed

2 https://www.cleansky.eu/technology-evaluator-te
3 https://www.cleansky.eu/sites/default/files/inline-files/Skyline%2021.pdf
4 https://www.cleansky.eu/
5 https://www.cleansky.eu/news/glimpse2050-how-regulation-can-reduce-aviations-environmental-footprint
6 https://www.europarl.europa.eu/ftu/pdf/es/FTU_2.4.5.pdf
7 https://er.jsc.nasa.gov/seh/pg36s95.html#:~:text=Therefore%2C%20NASA%2C%20other%20government%20agencies,ways%20to%20enhance%20the%20safety%2C

specifically at engine technologies, was divided into six major projects, along with potential reductions in CO_2 and NOx emissions, the latter for the LTO cycle [77].

In 2006, NASA, based on the technology it had developed in AST and UEET, established the Fundamental Aeronautics Program (FAP) to develop advanced propulsion technologies in a period of five to fifteen years, also known as Generation N + 1 a N + 2 and for the N + 3 generation, or beyond 2025. Four different projects were created, Subsonic Rotary Wing (SRW), Supersonic, Hypersonic and Subsonic Fixed Wing (SFW) [35] Subsequently, NASA established the Integrated Systems Research Program (ISRP) to carry out large-scale system demonstrations of the technologies developed under SFW. The Environmentally Responsible Aviation Project (ERA) [59] was also created in 2009 to develop these integrated systems demonstrations in the 2020-2025 period, or N + 2 generation of aircraft systems.

The ERA project ended in 2015 and focused on exploring and documenting the feasibility, benefits and technical risk of 8 important technologies related to structures, aerodynamics and engines [8]:

- Small integrated nozzles that blow air onto the surface of an aircraft's vertical stabilizer showed that future aircraft could be safely designed with smaller tails, reducing weight and drag.
- New process to assemble large sections of composite materials to create 20% lighter damage tolerant structures. Nuevo proceso para unir grandes secciones de materiales compuestos para crear estructuras tolerantes al daño un 20% más ligeras.
- Radical new wing technology that allows flap extension without leaving gaps that increase noise and induce drag.
- With GE, redesign of the fun stage of a turbine engine to improve its aerodynamic efficiency that could save 2.5% in fuel consumption.
- With Pratt & Whitney, an advanced fan design to improve propulsion efficiency and reduce noise, being able to reduce a 15% in fuel consumption and significantly improve noise.
- With Pratt & Whitney, in an improved design for the combustion chamber of a jet engine to reduce NOx, and it was possible to reduce the emission about 80%.
- New design tools were developed to reduce noise from deployed ailerons and landing gear during take-offs and landings.
- Significant studies on a hybrid wing body concept in which the wings are attached to the fuselage in a continuous and seamless line and the jet engines are mounted on top of the aircraft at the rear, fuel consumption is minimized, and noise is reduced.

Furthermore, the FAA developed the CLEEN (Continuous Lower Energy, Emissions and Noise) program with an investment of $ 250 million and $ 100 million in CLEEN I and II respectively, which was the main environmental effort from the FAA to accelerate the development of new aeronautical and engine technologies, advance in the use of alternative fuels and achieve the modernization of the United States air transport system to make flying even safer, more efficient and more predictable and, at the same time, shape the Air Transportation System of Next Generation or Nextgen. In this program, the technologies addressed were related to revolutionary engine designs, wing technologies, flight

8 https://www.nasa.gov/sites/default/files/atoms/files/green-light-for-green-flight-tagged.pdf

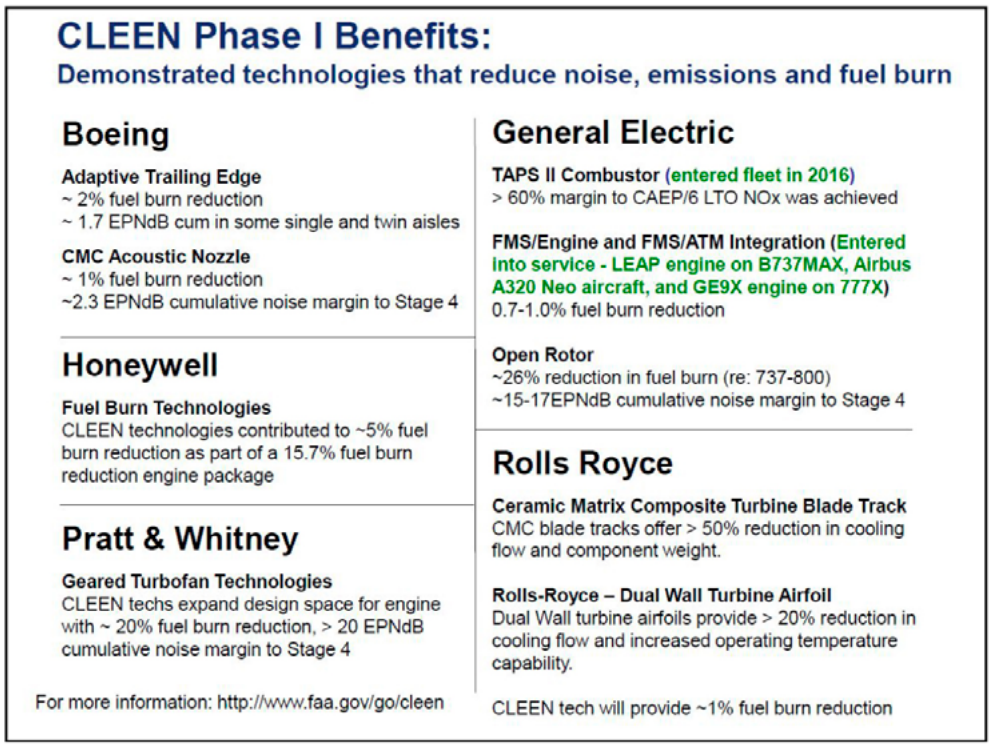


Figure 22. Proven technologies for reducing fuel, emissions, and noise [37]

management system improvements, combustion chambers and improved fuselage redesign.

The design of the Nextgen aircraft is based on previous projects such as ERA or the mentioned N + 3 designs, and on new projects such as: electric and hybrid propulsion, small core gas turbine, Truss-Braced Transonic Wing (TTWB) and greater use of composite materials, which will be discussed in more detail in section 6.3.4. Electric and hybrid propulsion will be covered in chapter 6.5

As it has been commented throughout the report, to make aviation more sustainable it is necessary to reduce its environmental impact and especially its impact on climate change. For this, greenhouse gas emissions must be reduced (CO_2 is the one that contributes the most), and for this, the amount of fuel burned or use sustainable fuels. To reduce this amount of fuel burned, it is necessary to make the aircraft move more easily and with the least possible energy, that is, the aircraft must be more efficient, lighter and more aerodynamic. Therefore, to make aircraft more sustainable, technologies focused on propulsion, aerodynamics and weight have to be developed.

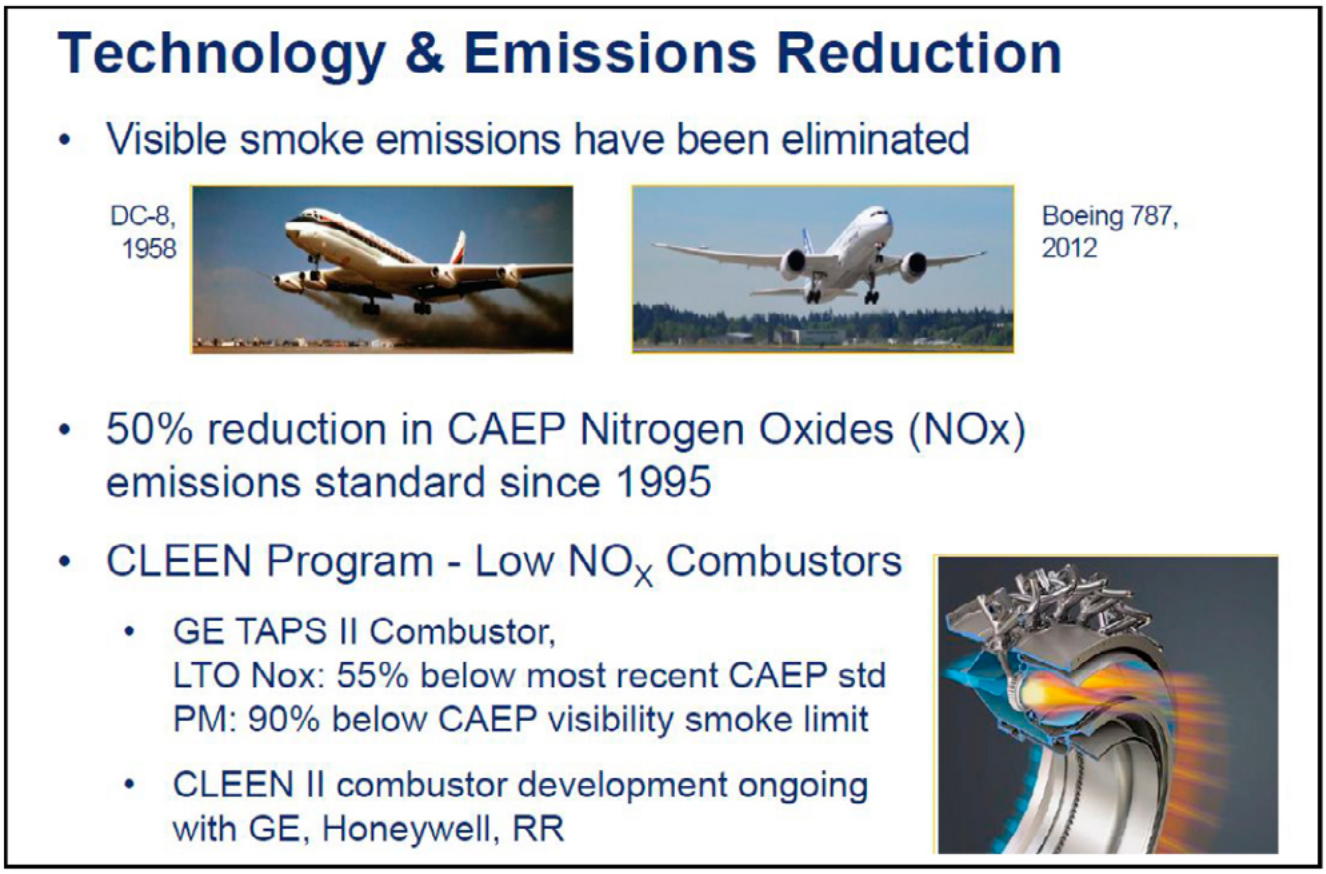


Figure 23. Evolution in emission reduction technology [37]

6.3.2. Propulsion.

Reduction of specific fuel consumption (SFC)

To reduce the SFC, it is necessary to increase the thermal and/or propulsive performance values for a given flight speed and type of fuel. In the case of a turbofan, the thermal performance is largely determined by the Overall Pressure Ratio (OPR), the turbine inlet temperature (TIT) and the performances of the individual components (fans, turbines and combustion chambers). Component efficiency levels have a direct effect on fuel consumption, and remarkable progress has been made in the last 30 years, with nearly all turbofan components achieving polytropic efficiency levels of over 90%, thanks to development of precise design CFD codes. Controlling secondary flows through the turbomachinery will provide component performance increases, but performance improvements will occur when increasing TIT and OPR together.

Currently, with the aim of reducing specific consumption, three engine configurations are being considered: Direct Drive Turbofan (DDTF), engines with a reduction gearbox (Geared Turbofan, GTF) and open rotor engines.

DDTF.

They constitute the conventional engines, where the fun and the core components (compressor and turbine) rotate on the same shaft and operate at the same rotation speed, thus the system is constrained by the component with the lowest speed, which is the fan in the propulsor., so the core must run at slower and less efficient speeds. High performance and low weight technologies have been developed that offer an optimization between the fan and turbine requirements, reaching high performance. The figure below shows the evolution of the environmental performance of the Trent engine family (Trent XWB -eXtra Wide Body-models that equip the A350 and with the new Advance and Ultrafan developments, the latter within Clean Sky 2) in relation to with ACARE 2050 goals.

GTF

In the GTF engines, the compressor and the core components are separated by a gear system. The gear system allows the fan and the core to operate at different, more efficient speeds. The core can then operate more efficiently and produce a given thrust level at the fan with fewer compressor and turbine stages compared to a direct drive engine, thereby reducing the engine weight and the fuel required to carry that weight around on the aircraft. The

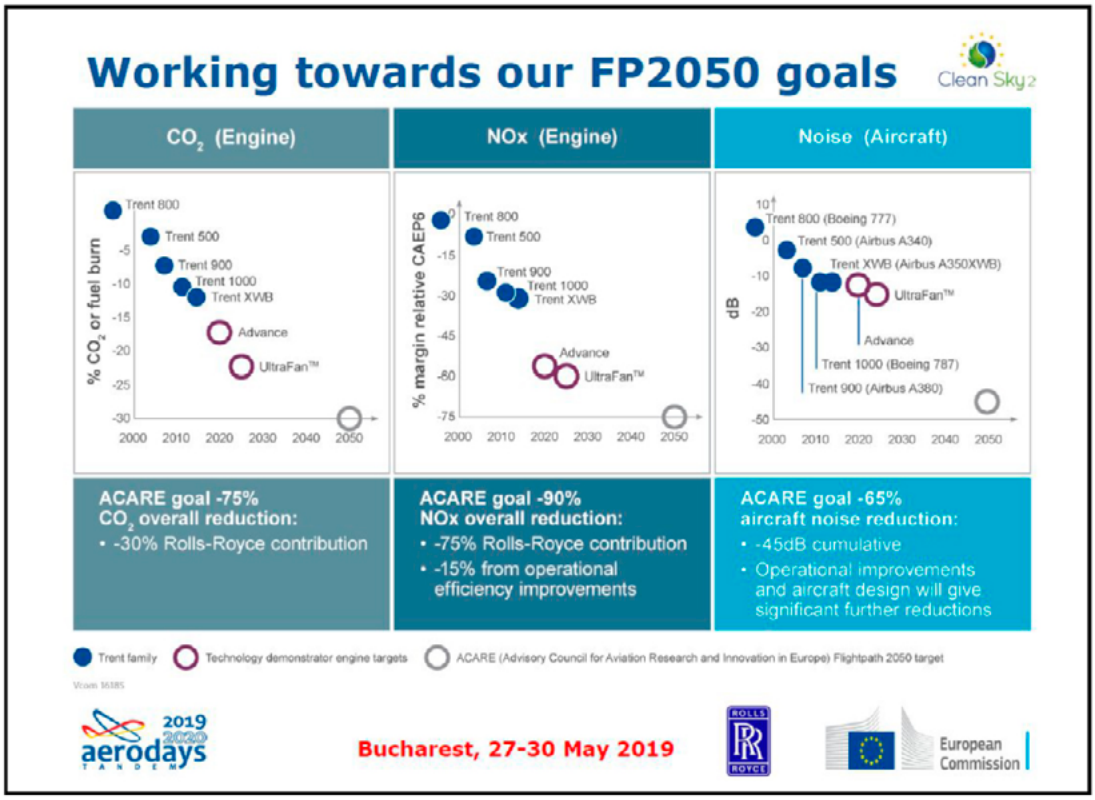


Figure 24. Evolution of a family of engines vis a vis the ACARE 2050 objectives

Photo Archive

Figure 24. http://www.tandemaerodays19-20.eu/presentations/

advantages of the GTF engine cycle, in terms of fan efficiency, compared to the conventional turbofan cycle and the open rotor or propfan cycle, are shown in Figure below.

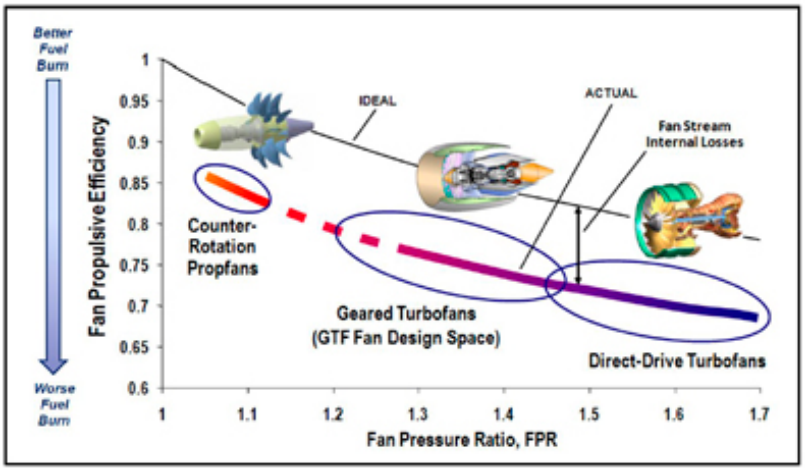


Figure 25. Trend in fan propulsion performance vs. its pressure ratio [40]

The first generation GTF in the USA was developed by Pratt & Whitney (P&W) in collaboration with NASA and is considered an N + 1 technology. Technological areas investigated included low speed, low pressure ratio fan, fan gear system, low emissions combustor, and high speed, compact, low-pressure spool. These technologies allowed the engine bypass ratio (BPR) to reach the Ultra High Bypass (UHB) ratio range of 12 or greater, while allowing the fan pressure ratio (FPR) to be reduced to between 1,3 and 1,4 to achieve higher fan efficiencies.

Once a maximum benefit point will be reached for this level of technology as the design BPR continues to increase and the FPR decreases. A second paradigm shift in technology is needed to extend the beneficial fuel burn tend line. NASA and P&W are again partnering to investigate a second generation of GTF propulsor (fan, stators, and nacelle) technologies to help meet those goals, enabling a BPR up to 18 and a FPR between 1,25 and 1,3 to be achieved. The Figure 26 bellow shows the projected reductions in fuel burn (a fuel burn reduction of 15% or 25%-30%) that can be achieved by the GTF engine cycle (Gen1 y Gen 2) is compared with a current technology A320 aircraft and V2500 engine combination.

In Europe, engine manufacturers established a plan throughout the 5th, 6th and 7th Framework Program with various projects, and later in the Clean Sky program for the development of technologies that facilitate the design and manufacture of new, more efficient and less environmental impact engines:

VITAL Project (enVIronmenTALly friendly aero engines, 2009) has investigated a series of new technologies for the engine low pressure system, to facilitate the development of light and low noise fan architectures for UHBR (Ultra High Bypass Ratio) engines, considering the three different configurations for low noise and high efficiency power plants mentioned above, which are the DDTF led by Rolls-Royce, the GTF by MTU and the CRTF by Snecma. The DDTF architecture offers an optimized compromise between fan and turbine requirements considering the low weight technologies introduced by the program. The GTF combines a fan with a reduction gear train, to allow different rotating speeds for the fan on one hand, and the booster and turbine on the other. The CRTF offers a configuration with two fans turning in opposite directions, allowing for lower rotational speeds, since the two fan rotors split the loads involved.

The technologies being built into these engines include but are not limited to, the following:

- New fan concepts with the emphasis on two types: counter-rotating and lightweight fans.
- Polymeric composites and advances in metallic materials.
- Low pressure turbine weight savings through ultra high lift air foil design, ultra high stage loading, lightweight materials and design solutions.

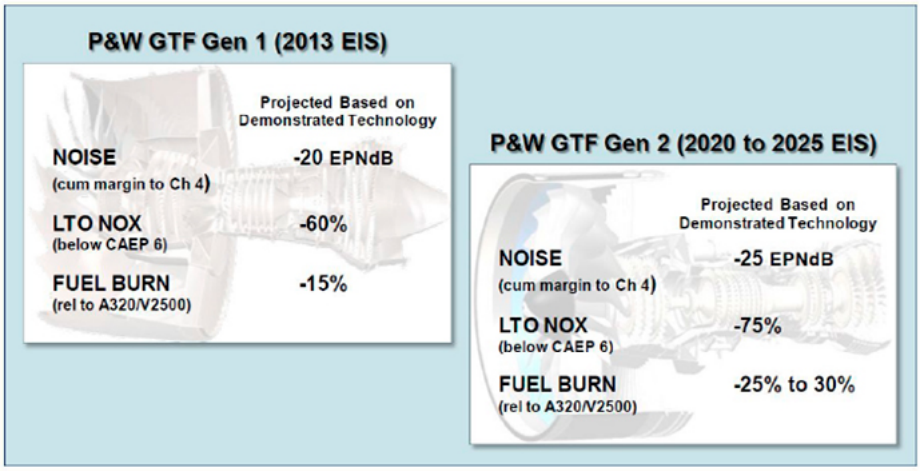


Figure 26. Projections of reductions in fuel consumption and other environmental impacts with the GTF engine of P&W [40]

- Technologies for light weight and low drag installation of high bypass ratio engines related to nozzle, nacelle and thrust reverser

Ultrafan

It is being developed by Rolls-Royce and allows the fun and turbine to be independently optimized by introduction of a power gearbox capable of operating at anything up to 100,000 HP to deliver greatly improved propulsive efficiency. It will deliver 25% improvement in fuel efficiency compared to the first Trent engines, and OPR to more than 70:1 It is being designed to meet potential noise and emissions stringency levels for aircraft entering service before 2030.

OPEN ROTOR ENGINES.

El diseño está destinado a ofrecer la velocidad y el rendimiento de un turbofán, con la economía de combustible de un turbohélice. Este concepto aumenta la relación de derivación al eliminar el conducto del fan y ofrece ganancias de eficiencia de dos dígitos debido a una relación de presión del fan más baja. A mediados de los años ochenta, la NASA, en asociación con varias industrias de motores de EE. UU., investigó esta nueva tecnología radical de propulsión y resurgió dentro del 7º Programa marco en el proyecto DREAM (*valiDation of Radical Engine Architecture systeMs*, 2011) y en el *Clean Sky*. En la Figura 28, el rendimiento previsto de los sistemas de propulsión de rotor abierto muestra importantes beneficios en el consumo de combustible incluso en comparación con los actuales motores turbofán de alta relación de derivación (HBPR).

Figure 27

SAGE2 counter-rotating open rotor, CROR.

In 2017, the Sage2 CROR successfully demonstrated new technologies including composite propeller blades, pitch control system, contra rotating reduction gearbox and aero acoustic optimization at the Safran test facility, confirming the technical feasibility of a CROR, the expectation of significant fuel burn improvements (-30% vs year 2000) and the capability to satisfy the current ICAO Chapter 14 noise requirements[1].

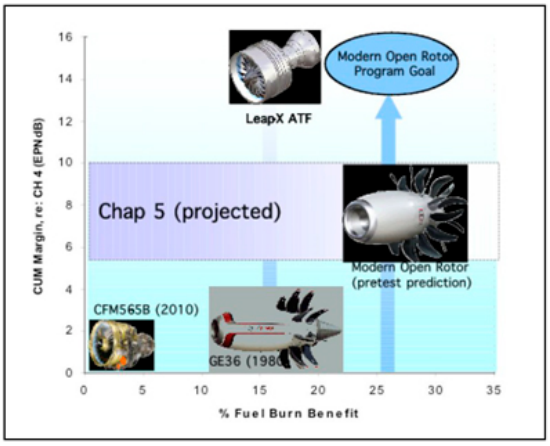


Figure 28. Performance benefits of open rotor technology compared to current turbofans

Revolutionary Innovation for Sustainable Engines, RISE.

This RISE program[2] was launched around June 2021 by CFM International partners, GE Aviation and Safran, on the way for a new generation of fuel-efficient open fan-engines to enter service around the mid-2030s. With the target of a 20% reduction in fuel consumption and CO_2 emissions compared to current engines. Unlike SAGE 2, which focused principally on system integration and propulsive efficiency, the RISE open fan will include a new compact core to boost thermodynamic efficiency, as well as new low-emission combustors and motor-generators for hybrid-electric systems. This configuration incorporates a compact high-pressure core, high-speed booster compressor and a high-speed, low-pressure-shaft-driven front gearbox.

Engine core technologies.

In the core turbomachinery area, the emphasis within NASA projects to reduce fuel burn is on increasing the power density of the engine core resulting in smaller units for a given thrust requirement. Increasing the core compression system overall pressure ratio (OPR) while maintaining or improving aerodynamic efficiency is one area of focus. Another area is increasing the turbine inlet temperature (TIT) to enable improved thermal efficiency.

1 https://www.easa.europa.eu/eaer/topics/technology-and-design/stakeholder-actions

2 https://aviationweek.com/aerospace/cfm-unveils-open-fan-de-monstrator-plan-next-gen-engine

Higher OPR and TIT are tough challenges that require a combination of developing advanced aerodynamic component designs, higher strength, and higher temperature materials, and improved computational analysis techniques.

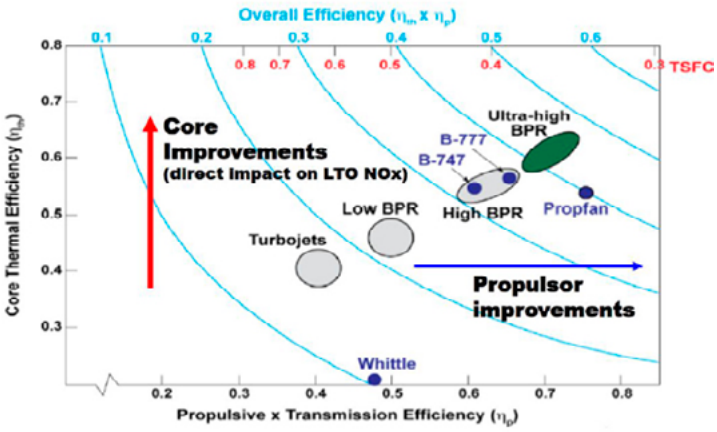


Figure 29. Trends in efficiencies with core and propulsor improvements.[36]

In Figure 29, the relationship between core thermal, propulsive and overall efficiencies are shown, along with the historic fuel burn trend with engine cycle and the goal for advanced engine technologies including the Ultra High Bypass ratio (UHBPR) engine cycle.

The technologies to develop high power density cores require, on the one hand, advanced aerodynamic designs and, on the other, the use of advanced, lighter and stronger materials for the main components. Figure 30 and Figure 31 show the main technologies under development in these two fields of action.

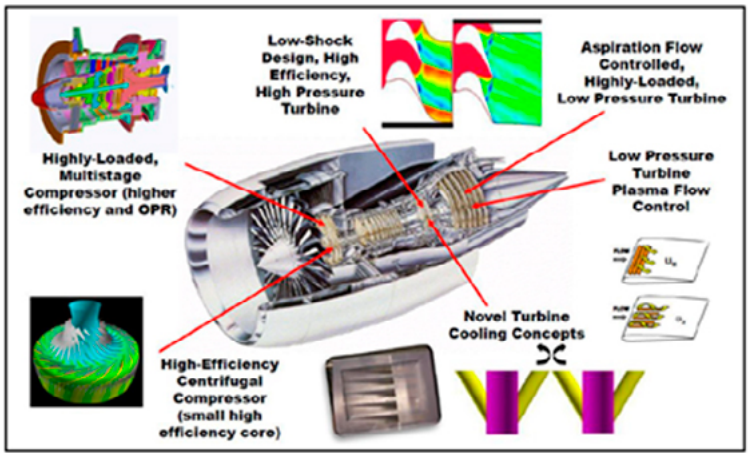


Figure 30. Technologies based on aerodynamic core design for advanced engines [36]

The introduction of ceramic matrix composites (CMC) has given rise to opportunities for revolutionary changes in propulsion system design and operation. The lower density and higher temperature capability of CMC components, relative to that of metallic components, offer multiple engine advantages, such as weight saving, efficiency and thrust improvements, and reduced specific fuel consumption. Figure 31 shows areas within a typical aircraft engine core where CMC technology can be applied, as well as design characteristics, and potential benefits for the engine.

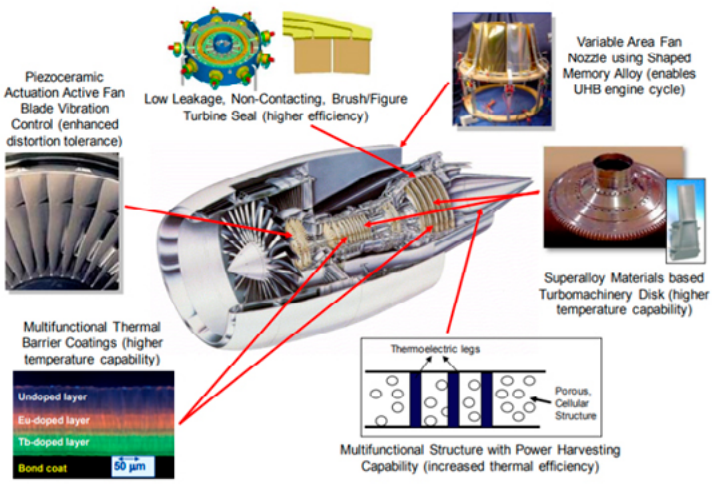
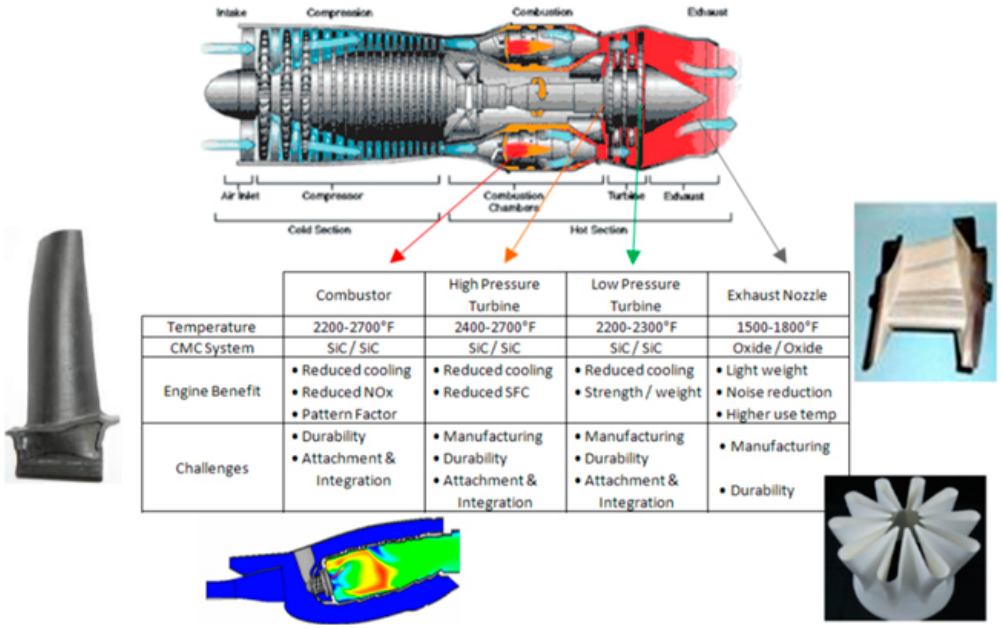


Figure 31. Engine core materials-based technologies enabling advanced engine cycles [40]

New core configurations have been developed using heat management (intercooler, cooling air cooler, recuperator), improved combustion, active systems and other to strongly reduce CO_2 and NOx emissions: NEWAC project (New Aero engine Core concepts, 2006-2011) of the 6th Framework Program. NEWAC was complementary to past and existing EU projects in this field, EEFAE (CLEAN and ANTLE) developed in FP5 and VITAL in FP6. The new core configuration proposals discussed in NEWAC[3] are four, each one, for a different type of turbofan:

- Intercooled Recuperative Core for the geared-fan intercooled recuperative aero engine (IRA) operated at low overall pressure ratio (OPR) and using a Lean Premixed, Pre-vaporized (LPP) combustor.
- Intercooled Core (IC) for a high OPR engine concept based on a 3-shaft direct drive turbofan (DDTF) using a Lean Direct Injection (LDI) combustor.
- Active Core (AC) with active systems applied to the geared turbofan (GTF) concept at medium OPR and using a Partial Evaporation and Rapid Mixing (PERM) or LDI combustor.
- Flow Controlled Core (FCC) with flow control technologies applied to the counter rotating turbofan (CRTF) with medium OPR and using a LDI or a PERM.

3 https://trimis.ec.europa.eu/sites/default/files/project/documents/20121029_130736_70767_Publishable_Final_Activity_Report.pdf



	Combustor	High Pressure Turbine	Low Pressure Turbine	Exhaust Nozzle
Temperature	2200-2700°F	2400-2700°F	2200-2300°F	1500-1800°F
CMC System	SiC / SiC	SiC / SiC	SiC / SiC	Oxide / Oxide
Engine Benefit	• Reduced cooling • Reduced NOx • Pattern Factor	• Reduced cooling • Reduced SFC	• Reduced cooling • Strength / weight	• Light weight • Noise reduction • Higher use temp
Challenges	• Durability • Attachment & Integration	• Manufacturing • Durability • Attachment & Integration	• Manufacturing • Durability • Attachment & Integration	• Manufacturing • Durability

Figure 32. Engine component applications for CMC materials and potential benefits [20]

there is a limit in the BPR due to the maximum size of the nacelle, and this drawback is overcome by making the core smaller in diameter and taking advantage of previous studies on materials and internal geometries to control the increased temperatures and pressures that are a natural result when managing combustion in tighter quarters. This is one of the goals of the small gas turbine research effort.

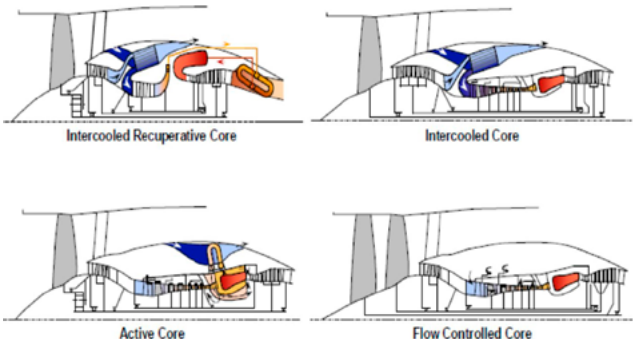


Figure 33. Four NEWAC engine concepts.

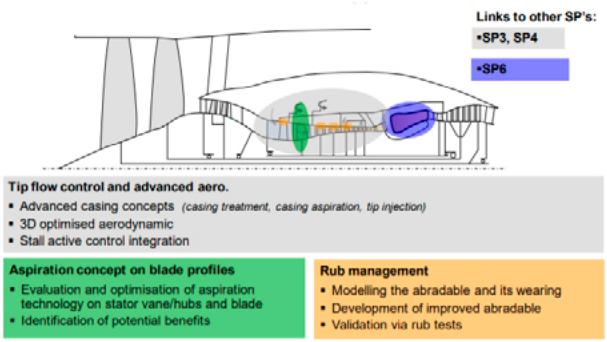


Figure 34. Flow controlled core – Technical approach.

Small Core gas turbine.

Another way to get more fuel efficiency of an engine, as seen previously, is to change its configuration in terms of how air flows through it is changed, together pressures and temperatures. For years, jet engines have become more efficient by changing the amount of air flowing through the hot jet core of the engine by diverting the flow, creating the concept of the bypass ratio (BPR).

In general, the higher the bypass ratio the more efficient the engine can be at generating thrust. But

Figure 35. Small core gas turbine

NASA researchers are studying ways to make the core of engines smaller in diameter in order to increase fuel efficiency . As part of the NASA Advanced Air Vehicles Program (AAVP), a new project is being formulated called Hybrid Thermally Efficient Core (HyTEC) in which NASA intends to accelerate the development of small turbofan engine core technologies, culminating in an advanced core demonstration in the 2026 timeframe. The HyTEC goal is to demonstrate increased thermal efficiency with integrated high power-density core engine technologies achieving a 5- to 10-% fuel burn benefit, versus 2020 best-in-class, for early 2030s entry into service (EIS) single-aisle aircraft.

Photo Archive

Figure 33. Assessment of New Aero Engine Core Concepts and Technologies in the EU Framework 6 NEWAC Programme, January 2010. Conference: ICAS 2010 Congress Proceedings, Paper No. 408.Project: NEWAC (EC FP6

Figure 34. https://trimis.ec.europa.eu/sites/default/files/project/documents/20121029_130736_70767_Publishable_Final_Activity_Report.pdf

REVOLUTIONARY PROPULSION TECHNOLOGIES.

The new propulsion concepts are expected to have a considerable impact on reducing fuel for the future fleet. Currently, the open rotor, boundary layer ingestion and electric aircraft are the most important innovations when it comes to aircraft propulsion technologies.

Electric, hybrid or battery- powered aircraft propulsion.

Conventional internal combustion and electric engines are used during the flight in different combinations, electric or Hybrid-Electric. This latter propulsion system is e among the most promising technologies (see chapter 6.5).

Boundary layer ingestion.

With the aim of reducing the weight and drag of high propulsive efficiencies generated by conventional systems integrated in the aircraft, a promising approach of distributing the propulsive thrust on the main structures of the airframe is considered. This idea is referred to as the "Propulsive Fuselage Concept" (PFC), which allows the whole fuselage to act as a propulsive thrust. The most straightforward way to implement this concept is by full annular boundary layer ingestion (BLI). The concept of wake-filling through BLI has been thoroughly investigated in various projects. Some of those include FuseFan and STRAC-ABL of NASA, Claire Liner of Bauhaus Luftfahrt and D8 concept of MIT.

With the BLI technology, engines are located near the rear of the aircraft so that air flowing over the fuselage becomes part of the mix of air going into the engine air inlet and is then accelerated backwards. According to NASA analytical studies, the BLI technology is capable of reducing the aircraft fuel burn by as much as 8.5% compared to aircraft operating today. As part of the Horizon 2020 Program, a project was being carried out to demonstrate the validation of the PFC concept, called CENTRELINE (Concept validatioN sTudy foR fuselagE wakefilLing propulsion integration). The specific PFC configuration investigated in CENTRELINE features a twin-engine, turbo-electric PFC systems layout with the aft-fuselage BLI fan being powered through generator offtakes from advanced Geared TurboFan (GTF) power plants podded under the wing. The PFC design mission fuel benefit based on 2D optimized PFC aero shaping is 4.7%[4].

MTU Aero Engines company is currently focusing on what is known as a WET engine (Water-Enhanced Turbofan). With this concept, water is evaporated in a heat exchanger in the engine and injected into the combustor. The exhaust heat is used to evaporate the water, which can significantly improve the propulsion system's efficiency. Moreover, wet combustion prevents NOx emissions almost entirely. This concept reduces fuel consumption by more than 15% regardless of fuel type, considerably lowers all emissions – especially NOx levels – and, according to initial estimates, also reduces formation of contrails. if the water-enhanced turbofan (WET engine) concept is used in conjunction with SAFs, it would offer the potential to drastically cut emissions, even for long-haul aircraft[5].

4 January 2021, https://www.mdpi.com/2226-4310/8/1/16/htm

5 https://aeroreport.de/en/innovation/new-propulsion-systems-hydrogen-is-the-future

6.3.3. Aerodynamic.

Aerodynamic technologies have been progressing continuously throughout the history of aviation to achieve a reduction of fuel consumption and therefore, of emissions:

- CFD advances.
- Airfoil/wing technology advances.
- LE/TE high lift device advances.
- Higher Reynolds number wind tunnel testing.
- Improved structural concepts.
- More integrated wing/engine/pylon configurations.
- Multidisciplinary optimization.

For current aircraft configurations, remaining areas for significant fuel-burn improvement in next years are Propulsion/propulsion integration, Aerodynamic drag reduction and Multidisciplinary optimization. Alternate aircraft configurations may allow further integrated improvements from systems, materials and engine technologies.

A typical Drag breakdown is shown in the Figure 36: Viscous and lift-induced drag are dominant drag components for subsonic aircraft in cruise. Viscous drag is remaining area with potential for further drag largest reduction.

Advances in aerodynamics, as well as in materials and structures, have allowed a significant reduction in drag induced by lift:

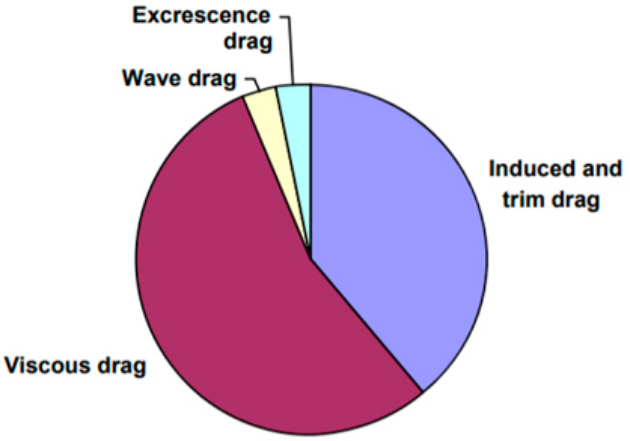


Figure 36. Drag breakdown [32]

- Maximizing effective span extension using composites.
- Incorporating advanced wing-tip devices (winglets) that increase aerodynamic efficiency and reduce fuel usage.

Aerodynamic technology could be classified into three areas:

- Aerodynamic tools, processes, and capabilities.
- New airplane configurations.
- Aerodynamic product technologies.

Advances in Aerodynamic tools, capabilities and processes such as CFD, flight and wind tunnel testing have allowed the development and evaluation of new aerodynamic technologies and improve aerodynamic designs and analysis.

New airplane configurations such with more integrated wing/engine/pylon configurations have increased the aerodynamic efficiency.

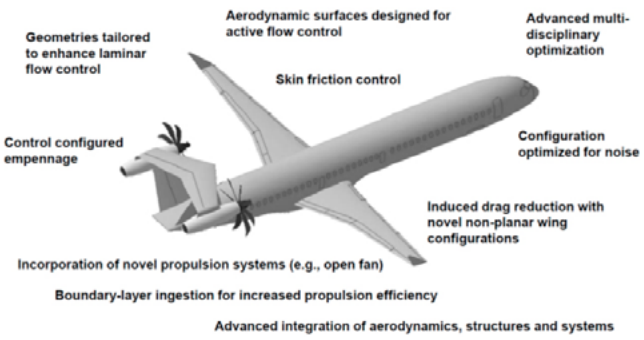


Figure 37. New airplane configurations [32]

Advances in aerodynamics products technologies are enabling significant reduced lift-induced drag by increasing the effective wingspan as advanced wing-tip devices or maximize effective span extension due to composite materials. Examples of these advances are shown on the figure bellow.

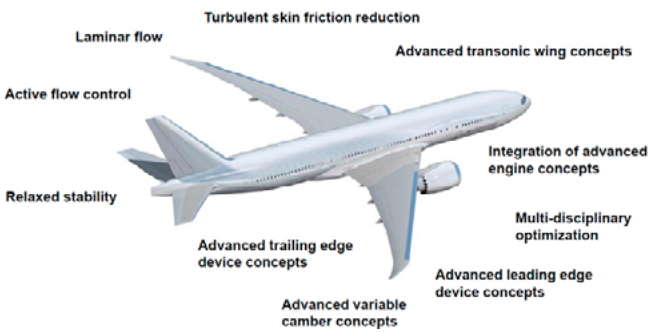


Figure 38. Aerodynamics products technologies [32]

Wingtip devices: Winglet.

The wingtip devices increase the lift generated at the wingtip and reduce the lift-induced drag caused by wingtip vortices, improving lift-to-drag ratio. This increases fuel efficiency in powered aircraft and speed in gliders, in both cases increasing range.

A winglet is a near vertical extension of the wing tips. Its shape as well as its size are critical for correct performance. The vortex which rotates around from below the wing strikes the cambered surface of the wingtip, generating a force that angles inward and slightly forward. It converts some of the otherwise wasted energy in the wing tip vortex to reduce drag. Another potential benefit of winglets is that they reduce the strength of wingtip vortices, which trail behind the plane and therefore reduce the turbulent air in its contrail, which could cause control problems for aircraft crossing it.

Laminar Flow and Active Flow Control.

A field of R&D of great importance is laminar flow since its application in various parts of the aircraft also contributes to the reduction of drag, reducing consequently the fuel consumption. Natural laminar flow control (NFL) is achieved only by designing the surfaces of the wings and other parts of the aircraft in a suitable shape and `forced' or "active laminar flow (LFC) and Hybrid Laminar Flow Control (HLFC), the laminar flow over the aircraft surface is maintained or achieved applying suction to the boundary layer.

The NLF or LFC technology is being studied, for example, in the BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe project, which is part of the Clean Sky. This demonstrator is tasked with assessing the feasibility of introducing laminar flow wing technology on a large airliner with the goal of reducing aircraft drag by 10% and CO_2 emissions by up to 5% [26].It is the first in the world to combine a transonic laminar wing profile with a true internal primary structure, in which the outer wing sections, about 10 meters wide, were replaced by laminar profiles. From these tests, it is estimated that the Natural laminar flow (NLF) fuel economy potential for an 800 nautical mile flight would be around 4.6%.

HLFC technology is particularly suitable for swept wings and empennage. NASA, in the framework of its Environmentally Responsible Aviation (ERA) research program, carried out a series of flight tests on a B757 equipped with an HLFC system to evaluate the dependence of laminar conditions on factors such as surface manufacturing, suction devices and surface coatings to prevent contamination.

It has been demonstrated in aerodynamic flight tests that scale and sweep affect laminar-flow application (NLF vs. HLFC) also observing that the benefits in environmental impact will depend on scale of application The estimated net potential fuel burn benefit of laminar flow for subsonic transports is 5 – 12 % approx.

Currently laminar flow research activities are being promoted in Europe within Clean Sky: Clean Sky 2 activities are being carried out in NLF and HLFC as indicated Figure 39 and Figure 40 respectively, which are in an advanced stage of development.

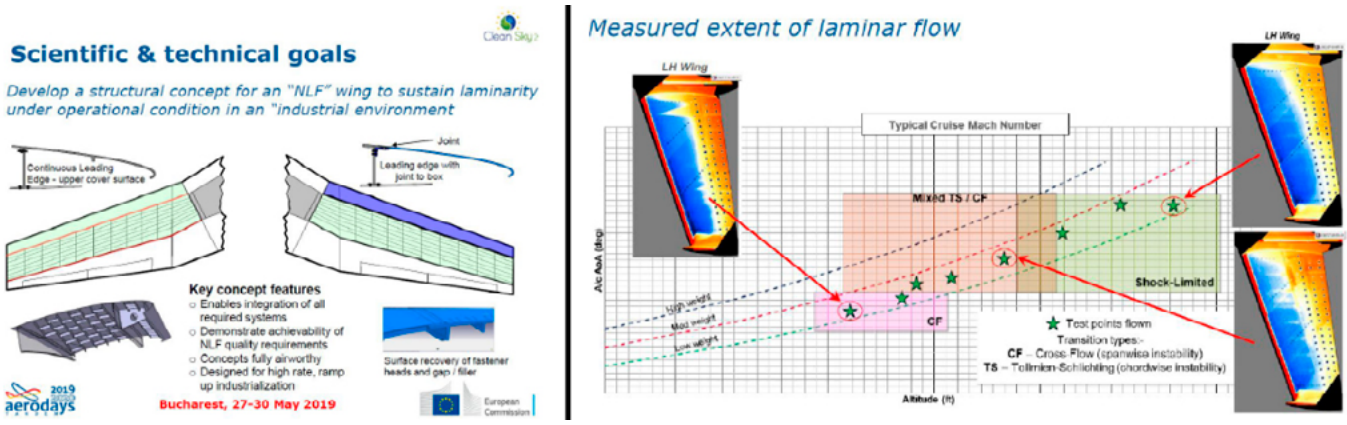


Figure 39. Natural laminar flow activities in Clean Sky 2 [52]

Technology of turbulent friction drag reduction: ribbed structures on the surface of the wing (riblets), demonstrating, through tests in tunnel and in flight, that they passively reduce the local turbulent friction around 6% [32], thus reducing the drag of the turbulent flow. Research carried out by the DLR in Berlin achieved reductions in turbulent drag of up to 10% by optimizing the shape of the riblets.

Variable curvature technology at the trailing edge. NASA has developed and combined the concept of

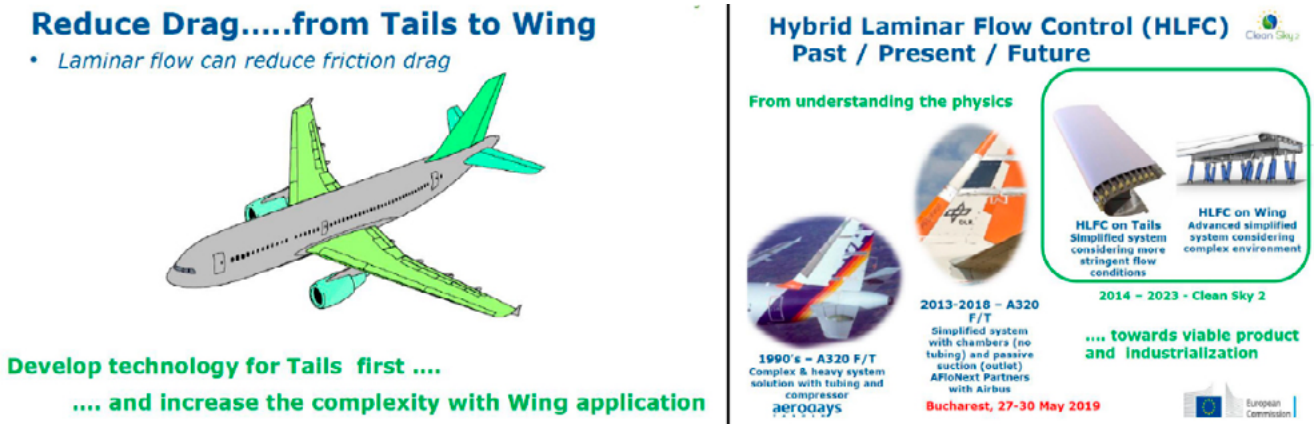


Figure 40. Hybrid laminar flow activities in Clean Sky 2 [38]

a continuously variable curvature flap or slat with the concept of active wing shape control to reduce drag and subsequent fuel consumption. Active Wing Shape Control is designed to aero-elastically change the wing shape in flight in order to achieve a shape for optimal drag reduction.

Aerodynamic effects on propulsion-cell integration.

Increasing nacelle outer diameter due to increased bypass ratio (BPR), main landing gear height limitations and demand for enough ground clearance require a close fit between wing and engine for installation of high BPR engines. Therefore, the integration of the powertrain is of great importance, since otherwise the increase in engine efficiency can diminish by increasing resistance due to installation.

Within the EU framework programs, various projects have been carried out dedicated to the integration of propulsion totally or partially, such as the called ENIFAIR (Engine Integration on Future Transport Aircraft) with the main objective of mitigating the aerodynamic impact of. engine-pylon-wing interferences. On the other hand, for new unconventional aircraft configurations the potential or risk of the same regarding the installation of the engines has also been investigated, as in the ROSAS project (Research on Silent Aircraft Concepts) as shown in Figure 41.

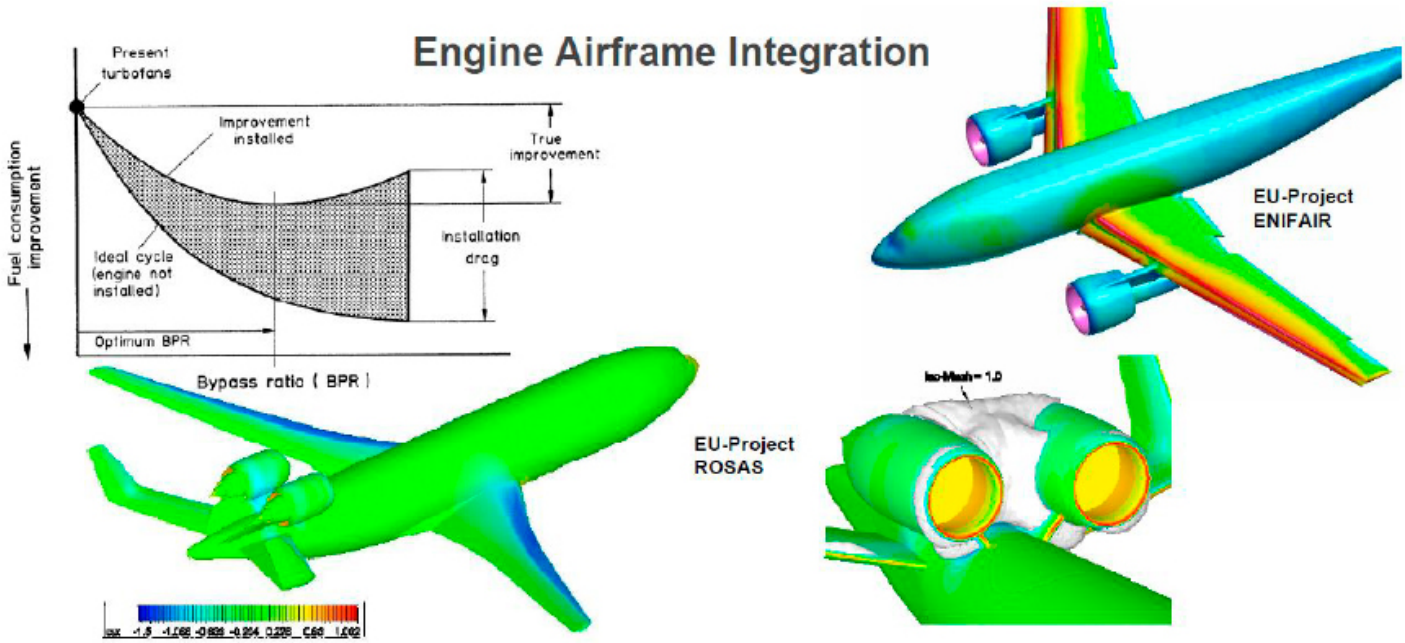


Figure 41. Propulsion-cell integration in conventional and unconventional configurations [65]

REVOLUTIONARY AERONAUTICAL CONFIGURATIONS.

NASA has promoted research on revolutionary aircraft configurations in the United States since approximately 2000, through public-private collaboration programs, with R&D activities in the industry. Between these technologies are distinguished[1]:

The strut-braced wing (SBW) concept allows without increasing the weight to increase the wingspan and therefore less thrust is required. SWB aircraft was design by Boeing in "Subsonic Ultra Green Aircraft Research" (SUGAR) project in which configurations approximately 29% more fuel efficient were achieved on a 900 nm mission (3,500 nm design range) than a Boeing 737-800 with CFM56 engines. Additional wing weight optimization combined with an open rotor engine could lead to fuel savings of up to 53% compared to the reference fleet.

Transonic Truss-Braced Wing. Studies to increase aerodynamic efficiency through the Transonic aircraft concept with Truss-braced wing (TTBW). The TTBW is essentially a classic tube and wing aircraft, but with an extremely long and thin wing. So long and thin, in fact, that it needs a little help on both sides of the fuselage to hold it up. This type of wing creates the same amount of lift as the thicker, shorter wings seen on airliners today, but does so with much less drag. By narrowing the thickness of the wings and extending their length, drag is reduced, and 5-10% less fuel is burned than comparable narrowbody aircraft.

TTBW technology is the one that could be developed earlier, in about 10 years, while the previous ones would need between 5 and 10 more years

The blended wing body (BWB), also called hybrid wing body (HWB), is mainly a large flying wing, which contains a payload area (passenger cabin or cargo storage area) within its centre section. The shape of the centre body and the outer wings are smoothly blended.

Fuel efficiency forecasts for various large BWB designs typically vary between 27% and around 50% lower than current aircraft of similar size and range. For the new small BWB design, fuel efficiency estimates are around 30% below current reference aircraft80.

There are also initiatives to combine the benefits of electric propulsion and the design of the blended wing body, BWB or HWB. NASA has been studying BWB concepts with distributed turboelectric propulsion systems for the past decade, and the predicted fuel economy is on the order of 70%. Recent advancements in the design of small BWBs could lead to new opportunities in this area. Small BWBs typically cover the 100-150 seat category, which is much better adapted to various concepts of hybrid, and potentially battery, electric propulsion than very large aircraft. An electric BWB could build upon the combined progress in airframe and propulsion design, which are expected to occur in parallel in the next decades.

Another promising flying-wing concept is the "Flying-V", a V-shaped highly swept double wing configuration designed for a similar number of passengers and range as the A350. The two wings accommodate the passenger cabin, hold, and fuel tanks. Similar to the BWB configuration, the Flying-V has lower aerodynamic drag and is 20% more fuel efficient than a comparable tube and wing aircraft.

Double-bubble fuselage, for example the Aurora Flight Sciences D8 design for NASA, whose main feature is a "double bubble" fuselage consisting of two blended side-by-side tubes. The flattened fuselage body generates additional lift and therefore, the wings can be designed smaller and lighter to carry the weight of the aircraft, reducing the amount of fuel burned over a comparable conventional configuration. Additionally, motors attached to the rear of the fuselage allow air to flow over the top of the aircraft and into the engines, reducing overall drag. This concept is known as boundary layer ingestion. The D8 configuration has the potential to achieve up to a 20% improvement in efficiency compared to the A320neo.

Box- / Joined-Wing, this box wing configuration, which was first proposed by Ludwig Prandtl in 1924, connects the tips of the two wings. For a given lift and wingspan, this configuration ensures minimal induced drag and fuel economy savings compared to conventional aircraft. Parsifal project[2] is a research project with the aim at designing an aircraft with the same wingspan as an Airbus A320 or Boeing B737, with the same capacity as an aircraft of a larger category, such as an Airbus A330 or a Boeing 767, and the fuel consumption of the smaller aircraft.

A new concept widebody aircraft, the SE200[3], with 264 seats, March 2021, has been unveiled by an Alabama start-up, SE Aeronautics (the SE standing

1 IATA Technology Roadmap for Environmental Improvement Fact Sheet, 2019-2 https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf

2 https://cordis.europa.eu/project/id/723149/results

3 https://www.seaeronautics.com

for Super-Efficient) have reworked the entire concept of an airliner, and revealed an innovative tri-wing aircraft that they say will have lower an 70% fuel consumption and an 80% lower carbon footprint than similar traditional planes.

The **Celera 500L airplane** is a revolution in private aviation with extensive use of laminar flow surfaces results in a ~59% reduction in drag compared to a similar-sized conventional.

It reduces carbon emissions by over 80% relative to comparable business aircraft) and over 40% relative to the most efficient commercial aircraft on a per-passenger basis (8 times lower fuel consumption) and 5-7 times reduction in operating cost. The Celera 500L's reduction in carbon emissions beats FAA and IACO target emissions standards for aircraft entering service in or after 2031 by over 30% The Celera 500L design lends itself well to future adaptations of electric or hybrid propulsion technology.

Figure 42. Celera 500L airplane.

Photo Archive

Figure 42. https://www.ottoaviation.com/technology

6.3.4 Structures and Materials.

Regarding improvements in structures and materials, highlight the following advances and innovations:

Additive 3D manufacturing.

This new technique for building aerospace parts involves adding material, layer upon layer, in precise geometric shapes. This enables complex components to be produced directly from computer-aided design information. It allows quicker and more flexible production and reduces material waste compared to traditional approaches such as milling. It also results in much lighter parts which reduces aircraft weight and consequently fuel burn. 3D-printed parts are already flying on Airbus A320neo and A350 XWB test aircraft (e.g., cabin brackets, bleed pipes, combustor fuel nozzles on the CFM LEAP engine).

High-rate composite in aircraft structures.

Although better metals and manufacturing procedures are available, composite materials have been used in aerospace for decades. and structures are increasingly more complex and structurally better and lighter than metal. The use of composite materials (composites) is increasingly preferred for structural components in all new designs. According to ICCAIA (International Coordinating Council of Aerospace Industries Associations), the potential for total weight savings with metals is in the range of 5 ± 2%. With advanced composites, the potential savings would be 8 ± 2% for single-aisle aircraft and 4 ± 2% for two-aisle aircraft [43]. There are other weight reduction technologies under study that could produce savings of around 2.5% for small aircraft and 4% for large aircraft [43]. Currently, airplanes such as the Boeing 787 Dreamliner or the A350 have 50% and 53% of parts made of composites compared to 1% in the 747 and 11% in the 777 [63]. But there remain opportunities to increase use composites in aviation, especially in the construction of big airplanes. Three challenges related to a significantly increased use of composites need to be overcome: The first has to do with reducing the time it takes go from concept, through design, fabrication, testing and then certification of materials, the second has to do with increasing the rate at which composite parts – especially larger structural components – can be manufactured and the third, the recycling process. NASA has completed the Advanced Composites Project on the first challenge, using new design methods, improved modelling capabilities, inspection methods and processes for automation to reduce certification time.

Use of advanced materials in Engines

In addition to the use of advanced materials in tie aircraft structure, important development efforts have been made to improve materials or coatings in the aircraft engines through using new materials and processes such as hight strength and temperature metal alloys and the Ceramic-matrix composites (CMC), already mentioned above in propulsion chapter, offering opportunities for revolutionary changes in propulsion system design and operation.

Improved materials or coatings, such as superalloys, and the processes for making fan, compressor, combustion chamber and turbines have had a major impact on the capability of modern gas turbine Engines.

Circular economy

Circular economy is an emerging concept for the aviation, while its application is still not widespread, the utilization of circular economy concepts could provide valuable learning opportunities for the future. The application of the circular economy principles to the aviation sector would primarily focus on two elements: aircraft and airports.

For aircraft, the circular economy model can be applied into aircraft operations and for the management of aircraft end-of-life. Example of the circular economy applications are Air France-KLM Group which adopted circular economy strategy in their flight operations since 2015, Airbus with the PAMELA project, Boeing with the Process for Advanced Management of End-of-Life Aircraft project, and Boeing and the Aircraft Fleet Recycling Association, which aims to set-up a new standard for an environmentally responsible management of end-of-life aircraft.

At airports, the application of circular economy has also demonstrated great potential for environmental and economic benefits. Examples of circular economy in airport are Schiphol Airport and Philips which developed a partnership to provide a circular lighting solution for airport. And the redesign waste management system in Gatwick airport.

REVOLUTIONARY TECHNOLOGIES IN STRUCTURES AND MATERIALS

Spanwise Adaptive Wing (SAW) project[1] of NASA, wings are being researched that can adapt to each phase of flight by modifying the shape of different parts of it, with the aim of reducing weight and resistance, thus improving efficiency. fuel. It is a Revolutionary concept in structure and material t which employs a high-force, solid-state Shape Memory Alloy (SMA) to develop a structurally efficient and reliable method of deflecting a portion of the wing in-flight with the aim of reducing weight and resistance.

Another promising technology is the **"morphing wing"** , under study by NASA and MIT. This new wing architecture could greatly simplify the manufacturing process and reduce fuel consumption by 2-8% by improving the aerodynamics of the wing, as well as improving its manoeuvrability. This mechanism involves the entire wing, which would be covered by a skin made of overlapping pieces, resulting a wing that is much lighter, and thus much more energy efficient, than those with conventional designs, whether made from metal or composite while reducing fuel consumption. It can change shape to control the plane's flight, improving the wing's aerodynamics and flight efficiency as well as improving its manoeuvring capabilities.

1 https://technology.nasa.gov/patent/TB2016/LEW-TOPS-124#:~:text=The%20Spanwise%20Adaptive%20Wing%20(SAW,of%20the%20wing%20in%2Dflight

6.4. SUSTAINABLE AVIATION FUELS

As seen previously, the strategy to turn commercial aviation into a fully sustainable activity is based on different elements and coordinated actions over time. If emissions offset mitigates the environmental impact in the short term, the introduction of fuels with low net CO_2 emissions are a fundamental tool in the medium to long term. Sustainable aviation fuels (SAF), already in use in commercial aviation, include different solutions under the same purpose: to reduce or cancel the net impact of carbon emissions from conventional aviation engines. This is the key factor that makes SAF so interesting for the sustainability of the aviation sector, since it will not require upgrading the current fleet of commercial aircraft to improve their environmental performance.

In 2013, a working group (AFTF[1]) was established within ICAO to assess the full life cycle of alternative aviation fuels. This initiative has been consolidated and will provide the necessary standards for environmental certification and accounting within CORSIA of the use of sustainable fuels[2].

In Europe, the RED II directive defines the sustainability criteria to be met by SA, with special attention to avoiding indirect negative impacts, such as deforestation or competition with food crops, due to the production of biofuels[3]. This fundamental regulation addresses problems identified in the previous legislation. Although it entered into force just in 2021, the European Commission has already announced a revision proposal to broaden its objectives and improve its safeguards [24].

Figure 43. Biofuel refuelling at Los Angeles airport.

There are two types of SAF: biofuels, produced from organic feedstocks, whether grown directly for this purpose or waste processing; and those produced synthetically from CO_2 and hydrogen, which are known as electrofuels, e-fuels or also Power-to-Liquid fuels (PtL). In both cases, its commercial use is based on the 'drop-in' concept, allowing blending with regular kerosene to feed conventional turbojets. Currently, this mix can include up to 50% SAF (Figure 48)), a limit by regulation that is likely to expand to 100% in the near future [14].

In fact, SAF is the main tool towards decarbonization in the sustainability path of major aviation companies such as Boeing, which announced in January 2021 its commitment to certify its aircraft to be able to run on 100% SAF by 2030[4]. This challenge has been also assumed by Embraer and other manufacturers. The compatibility with sustainable fuels is a key target for newly designed aircraft, but also for upgrades such as the D328eco[5] (Figure 44).

Airbus, for its part, also combines its sustainable hydrogen-based proposals with research into sustainable fuels. In March 2021, it made the first 100% SAF flight with an A350, as part of a project to evaluate the environmental performance of these fuels (ECLIF3). Run by a consortium including also Rolls & Royce, DLR and Neste, the emissions from these flights are exhaustively measured under real-world conditions. The aim is to consolidate the existing evidence on the additional environmental benefits from the use of these fuels, in particular with regard to the formation of contrails[6].

Since no major technical problems are anticipated, the main hurdle delaying the widespread use of sustainable fuels is the limited production capacity, currently marginal when compared to aviation demand. However, there is a frenzy of industrial projects being launched to increase this capacity,

1 Alternative Fuels Task Force, dentro del Committee on Aviation Environmental Protection (CAEP).
2 https://www.icao.int/environmental-protection/Pages/CAEP-FTG.aspx
3 https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii
4 https://boeing.mediaroom.com/2021-01-22-Boeing-Commits-to-Deliver-Commercial-Airplanes-Ready-to-Fly-on-100-Sustainable-Fuels
5 Flight International. August 2021.
6 https://www.airbus.com/newsroom/stories/A350-fuelled-by-100-percent-SAF-just-took-off.html

Photo Archive

Figure 43. https://www.dailybreeze.com/2019/06/05/lax-welcomes-eco-friendly-united-airlines-flight-powered-by-biofuel/

Figure 44. D328eco, 100% SAF compatible project, with a possible hydrogen-powered version.

with up to dozen announcements made only in the first three months of 2021[7].

Regulatory action also has a decisive role to play for SAF to achieve a significant percentage of aviation fuel consumption. In this regard, the recent proposal of the European Commission known as Refuel EU, part of the environmental package presented on the 14th of July 2021, seeks to establish mandatory refuelling quotas with SAF for all aircraft taking off in Europe. Progressively (Figure 45), and with specific sub-quotas for synfuels, this regulation would be a definitive boost for the introduction of sustainable aviation fuels. The obligation to refuel before any take-off would have the additional benefit of preventing the practice of tankering[8], which involves unnecessary fuel consumption, and therefore emissions[9], for economic reasons [16]. Norway leads the implementation of this type of progressive measures with the obligation to comply, by 2020, with a 0.5% SAF quota, a mandate that will reach 30% in 2030.

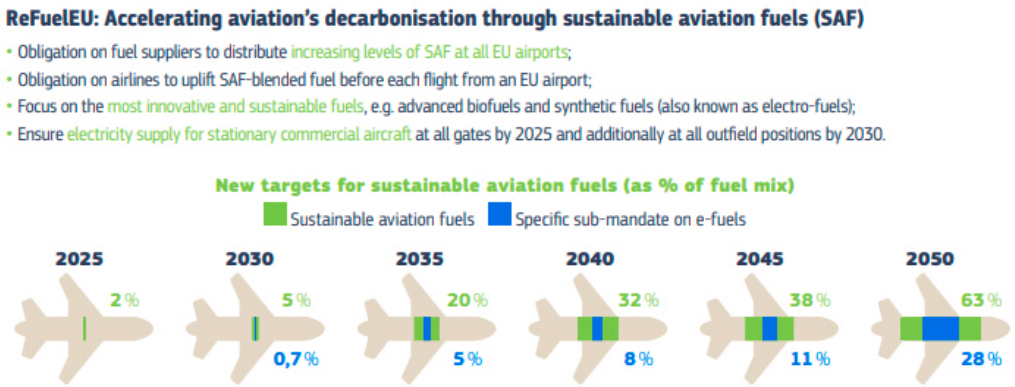


Figure 45. RefuelEU. European Commission SAF mandate proposal.

On the other hand, in the US where SAF seems to play a dominant role in the effort to reduce aviation emissions, the approach is based on economic incentives, as reflected in two recent legislative initiatives[10]. Additionally, in September 2021 the US government announced the Sustainable Aviation Fuel Grand Challenge[11], with the ambitious target of producing more than 11 billion litres of SAF in 2030, which would cover approximately 10% of the country's demand.

SAF introduction is a clear step forward towards sustainable aviation, moving forward from the palliative emissions offsetting, while gaining time for the implementation of disruptive propulsion technologies. Moreover, sustainable aviation fuels are today the only solution envisaged to effectively reduce the environmental impact in long-haul flights.

7 Flight International. April 2021.

8 Taking more fuel than needed from airports with cheaper fares. The difference in prices makes up economically for the extra fuel burned due to the additional weight carried.

9 Estimated around an extra 0,5% in intra-European flights.

10 Sustainable Aviation Fuel Act and Sustainable Skies Act

11 https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21.pdf

Photo Archive

Figure 44. Source: Deutsche Aircraft.
Figure 45. Source: EC.

6.4.1. Biofuels.

The mechanism by which biofuels reduce net CO2 emissions is quite simple: the plants or organic feedstocks used to manufacture them first captured carbon dioxide from the atmosphere while growing. Once transformed into biofuel, burning it in aeroengines releases the very same CO_2, theoretically achieving net-zero carbon emissions. Of course, it is essential to evaluate the complete lifecycle of each type of biofuel to ensure that the carbon footprint associated with the process still allows for an acceptable emissions reduction when compared to fossil fuel.

ASTM APPROVED PROCESS	DATE OF APPROVAL	FEEDSTOCK OPTIONS	BLENDING RATIO BY VOLUME
FT-SPK Fischer-Tropsch hydro-processed synthesised paraffinic kerosene	2009	**Lignocellulosic biomass** *Agricultural and forestry residues (e.g. sugarcane bagasse, sugar cane trash, treetops, corn stover and corn stalks) and municipal waste*	Up to 50%
HEFA-SPK Synthesised paraffinic kerosene produced from hydro-processed esters and fatty acids	2011	**Oils and fats** *Camelina, jatropha, castor oil, palm oil, animal fats, and used cooking oil*	Up to 50%
HFS-SIP Synthesised isoparaffins produced from hydro-processed fermented sugars	2014	**Microbial conversion of sugars to hydrocarbon** *Sugarcane, cassava, sorghum, and corn*	Up to 10%
FT-SPK/A Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	2015	**Lignocellulosic biomass** *Agricultural and forestry residues (e.g. sugar cane bagasse, sugarcane trash, treetops, corn stover and corn stalks) and municipal waste*	Up to 50%
ATJ-SPK (isobutanol) Alcohol-to-jet synthetic paraffinic kerosene	2016	**Biomass used for sugar production and lignocellulosic biomass** *Sugarcane, cassava, sorghum, corn, and ethanol*	Up to 50%
ATJ-SPK (ethanol) Alcohol-to-jet synthetic paraffinic kerosene	2018	**Biomass used for sugar production and lignocellulosic biomass** *Sugarcane, cassava, sorghum, corn, and ethanol*	Up to 50%
CHJ Catalytic hydrothermolysis synthetic jet fuel	2020	**Triglyceride-based feedstocks** *Waste oils, algae, soybean, jatropha, camelina, and carinata*	Up to 50%
HHC-SPK High hydrogen content synthetic paraffinic kerosene	2020	**Biologically derived hydrocarbons** *Algae*	Up to 10%

Figure 46. Certified processes for the production of sustainable aviation biofuels.

Biofuels have been used intensively for years in countries like Brazil, with automotive ethanol based on sugar cane since the 1970s. Together with other crops such as corn or soybeans, they were the feedstock for first-generation biofuels. However, the impact on land use and the competition with food production, associated with these crops, led to the search for alternatives. The second generation of biofuels use a wide range of organic feedstocks as vegetable wastes, animal fats, crops on marginal lands (camelina, jatropha) or even urban garbage (MSW[1]). Advanced biofuels also include a third and even fourth generation produced from microalgae.

At present, there are several certified processes for the production of biofuels already in industrial use (mainly HEFA-SPK), and some others still in development (Figure 46). The net reductions in CO_2 emissions, when compared to fossil fuel, depend on the feedstock and the production process used. It is important to point out again that this calculation must take into account the complete life cycle, including derived impacts such as the change in land use (LUC), both direct and indirect. As an example, it is necessary to account for the additional carbon emissions released if an area were deforested to give room for biofuel crops.

Figure 47, where the dashed line indicates the emissions associated with conventional aviation fuel, show the complete calculation of greenhouse gases associated with the use of different biofuels (LCA[2]). In some cases, the reduction in emissions reaches CO_2 neutrality, but there are also biofuels with unacceptable carbon footprints. This is why, before launching the industrial production of any biofuel, it is critical to carry out a comprehensive analysis of viability and environmental efficiency, with standardized criteria, which includes indirect effects such as the displacement of food crops.

The graph also shows some cases with negative net balances in greenhouse gas emissions. This is the case of biofuels whose complete cycle of production and

1 Municipal Solid Waste
2 Life Cycle Assessment

Photo Archive

Figure 46. https://rsb.org/wp-content/uploads/2020/06/RSB-Aviation-Report-WEB_Final.pdf

use extracts CO_2 from the atmosphere. For example, by-products from its manufacture are used to generate additional energy and replace fossil fuels. Other ways to obtain biofuels with a negative CO_2 footprint, still in the development phase, include carbon sequestration (BECCS[3]) in the process. This could be achieved during the growth of plants or by obtaining biochar as a by-product. Biochar is stable for millennia, effectively removing CO_2 from the atmosphere, and could be used in agriculture without releasing new emissions[4].

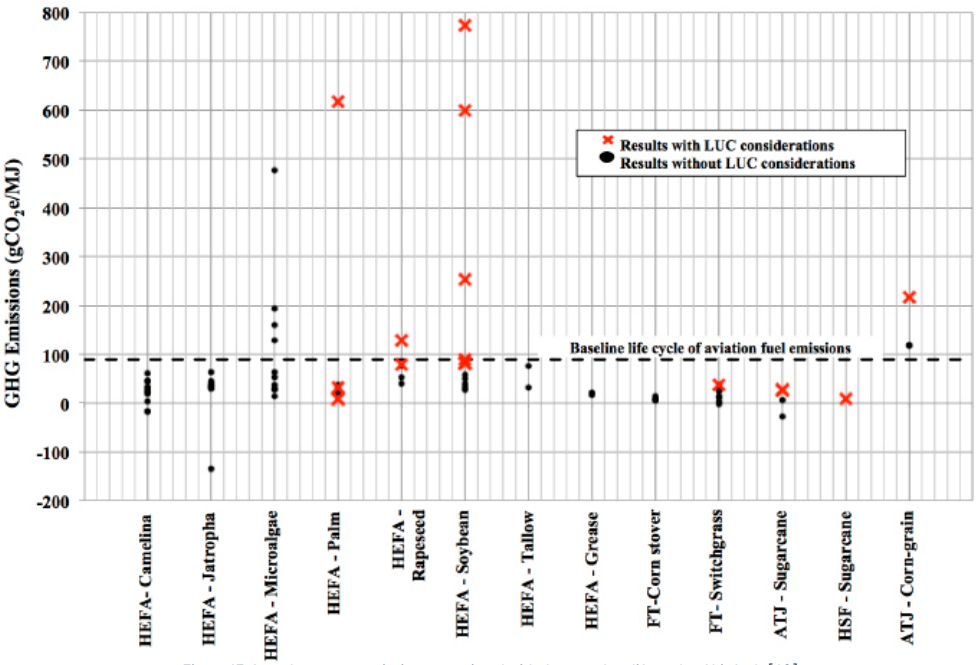


Figure 47. Greenhouse gas emissions associated with the complete life cycle of biofuels [48]

Focusing on projects already in the industrial phase, and as an example, in January 2019 a biofuel for aviation, obtained from waste products, obtained a full cycle environmental certification that ensured a reduction of more than 60% in emissions[5] with respect to conventional kerosene. Despite the successful commercial application, its price and production scalability are still a challenge [51]. The environmental performance of biofuels is constantly improving, from the current reductions of around 80% in CO_2 emissions targeted today, to the desired carbon neutrality[6].

Since the first flight with biofuel in 2008[7], much progress has been made in its introduction for commercial use. The total number of flights powered by SAF blends exceeds already 300,000 and airports all around the world supply sustainable aviation fuel[8]. In 2021 an estimated 100 million litres of SAF are expected to be produced globally, compared to 15 million in 2018. However, these figures should be contextualized since the latter covered less than 0.1% of the total aviation fuel used in that year. Increasing production to supply at least 2% of the demand will definitely launch the biofuel market. This goal seems within range in view of the multiple industrial and commercial developments underway, incentives for its use through mechanisms such as CORSIA and EU ETS (the use of these sustainable fuels discount offset obligations) and, above all, the legislative initiatives already mentioned in Europe and in the US. If in 2019 there were a total of 6,000 million litres of SAF committed to be supplied in the medium term to airlines around the world [53]. Furthermore, in September 2021 a single advertisement by a company reached practically the same figure[9]. Industry forecasts estimate that sustainable aviation fuels could mitigate up to 75% of its CO_2 emission reduction target [4].

To achieve these goals, biofuels must overcome the current shortage of feedstock available for their production, always respecting environmental quality throughout their entire life cycle. In Europe, a comprehensive review concluded that the available sources could meet up to 5.5% of the aviation fuel needed by 2030 [61]. Other studies indicate that only with the volume of used oil and fats available, SAF could be produced to cover 2% of the demand on the European continent [26].

The advances in the production of biofuels from urban waste[10] and by-products of the agricultural and wood industry are of particular interest, since they allow access to a large volume of supplies, at low cost and without land use impact. On the contrary, these feedstocks could solve existing problems such as landfills for urban garbage, with biofuel factories

3 BECCS: Bioenergy with Carbon Capture and Storage
4 https://www.stiesdal.com/fuels/the-skyclean-technology-explained/
5 https://rsb.org/2018/01/29/altair-rsb-certification-biofuel-refinery/
6 https://www.greenairnews.com/?p=1201
7 http://news.bbc.co.uk/2/hi/7261214.stm
8 https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/
9 https://www.ainonline.com/aviation-news/air-transport/2021-09-09/united-honeywell-partner-massive-saf-investment
10 https://www.greenairnews.com/?p=1046

already built such as Fulcrum Bioenergy in Nevada[11], or projects such as Wastefuel for Manila, where the target is to annually transform one million tons of municipal waste into 113 million litres of sustainable aviation fuels by 2025[12]. Another example comes from forest residues, the objective of the Rewofuel project funded by the European Union, which seeks to develop the potential of this large feedstock for the production of SAF[13]. In the US, a study on the energy potential of different wastes, with the technology already available, estimated that only with the manure from cattle and swine farms up to 10% of the country's aviation fuel needs could be met in 2016 [70].

The other key factor for biofuels to take off is the economic competitiveness against kerosene. With normal oil prices (50-100 $/barrel) the production cost of conventional fuel is in the range of 0.3-0.6

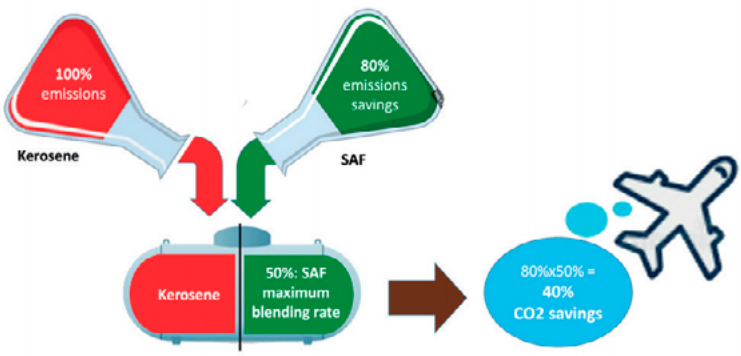


Figure 48. Calculation of emissions reduction from a 50% SAF blend [16]

$/L, compared to 0.7-1.0 $/L for SAF from the HEFA-SPK process [53]. This result is consistent with other studies on the production of sustainable fuel from used cooking oil, with a cost between 50% and 75% higher than kerosene [26].

The economic disadvantage of biofuel, which has been reducing considerably in recent years [44], could be totally overcome in scenarios of higher oil prices, through decisive political actions that foster its use and that are already underway (SAF mandates and incentives, taxes on fossil fuels) but also through technological advance and economies of scale. An alternative way to fund the gap could come for airlines transferring the extra cost of biofuels into the ticket price, appealing to the environmental sensitivity of passengers. As an estimate, the additional cost of flying between London and New York with a 15% SAF blend would be met with an extra charge of $ 10 by ticket [53].

An additional environmental advantage of biofuels already mentioned is that, according to an international study led by NASA and the DLR, their use can be associated with a mitigation of other negative

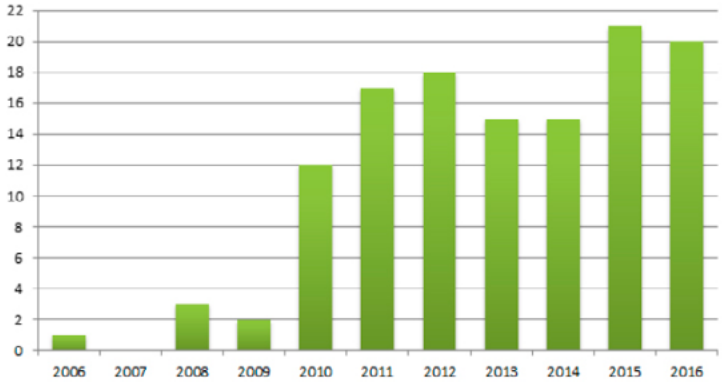


Figure 49. Number of active biofuels projects (ICAO GFAAF, 2017) (ICAO GFAAF, 2017) [48]

effects on climate change such as the formation of contrails and AIC [68]. This benefit would be achieved thanks to the fact that its combustion produces, among other differences, fewer soot particles than burning conventional kerosene, which would lead to a smaller number and greater size of the microcrystals that make up the contrails. More recent studies confirm this advantage by testing different blends in flight, with an optimal mix of 30% SAF that managed to reduce this type of emissions by 70% [76].

Other additional benefits already identified are a lower release of sulphur oxides [58], and even an increase in fuel efficiency by between 1 and 3% [14]. It is expected that the flight tests currently underway within the Emission and Climate Impact of Alternative Fuels (ECLIF3) project, mentioned above, will be able to consolidate these promising results.

11 https://fulcrum-bioenergy.com/wp-content/uploads/2021/07/2021-07-06-Sierra-Construction-Completion-Press-Release-FINAL.pdf
12 https://www.netjets.com/en-us/waste-fuel-sustainable-aviation-partnership
13 https://www.rewofuel.eu/

6.4.2. Electrofuels.

The synthetic production of fuels from renewable sources, also known as synfuels, represents a qualitative leap in terms of aviation sustainability. Its production process replicates, in a certain way, the biofuel cycle. Carbon dioxide is directly extracted from the atmosphere (DAC) or captured in industrial processes (point source), and then transformed into hydrocarbon by combining it with hydrogen, which in turn is obtained, for example, from water by electrolysis (Figure 51). The origin of the energy to feed the process, especially the generation of hydrogen, is what will determine the net balance of CO_2 emissions. If renewable sources are used, such as solar or wind energy, the resulting power-to-liquid fuel could be practically CO_2 neutral.

There are different processes available to obtain hydrocarbons from the synthesis gas (H2 and CO), such as Fischer-Tropsch (FT) or through the synthesis of methanol. These technologies are fully validated in small-scale demonstrators, and their industrial implementation is making progress, although hampered by the high associated production cost. In 2020 the price of PtL moved in the range of 1.3 to 2.2 €/L, which means 2 to 3 times the price of fossil fuel [75] Figure 50 shows this variability of SAF prices, both synthetic and organic, breaking them down by production technology. On the other hand, it is expected that technological improvements, such as high temperature electrolysis, and the economies of scale associated with industrial production will be able to reduce these costs significantly [30].

Despite being one step behind biofuels, both in industrial application and in cost, e-fuels have the advantage of requiring much less land and water per unit produced and, above all, avoiding all the problems of direct and indirect changes in the use of arable land and potential associated deforestation. The production of one litre of PtL consumes only 1.3L of water.

Among several industrial initiatives underway, it can be highlighted the ambitious project announced in June 2020 by Norsk e-fuel for the production of PtL for aviation in Norway from renewable energy. Production will begin in 2023 with an annual capacity of 10 million litres, and the aggressive expansion plans contemplate multiplying it by 10 in just 3 years, serving as a model for other production plants. It is obvious to link the viability of this industrial

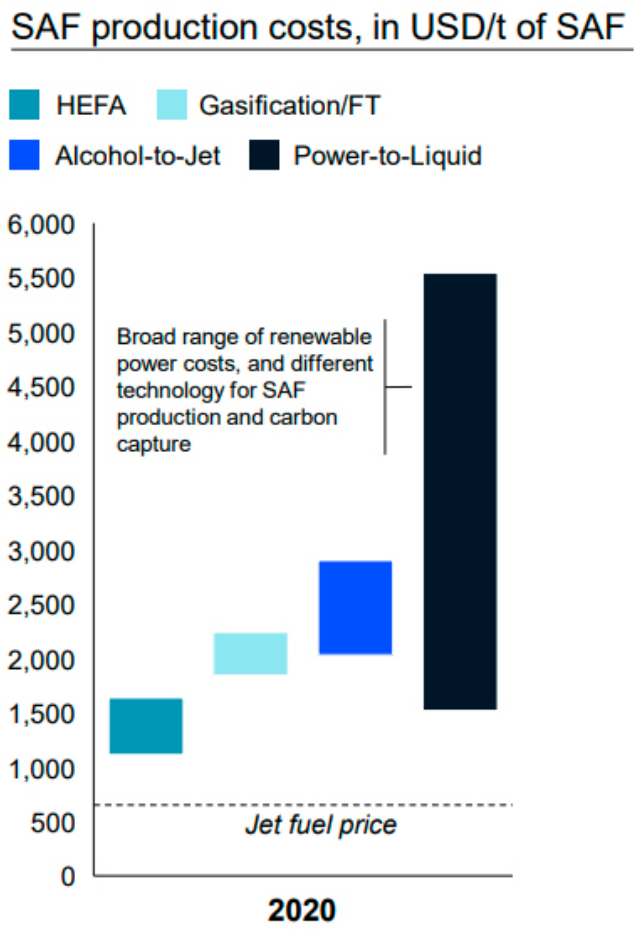


Figure 50. Comparison of prices between sustainable and fossil fuels.

initiative with the SAF mandate already indicated in the Scandinavian country, a lever that could be multiplied at European level with the sub-quota of PtL proposed in the legislative initiative of the European Commission Refuel EU (Figure 45). Germany, for its part, also announced in May 2021 its own strategy for the promotion of electrofuels for aviation .

Other examples of PtL projects are the production demonstrator launched in May 2019 by an international consortium around Rotterdam-The Hague airport, or the initiative announced by the Canadian SAF+ consortium, with the support of Airbus, which will start its activity in 2021 . Unlike those previously described, in this last plant the CO_2 will be captured from the emissions of an existing factory. Although the environmental credentials of direct capture

Photo Archive

Figure 50. Source: WEF Clean Skies for Tomorrow expert interviews, McKinsey

from the atmosphere are more robust, as noted by a recent study reviewing DAC technologies for the production of sustainable synthetic fuels, there are also advantages in using industrial CO_2 emissions, in the strategy known as point source. While the technology for atmospheric capture is being developed and consolidated, this alternative would simplify and reduce the cost of PtL production during a transitory period [12].

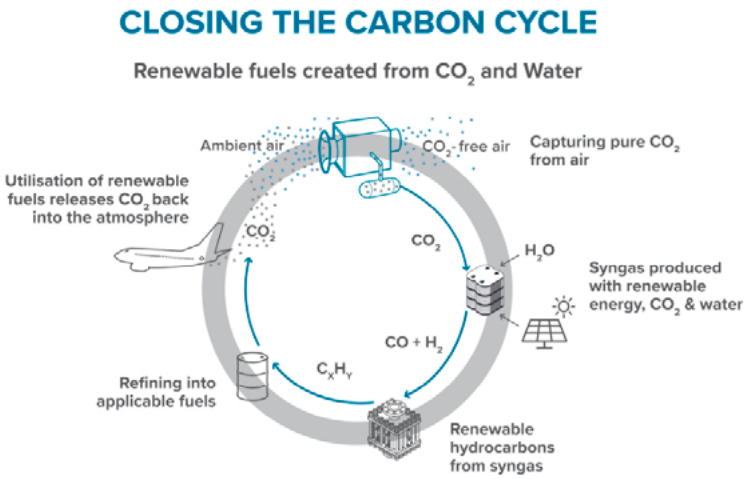


Figure 51. Life cycle of e-fuel from DAC.

A different technological approach for the production of synfuels, based on high-temperature thermochemical reactions, has been tested in the Sun-to-Liquid project[1], funded by the European Union and Switzerland. A reactor fed with concentrated sunlight manages to transform CO_2 and water into synthesis gas, to then proceed with the synthesis of aviation fuel by the FT process (Figure 52). The pilot plant is located in Móstoles, Spain, and by the end of 2019 it was successfully completed the validation of the full industrial scale production cycle.

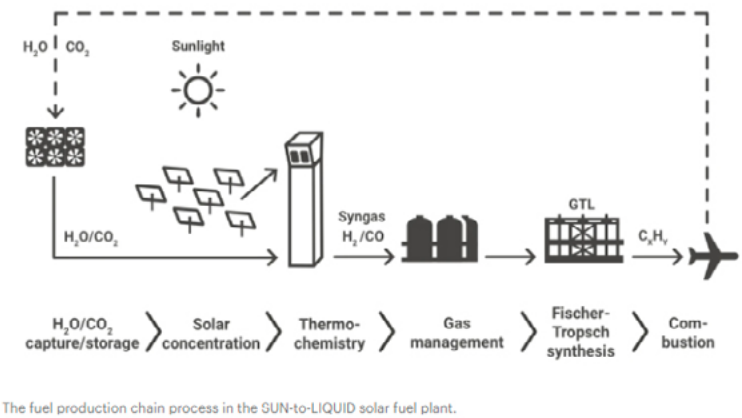


Figure 52. Sun-to-Liquid process to obtain PtL fuel.

1 https://www.sun-to-liquid.eu/

These examples highlight the enormous current push in research and development of sustainable synthetic fuels, whose commercial use seems to be just around the corner. Its advantages over biofuels seem to secure them a space of its own in the medium term on the path to fully sustainable aviation. An important milestone was reached in January 2021 with the first commercial flight powered with a blend of conventional and synthetic fuel, between Amsterdam and Madrid.

Finally, it is worthwhile to remember that none of these sustainable fuels have the potential to completely eradicate other environmental impacts of aviation, beyond CO_2 emissions. This is the case of induced cloudiness or soot emissions, although, as already noted above, they would possibly be mitigated with the use of SAF. Meeting these challenges will require radically changing the propulsion of aircraft, which will be explored in the next chapter.

Photo Archive

Figure 51. https://ineratec.de/rotterdam-the-hague-airport-renewable-fuel-from-air/
Figure 52. Source: Sun-to-Liquid.

6.5. ELECTRIC AVIATION

After a long period in which it remained an aspiration, the electric revolution is now a reality in the field of road transport and, as shown in Figure 3, the number of electrical projects in aviation have also skyrocketed recently[1]. The incentives to develop this type of propulsion are diverse, although the fundamental one is environmental: as of today, it is the only way to fly with zero environmental impact, assuming that the electricity comes from renewable sources and leaving aside the evaluation of the battery life cycle.

Los plazos para convertir en realidad esta promesa The timeframe to turn this electricity promise into reality is undoubtedly uncertain, given its dependence on the development of new technologies, but within the horizon of this decade it is expected the start of its commercial deployment. An electric aircraft for 20 passengers could be operating around 2025, with designs for 50-80 passengers not expected to entry into service until 2030 [14].

Of course, there are still considerable obstacles to overcome before the widespread introduction of this type of aircraft, some of them that are only expected to be resolved in the long term[2]. However, given the environmental potential of electric aviation, and its flexibility to be combined with other technologies, it will become, in all probability, a fundamental piece in the sustainable future of aviation.

There are different strategies and approaches under the electrical label, each with its own advantages and drawbacks, depending on the propulsion system of the aircraft [66]. Starting with the growing electrification process in conventional propulsion aircraft, it will be reviewed next the different hybrid options, before finally address the 100% electric proposals. Given the special characteristics of hydrogen as an energy vector, which allow its use in fuel cells powering electrical configurations or burning it directly in turbojets, we will deal with the proposals based on this fuel in the next chapter.

As it has been pointed out previously in this report, the path towards the environmental sustainability of the aviation industry should not be understood as a competition between options, but more as a combined effort with several solutions covering the diverse needs of commercial aviation in different timeframes.

1 https://www.icao.int/environmental-protection/Pages/electric-aircraft.aspx
2 https://leehamnews.com/2020/05/01/33297/

6.5.1. More electric aircraft and turboelectric.

The progressive introduction of electrical systems and capacities in conventional designs is the strategy known as More Electric Aircraft (MEA). The heavy and complex hydraulic, pneumatic and mechanical systems are replaced by electrical motors and actuators, with the consequent weight reduction, and improving the efficiency of the main engines dedicated exclusively to propulsion. In addition, electrical systems are significantly simpler, which increases safety and reduces maintenance costs.

An example of this strategy are the thrust reversers of the A380, where the conventional hydraulic system was replaced by an electric one. Airbus continues on this path with plans to replace the mechanical rudder system of the A320neo with electric actuators[1].

More recently, the Boeing 787, despite some initial problems with the batteries, took a further step by eliminating the usual bleeding from the engines to feed the cabin air conditioning system. It was substituted by electric compressors, improving the overall energy efficiency of the airplane [69].

Figure 53. eTaxi system. Electric drive of aircraft during ground operations.

Another example of this approach is the e-taxi system, developed by Safran, which allows the drive of the aircraft in ground operations by means of an electric motor connected to the landing gear and powered by the APU[2]. In this way, fuel and emissions savings (up to 4% in short and medium distances [26]) are achieved by avoiding the operation of the main engines in inefficient regimes, in addition to a considerable reduction in noise. In the helicopter industry we also find the prototype EDAT from Bell, which replaces the tail rotor by a system of four electric propellers[3].

The next qualitative step in the use of electrical energy to reduce polluting emissions is the turboelectric architecture, in which a gas turbine, powered by conventional fuel, moves an electric generator that in turn feeds the electric motors generating the thrust (Figure 54).

Although kerosene remains the primary energy source, this configuration makes it possible to optimize the regime of the gas turbine, dedicated exclusively to the generation of electrical energy, which significantly increases its efficiency. On the other hand, propulsion by electric motors allows access to other design advantages that will be reviewed later.

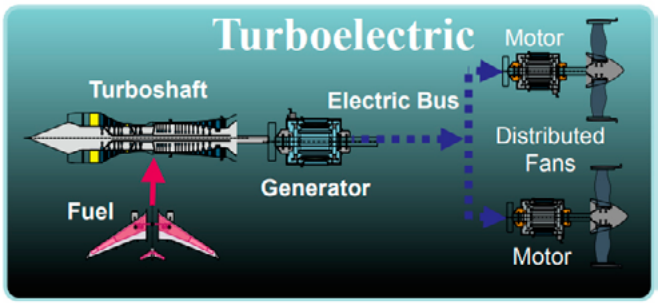


Figure 54. Diagram of a turboelectric propulsion system [27]

In principle turboelectric designs are more efficient compared to conventional aircraft, therefore reducing polluting emissions, but this concept also avoids the main drawback of 100% electric propulsion: flying range, by being able to store the

1 https://www.flightglobal.com/air-transport/airbus-switching-a320neo-family-from-mechanical-to-electronic-rudder-control/143203.article

2 Auxiliary Power Unit.

3 https://news.bellflight.com/en-US/193412-the-next-steps-for-bell-s-electrically-distributed-anti-torque

Photo Archive

Figure 53. Source: SAFRAN.

same amount of fuel in the conventional tanks. Additionally, its environmental performance can be further improved by resorting to sustainable fuels, or treating emissions on board, as proposed by MIT[4], with a potential reduction of 95% in NOx.

Several theoretical case studies have been carried out on the application of turboelectric architectures, among which the ESAero ECO-150 stands out (Figure 56) potentially halving the consumption of a Boeing 737-700 on an equivalent journey [27]. NASA's futuristic N3-X (Figure 55), a flying wing with gas turbines at the tips and a superconducting electrical system, would improve energy efficiency by 72% compared to the equivalent Boeing 777 [27], although the horizon to make it technically feasible is a long way off.

Figure 56. ESAero ECO-150 [56]

Figure 55. NASA N3-X.

Within a shorter timeframe, there could be commercial applications similar to the STARC-ABL design also from NASA (Figure 57), a hybrid system in which two conventional turbofans also provide energy to an electric engine in the rear fuselage. Boundary layer ingestion (BLI) increases the efficiency of the rear engine, reducing the fuel consumption by 10% [27]. A BLI design with a conventional turbofan would be hardly feasible on such a location.

4 https://news.mit.edu/2021/hybrid-electric-plane-pollution-0114

Figure 57. NASA STARC-ABL

Several projects are already testing the application of turboelectric systems as EcoPulse (Figure 58), developed by Daher, Safran and Airbus, in which a turboprop engine provide both thrust and power for 6 distributed electric motors on the wings[5]. A similar concept has been announced by Embraer, already at a commercial level, with its STOUT military transport project[6]. Another commercial project based on a turboelectric architecture, and with a clear environmental claim adding full SAF compatibility, is Faradair's BEHA[7].

Figure 58. EcoPulse Project. A hybrid turboelectric demonstrator.

Despite the relevance of the advances described, and the interesting possibilities that the turboelectric concept opens up, the common denominator of all the models reviewed so far is that the source of all the energy used for propulsion comes from the combustion of hydrocarbons.

Figure 59. BEHA Project.

5 https://www.daher.com/en/the-ecopulse-demonstrator-achieves-its-first-key-milestone/

6 https://www.aviacionline.com/2020/11/embraer-y-la-fuerza-aerea-brasilena-presenten-su-proyecto-de-avion-militar-de-propulsion-hibrida/

7 https://www.faradair.com/

Photo Archive

Figure 55. https://www.nasa.gov/content/hybrid-wing-body-goes-hybrid
Figure 57. https://sacd.larc.nasa.gov/asab/asab-projects-2/starc-abl/
Figure 58. Source: Airbus.
Figure 59. Source: Faradair.

6.5.2. Hybrid-electric propulsion.

The next critical milestone towards sustainability, at least in some sectors of aviation, will likely involve electric propulsion during some phases of flight, powered by batteries or fuel cells. This hybrid-electric propulsion architecture, in its different variants, could take advantage of the higher specific energy of kerosene to cover phases of high demand, such as take-off and climb. Saving the electric thrust for the cruise would eliminate harmful emissions in altitude, avoiding other negative effects associated with jet propulsion such as contrails.

There are several types of hybrid-electric architecture, each with its pros and cons, depending on the combination of different energy sources and the type of engines used for propulsion. In fact, the optimization and technological development necessary for the introduction of these hybrid-electric concepts is the objective of research projects such as the European Imothep[1]. The two generic configurations that we are going to describe are the most common, but it must be taken into account that the great flexibility of the propulsion systems and electric generators allow alternative combinations or the superposition of both.

The parallel hybrid system maintains turbojet engines to achieve thrust, but they could run with two different regimes according to needs: one conventional with fuel, and the other driven by electric motors connected to the shaft of the first compressor or propeller. The electrical energy supply would come from batteries or fuel cells (Figure 60).

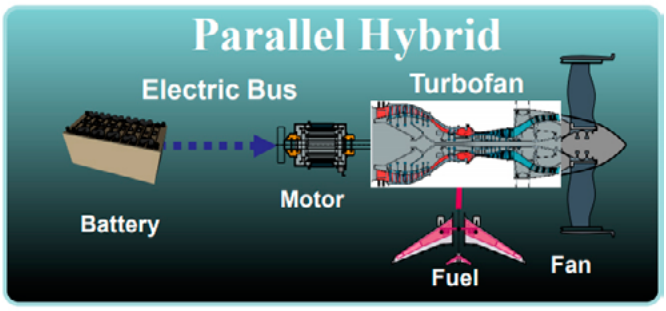


Figure 60. Diagram of a parallel hybrid-electric propulsion system [27]

This parallel system has the advantage of keeping the thrust power of current engines intact, as well as the autonomy derived from the consumption of kerosene, while reserving the use of electrical power for the most critical flight segments in terms of environmental impact. The extra electrical drive would also allow for optimized jet engines, as they are currently sized to achieve the peak thrust at take-off. As an example of this architecture, we can point out the SUGAR Volt (Figure 61), a Boeing concept design with an estimated fuel saving of around 60% compared to the conventional equivalent [27]. The technological feasibility of this proposal depends on the development of high-power electrical motors and systems.

Figure 61. Boeing Sugar Volt. Parallel hybrid-electric concept [27]

The other main hybrid-electric option leaves thrust to be delivered exclusively by electric motors, which in turn would be fed alternatively from batteries or by a conventional engine connected to an electric generator. These systems are called series hybrid (Figure 62), and they share with the turboelectric option the advantage of being able to optimize the design point of the conventional engine, either of internal combustion or a gas turbine, as it is exclusively dedicated to generating electricity. As in the previous option, the battery-powered regime would totally eliminate emissions during some phases of the flight. On the other hand, the main price to be paid for having two energy sources in the aircraft is adding complexity to the whole system, with the corresponding extra burden in maintenance and increased weight.

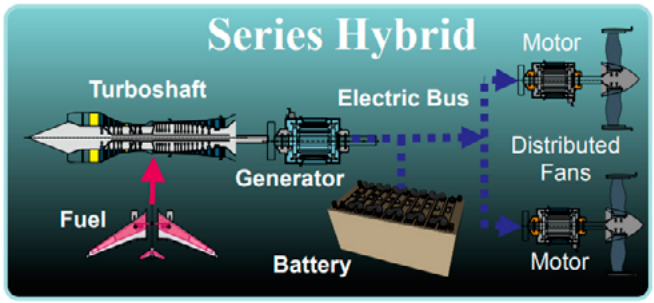


Figure 62. Diagram of a series hybrid-electric propulsion system [27]

1 https://www.imothep-project.eu/

The first flight test of an aircraft with this configuration, the E-star, dates back to 2011[2] (Figure 63). Currently there are several companies that have already carried out flight tests of hybrid propulsion systems (Electric EEL by Ampaire in 2019, see Figure 68, and Voltaero in 2020, see Figure 67), although the associated commercial projects are aircraft of limited capacity.

Figure 63. E-star (2011)

Figure 64. Dash8-100 Hybrid-electric demonstrator. First flight scheduled for 2024.[3]

Keeping conventional fuel as part of the energy supply expands the flight range significantly, thus avoiding one of the main hurdles faced by 100% electric propulsion. However, there is still a lot of work ahead to ensure the scalability of the electrical systems to the necessary dimensions for flights of more than 20 passengers. In this last aspect, the cancellation of the E-fan X project in 2020[4] (Figure 65), promoted by Airbus, Rolls-Royce and Siemens, was a serious setback. This series hybrid test bench paved the way for high-power electric engines (2 MW) and high-capacity electronic management systems. Opportunely, R&R recently announced the first tests of the PSG1 project, which is resuming its commitment to developing a high-power hybrid-electric drivetrain[5]. In the long term, this technology could be applied to innovative designs such as the Airbus E-Thrust[6] (Figure 66).

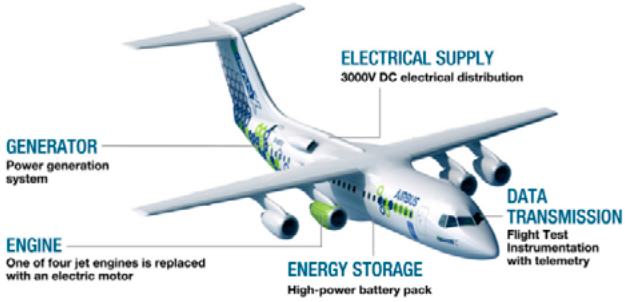


Figure 65. E-Fan X. Hybrid-electric demonstrator based on a BAe 146.

Figure 66. Airbus E-Thrust. Series hybrid-electric concept.

Finally, it is also worth describing the two opposite strategies adopted in the different projects with a hybrid approach and, as a matter of fact, to all new disruptive propulsion projects. On the one hand, there are upgrades incorporating new propulsion systems to existing conventional aircraft, which shortens the timeframes for their entry into service. This is Ampaire's plan, whose objectives are the re-motorization of the Grand Caravan EX (Figure 73) and the Eco Otter SX with 19 seats and 370 km of autonomy[7]. Similarly, De Havilland Canada and P&WC also are committed to flight test its hybrid-electric technology in a demonstrator based on the Dash8-100 (Figure 64).

2 https://www.flyingmag.com/news/eadsdiamond-unveil-electric-hybrid/
3 Flight International. August 2021.
4 https://www.airbus.com/innovation/zero-emission/electric-flight/e-fan-x.html#ove
5 https://www.rolls-royce.com/media/press-releases/2021/03-06-2021-rr-starts-testing-most-powerful-hybrid-electric-propulsion-system-in-aerospace.aspx
6 https://www.airbus.com/newsroom/press-releases/en/2019/05/airbus-and-sas-scandinavian-airlines-sign-hybrid-and-electric-aircraft-research-agreement.html
7 https://www.ampaire.com/vehicles/Eco-Otter-SX-Aircraft

Photo Archive

Figure 63. Source: Diamond Aircraft.
Figure 64. Source: DHC.
Figure 65. Source: Airbus
Figure 66. Source: Airbus

The other strategy, with a more ambitious approach, are clean sheet designs taking full advantage of the benefits from electric propulsion, such as the Zunum project, with capacity for 12 passengers and 1,300 km of range[8]. However, and as also exemplified by this case, the obvious design advantages when starting from scratch implies, on the other hand, a great challenge when it comes to ensuring the business viability of projects based on innovative technologies.

Figure 67. Cassio 1 hybrid-electric demonstrator.

Figure 68. Flight test of Electric EEL, a hybrid-electric upgrade.

For the longer term, there are intensive efforts in research to develop the technologies for higher capacity aircraft with hybrid-electric propulsion. As an example, the international consortium FUTPRINT50[9], funded by the European Union, is focused on removing the stumbling blocks for a 50-seater to enter into service before 2040. All in all, with the scenarios currently on the table, the path to a sustainable air transport seems very likely to include, at least as a stopover, some form of hybrid-electric propulsion.

Photo Archive

Figure 67. Source: Voltaero.
Figure 68. Source: Ampaire.

8 https://zunum.aero/aircraft/
9 FUTPRINT50: Future propulsion and integration: towards a hybrid-electric 50-seat regional aircraft. www.futprint50.eu

6.5.3. Batteries.

We started the gradual evolution towards electric aviation with the concept of more electric aircraft (MEA), to later move on to hybrid configurations and, finally, reaching now the category of 100% electric aircraft or All Electric Aircraft (AEA). In this architecture, the energy necessary for flight is stored in batteries or generated in fuel cells, from where it is transmitted directly to the electric engines delivering thrust (Figure 69).

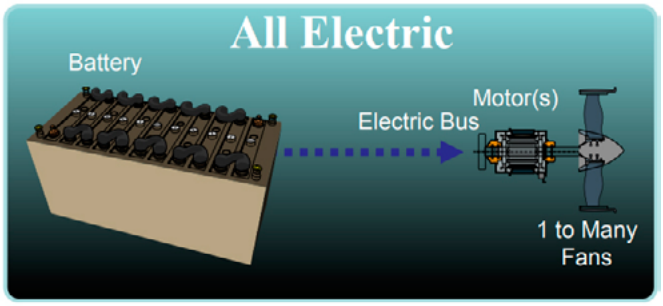


Figure 69. Diagram of a 100% electric propulsion system [27]

Al igual que la híbrida en serie, esta configuración Similarly to the series hybrid-electric design, this configuration allows for a distributed propulsion across the aircraft. In contrast to turbojet aircraft, there is no penalty to spread the thrust between several relatively small electric motors. Quite the contrary, since this design is able to limit the size of the electric engines around 1 MW, which simplifies its implementation, the transmission of electrical power and the necessary electronic systems.

Another potential advantage of electric thrusters is that their weight and size allow them to be positioned at the wingtip, which would open the possibility of reducing induced drag by counteracting tip vortices. These advantages will be tested with the NASA X-57 experimental aircraft, currently being assembled (Figure 70).

Figure 70. NASA X-57. 100% electric demonstrator.

The progress towards electric aviation, as well as the timeframe and missions covered in competition with other disruptive propulsion technologies, depends heavily on a crucial parameter: the specific energy of each energy storage system. This coefficient indicates the amount of energy contained per mass unit, and Table 4 reveals the main challenge of electric aviation on batteries: conventional fuel delivers at least 40 times more energy for the same weight. The direct consequence is that, with the current state-of-the-art, battery-electric aircraft are still significantly limited in range and payload.

	Kerosene (Jet A-1, a 15 oC)	**Lithium-ion Batterie**	**Hydrogen gas** (700 bar, 0 °C)	**Liquid Hydrogen** (20 K)
Specific Energy (W•h/kg)	12.386	100-265	33.333	33.333
Energy Density (W•h/L)	9.909	250-670	1.400	2.367

Table 4. Comparison of energy vectors for commercial aviation (own elaboration from several sources [1]

[1] IATA 2015. Guidance Material for Sustainable Aviation Fuel Management 2015 - https://www.cei.washington.edu/education/science-of-solar/battery-technology/ - https://energia.jcyl.es/web/es/biblioteca/combustible-hidrogeno. - https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored

Photo Archive

Figure 70. https://www.nasa.gov/specials/X57/

A number of studies have tried to determine the specific energy thresholds in batteries from where it is possible to think about developing viable electrical solutions for the various categories of commercial aviation. This development race, according to some opinions [74], could be launched from batteries reaching 400 W•h/kg.

However, for the small aircraft used in general and regional aviation, 100% electric flight seems already viable with the current capacities of Lithium-Ion batteries. This is demonstrated by examples such as Pipistrel's Alpha Electro, a trainer which achieved in 2020 the first type certification by EASA of a clean sheet design 100% electric light aircraft[2] (Figure 71). Much progress has been also made by several projects using electric engines to upgrade existing aircraft such as the De Havilland Beaver for 6 passengers (Harbour Air and Magnix, first flight test in 2019[3]. Figure 72) or the Cessna Grand Caravan with up to 9 passengers (Aerotec and Magnix, first flight completed in 2020. Figure 73). In the same vein, it was recently announced the Tecnam P-Volt project[4], with Rolls-Royce engines.

Figure 71. Pipistrel Alpha Electro. Electric trainer certified by EASA in 2020.

Figure 72 DHC-2 De Havilland Beaver from Harbour Air modified with an electric engine by Magnix (2019)

2 https://actualidadaeroespacial.com/la-easa-certifica-el-primer-avion-totalmente-electronico/
3 https://www.bbc.com/news/business-50738983
4 Flight International. April 2021.

Figure 73. eCaravan from AeroTec and Magnix.
A 100% electric 9-seater with a range of 180 km.

Current battery performance also seems able to power eVTOL[5], small aircraft intended for urban air transport, whose development is currently a tight race with many projects already in the flight test phase. The contenders include large aircraft manufacturers (Airbus[6] or Boeing[7]), new players with mobility experience (Uber[8], Hyundai), but also a multitude of start-ups (Archer Aviation, Joby Aviation, Volocopter, Lilium).

The breakthrough in batteries to power 100-seaters aircraft is estimated around 1,000 W•h/kg, although relaying on hybrid architectures. Eventually, this type of aircraft with 100% electric propulsion would require batteries with a specific energy around 1,800 W•h/kg [58]. This technological threshold still seems a far-off goal, although there is rapid progress in alternative technologies such as lithium-sulphur batteries (Oxis Energy announced commercial batteries with 471 W•h/kg, although it seems now is facing serious financial problems), solid-state batteries (Cuberg has demonstrated lithium cells with 369 W•h/kg for aeronautical applications[9]) and other approaches including graphene technology [58].

Another crucial aspect to be developed is the efficient and safe management of high-power electric systems, which takes us directly to the next key parameter: specific power (kW/kg). A promising alternative to current technology is based on silicon carbide, which would facilitate the design of higher power components. Cryogenic technology, often included in the predictions for future electric aircraft, would lead to substantial improvements in the capabilities of electrical motors and systems.

5 Electric vertical take-off and landing
6 https://www.airbus.com/innovation/zero-emission/urban-air-mobility/cityairbus.html
7 http://www.boeing.com/NeXt/index.html
8 https://www.uber.com/us/en/elevate/uberair/
9 https://cuberg.net/product/

Its application in the aviation industry still seems far from reaching distance [58], although, as we will see later, the introduction of liquid hydrogen as energy vector could change this situation.

The most ambitious commercial projects with 100% electric propulsion with batteries start by regional transports such as the eFlyer 800 (Figure 77) or the Eviation Alice[10], with orders already signed and the first flight schedule before 2022 (Figure 76). On the high-capacity end, Wright Electric is developing an airliner to carry 186 passengers with an entry into service estimated for 2030 (Figure 74). A prototype of the 2 MW engines that will power the aircraft was ground tested in September 2021[11].

One of the most promising battery-electric programs

Figure 77. Bye Aerospace eFlyer 800 with SAFRAN engines.
100% electric with 8 pax and a range of 900 km.

Figure 76. Eviation Alice, powered by Magnix. An electric aircraft
on batteries with a range of 800 km and 9 pax (EIS 2024)

Figure 74. Wright battery-powered airliner carrying 186 pax (EIS 2030)

is Heart Aviation's ES-19, with 400 km of range and 19 seats. It has recently received significant investment and order commitments from Finnair and United Airlines[12]. Entry into service is scheduled for 2026 (Figure 75).

Figure 75. ES-19. 100% electric project on batteries
from Heart Aviation carrying 19 pax up to 400 km (EIS 2026)

The capabilities of 100% electric aviation in the short to medium term, even in the best of scenarios, are undoubtedly modest when compared to the current state of commercial aviation. However, the enormous potential and fast-track development of these new technologies must be taken into account, as well as their ability to reduce the environmental impact of regional and single-aisle commercial aviation, whose carbon emissions in 2018 accounted for 58% of the total CO_2 from commercial aviation [33]. If this objective is to be achieved, decisive regulatory and political support needs to be in place, such as that of Sweden and Norway, including an integrated platform for the development of electric aviation (NEA[13]). In fact, all short-haul flights must be 100% electric from 2040 in Norway.

The next step to larger capacities, with long-haul, double-aisle aircraft, seems for now a very remote possibility for electric aviation. The specific energy needed for those missions would require a revolutionary leap on battery technology. Coming back to Table 4, the growing interest on hydrogen as an energy vector is therefore explained. Whether through fuel cells powering an electric aircraft, or burning it directly in turbojets, hydrogen is presented as a direct solution to the problem of energy storage in sustainable aviation. As we will see below, and despite its own limitations, it opens up promising new possibilities to drastically reduce, and even eliminate the polluting emissions from commercial aviation.

10 https://www.reuters.com/business/aerospace-defense/dhl-orders-12-eviation-planes-plans-first-electric-network-2021-08-03/
11 https://www.weflywright.com/technology#motors
12 https://www.bloomberg.com/news/articles/2021-07-13/united-air-mesa-ink-deal-for-up-to-200-small-electric-planes

13 Nordic Network for Electric Aviation

Photo Archive

Figure 77. Nordic Network for Electric Aviation.

6.6. HYDROGEN

6.6.1. Sustainable energy vector

Hydrogen has been suggested, for decades, as a potential alternative to fossil fuels to power transport vehicles. One of its main characteristics, which largely explains this interest, is that theoretically its combustion produces only water as by-product, with the tremendous environmental advantage that this implies.

It is important to remember that, even though it is the most abundant element in the universe, hydrogen is not directly available on Earth, so it cannot be considered an energy source, but rather an energy vector. This means that to produce this fuel it is necessary to invest a certain amount of energy first, for example in the electrolysis of water. In other words, hydrogen is simply a way of storing existing energy. Therefore, using hydrogen as a fuel does not direcly imply sustainable transport. This will depend on the energy sources used to produce it, and the emissions associated with its complete production cycle, in a similar way as with electric propulsion on batteries.

By using renewable sources with a process without environmental impact, it will be obtained what is known as green hydrogen, which does imply a great step towards sustainable transport. It must be taken into account that the industrial production of hydrogen, nowadays, is carried out mainly from coal, hydrocarbons or natural gas, with no environmental benefits (grey hydrogen). An intermediate case, foster to some extent by the political authorities in Europe, is labelled as blue hydrogen[1], also produced from fossil resouces but with a system in place to capture and store the CO_2 released during the process (CCS[2]). The use of this alternative is seen as a temporary solution to decrease the cost of low-emission hydrogen, still not competitive, and to secure sufficient supply. There are other ways to produce hydrogen, each with its own environmental impact and the corresponding color tag[3].

The challenge of reducing the production costs of green hydrogen has been the first of the initiatives for the promotion of clean energies of the United States government within the Energy Earthshots program, announced in June 2021. Known as the Hydrogen Shot, it aims to produce green hydrogen 80% cheaper than today, reaching 1 $/kg within a decade[4]. As can be seen, hydrogen has become one of the most relevant decarbonisation tools on a global level. In the field of air transport, this governmental support is also needed to develop the critical technologies to use the hydrogen in new propulsive systems, so that investments are economically viable.

Again in Table 4, it can ben seen why hydrogen is so interesting for sustainable aviation: contrary to the specific energy issue of batteries, each kg of H2 has 2.7 times more energy than its equivalent of conventional Jet fuel. This fact solves, in principle, the autonomy problem that plagued electric aviation. However, as we also see in that table, the energy density of H2 - the amount of energy stored per litre - is at least four times lower than kerosene. This implies that, even with higher specific energy, aircraft running on hydrogen will need much more storage space. Furthermore, the geometry and systems needed to store H2 in cryogenic (-253 ºC) or high pressure tanks (350 or 700 bar) pose a challenge for the architecture and dimensions of current commercial aircraft. Hydrogen tanks, much more complex and heavier than those of kerosene, will determine in each application case if the use of a much lighter fuel such as H2 overall saves weight in the aircraft. It has been estimated that the take-off weight of an aircraft powered by hydrogen combustion will be, depending on its mission and configuration, between 4.4% greater and 14.8% less than its conventional equivalent [3].

On the other hand, the introduction of hydrogen as aviation fuel will require a large investment in airport and distribution infrastructure to allow

1 https://www.greentechmedia.com/articles/read/eu-sets-green-hydrogen-targets-now-blue-hydrogen-has-to-keep-up
2 Carbon capture and sequestration
3 https://www.enapter.com/hydrogen-clearing-up-the-colours
4 https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net

refueling. Although there are already airports with some availability (Hamburg, Memphis), a coordinated political and industrial push will be necessary to make hydrogen accessible for widespread use. In this regard, it is worth highlighting the example of countries promoting this fuel such as Germany, France or Japan, with emerging refueling networks for road transport. In fact, Japan launched a national strategy to achieve a hydrogen economy back in 2017, with milestones to reduce production costs, fostering technological development and distribution infrastructures.

Along the same lines, on the 8th of July 2020, the European Commission launched the European Clean Hydrogen Alliance [18], with a series of initiatives to promote the use of this energy vector from sustainable sources. Among other objectives, the current H2 production capacity through electrolysis is set to be multiplied by 12 before the end of 2024. This decision is part of the commitment to achieve a European society with zero net CO_2 emissions by 2050, with sustainable H2 playing a fundamental role decarbonizing industry and transportation. Spain has also joined this strategic drive by approving in October 2020 its own roadmap for the promotion of green hydrogen, which includes the installation of hydrogen supply points at the main airports[5]. To make it possible, the Recovery, Transformation and Resilience Plan[6] will serve as a framework for projects that develop the green hydrogen value chain at national level. In 2021 the UK also announced its own hydrogen strategy.

The use of hydrogen to power aviation can be applied with two types of technologies: fuel cells, feeding an electric propulsion system, and direct combustion in conventional engines. Each of these options has significant advantages, but also some drawbacks that need to be overcome before its commercial introduction. In addition to this, it was already described how hydrogen was part of the production process of Power-to-Liquid fuels. Given this range of potential applications, it seems clear that, in one way or another, this energy vector is going to be of paramount importance in the sustainable future of the aviation industry.

Figure 78. Green hydrogen production facilities in Fukushima (March 2020)

5 https://www.lamoncloa.gob.es/consejodeministros/Paginas/enlaces/061020-enlace-hidrogeno.aspx
6 https://planderecuperacion.gob.es/

Photo Archive

Figure 78. https://www.japan.go.jp/tomodachi/2020/earlysummer2020/hydrogen.html

6.6.2. Fuel cells.

Fuel cells convert the chemical energy of fuel into electricity, with no combustion. In the case of hydrogen, besides power the only output is water (Figure 79), which can be stored for reuse in the aircraft, or released when it does not pose any environmental risk, avoiding the formation of induced cloudiness.

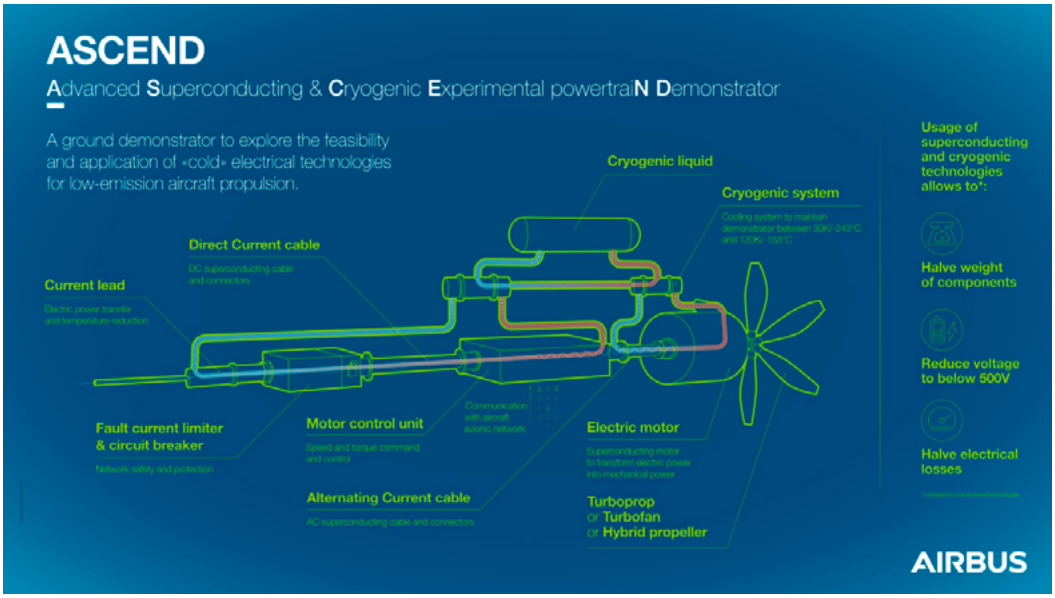


Figure 80. ASCEND research project, combining cryogenics and superconductivity.

The electricity generated by this system can then be applied in an equivalent way to the power from batteries in the different versions of electric aviation, including hybrid-electric, exposed in the previous chapter. This technology is already at a high level of maturity, with consolidated commercial applications in the road transport sector, both in cars (the Toyota Mirai has sold more than 10,000 units since 2014, with a range of 500 km and refuelling in just 3 minutes[1]) as in buses and other industrial vehicles.

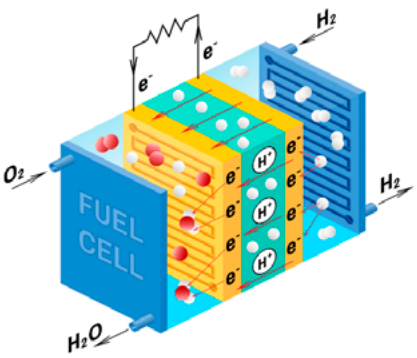


Figure 79. Diagram of a hydrogen fuel cell.

In terms of its aeronautical application, the challenges of electric propulsion remain with hydrogen cells, but also the benefits for the environment and those potentially derived from distributed propulsion. However, now a considerable advantage is added: the storage of energy in the form of hydrogen largely removes the limitations in range of batteries. Moreover, a synergenic design with great potential, which is the object of research in Airbus's ASCEND project[2], takes advantage of the cryogenic cooling necessary to store liquid hydrogen to, in addition, make possible superconducting electric motors and systems (Figure 80).

The first flight test of an aircraft powered by hydrogen cells was carried out in Spain in 2008 by Boeing (R&T-Europe) with a hybrid modification of a Diamond Dimona, also powered in parallel with batteries (Figure 81)[3]. The first flight exclusively supported by hydrogen cells was carried out by the Antares DLR-H2 in 2009. Among other hydrogen-electric projects launched since then, it is worthwhile highlight the HY4, a test bed for the development of a hydrogen propulsion train with commercial purpose (Figure 82). H2FLY, partner on this aircraft, is also part of the MAHEPA project[4], for the study of modular hybrid-electric solutions. It recently announced its partnership with Deutsche Aircraft to develop a hydrogen-powered version of the aforementioned D328eco (Figure 44), which could also take advantage of the modular tank technology from Universal Hydrogen[5] (Figure 88).

1 https://www.toyota.es/world-of-toyota/articles-news-events/new-toyota-mirai
2 https://www.airbus.com/newsroom/stories/ascend-cryogenics-superconductivity-for-aircraft-explained.html?
3 https://www.abc.es/ciencia/abci-boeing-prueba-exito-espana-primer-avion-pila-hidrogeno-200804040300-1641769545030_noticia.html
4 Modular Approach to Hybrid Electric Propulsion Architecture
5 https://www.deutscheaircraft.com/news/deutsche-aircraft-and-universal-hydrogen-partner-on-zero-emissions-regional-aviation

Photo Archive

Figure 79. Source: Airbus.
Figure 80. Source: Airbus

Figure 81. Hydrogen fuel cell hybrid demonstrator by Boeing (2008)

Figure 82. HY4, powered by hydrogen fuel cells. (2016)

The extended flight range offered by hydrogen cells technology is a key competitive advantage, as wielded in the eVTOLs market by Skai[6] or Piasecki[7]. It also led ZeroAvia to select hydrogen to power its program of remotorized regional aircraft (Figure 83), with a typical capacity of up to 19 passengers and 900 km of range[8]. To do this, it is developing a 600 kW powertrain to be flight-tested on the Dornier228 platform, the same one selected by the MTU company and the DLR for its own hydrogen-powered electric engine[9].

ZeroAvia, which in 2021 tested on ground this new powertrain, already flown in 2020 a first version of its hydrogen-electric propulsion system on a 6-seater Piper M-class[10]. That year he also flight-tested the same model running on batteries.

This decision to move towards sustainable aviation powered by hydrogen cells, as opposed to the electric option with batteries, seems to be part of a more general trend. This has also been the case in other regional transport projects such as the Fresson[11], or the new development from Pipistrel[12].

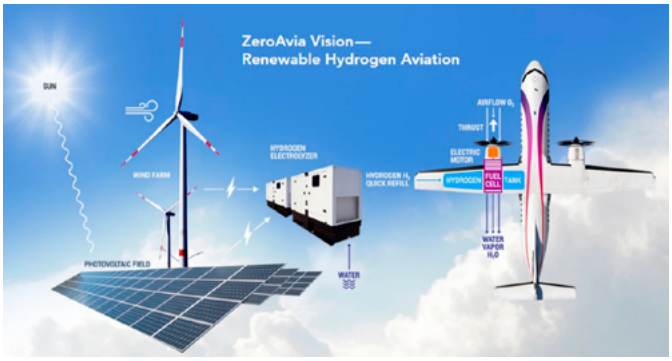


Figure 83. Green hydrogen life cycle powering zero emissions aviation.

On the other hand, the future of hydrogen-electric engines is not limited to the regional aircraft sector, but it can potentially power large-capacity airplanes such as Airbus's concept desing ZEROe Pod[13]. This configuration, where both hydrogen tanks and fuel cells would be housed in the nacelles, could benefit from some of the design solutions already mentioned, such as replaceable pods or cryogenics-superconduction synergy (Figure 84).

Figure 84. ZEROe Pod. Zero emissions concept design by Airbus with hydrogen fuel cells.

In summary, as proven by the current flow of announcements and projects, hydrogen cells are an available high-energy option with zero emissions that also opens up new possibilities for hybrid configurations. This is particularly interesting in the case of its combination with hydrogen combustion engines.

6 https://www.skai.co/
7 https://evtol.com/news/hypoint-piasecki-evtol-hydrogen-fuel-cell-systems/
8 https://www.zeroavia.com/19-seater-release
9 https://fuelcellsworks.com/news/dlr-and-mtu-aero-engines-research-aircraft-propulsion-using-fuel-cells/
10 https://www.zeroavia.com/press-release-25-09-2020
11 https://www.cranfieldaerospace.com/2021/project-fresson-hydrogen/
12 Flight International. April 2021.
13 https://www.airbus.com/newsroom/stories/hydrogen-pod-configuration.html

Photo Archive

Figure 81. Source: Boeing
Figure 82. Source: Mahepa
Figure 83. Source: ZeroAvia
Figure 84. Source: Airbus

6.6.3. Combustion

Turbojet propulsion running on hydrogen is an alternative solution, identified long ago, as a potential substitute for the conventional kerosene-burning engines. In fact, the first jet engine built in 1937 (von Ohain) initially used H2 as fuel. Apart from some limited tests in the US in the 1950s, and numerous feasibility studies in the 1970s[1], it took until 1988 for the first flight test of a commercial aircraft partially powered by hydrogen turbojet engines, with the Tupolev Tu-155 demonstrator (Figure 85).

As we have already pointed out, the reaction of hydrogen with oxygen produces water as a result, with the enormous environmental advantage of achieving combustion without CO_2 emissions. However, compared to fuel cells, the direct use of hydrogen in jet engines has some drawbacks, as nitrogen oxides (NOx) are produced and H2O is also released directly into the atmosphere with the consequent risk of contrails formation.

Research is being carried out in order to mitigate NOx emissions, a byproduct due to the high temperatures reached in the combustion chambe. New technologies in the chamber feeding system (micromix combustion technology) allow to foresee reductions of the order of 66% [62] compared to advanced conventional engines. Other estimates place the potential for these reductions at 80%[2].

On the other hand, the emission at high altitude of water vapor, a greenhouse gas, would be 2.6 times higher with hydrogen-burning engines [3], and could also induce cloudiness and the consequent impact on global warming. However, various studies revealed that the microcrystals, that make up contrails, would be less numerous and larger than with the combustion of fossil fuel, an advantage shared with SAF, and the total warming effect at least 11% lower [62]. Additional measures, such as changes in the flight altitude profile, could contribute significantly to mitigating this problem. In any case, as already pointed out, these global warming effects beyond CO_2 still need some additional research to better understand their dynamics and environmental impacts.

The pros and cons of this type of propulsion was analyzed in detail in the Cryoplane report [3], published in 2003 and funded by the European Union, with the participation of Airbus among other public and private entities. In this project, the feasibility of a direct combustion hydrogen engine for commercial aviation was comprehensively reviewed. The conclusions confirmed that there was no identifiable technical obstacle that prevented the development of this configuration. No weight or range penalties were foresawn, althouht it was pointed out the need for a greater storage volume for the hydrogen, for which different design solutions were proposed.

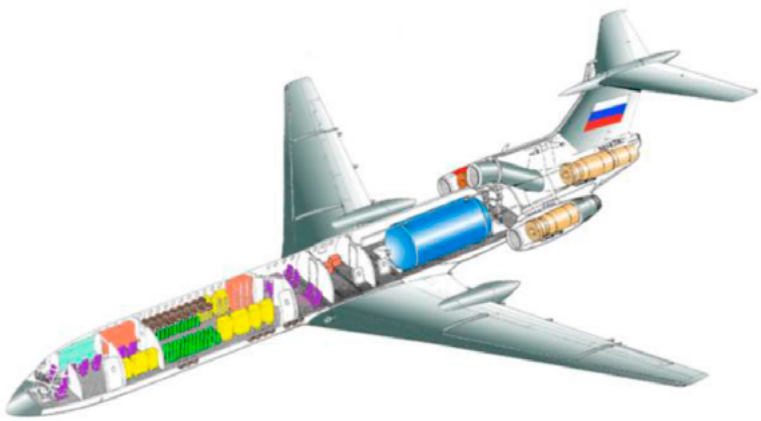


Figure 85. Experimental aircraft Tupolev 155 powered by liquid hydrogen (tank in blue) (1988)

The report also stressed the need for strong support, both economic and regulatory, from the political authorities if such a challenging change was to be launched in the aviation industry. This support would be justified by the significant advantages of hydrogen as fuel in regards to sustainability, a fact confirmed in the study.

Another key aspect cleared by the Cryoplane project was the safety of using hydrogen as aircraft fuel, concluding that it would be at least as safe as kerosene. Subsequent studies pointed to even higher levels of safety in the case of aircraft powered by liquid hydrogen [14].

1 G. D. Brewer
2 https://leehamnews.com/2020/09/18/bjorns-corner-the-challenges-of-hydrogen-part-9-hydrogen-gas-turbines/

Photo Archive

Figure 85. https://www.globalsecurity.org/military/world/russia/tu-155.htm

Figure 86. Hydrogen-powered ZEROe program.

In September 2020, Airbus made a commitment to hydrogen propulsion by launching the ambitious ZEROe program mentioned above, initially consisting of three conceptual proposals for short and medium-range hydrogen-burning aircraft (Figure 86). Liquid hydrogen would be used not only to power the turbojets responsible for thrust, but also to provide all the necessary electrical energy on board through hydrogen cells. This limited hybridization, which takes advantage of fuel cells and optimazed engines, fully responds to the already described concept of more electric aircraft. Although it is actually a research framework for technologies on hydrogen propulsion, a flying demonstrator with the selected solution is scheduled for 2025, and a hypothetical entry into service around 2035.

The viability of a project of this magnitude will depend, to a large extent and as already indicated, on the political and social support for its development and implementation. In this regard, it is perfectly clear that the generalization of hydrogen in aviation would be a powerful tool in the fight against climate change, which would justify the promotion of such a disruptive move. In fact, going back to Figure 9, it shows that Airbus has focused its concept designs on the most polluting sector of commercial aviation in terms of CO_2 emissions.

Nowadays, the push for a more sustainable aviation based on hydrogen is a reality. In addition to the initiatives already mentioned, in 2014 the public-private initiative Fuel Cell and Hydrogen 2 was launched, and since 2018 the EnableH2 project[3], also with funding from the European Union, seeks to define and advance technologies for the commercial use of these propulsion systems. Focused on liquid hydrogen, its objective is to demonstrate the technical and economic feasibility of flights with zero CO_2 emissions and minimal NOx impact. France, for its part, is financing the Hyperion project, a framework in which Safran, Airbus and Ariane Group will develop the technology necessary for a future cryogenic hydrogen-burning engine[4].

In 2021 the progress towards hydrogen-powered aviation has been confirmed. The announcements follow one another, and even new turbojet developments such as the aforementioned CFM RISE (Figure 87) will include a hydrogen version . There is no doubt that there are hurdles ahead still to be solved, both in the technical aspect and in the area of logistics and infrastructure. However, as already pointed out by Fuel Cells and Hydrogen 2 and the Clean Sky 2 program in a joint study in 2020, political, technological and economic factors seem aligned to realize the enormous sustainability potential of this energy vector [28].

Figure 87. RISE open-rotor engine project, compatible with SAF and hydrogen

Figure 88. Computer graphic of a refuelling process with Universal Hydrogen Modular Tanks

3 https://www.enableh2.eu/

4 Flight International. June 2021.

Photo Archive

Figure 86. https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html
Figure 87. Source: cfm aeroengines
Figure 88. https://www.hydrogen.aero/about

6.7. NOISE

The origin of noise in aviation comes from operations carried out in the air, on the ground and mixed operations. Noise mitigation opportunities can be found considering different aspects: technology, operational improvements, better land use planning, operational restrictions and a fifth related to better communication and community engagement [73], based on ICAO balanced approach[1].

2019 has been the celebration of 50 years since the adoption of the first global standards for aircraft noise certification. Over the past 50 years, aircraft have reduced their noise output by 75% and this progress continues. Today's aircraft entering service have on average, a noise footprint that is 30-50% lower than the aircraft they are replacing thanks to new engine and airframe design, technology and noise international regulations. Great progress has been made [72]: the following image shows the significant reduction in the footprint of the Boeing 787-8 aircraft compared to that of its predecessor which it replaces, which is 2.4 km2 smaller.

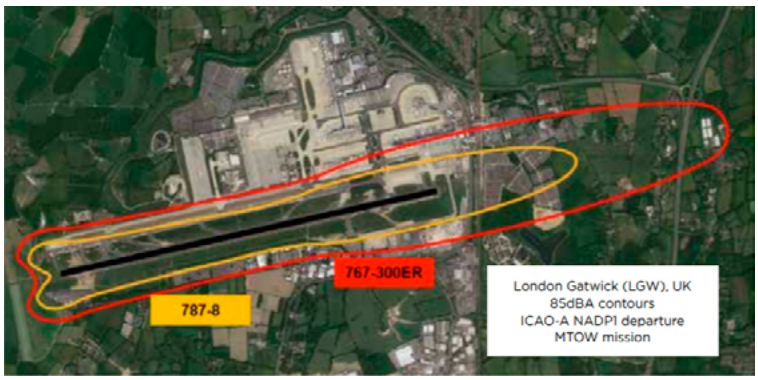


Figure 90. Noise footprint [72]

Other examples: the design noise footprint of the A320neo is nearly 1 km2 smaller than older A320 aircraft25, that of the Boeing 737 MAX is more than 1.7 km2 smaller than that of the 737 Next Gen, the A350-900 is to over 2.5 km2 smaller than that of the A340-300. The Boeing 787-8 noise footprint is more than 2.4 km2s smaller than the aircraft it replaces.

On the other hand, aviation is a highly regulated industry, and the noise generated by airplanes is subject to a lot of control both internationally,

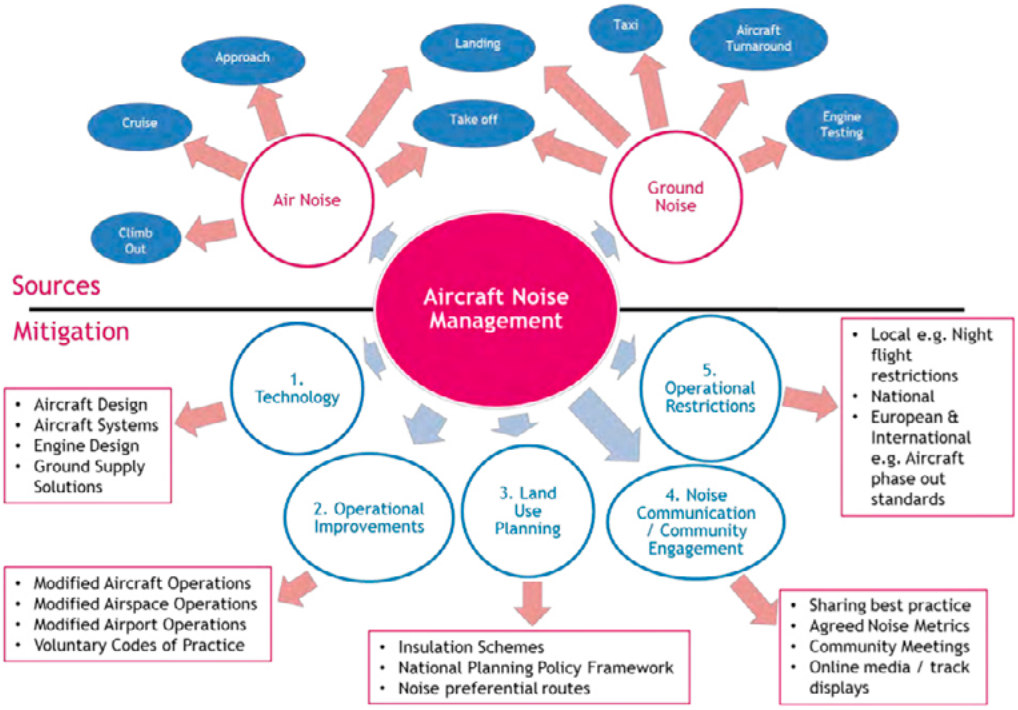


Figure 89. Aircraft Noise Management [73]

1 https://www.icao.int/environmental-protection/pages/noise.aspx

nationally and locally, an example of this is the EU directive on the management and evaluation of noise environmental, Environmental Noise Directives 2002/49/EC[2] and in Spain, 37/2003 noise law, of November 17[3]. Limiting or reducing the number of people affected by aircraft noise is one of the ICAO key environmental goals and main priorities as aircraft noise is the most significant cause of adverse community reaction related to the operation and expansion of airports. That is the reason why in the last five decades, aircraft Noise volume I—of Annex 16 - to Chicago Convention on International Civil Aviation has undergone several changes and more restrictive Regulations and Recommended Practices (SARPs) have been incorporated in order to encourage the introduction of the best noise available technology in new aircraft designs, consequently, the requirements are becoming more stringent, following the progress of technology resulting chapter 2,3,4 and 14 The chapter 14 was adopted by ICAO Council in 2014 and will be the mainstay ICAO Standard for subsonic jet and propeller-driven aeroplane noise for the coming years. It is applicable to new aeroplane types submitted for certification on or after 31 December 2017, and on or after 31 December 2020 for aircraft less than 55 tonnes in mass

Thus, at the international level, the ICAO (International Civil Aviation Organization) to grant a civil aircraft the type certification necessary to enter service, requires a complex program of tests to demonstrate that the aircraft has been designed and tested following the standards and procedures approved and therefore considered safe for flight. Among these tests are some acoustic certifications, showing that noise levels do not exceed the maximums established by Annex 16, Volume I, to the Chicago Convention, which are set by the ICAO Committee for Environmental Protection (CAEP) and are a function of the aircraft maximum take-off weight (MTOW).

This certification scheme measures noise at three points, one under the take-off path, another under the landing path and a third on a line parallel to the axis of the runway under predetermined temperature, humidity, and wind conditions. The unit of measurement chosen is the Equivalent Perceived Decibel (EPNdB), which takes into account the noise nuisance level, the pure tones of the frequency spectrum and the duration of the noise.

Great progress has been made in noise, but these benefits are not always perceived by the community. Reactions to noise and the perception of noise are a complex problem due to the convergence of many variables. Aviation can only act and influence some of them, such as the volume, duration and frequency of noise events, as well as the time of day or population density, but not in atmospheric conditions, in existing background noise or in individual perception of noise [73]. In addition, it is concluded:

- The number of people affected by each variable is not constant, for example, a noisy airplane action on a windy morning generally results in fewer annoying people than the same action on a quiet, foggy morning.
- Research is required to understand in more detail the weighting and the specific interrelationships each of the variables has on the result

Additional considerations to take into account are the subjective nature of noise, as the noise perception depends on the sensitivity to noise of each person, and the current greater sensitivity of the population to ambient noise, considering today as a significant nuisance level of noise tolerable a few decades ago. Furthermore, the nature of the noise problem can also change over time due to existing interdependencies, such as when reducing engine noise makes aerodynamic noise dominant. All of the above makes the job of measuring, managing and reducing the number of people affected by noise from aircraft a challenge.

Comparing the accumulated noise of newly certified aircraft with the current noise targets for 2020 and 2030 established by the ICAO Committee on Aviation Environmental Protection (CAEP) in early 2013 following the recommendations of the IER2, second review of experts in independent noise, it is observed that [43], in all cases the noise levels for the four categories of aircraft considered recent (business jets-BJ, regional jets-RJ, one-aisle-SA and two-aisle aircraft- TA) are well below the regulatory noise level of ICAO Chapter 14.

The mitigation policy adopted by ICAO, under the name of "Balanced Approach" [46], recommends a case-by-case study of the situation at each airport and applying the most efficient mix of four elements (see Figure 91)[4].

Reduction of noise at the source, which is the first pillar according to ICAO for the management of aircraft noise, optimization of operating procedures, land use policies and restriction of operations of the noisiest aircraft. The European Union adopted this policy from 2003.

2 https://ec.europa.eu/environment/noise/directive_en.htm
3 https://www.boe.es/buscar/act.php?id=BOE-A-2003-20976
4 https://www.easa.europa.eu/eaer/topics/airports/noise-management-strategies

In recent years, ICAO has also intensified its work on another essential aspect of noise management, community engagement.

Figure 91. Balanced approach to airport noise management.

Reduction of Noise at source

The noise at the source is regulated through the aircraft type certificates as indicated above and reducing this is the one that has the highest priority.

In the last 50 years, aircraft and engine manufacturers have applied technologies to drastically reduce noise levels, so that compared to the first jet aircraft, modern aircraft noise [73] [73] has been reduced by 97% in operation. output (at 15dB reduction), and 94% in arrival operations (at 12dB reduction), these noise reductions were achieved while reducing the amount of fuel burned and therefore CO_2 emissions. To put these improvements in context, 15dB is considered equivalent to a 65% reduction in annoyance and 97% noise energy reduction means 33 modern aircraft departing simultaneously from an airport produce together the noise of one jet aircraft of the same size departing in the 1960s.

The primary noise source is the engines, and the secondary is the one originates in the airflow surrounding the moving plane (aerodynamic source or airframe source). The Engine noise comes from jet, fan and compressor and the airframe noise is due to the discontinuities of the aircraft structure, such as high-lift devices, trailing edges where there is a speed shearing, turbulent boundary layer on the fuselage and the landing gear.

Historically, noise reductions have come because of technology principally aimed at reducing fuel burn by reducing jet velocity. At the present, jet noise is no longer the major source for larger aircraft because of the increasing of the propulsive efficiency by reducing the fan pressure ratio has been reduced and thereby the jet velocity.

In a modern twin-aisle aircraft: the engine noise, although dependent on Engine type, is generally dominant in take-off operations with the fan being the major component and jet noise some 5dB lower. For approach and landing of modern aircraft, both noise, propulsive and aerodynamic levels are comparable, although the airframe noise dominates due to the landing gear contribution.

In recent years, different noise reduction technologies have been applied, these technologies have focused mainly on:

Technologies for Engine Noise Reduction

There are two main noise sources in today's commercial turbofan engines: fan/turbine/compressor turbo machinery noise and the exhaust, also referred to as the jet.

The modern very-high-bypass-ratio turbofans have significantly reduced jet velocities for the same thrust and consequently make much less noise so that the fan noise is becoming the dominant source of aircraft noise.

Advances in materials and manufacturing technology have allowed these very-high-bypass-ratio engines to avoid incurring unacceptable weight and drag

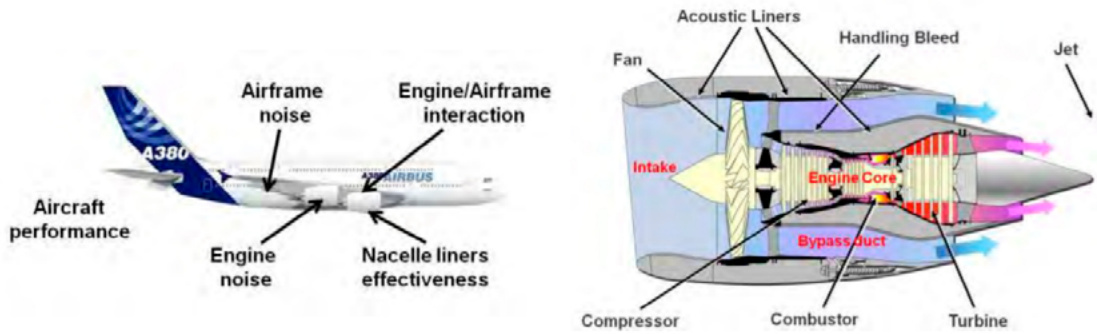


Figure 92. Features of the Aircraft and the Jet Engine that influence noise [45]

penalties on the aircraft, in fact delivering reduced aircraft noise while simultaneously reducing fuel burn.

GTF Geared Turbofan, mentioned in propulsion technology session is a necessary solution to large bypass ratios together with much reduced jet velocities for reduction of jet noise down to an acceptable level.

Various methods have been developed to reduce jet noise in turbofan engines., such as the use of eccentric and actuate nozzles instead of conventional axial nozzles, the installation of chevron mixer modifying the shape of the exhaust nozzle, applying fan flow deflectors (FFD) at the exit of nozzles and install a series of microjets around the rim of the exhaust.

Other technologies to reduce the engine noise are "Shape Optimization" by controlling the geometry of engine ducts and/ or using noise absorbers material, called acoustic liners, in nozzle, fan ducts, inlet, etc and by increasing the acoustic treatment area on the tip of the Nacelles, called Lip treatments, which are extension of the surfaces treated with absorbers material.

The larger the fan, the stronger the fan noise source so that various technologies are considered to reduce the noise from the fan. Basically, two general strategies are being experimented to reduce fan noise: optimizing the fan system or to directly act on the air flow in order to reduce its speed.

Optimizing the Design features of the fan system for minimum noise, consists of optimizing the blade shape, choosing the number of rotating blades, the distance between these two rows of blades/vanes, etc.

Other technologies are Variable area fan nozzle which allows an optimum operation of the fan by changing the fan pressure ratio independently of the fan speed., Active noise control: or active noise cancellation which reduces the noise by adding reverse sound wave, specifically Active stators do not reduce the space available in the nacelle for passive liners; therefore, they are a promising concept.

Technologies for Aerodynamic Noise Reduction.

The airframe is the other major source of noise. As for the engine noise, this category may be divided into several subcategories, among which the two main contributors are the landing gear and high-lift devices (HLD). As expected, the larger the plane, the more significant the effect of the landing gear is compared to that of the High lift devices.

Some technologies to reduce landing gear noise have been applied to the most recent aircraft, such as the Airbus A380 or A350 where caps are used on cavities or rims are applied on wheels, and smart dressing techniques are used in order to avoid putting cables, wires and accessories high flows. It is called "slow down flow" concept –. Fairings covering part of landing gear could allow a significant overall reduction for the landing gear noise, but it is unrealistic from an industrial point of view.

Compared to landing gear, the progress made on flaps and slats noise reduction appears to be quite less mature. This is mainly due to the fact that known technologies to reduce this noise strongly reduce the lift performance. Currently, few technologies are used to limit HLD noise. On the recent A380 and A350, the slats are tilted to avoid any gap between them and the wings, so that the air flow cannot pass in between. It is quite effective, both from the acoustic and performance standpoints, even though this solution can be applied only on limited parts of the wing.

In addition to Landing gear and HLDs, cavities are also a matter of concern for noise. Actually, numerous devices are embedded in the surfaces of aircraft, which have surface irregularities (hatches, hooks, slits, holes) globally termed as "cavities". These cavities usually trigger detachments of the turbulent boundary layer, which act in turn as a noise source, the theoretical way to avoid this spurious noise source is simple basically filling the cavities.

More advanced solutions that are being investigated:: HLD edges made of porous materials, slat chevrons or fractal spoilers are included (TIMPAN and OPENAIRA research programs), adaptive leading edges with shape memory alloys or through actuator that would suppress slat gaps and Unique Flap Device developed by NASA Research Centre, termed the FLEXSEL (flexible side edge link), this flexible structural link design makes use of hyper-elastic materials to provide a smooth geometric transition of minimal spanwise extent between the flap side edge and the main wing

Future Noise Reduction Technologies[5]

The Ultra High Bypass Ratio engines (UHBR) have very hard integration issues, since the fan diameter is even greater than that presently used. With this option, noise reduction would basically entail pushing the same technologies as presented previously. However, it must be kept in mind that new noise sources could emerge from these more "open" engines, especially if traditional ones, such as fan

5 https://hal.archives-ouvertes.fr/hal-01184664/document

and jet, are lowered. In this case, core machinery noise, such as compressor noise, turbine noise or even combustion noise would need to be considered.

In addition to UHBR, another strategy could also be to continue increasing BPR using the Open Rotor architecture (OR). Noise is then the most critical issue, along with safety. Ongoing research activities are facing this drawback and several tricks are being investigated to lower this excessive noise. Currently, there is reasonable confidence that Open Rotors will be able to meet the strictest regulation of Chapter 14 in a few years

A breakthrough in noise could come from new airframe designs, shown on aerodynamic chapter 6.3.3, that offer the potential for significantly reducing noise, not just by reducing airframe noise and by reducing and shielding engine noise, but also by reducing the engine thrust required on take-off. However, there are many very significant technical issues that need to be addressed before any such aircraft enters service.

Another issue are the interdependencies between reducing noise and reducing fuel-burn or CO_2 emissions and there remains uncertainty as to what will be the future balance of priorities.

Noise Reduction: Operational Improvements.

Noise benefits from operational changes will be experienced at varying points along the flight path depending on the measure employed, aircraft type and local population distribution. This point is important since for any given noise reduction technique there will be some areas close to the flight path which will benefit more than others. The exact noise benefit will vary for different locations depending on the current noise exposure and the local scope for adopting new noise mitigation measures.

It is also important to note that several operational techniques will have implications on other environmental factors due to Inter-dependencies between emissions of CO_2, NOx & Noise. For example, any technique that affects the thrust required (e.g., different flap settings for take-off) will have consequences on the emissions of NOx and local air quality.

Operational improvements give the opportunity to influence noise both close into the airport and further away. The Figure 93 y table below [43] show some of these operational techniques to reduce noise. See chapter 6.2 for more information. It is important to note that the choice of one or another operating procedure will depend on many factors, not only on the benefits in terms of noise, since there are many interdependencies to take into account such as CO_2 emissions, safety, capacity, etc. So that each airport chooses the optimal procedures.

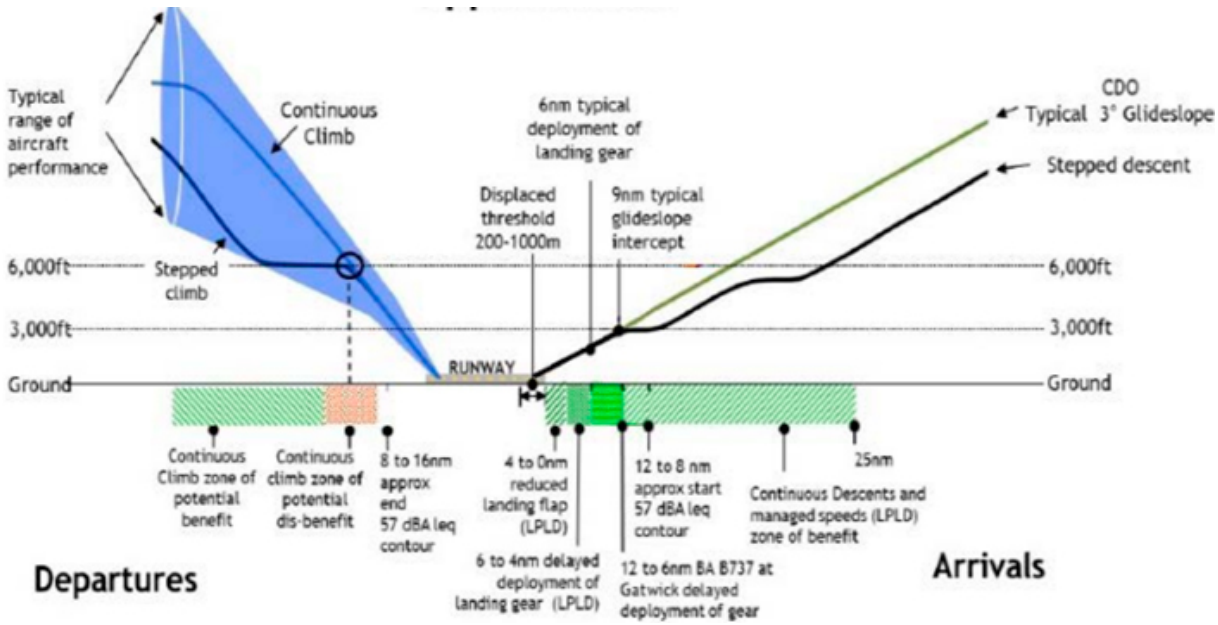


Figure 93.Oportunities for noise mitigations [73]

	Vertical noise mitigation (Effective noise reduction by creating greater distance between noise source and receptor)	**Horizontal noise mitigation** (Opportunity to share noise when there is favourable geographic distribution of population)	**Aircraft operational practice** (Noise reduction at source)
Arrivals	• Continuous descents. • Displaced threshold. • Steeper approaches and segmented steeper approaches.	• Curved approaches. • Adjusted joining point. • Runway alternation. • Defined Standard Arrivals Routes (STARS). • Runway directional preference.	• Low power low drag e.g., Reduced landing flap Delayed deployment of landing gear. • Managed approach speeds. • Avoiding reverse thrust on landing.
Departures	• Ascenso continuo. • Control del empuje de ascenso.	• Off-set SID departures. • Runway alternation. • Defined standard. • Instrument departures (SIDs). • Noise preferential routes (NPRs). • Runway directional preference.	• Noise management.
Airspace Structure	• Single European Sky ATM. • Research Programme (SESAR). • Terminal Control Area airspace. improvements. • Airspace Management Programme.	• SESAR. • Flexible use of airspace between civil aviation military and general aviation and airspace users. • Route availability improvements, conditional routes through military air zones and procedural improvements.	
Ground Noise	• N/A.	• Siting of aircraft engine test facilities at airports.	• Reduced engine taxi • Use of Fixed Electrical Ground Power and Pre-Conditioned Air.

Table 5. Summary of noise mitigation operational opportunities [49]

There is significant scope to mitigate aircraft noise by adopting appropriate operational procedures. In most cases these improvements can be delivered more rapidly and cost effectively than the equivalent noise reductions derived from airframe and engine technology improvements. A summary of operational improvements to mitigate noise from landing, approaches and departures aircraft is given on the table above. The wider adoption of long-established techniques (such as CDAs, inset thresholds, low power low drag, etc.) along with new uptake of innovative procedures (such as steeper approaches and predictable noise respite) can deliver an average of between 1 to 5 dB noise reduction at various points along the arrivals flight path.

Options for operational noise mitigation on departures are fewer but more CCOs and predictable noise respite, for example, offer the ability to redistribute noise and may reduce intolerance to noise.

The following table shows potential operational noise mitigation techniques as rules of thumb. with the noise benefits and regions of effect:

Operational noise mitigation measure	Potential noise benefit where known* (*Not cumulative or comparative as different metrics apply)	Approximate region of noise benefit below flight path
Arrivals		
Continuous Descent Approaches (CDA).	1-5 dBA[6] SEL[7].	25 nm to 9 nm from touchdown.
Managed approach speeds (LPLD).	1-3 dBA SEL.	20-12 nm from touchdown.
Displaced threshold Example 1000m displacement.	2-4% Reduction in area of 57 and 72 dBA Leq contours respectively.	200m-1000m displacement of noise effect.
Slightly steeper approaches – up to 3.2 degrees.	0.5-1 dBA SEL.	Approx. 25nm to touchdown.
Steeper approaches – 3.25 to 4 degrees.	1-2 dBA SEL. Approx. 0.5 dB reduction per quarter degree increase in final approach angle.	Approx. 25nm to touchdown.
Delayed deployment of landing gear.	Up to 2 dBA SEL.	6-4 nm from touchdown.
Reduced landing flap.	Up to 1dBA SEL.	4nm to touchdown.
Departures		
Continuous climbs enabled where airspace and traffic conditions allow.	2-8 dB (LAmax) zone of theoretical dis-benefit followed by 2-8 dBA (LAmax) zone of benefit.	Approx. 10-20nm from take-off.
NADP 1 or NADP 2[8] .	Up to 5dAB noise difference between the two techniques.	Close-in benefit 0-11 nm from take-off. Distant benefit 5-15nm from take-off.

Table 6 Potential Noise Benefits from Operational Improvements [49]

6 dBA, Units of sound level on the A-weighted scale, which incorporates a frequency weighting approximating the characteristics of human hearing

7 SEL, the Sound Exposure Level generated by a single aircraft at the measurement point, measured in dBA. This noise metric accounts for the duration of the sound as well as its intensity.

8 NADP1 and NADP 2, ICAO Noise Abatement Departure Procedures 1 and 2, 2

Noise mitigation: Land Use Planning.

An effective Land Use Planning seeks to protect the areas around airports that are affected by higher levels of aircraft noise from inappropriate noise sensitive development, particularly residential development.

Outside the airport area, land use restrictions are normally the responsibility of local authorities, limiting the type of land use subject to certain cumulative noise levels. Generally, these restrictions are applied using acoustic footprints and airports may have to bear the cost of acoustic insulation of houses and even the transfer of their inhabitants to other places. The prohibition of building houses in the affected areas causes a significant loss of land value, so that the local authorities and local communities themselves are usually the most interested in reducing the acoustic impact of airports as much as possible. Although all the available figures indicate that, since the 70s, there has been a significant and continuous decrease in the number of people seriously affected by airport noise.

Opportunities related to land use planning to mitigate aircraft noise or reduce the numbers of people affected by airports:

- Definition of noise metrics for planning at airport in order to maintain a common method for setting performance criteria would provide better comparisons of trends at individual airports and between airports, and give greater transparency to local authorities and local communities
- Active participation of airports in in contributing to and shaping local planning policy to ensure that, where possible, development in noise sensitive areas, and population encroachment into previously noisy areas, are prevented.
- Any planning controls or agreements should be related to the area of the noise contour of airport rather than the population within it.
- Sound Insulation Grant Schemes. The principal mitigation measure is the provision of acoustic insulation, generally double or secondary glazing
- Airports to acquire Land and property in areas of high levels of noise or assistance to residents relocating from noisy to quieter areas.
- Airports to provide a wide range of material to local communities and to potential property purchasers to ensure that as much information as possible is available on the local noise environment.
- Construct noise mitigation measures within their sites: noise barriers or noise bunds and engine test pens that mitigate the effect of aircraft engine testing

Noise mitigations in Communication and Community Engagement

Over recent years the industry has put significant effort into improving noise abatement techniques, particularly through the technological development of aircraft and operational improvements. However, as commented before, perceptions of noise by local communities have not always improved in line with these developments, given the very subjective nature of individual perception of noise.

The impact of aircraft noise differs between airports and communities so engagement must be tailored to the community so that a one-size-fits-all approach is not appropriate and a good communication between implied parts is necessary.

Measures to improvements which are related with the engagement and communications are Promote open and transparent engagement with communities affected by noise:

- Promote open and transparent participation with communities affected by noise.
- Ensure that any changes to noise impacts or noise mitigation efforts are clearly communicated.
- Present the best practice engagement mechanisms from the road map to local stakeholders
- Work with local communities to establish a variety of engagement techniques
- Elaborate annual reports, targeted briefings, news bulletins and updates, providing direct access to information

Noise Mitigation: Operational Restrictions.

The more developed states tend to use the Annex 16 regulations as a system to gradually withdraw the loudest models, as new regulatory limits appear, in a sequence that first prohibits the manufacture, then the import, and finally the operation of such aircraft. Thus, in the early 1990s, most OECD countries prohibited the operation of airplanes without a noise certificate. While, between 2000 and 2002, they did the same with those that only complied with the limits of Chapter 2. The approval by the ICAO Assembly of Chapter 4, applicable to new models certified after 01/01/2006, had attached the condition that this rule is not used to promote the forced withdrawal

of models that only comply with Chapter 3. Despite this, many airports (not countries) are proceeding to restrict the access of airplanes during certain periods "Chapter 3 minus 5 EPNdB" or other similar mechanisms

In addition, many Airports establish noise reduction policies, as we saw in operation improvements session, by introducing operations restrictions according to noise values of arrival operations, the noise values taken can be certified values according to the aircraft type certificate or actual noise values measured by a monitoring system through the use of microphones at strategic points in the airport. Many airports have installed an acoustic surveillance system that, together with radar tracking of the trajectories, makes it possible to determine if each operation is precisely adjusted to the minimum acoustic impact paths designed for each aircraft model. It is important to note the unintended consequences that could arise due to the application of operating restrictions since restricting the time and operating mode of a runway can alter the size and shape of noise footprints, or compound delays which result in operations occurring at more sensitive times.

Example of currently imposed operational restrictions:

- Airplanes that do not meet certain limits, are not allowed to operate at the airport; access to models: models that do not comply with Chapter 3 since April 2020 are not accepted in the European Union, or by introducing a system of noise-related fees certified as at French airports.
- Establishment of absolute noise level categories (not based on MTOW): Heathrow and Barajas prohibit night flights of aircraft that are not below limits set by two parameters: certified landing noise and average certified take-off and side noise.
- Establishment of noise quotas for programming seasons for each airline, granting authorizations to companies until they reach a cumulative certified noise figure, as Charles De Gaulle does throughout the day and Barajas in the night period (23:00 to 07:00).

In other cases, an acceptable maximum noise level is set with actual noise values:

- A fine is received if the levels are exceeded and, if it is a repeated fact, it can be reached until the prohibition of operating a certain type of aircraft such as at J.F. Kennedy Airport in New York.
- The nosiest the noisiest airplanes according to standards of ICAO Annex 16, Chapter 3, are not allowed to operate at the airport; aircraft within a certain category (e.g. 100 to 150-seaters), receive an economic penalty according to the actual noise statistic measured at certain points in the airport precinct, as is done in Frankfurt and other German airports.

Other actions to reduce noise at airports:

- They establish preferential runways for night landings, and continuous descent approaches (CDA), in which the aircraft starts descending at the minimum engine speed setting much earlier than regular approaches, thus reducing the acoustic impact.
- Prohibition of the use of thrust reversers to help brake the aircraft at night.
- Restriction on the use of auxiliary power units (APUs) and test runs of engines in certain areas or at certain times.

In conclusion, there is a strong commitment from government and industry in many countries to address the technological aspects of this balanced ICAO approach. Being the general trend of large research initiatives to address a global environmental agenda, considering compensations and interdependence aspects in the scientific and technical work programs. The following figure shows the research projects in noise technology at a global level, covering a period of 15 years (2006-2020) involving large aircraft manufacturers (Airbus, Rolls-Royce, Safran, MTU, GKN, Leonardo) and leading research centres (DLR, Onera, NLR, CIRA) that reflect the global commitment to continuously support technology in noise reduction.

All these projects have given rise to different advances in noise reduction technology, acting on the engines (Huff [39], Gliebe [31]) with modifications in the nacelles and the fan, or on the jet noise by means of chevrons or variable area nozzle design and others; acting on the structure, introducing modifications in flaps or trailing edges, designing fairings for landing gears, (Dobrzynski [11] , Manoha [57]).

In the long term, towards 2050, radically new aircraft configurations will be required to significantly reduce noise, fuel consumption and consequently CO_2 emissions (see chapter 6.3). Thus IATA, NASA and different European and American companies such as Boeing, Airbus, etc. are carrying out R&D activities through public-private collaboration programs, with the aim of achieving innovative and promising technologies (Bradley [5]), such as various

revolutionary airframe and propulsion configurations, especially hybrid electric propulsion as fully electric (see chapter 6.5).). The impact on noise of electric aircraft will depend on the design configuration, but assuming a conventional configuration aircraft, without using the added design advantages of electric propulsion, a 36% reduction in the noise footprint is estimated at take-off and landing compared to the most competitive best-in-class aircraft in noise; more reduction during take-off (50% smaller) and smaller reduction during landing (15% greater [66].

The combination of aeronautical technology, new on-board systems and operations management have contributed to more effective noise reduction procedures and will continue to contribute as advances in the different technologies are incorporated.

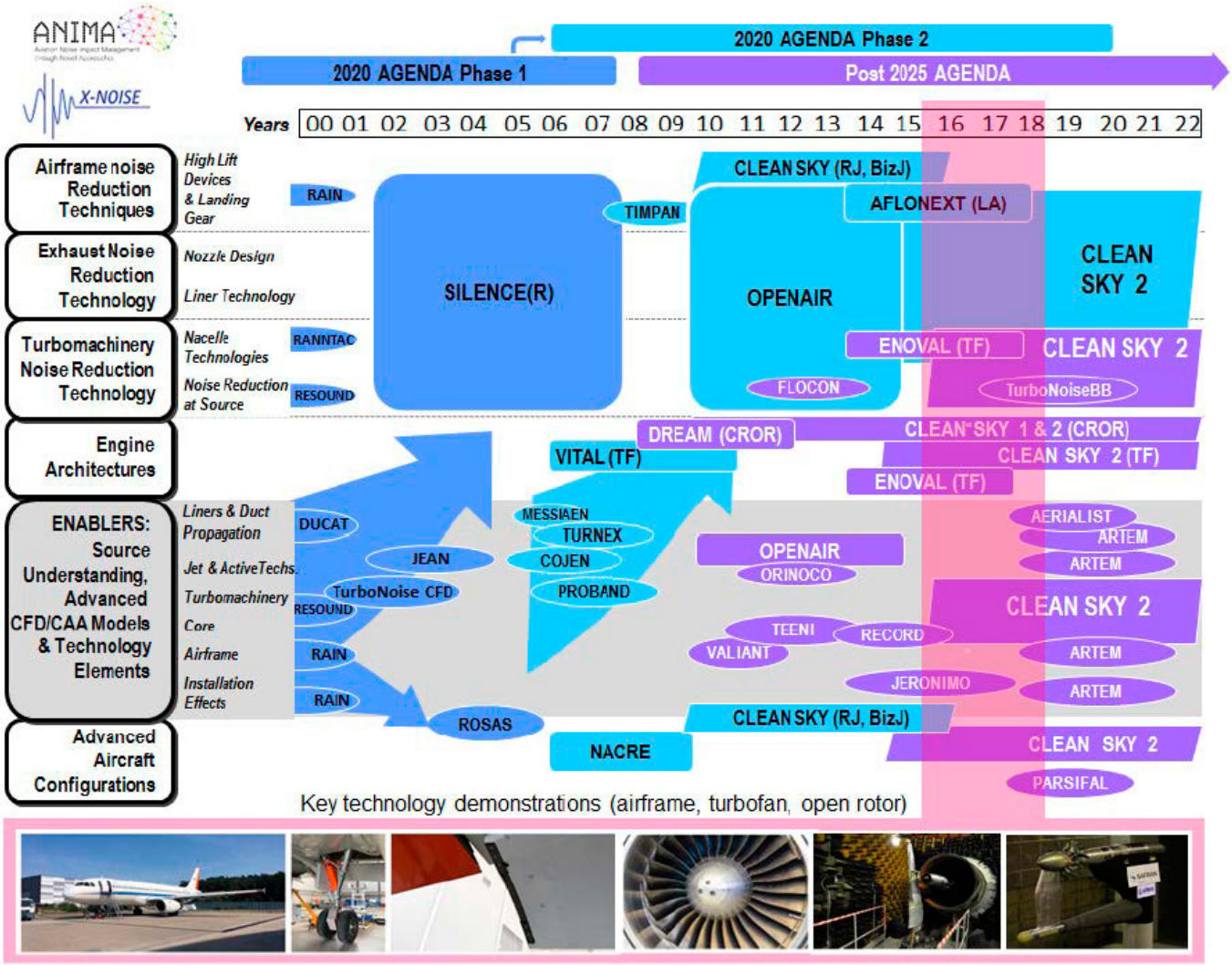


Figure 94. European noise projects and key technology demonstrators [43]

7 CONCLUSIONS

The aviation industry emerged and developed due to a long history of innovation and technical problem solving. The challenge of sustainability and the elimination of its environmental impact is faced in the same spirit, and the results are not long in coming. In addition to CO_2 emissions and noise mitigation, considered priority objectives in different areas, nowadays attention is also extended to other types of emissions such as nitrogen oxides (NOx) and the formation of cloudiness induced by contrails. Despite not being, by far, the transport sector with the greatest impact on global warming, aviation was the first having a coordinated plan with clearly established milestones to deal with climate change. The Commitment to Action on Climate Change, signed in 2008, established a set of environmental goals for the short, medium and long-term.

In the first step, the industry committed, until 2020, to a 1.5% annual improvement in aircraft efficiency which is directly related to the level of emissions. This objective has been more than met thanks to gradual technological development, a process that will continue making a decisive contribution to reducing fuel consumption. To the widespread application of already known solutions (winglets, advanced and lighter materials, flight control systems), will be added aerodynamic innovations (laminar flow control) and new engine developments (increment of bypass and pressure ratios). Improvements in air control and operating procedures will also bring significant emission reductions, besides mitigating noise problems.

For the short and medium term, 2021 was set as the start of air traffic growth that would not imply increases in net CO_2 emissions. To meet this commitment, the international civil aviation organization, ICAO, launched the CORSIA emissions offsetting regulatory framework which, despite its shortcomings, was a milestone when was supported by the member countries and the aviation industry as a whole. This initiative, together with other offsetting and emissions trading schemes such as the EU ETS, is a short range implementation tool that will help contain and potentially reduce emissions from an ever-growing commercial aviation sector.

The strong growth of sustainable aviation fuels, with broad support from industry and governments around the world, makes them a key medium-term solution, and today the only tool identified to decarbonize long range flights. Over this horizon, up to 2030-2035, significant technological contributions can be expected with disruptive designs (strut-braced wings, boundary layer ingestion) and new propulsion modalities (open rotors, hybrid and electric engines, hydrogen propulsion).

From 2035 onwards, the incorporation of revolutionary new technologies and configurations is expected, as well as an exponential growth of promising sustainable synthetic fuels. If the forecasts are fulfilled, it could also mean the irruption of high-capacity hydrogen-powered aircraft, as well as high-capacity batteries that would broaden the possibilities of electric aviation.

In the long term, in 2050, the initial commitment of the industry to halve its emissions has evolved in response to current environmental urgency, broadly in line with total decarbonization by that year. With such a long time ahead, it is difficult to foresee the path that will be taken to achieve it, without excluding the emergence of new solutions not considered in this report, such as the use of ammonia as aviation fuel. In any case, it seems very likely that each of the technologies and innovations mentioned above will play their part in achieving this ambitious goal.

Table 7 and Table 8 provide an indication of the development timeframe and the potential reduction in fuel consumption — directly related to CO_2 emissions - for different technological solutions in the configuration of commercial aircraft.

As an example of the results that this multi-strategy approach to emissions reduction could achieve, and on the basis of current technology alone, EUROCONTROL estimates that intra-European flights could reduce their emissions by 25% by 2030. This objective would be reached through a combination of measures including increased use of sustainable aviation fuel, more efficient use of airspace with different technological solutions in the European ATM network, and fleet modernisation by airlines [106].

	Timelines and examples of propulsive technologies	Impact on Jet Fuel Burn compared to baseline
Current - Operational	**2010–2019:** Higher bypass and pressure ratios, lighter materials	**10- 15%***
Evolutionary development	**~2020-25:** High pressure core + ultra-high by-pass ratio geared turbofan	**20-25%***
Revolutionary development	**~2030:** Open rotor	**30%***
	~2030-40: Hybrid electric propulsion (depending on battery use)	**40 to 80%***
	~2035-40: Fully electric propulsion (primary energy from renewable source)	**up to 100%***

All values compared to **baseline tube-and-wing aircraft of technology level widely in service in 2015*

Table 7. Fuel-saving potential from propulsion technologies according to IATA [42]

	Timelines and examples of aircraft design technologies	Impact on jet fuel burn compared to baseline
Evolutionary Technologies	**Currently: Airframe Retrofits** (winglets, riblets, lightweight cabin furnishing)	**6 to 12%**
	Currently: Materials and Structure (composite structure, adjustable landing gear, fly-by-wire)	**4 to 10%**
	2020+: Electric Taxiing	**1 to 4%**
	2020-25: Advanced Aerodynamics (hybrid/natural laminar flow, variable camber, spiroid wingtip)	**5 to 15%**
Revolutionary Technologies	**~2030-35:** Strut-braced*	**30%**
	~2035: Double bubble fuselage*	**35%**
	~2035-40: Box/joined wing*	**30-35%**
	~2040: Blended wing body**	**27 to 50%**
	~2035-45: Full electric aircraft (short range)	**Up to 100%**

*With advanced turbofan engines ** With hybrid propulsion

Table 8. Fuel-saving potential from aircraft design technologies according to IATA [42]

On the other hand, to achieve sustainable aviation, as mentioned before, it is necessary to assess the environmental impact of the whole life cycle, including the assessment of noise and other emissions in addition to CO_2. The most promising solutions for this holistic approach are shown in Table 9, detailing their pros and cons, as well as their most likely application profile.

All factors being considered, the climate impact reduction potential for hydrogen-powered aircraft is estimated to be between 75% and 90% compared to conventional models. Hydrogen combustion propulsion is estimated at between 50% and 70% mitigation. And, sustainable synthetic fuels would be in the range of 30-60% [28].

If until recently it seemed impossible to accomplish an environmentally sustainable commercial aviation, it is now clear that there is a wide arsenal of tools to achieve it. It is certainly not yet known what the optimal solution will be, although it will most likely involve a combination of all these strategies in different sectors and timeframes. To make this possible, beyond technological advances, it will also be essential to have a regulatory and financing framework that fosters the development and implementation of these sustainable solutions, making them competitive in comparison to fossil fuels.

This sustainable future for aviation is necessary, it is possible and it is in our hands to make it a reality, but it will be required the involvement and effort of the whole aviation industry (manufacturers, airlines, airports and air navigation services), governments and international organisations, as well as the commitment of passengers themselves.

Comparison of new technology and sustainable aviation fuels and new technologies

Comparison vs. kerosene	Biofuels	Synfuels	Battery-electric	Hydrogen
Commuter <19 PAX	No limitation of range	No limitation of range	Maximum ranges up to 500-1,000 km due to lower battery density	No limitation of range
Regional 20-80 PAX				
Short-range 81-165 PAX				
Medium-range 166-250 PAX			Not applicable	Revolutionary aircraft designs as efficient option for ranges above 10,000 km
Long-range >250 PAX				
Main advantage ✓	Drop-in fuel – no change to aircraft or infrastructure	Drop-in fuel – no change to aircraft or infrastructure	No climate impact in flight	High reduction potential of climate impact
Main disadvantage ✗	Limited reduction of non-CO_2 effects	Limited reduction of non-CO_2 effects	Change to infrastructure due to fast charging or battery exchange systems	Change to infrastructure

Table 9. Comparison of new technologies and sustainable fuels [28]

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